Studies of dynamic interactions in hybrid ac-dc grid under different fault conditions using real time digital simulation

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Abstract

High Voltage Direct Current (HVDC) grid concept has recently been introduced as the next step to the point-to-point HVDC links to maximise the benefits of more power flow share, and reduce the impact of renewables intermittency. However, the integration of DC grid within existing AC systems is complex and very challenging. The compatibility between the two systems under different operating conditions needs to be fully understood. This will require sophisticated models and analysis of their behaviour using powerful tools. This paper presents a representative dynamic model of a hybrid AC-DC gird, and investigates the transient and dynamic interaction between the AC and DC grids under different fault conditions. The model represents a reduced AC UK power system interfaced to a detailed four-terminal DC grid. The developed mode is built in Real Time Digital Simulation (RTDS) using dual time steps simulation techniques.

1 Introduction

The international move toward low carbon energy and the pressure for more integration of large scale renewables, and the introduction of advanced power electronics and controls have stimulated the market of DC systems and technologies. Point-to-point HVDC transmission systems have already proven their effectiveness for transferring electricity over long distances in more controllable and efficient way compared to AC systems [1]-[3]. HVDC grid concept with Multi-Terminals (MTDC) has recently been introduced as the next step to the point-to-point HVDC links to maximise the benefits of more power share, and reduce the impact of renewables intermittency on the grid operation [4][5].

DC grids are still at an early stage of development, and no practical example exists. Their integration with existing AC systems will form a complex arrangement of hybrid AC-DC grid, resulting in significant technical challenges for protecting and operating the new emerged system. The compatibility between the two systems under different operating conditions needs to be fully understood [6]. This will require sophisticated models and analysis of their behaviour using powerful tools and analysis. Therefore, this paper presents a representative dynamic model of hybrid DC and AC gird, and investigates the dynamic interaction between the two systems under different faults. The model is built in Real Time Digital Simulation (RTDS) which is a powerful and efficient tool for Electromagnetic Transient (EMT) simulation, and enabling closed loop testing of hardware operation before the installation. Such features will provide stronger confidence in testing new technical protection and control solutions compared to other offline simulation tools [7].

The paper is structured as follows. Section 2 discusses the key technical challenges in hybrid DC-AC grid. Section 3 presents the developed dynamic model of the AC and DC grid. The AC grid represents a reduced dynamic model of the UK power system, and the DC grid model is based on detailed four terminals symmetrical bi-polar MTDC grid with five branches. In section 4, the simulation studies and results of the model validations, and the dynamic performance and interactions between the AC and DC grid under different fault conditions are presented. Finally, the paper conclusions are drawn in section 5.

2 Dynamic interaction and protection challenges in hybrid AC-DC grids

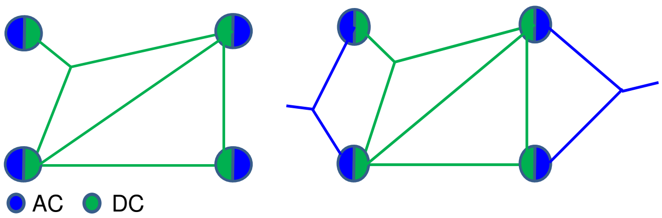


Figure 1: Meshed DC grid

DC grid can be connected to several points of the same AC grid, or surrounded by unsynchronised AC grids as shown in Figure 1. Meshed DC grid can have multiple power flow paths, and this will make the control of power flow within the grid is more challenging. DC power flow in each line cannot be controlled directly by the converter stations at the terminals. DC grid will also require fast acting and selective DC protection scheme which can detect and interrupt faults on the DC to ensure continued operation. This is because DC grids can carry large amount of power up to tens of GWs, and are very sensitive to faults on the DC sides, and to other contingencies such as sudden trip of converters in particular the converter controls the grid DC voltage. Unlike AC systems, the propagation of voltage disturbances can be very rapid, leading to the interruption and imbalance of large amount of power between DC grid and surrounded AC systems and important parameters such as DC voltages and AC frequency to be adversely impacted.

