Assessment of Disturbance Propagation between AC Grids through VSC HVDC Links using Reduced Great Britain Model

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Abstract

The growth in electricity demand, the low-carbon targets and the rising penetration of renewable energy sources are causing the electricity systems to work closer to their operational limits, therefore their reinforcement is becoming urgent. The construction of a European Super Grid, where existing AC systems are connected through High Voltage Direct Current (HVDC) corridors, is a valuable solution; the introduction of the HVDC links enhances system stability, improves power flow control and ensures protection from cascading disturbances. This paper investigates the ability of the HVDC links to act as a firewall against perturbations. Two reduced dynamic equivalent transmission systems resembling Great Britain are developed in DIgSILENT PowerFactory. A two-level Voltage Source Converter (VSC) HVDC link is designed for connecting the two grids. A variety of short-circuits fault were applied to the AC grids to test the extent to which faults in one grid propagate to the other. It was found that only minor power flow transients were caused in one grid by faults in the other. However, this is under the assumption that the HVDC converter stations are not called upon to provide post-fault damping services.

1 Introduction

Recent developments such as the intention to transfer heating and transport energy use to the electricity sector, the carbon reduction targets stated by European directives [1] and the increasing penetration of renewable energy sources are affecting transmission system operations and moving electricity networks closer to their operational limits. Consequently, the reinforcement of the existing power systems is becoming urgent.

In this perspective, the construction of the European Super Grid, a vast hybrid system merging existing AC national grids and new High Voltage Direct Current (HVDC) transmission corridors, capable of delivering power at a continental scale, represents a valuable solution. Because of its advantages for long distance transmission and for system reliability and control, HVDC is considered to be the best technology for the realisation of transmission links among countries. The application of HVDC links between weak AC systems already working in stressed conditions creates benefits such as enhancement of system stability, improvement in power flow control, and protection from cascading disturbances [2]. In [3], the authors provide a broad literature review of the reliability assessments for AC grids linked through HVDC corridors, their research stresses the necessity of having a full-scale transmission network model to quantify the firewall properties of the HVDC link in stability assessments for such systems. Hence, a full-scale transmission network model is recognised to be an essential tool for evaluating the performance of HVDC links among countries. An equivalent model of the Great Britain (GB) transmission grid, that consists of 29 nodes and includes both steady-state and dynamic parameters, has been designed in DIgSILENT PowerFactory and it is presented in this paper. It represents a reliable platform that overcomes the limitations and the assumptions embedded in the previous models [4], [5], [6], [7], [8], and offers the possibility of examining accurately the effects on power grid stability.

The ability of HVDC links to act as protection against faults has been evaluated by connecting two full-scale dynamic equivalent transmission systems through VSC-based DC link. Time-domain simulations have then been executed in DIgSILENT PowerFactory to investigate the performances of the HVDC corridor, such as its ability of behaving as a firewall in case of cascading disturbances and the degree of coupling of two AC systems connected by international HVDC ties. Although in [9] the authors explored the capability of the DC link of isolating disturbances, they do not consider the implementation of the latest available technology for the converters.

The realisation of a reduced GB dynamic equivalent model and its interconnection to a second realistic grid model through an HVDC link represents just the first stage of a wider project. The concepts discussed here should be regarded as a first step for future more detailed research. Considering the literature from [10] and [11], further studies will focus on the addition of the secondary control (i.e. frequency support and power oscillation damping) for the VSC converters as well as on the scaling up of the link itself, in terms of ratings and line lengths. At this stage, the presence of primary control alone in the converters is considered, meaning that the HVDC link does not participate in power oscillation damping and frequency support. The strength of coupling between two ac grids interconnected by HVDC links could very well be dependent on the VSC converters ratings and whether secondary control has been incorporated. These issues have been identified and addressed in the future research.

The paper consists of four further sections. Section 2 provides a description of a 29-bus reduced (equivalent) model of the Great Britain transmission grid in terms of steady-state and dynamics, its validation against reference schemes, and the modelling of the two-level VSC HVDC link. Second, a case study, describing the system used to investigate the ability of the DC link to act as firewall against disturbances, is illustrated. Third, time-domain simulations are presented and the outcomes explained. Finally, some conclusions are drawn.