In addition, a combination of different converters such as 2-level Voltage Source Converter (VSC), Neutral-Point Clamped (NPC) VSC, and (H-bridge or F-bridge) Multi level Modular Converter (MMC) can potentially be found in the future in one DC grid. This will create a complex architecture of different converters with different control and protection capabilities. Existing AC grids have also active control units such as FACTS and STATCOMs, and how such devices will interact with new added converters is still unknown. Such complexity requires a good level of understanding the behaviour of AC and DC grid in order to introduce an effective design of control and protection schemes which can be coordinated with the converters with different fault management, and ensure secure and optimal operation.

3 Hybrid AC-DC grid test network model

The test network model developed in this paper consists of a dynamic model of an AC grid representing a reduced UK power grid and a dynamic model of four terminals DC grid. Each model is developed separate with the appropriate time steps solutions, and then validated against practical data. The AC and DC models are then interfaced to each other to form the hybrid grid shown as a single diagram in Figure 2. These are discussed in more detail as follows.

3.1 AC test network model (large time step model)

The AC test network model as given in Figure 2 is developed within the large time step (50µs) in the RTDS. The model is developed as a simplified 8-bus aggregated dynamic model representing key generation and load areas in the UK power grid. The model is based on real power flow data of eight areas as presented in the Electricity Ten Year Statement (ETYS) of the UK National Grid (NG) [8][9]. Each AC generator is modelled as an aggregated large synchronous machine with set-up transformer (13.8/400kV) to represent the generation at the related area. The rating of each generator is set according to the predicted UK 2017 load flow [9].

Each generator is controlled by the widely used IEEE ST1 static type excitation system as given in Figure 3 [7][10]. The generator machines and excitation system date are obtained form [10] and presented in Table 1 and Table 2 respectively. Also, a GAST gas turbine and speed governor model (shown as block diagram in Figure 4) is added to each generator to control the speed and input torque to the machine. The load share between the generators is controlled by adjusting the load-frequency reference (shown as LR in Figure 4) of the governor. The gas turbine model parameters are obtained from [10] and listed in Table 3. The governor speed control parameters are tuned against a real recorded event for validation. This will be discussed in more detail in section 3.

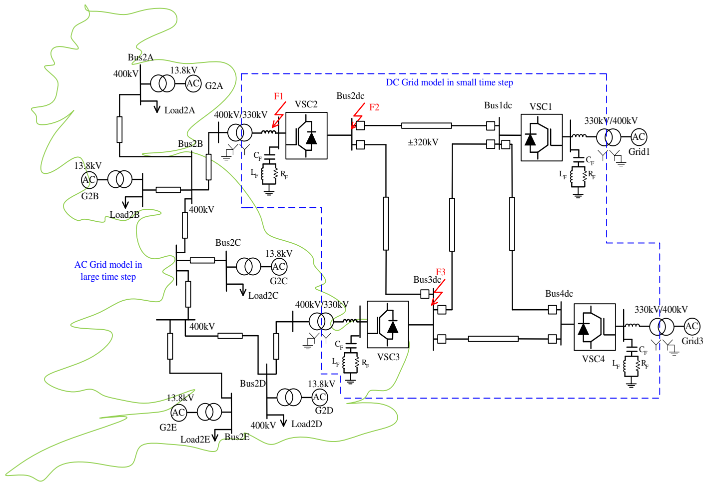


Figure 2: hybrid AC-DC test grid developed in RTDS

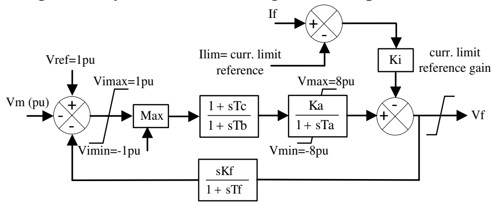


Figure 3: ST1A static excitation system model [7]

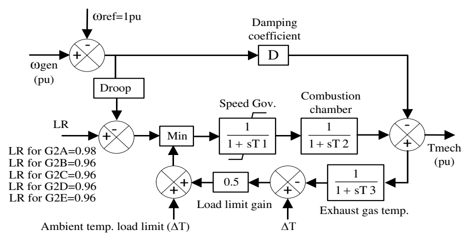


Figure 4: GAST gas turbine and speed governor model [7]