2 Modelling and Validation in DIgSILENT PowerFactory

This section outlines a dynamic equivalent model of the Great Britain (GB) transmission network and a description of a two-level VSC HVDC link, see Sections 2.1 and 2.2 respectively.

2.1 Great Britain Transmission Network

Steady-State Model

The steady-state GB transmission network model consists of 29 busses and 3 voltage levels (132 kV, 275 kV, 400 kV). The model has been built in DIgSILENT PowerFactory. It was based on and verified against those reported in [12], [13].

The network contains 29 nodes (bus bars), 24 synchronous generators, 22 wind farms sites (including Double-Fed Induction Generators and Fully-Rated Converters), 63 loads, 99 transmission lines, 70 two-winding transformers, 74 shunt filters and 10 Static VAr Compensators. Figure 1 illustrates a single line diagram of the network. The system is divided in two areas: Area #1 comprises of the northern part (Scotland), and Area #2 comprehends the southern part (England and Wales), lines 6-9 and 8-10 are the main transmission corridors between the two areas.

Several assumptions have been considered during the realisation of the model. Among the 29 nodes composing of the equivalent network, only 24 are equipped with generators. The generators are represented as synchronous machines, and every generator is an aggregate model including all the generation units of a selected geographical area. Wind farm sites are represented separately as Double Fed Induction Generators (DFIGs) or as Fully Rated Converter generators (FRCs).

The loads have been modelled as constant impedance loads, with their active and reactive power components defined according to the demand calculated with respect to the Annual Cold Spell winter peak [13]. As suggested in [12], additional loads have been inserted into the model to take into consideration the effects of network elements not represented. As a first approximation, the interconnectors to Ireland, France and the Netherlands have been modelled as loads.

Two types of switched shunts have been implemented in the systems: capacitive and resistive-inductive shunt filters, the former associates with injection of reactive power (Q), while the latter with absorption of Q. Static VAr Compensators (SVCs) are implemented to improve the voltage profile at the desired level [14]. SVCs are modelled in DIgSILENT as Static VAr Systems (SVSs) composed by Thyristor Controlled Reactors (TCRs) and Thyristor Switched Capacitors (TSCs).

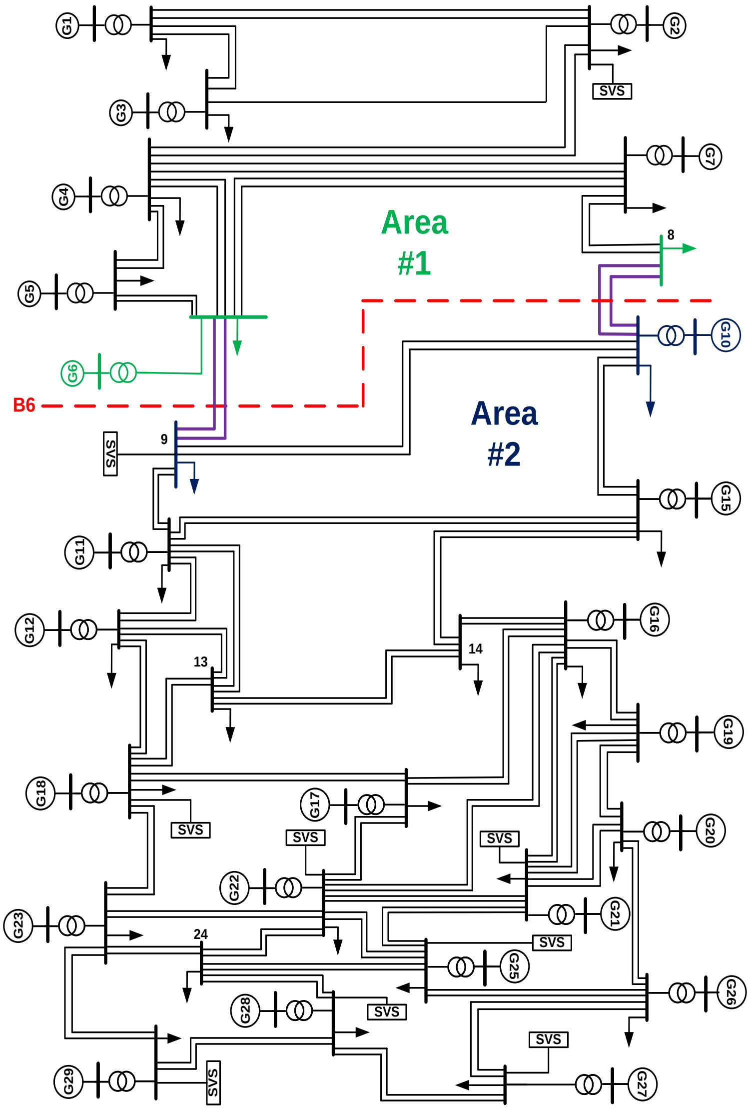

Figure1: Single line diagram of the GB transmission network.

Validation of the Steady-State Model

The steady-state model has been benchmarked against a reference scheme [12]. Unlike [12], the wind farms have been designed separately and they are not included in the synchronous generator aggregate units, the compensation systems have been tuned slightly differently and the quadrature booster transformers have not been implemented due to lack of available data. Table 1 shows the comparison of the main quantities between the reference scheme and the model.

As Table 1 depicts, the model developed here is in close agreement with [12] in terms of active and reactive power for generation and load, outputs from the slack generators and transmission losses. The small divergences are a consequence of the different assumptions taken during the modelling phase.

		Reference [12]	***Model***
Generation	MW	60,294	60,292
	MVAr	12,363	14,492
Load	MW	59,844	59,844
	MVAr	40,408	40,408
Losses	MW	450.5	447.9
Slack Generator	MW	996.5	994
	MVAr	416.2	371.3
Spinning reserves	MW	14,694	14,838

Table 1: Comparison of generation, load, losses between the reference scheme [12] and the model.

Dynamic Model

Dynamic models have been developed and incorporated into the system in order to capture the dynamic of the GB transmission network. The presence of the dynamic components is of crucial importance for performing short-circuits analysis and stability studies. Due to the unavailability of the dynamic data, a number of assumptions have been taken for the creation of a realistic GB dynamic model.

Initially, the dynamic control loop has been designed only for generators. It consists of an excitation system, also known as Automatic Voltage Regulator (AVR), and a Primary Controller Unit (PCU) composed by a Primary Controller (PCO), which has been modelled as steam governor, and by a Prime Mover Unit (PMU), chosen as a steam turbine. Due to the complexity and the size of the system, as a first approximation, all the synchronous machines are assumed to be equipped with a steam governor.

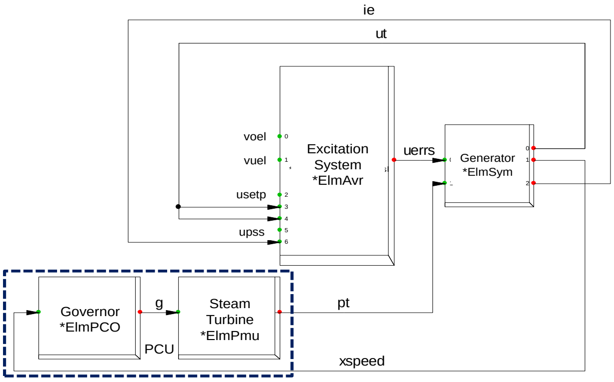

Figure 2: Control model for generators, including AVR and PCU.

In this paper the same dynamic control loop, shown in Figure 2, has been applied to all the generators. The generators have been represented by sub-transients model and they have been equipped with static AVRs ESST1A, chosen following the IEEE practice standards [15], and with steam governors, designed according to the literature [2]. The dynamic models do not include Power System Stabilizers (PSSs) yet.