V	X_d	X_q	X_d'	X_q'	X_d''	X_q''	T_{d0}'	T_{q0}'	T_{d0}''	T_{q0}''
13.8 kV	1.0 pu	1.0 pu	0.15 pu	0.3 pu	0.12 pu	0.12 pu	3s	0.5s	0.02s	0.02s

Table 1: Generator dynamic parameters

T_b	T_c	T_{b1}	T_{c1}	T_a	K_a	T_f	K_f	K_i	I_{limt}
20s	1.0s	0	0	0.02s	200	1s	0	4.54	4.4

Table 2: The ST1A exciter parameters

The AC transmission lines of the AC grid are modelled using PI-section line models with lumped resistance (R), capacitance (C), and inductance (L). The line parameters (R, C and L) are calculated from the power flow data (P, Q, |V| and voltage angel) provided by the NG ETYS for 2017 [9]. The same methodology for modelling UK transmission system as presented in [11] is used which calculates the line parameters based on the required power flow at each bus.

3.2 Dynamic DC Grid Model

Modelling of the DC grid in RTDS requires the use of small time step technique and it is more challenging. The four terminals DC grid presented in Figure 2 is modelled as a symmetrical bi-polar grid with floating ground return and five DC branches. The DC grid has ±320kV rated DC voltage, and provides asynchronous connection between three AC grids. Grid 1 and Grid 3 given in Figure 2 are modelled as 400kV voltage sources with X/R=11.9 and fault level equals to 12000MVA.

Detailed two-level IGBT-based VSCs with smoothing capacitor 75μF are used for interfacing the DC grid to the surrounding AC systems. Each converter station is simulated with high switching frequency (2kHz) using special small time step components available in the RSCAD Master Library and called "VSC bridges" for providing firing resolution with a time-step within 1.4-2.5μs [7]. Three small time step sub-networks (i.e. VSC bridges) are used to model the complete DC grid. The VSC1 and VSC4 as shown in Figure 2 are modelled together in one sub-network, while the VSC2 and VSC3 are modelled in separate small time step bridges. Each sub-network runs on a separate processing card GPCs (IMP PPC 750CXe, 1000MHz). The three processing GPCs are connected physically using fiber optic cables, and Bergeron T-line "cross-card" links are used to interface the sub-network solutions in the software. The Bergeron cable models are also used to represent the DC cables model between the four terminals of the DC grid. The Bergeron cable model is very similar to the PI-section model, and it is based on travelling wave theory and distributed LC parameters [7].

The converter station shown as VSC1 in Figure 2 is set as a reference bus to regulate the DC voltage and control the power flow balance between the DC grid and the associated AC grids. The remaining stations shown as VSC2-4 in the same figure are modelled as active and reactive power regulators. Each converter is fully controlled using oriented vector control with the well-known sinusoidal pulse width modulation (SPWM) technique. The vector control is implemented in the synchronously rotating d-q reference frame. The VSC1 (slack bus) controls the DC voltage through the outer voltage and inner current loops in d-q stationary synchronous reference frame as presented in Figure 5. The reference reactive power of the VSC1 is set to zero in order to operate the station in a unity power factor.

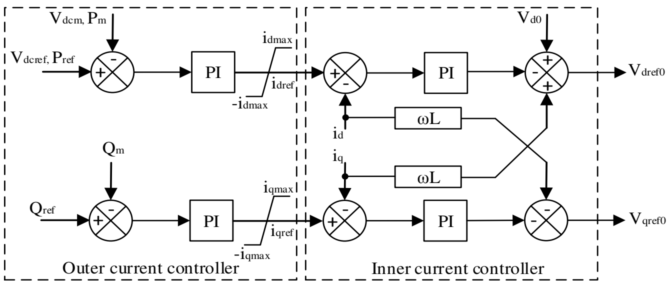


Figure 5: d-q inner and outer control loops of the converter station

The power regulators converter stations (i.e. VSC2-4) control the real and reactive power using a droop control strategy as illustrated in Figure 6. The measured real power of (P_m) and the reactive power (Q_m) of the converter are adjusted in accordance to the change in the DC voltage and the AC voltage respectively, and provides the current references i_{dref} and i_{qref} for the inner current loops.