Validation of the Dynamic Model

Due to the difficulty of direct access to the dynamic characteristics of the GB transmission network, several tests have been performed in order to validate the behaviour of the system model developed. The dynamic response of the model has been tested for load events of various magnitudes and for AVR events.

Figure 3 shows the deviation in system frequency in response to a 2GW step applied to load 11 (see Figure 1). Initially the frequency drops because of the imbalance 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 the new equilibrium point of 49.93 Hz. This test partially validates the design chosen for the dynamic model of generators and governors and demonstrates prompt recovery from events that disturb the frequency.

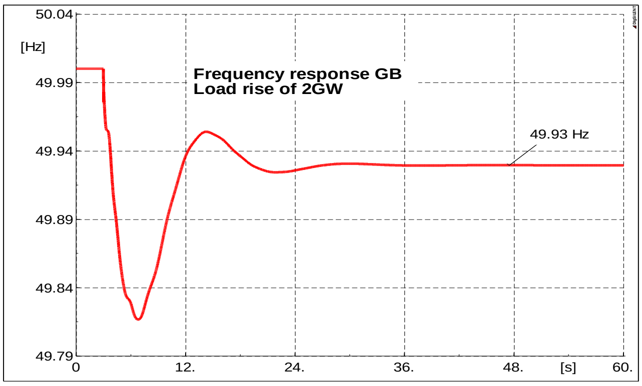

Figure 3: Frequency response of the system after a step-change of 2 GW applied at Load 11.

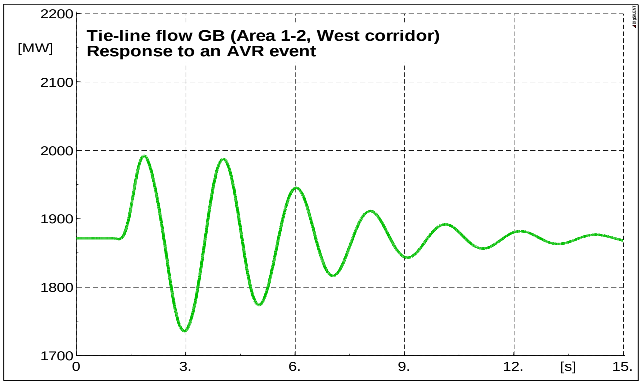

Figure 4: Tie-line flow in Line 6-9 in response to an AVR step-change event applied at AVR16.

The model has been further validated 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 AVR16 was increased by 0.05 p.u.

for 0.5s before returning to its nominal value. The dynamic response of the system in terms of tie-line flow passing through line 6-9, one of the main transmission corridors from Scotland to England, has been observed and it is shown in Figure 4. The system exhibited an inter-area mode of 0.487 Hz. The response to the disturbance was well-damped and settled in 15-20 s.

2.2 VSC HVDC Link Modelling

An HVDC link employing 2-level VSC in a balanced monopole configuration has been modelled to act as a connection between two AC grids. The converters are considered to use Pulse Width Modulation (PWM) at a high enough frequency to allow representation by an averaged model. A decoupled current control strategy in the synchronous reference frame (d-q) and standard PI controllers is considered [10]. The rectifier operates in P-Q control mode, while the inverter operates in V_{dc}-Q control mode, maintaining constant DC bus voltage and unity power factor on the point of common coupling [9].

The DC lines have been represented by a lumped parameter model; they are modelled as underground cables, rated at 150kV, 1.5kA and 100km long. Table 2 summarizes the principal features of the converters and the HVDC interconnector scheme is illustrated in Figure 5.

	VSC GB1	***VSC GB2***
V_{AC} [kV]	110	110
V_{DC} [kV]	300	300
S_{rating} [MVAr]	500	500
Control Mode	P-Q	V_{DC}-Q
Set-point	-450 MW	0.947 p.u.

Table 2: Properties of the VSC converters in the HVDC link.

The small rating of the HVDC link reduces the coupling between GB1 and GB2 to a quite small extent. If secondary control was incorporated, the DC link would be able to support the grid offering services in terms of oscillation damping and frequency recovery.