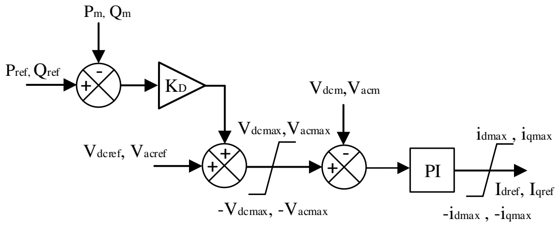


Figure 6: Droop control strategy

A second order high pass filter (HPF) to eliminate high frequency harmonics is added on the AC side of each VSC station as shown in Figure 2. The parameters of the filter are calculated in accordance to the following equations:

$$C_f = (Q_{filt})/(2\pi f_0 V_{L-L}^2) \quad (1)$$

$$R_f = 1/(2\pi f_{cutoff}\, C_f) \quad (2)$$

$$L_f = aR_f^2 C_f \quad (3)$$

Where, Q_{filt} is the filter reactive power rating. The Q_{filt} is assumed to be equal to 25% of the associated VSC reactive power capability. C_f, R_f, and L_f are the capacitor, resistor, and inductor of the filter respectively. a is a constant (normally ranges between 0.5~2).

4 Simulation studies

4.1 Model validation tests

The accuracy of the developed AC dynamic model and the DC grid model are tested separately before they are connected together. The AC dynamic model is validated using the two following tests. One is a load flow test to evaluate the steady state performance of the model. The load flow simulation is run to ensure that the power flow simulation data is closely matching the real data obtained from the ETYS for the winter peak 2017 demand [9]. This includes the generation and demand data at each region and the power flow across the boundaries of the regions.

The second test is dynamic frequency response evaluation. The dynamic response of the AC grid model is benchmarked against real historic frequency deviation event data recorded by PMUs that are located at various points of the UK power transmission network. The event was caused by the trip of the UK-France HVDC interconnector on 11^{th} of January 2016 with power loss of 900MW. The total generation and demand of the model is scaled to match the same values on the day of the event (total demand=59.56GW). The inertia constant, the governor time constant (T_1), the Droop, and the load reference parameters are tuned to ensure the model frequency response matching the real frequency response. This includes the adjustment of frequency steady state initial condition, the rat of change of frequency (RoCoF), the frequency oscillations, and the frequency nadir values. The tuned governor parameters are listed in Table 3, and the test results as presented in Figure 7 show the simulation results are faithful to the real data.

Droop	T_1	T_2	T_3	ΔT	D
0.13	4.8s	0.4s	0.1s	1	-0.2

Table 3: Governor and gas turbine parameters

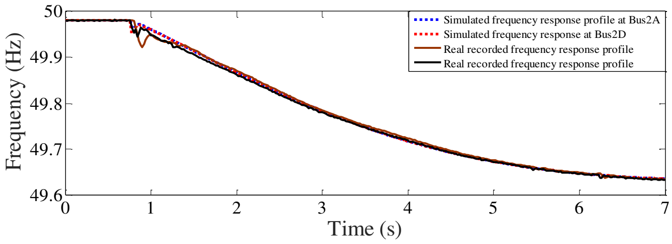
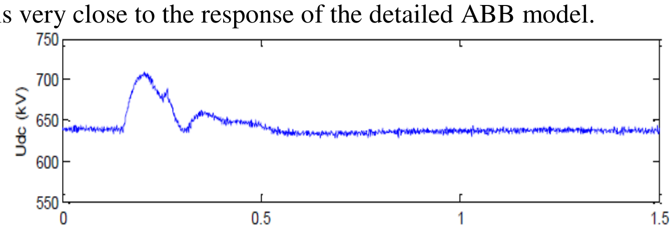
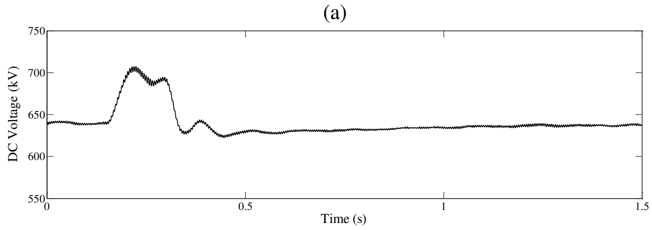