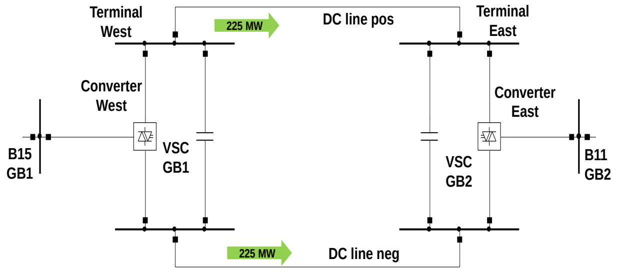

Figure 5: VSC HVDC link connecting GB1 and GB2.

3 Case Study

The full-scale GB transmission network has been duplicated and the resulting systems, whose characteristics in terms of supply and demand are shown in Table 3, have been referred to as 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 important to notice that GB2 is, as GB1, a full-scale dynamic equivalent network model. In order to investigate the ability of HVDC corridors to act as firewall against cascading disturbances, a two-level VSC HVDC link, as described in Section 2.2, has been implemented for connecting the two countries from bus 15 in GB1 to bus 11 in GB2. Figure 6 illustrates the final system where GB1 and GB2 are connected through the HVDC link.

		GB1	***GB2***
Generation	MW	60,294	60,292
	MVAr	12,363	14,492
Load	MW	59,844	59,844
	MVAr	40,408	40,408
Losses	MW	450.5	447.9
Spinning reserves	MW	996.5	993.98
		416.2	371.3

Table 3: Description of GB1 and GB2 in terms of generation and demand.

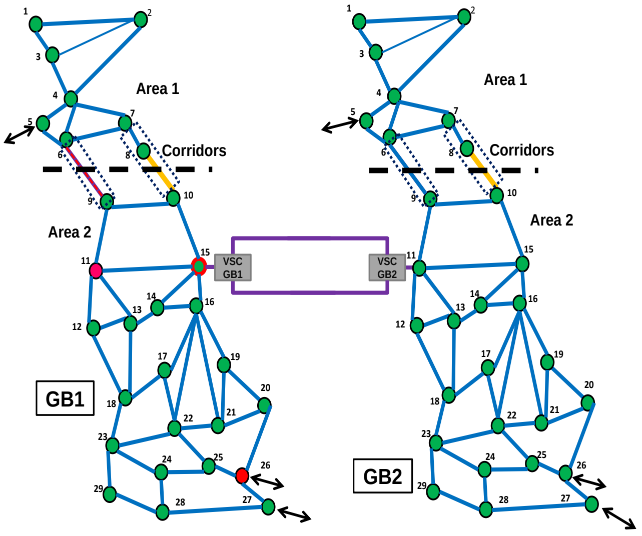

Figure 6: GB1 and GB2 connected through a VSC HVDC link.

4 Simulations in DIgSILENT PowerFactory

This section shows a representative set of time-domain simulations conducted in DIgSILENT PowerFactory to explore the ability of the HVDC interconnector to act as a firewall in case of cascading disturbances. Once the two grids have been connected through the DC link, a steady-state simulation was performed to validate the operation of the model in normal conditions.

The dynamic performance of the system has been examined for different fault conditions (three-phase short circuit faults on line and bus-bars, and loss of generation). The events considered are:

- A three-phase solid fault on line 6-9a, 6-9b in GB1 (a and b refer to the two parallel circuits that compose the whole line 6-9).

- A three-phase self-clearing fault on bus 15 in GB1 for 83ms.
- Loss of generation in generator G26 in GB1.

The disturbances always occurred in GB1 in order to observe their propagation to GB2 through the HVDC link and the degree of coupling of the two systems.