Figure 7: Simulated and real frequency response profiles following the trip of the UK-France interconnector with 900MW

The RTDS DC grid model is validated by using the same methodology in [12]. The DC grid is configured to operate as a point-point HVDC by switching the VSC3 and VSC4 off, and allow the operation of only station VSC1 and VSC2. Then, a three-phase fault with 100ms duration is applied on the AC sides of the VSCs, and the performance of the inner current controllers, DC voltage, and active and reactive power are tested. The simulation results are compared with industrial based data obtained from [12] and representing the response of the ABB PSCAD/MTDC offline HVDC detailed model. The DC simulated voltage response as shown in Figure 8 (b) is very close to the response of the detailed ABB model.



(a)



(b)

Figure 8: (a) ABB detailed model DC voltage profile, and (b) RTDS simulated DC voltage profile

After the validation of each grid model (i.e. the DC grid and the AC grids), the two grids are interfaced together. The two grids are split between two RTDS hardware racks, and cross-rack transformer models with ratio 1:1 are used to connect the DC grid VSC2 and VSC3 to the AC dynamic model.

4.2 Dynamic interactions and fault studies

The transient response and dynamic interaction between the AC grid and DC grid against stressed events including faults on the AC and DC sides are investigated. Under each fault condition, the dynamic performance of the DC grid voltage, the DC power, and the AC system frequency are examined.

AC fault: a 3-phase solid fault is applied on the AC side of the VSC2 at the location shown as F1 in Figure 2 with fault duration =100ms. The fault is followed by the trip of the associated VSC2 close to the fault (i.e. VSC2 with 900MW). During this fault, the real power of the VSC2 at the point of common coupling (PCC) on the AC side as illustrated in Figure 9 falls to zero. This will cause unbalance between the AC and DC power, resulting in the power on the DC side to be stored as electrostatic energy in the smoothing capacitors. This power unbalance during the fault has significantly impacted two important parameters, the DC voltage and AC system frequency. The results in Figure 10 show the increase in the DC voltages between the two poles. This increase in the voltage is a function of the size of the real power unbalance, the fault duration, and the size of the smoothing capacitor. The impact on the AC system frequency response during the fault is also considerable as shown in Figure 11 (a). The frequency response of the trip of the VSC2 following the fault is given in Figure 11 (b). The ROCOF will depend on how much power is transferred before the fault starts.

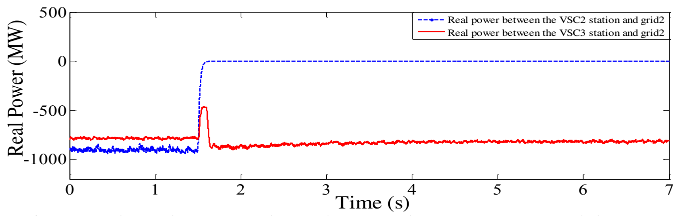


Figure 9: The real power exchange between the VSC2, VSC3 and the AC Grid2

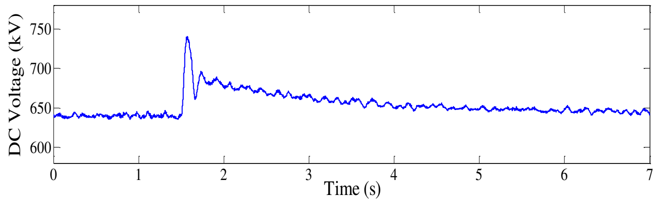
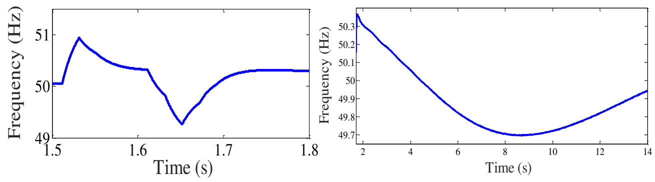


Figure 10: The pole-to-pole DC voltage profile following 3-phase short circuit fault on the AC side



(a) (b)

Figure 11: AC frequency response against 3-phase fault on the AC side of the VSC2 and followed by the trip of the VSC2