4.1 Three-phase Fault on Line 6-9 in GB1

A three-phase solid fault has been applied on lines 6-9a and 6-9b in system GB1. The disturbance is considered as both a self-clearing fault (cleared in 83ms) and as an outage. The dynamic response has been observed in each system and across the DC link. The location of the fault is regarded as a severe one since it affects one of the main transmission corridors carrying the power from Area#1 (Scotland) to Area#2 (England). The tie-line power flows across the other main transmission corridors were monitored in GB1 and GB2 and are shown in Figure 7 (a) and (b) respectively. The red curve indicates the self-clearing fault, whereas the green plot refers to the outage. The power flow across the HVDC inter-tie and the voltage at the sending end are illustrated in Figure 7(c) and (d) in case of a self-clearing fault and outage.

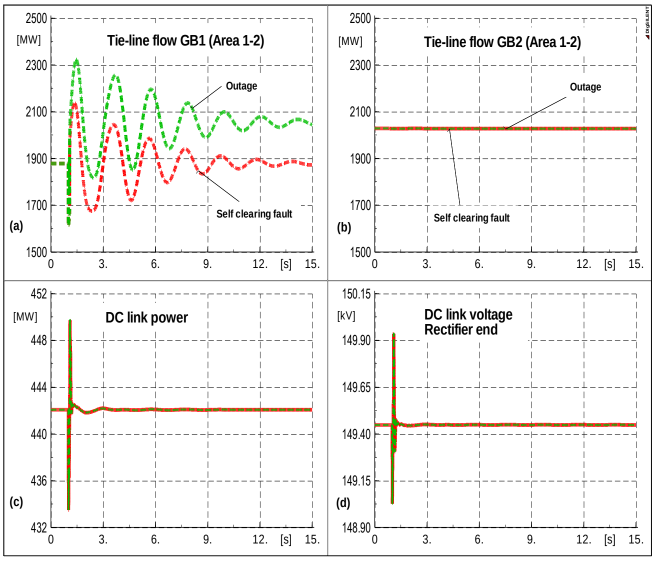

Figure 7: Dynamic performance of the system under a three-phase fault in line 6-9a and 6-9b in GB1. (a) Tie-line flow GB1. (b) Tie-line flow GB2. (c) DC link power. (d) Rectifier end DC link voltage. Red indicates self-clearing fault, green indicates outage.

As seen in Figure 7(a) and (b), the propagation of the three-phase fault from one system to the other is minimal, the HVDC link acts as a firewall, preventing the fault that occurred in GB1 from propagating into GB2. Even in the case of outage, the HVDC link is able to isolate the disturbance. The effects of the outage are more significant in GB1 where it occurs compared to GB2, where the consequences of the outage are similar to the self-clearing fault ones. After the disturbance the power flow and the voltage levels in the DC link recover promptly, as illustrated in Figure 7(c) and (d) respectively.

4.2 Three-phase Fault on Bus 15 in GB1

A solid, self-clearing, three-phase fault of 83 ms duration was applied on bus 15 (B15) close to the rectifier end in GB1. The fault causes a serious perturbation of GB1 and of the HVDC link itself but the effects of the fault are negligible in GB2. The HVDC link acts as a firewall preventing the propagation of the disturbance from one system to the other.

Figure 8 (a) and (b) show tie-line flows in GB1 and GB2. Although the perturbation affects GB1 to a more significant extent compared to the previous case (and this is likely to be due to the nature of the fault considered), the propagation to GB2 is still negligible. Figure 8 (c) and (d) illustrate the power flow and the voltage in the DC link. During the fault at the bus the power drops and the voltage at the sending end decreases, after the fault clearing in 83ms the situation is re-established at normal values.

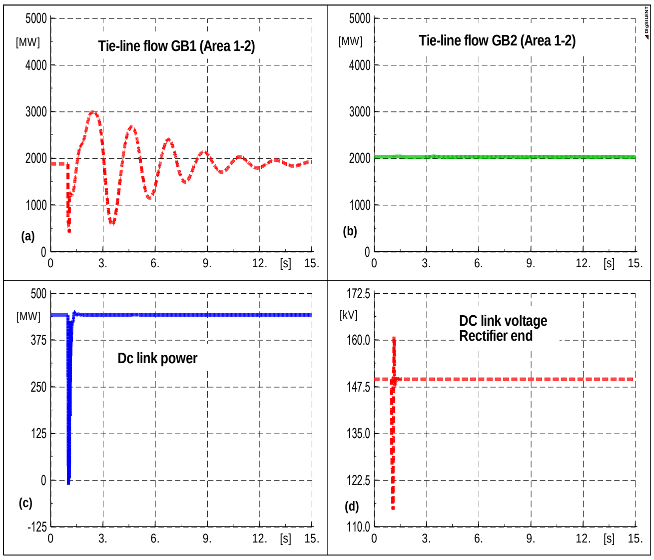

Figure 8: Dynamic performance of the system under a self-clearing three-phase fault at bus15 in GB1. (a) Tie-line flow GB1. (b) Tie-line flow GB2. (c) DC link power. (d) Rectifier end DC link voltage.

4.3 Loss of Generation at G26 in GB1

A loss of generation of 2GW has been applied to generator G26 in GB1, which is one of the largest synchronous generators in the southern area (Area#2) of the transmission grid, with a power output of more than 4GW. The partial loss of this generation unit affects the frequency in GB1, but it does not influence the frequency in GB2 to a significant extent.

Figure 9 (a) describes the loss of generation in generator G26 in GB1. The frequency response of the system is depicted in Figure 9 (b), the disturbances caused by the loss of generation are promptly recovered within 20s; afterwards the system gains a new steady-state equilibrium re-establishing normal conditions. Figure 9 (c) illustrates the power flow in the DC link and Figure 9 (d) shows the voltage variations at bus 15 in GB1 and bus 11 in GB2, that are the sending and the receiving ends of the HVDC links respectively. After the perturbation the normal situation is quickly re-established.

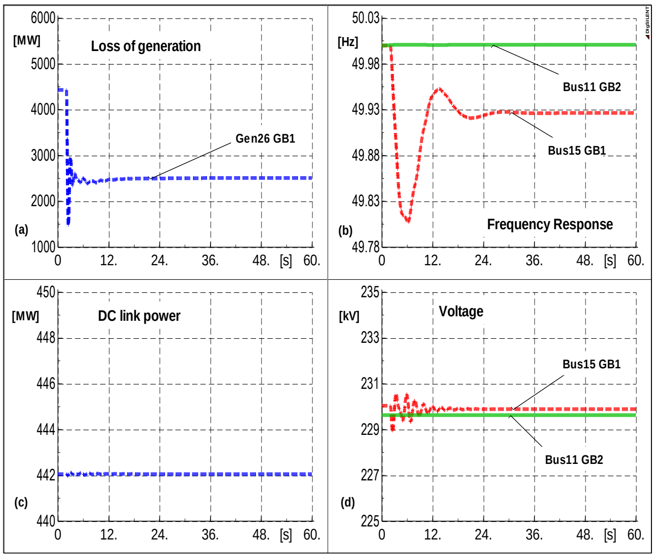

Figure 9: Dynamic performance of the system under a loss of generation event at G26 in GB1. (a) Power flow in G26 GB1. (b) Frequency response. (c) DC link power. (d) Voltage at bus15 in GB1 and at bus11 in GB2.

5 Conclusion

The ability of a VSC HVDC link (with P,Q and V_{dc}-Q primary controls) to act as a firewall against disturbances has been demonstrated through time-domain dynamic simulations. Several events that may have propagated a disturbance from one system to the other were tested, namely a three-phase short circuit fault on a line, a similar fault at a bus bar and a loss of generation. To facilitate this, a system model was built in DIgSILENT PowerFactory as an approximate representation of the transmission system in Great Britain. The two-level VSC HVDC link was connected between two such models. Prevention of the propagation of the disturbance originating in one system from passing to the other is of particular importance for a proper understanding of the performance of HVDC corridors connecting different countries in the prospective of the European Super Grid. This paper represents the first stage of a wider research project, where concepts such as the implementation of damping provision via secondary control in the VSC converters and connection through multi-terminal HVDC schemes will be considered.

Acknowledgements

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