DC fault: pole-to-pole DC fault is applied at the location F2 as shown in Figure 2, and the fault is cleared by tripping the bus Bus2dc within 20ms (i.e. the disconnection of VSC2 with 900MW). During the DC fault, the voltage of the DC grid as shown in Figure 12 is extremely stressed, resulting in large reactive power from the AC grids to be drawn as illustrated in Figure 13. The frequency response of the AC Grid 2 during and after the applied DC fault with 20ms duration is given in Figure 14. The impact on the frequency is limited compared to the fault on the AC side. The RoCoF as shown in Figure 15 has reached +0.2Hz/s and ≈-0.4Hz/s. The new modifications proposed recently by the UK distribution network operators

(DNOs) has increased the setting of the RoCoF Loss of Mains protection of distributed generation with ≥5MW capacity from 0.125Hz/s to 1Hz/s (started from 1st July 2016) [13].

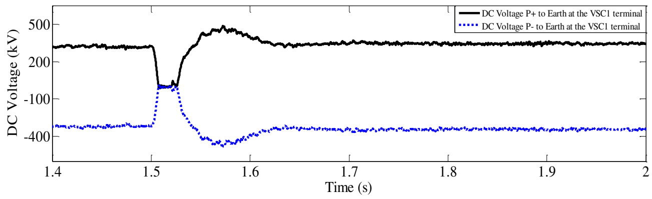


Figure 12: Pole-earth DC voltage profile during the pole-to-pole DC fault

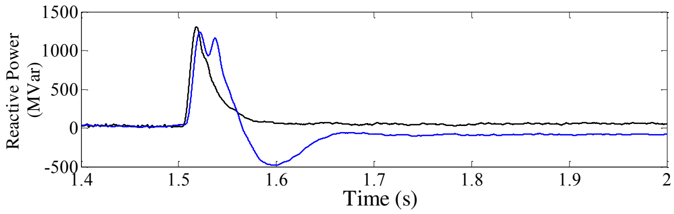


Figure 13: The reactive power drawn from the AC grid during the DC fault

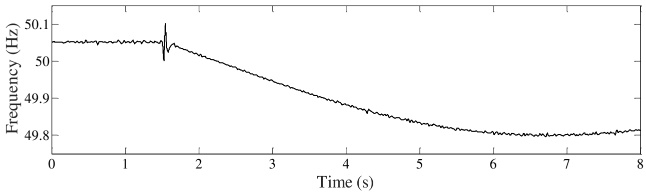


Figure 14: AC grid frequency response against the DC fault

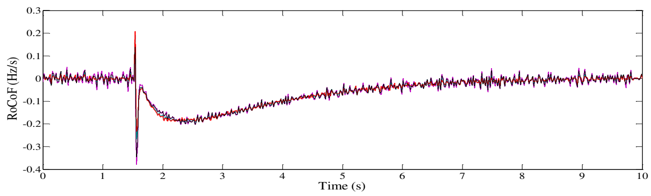


Figure 15: The RoCoF during the DC fault

The simulation results have demonstrated that there is need for further work to be done on advanced protection and control solutions at DC grid level to ensure the enabling of its active roles to support existing AC systems. For example, fast acting DC protection scheme to detect, locate, and isolate faults on DC and coordinated with the protection on the AC will reduce the impact of large unbalance in the power exchange during the fault, hence reduce the DC voltage rise and the severity of the RoCoF on the grid.

5 Conclusion

The paper has presented multi-rate Real Time Digital Simulation model of hybrid AC-DC grid, and investigated the impact of different AC and DC short-circuit fault conditions on the AC system frequency performance and on the dynamics of the DC grid converters. For DC grids interfaced by 2-level VSCs, reduced fault durations play an important role on reducing the adverse impact of the power unbalance between the AC and DC grid during the fault. Lower DC voltage rise and lower RoCoF will be experienced. This increases the need for fast acting protection scheme which can detect and disconnect the faults on the DC gird with good level of selectivity. The RTDS AC-DC grid model (tested against real data) presented in this paper provides useful tool with greater flexibility and reduced computation time for studies requiring proof of concept for new software and hardware HVDC protection and control schemes.

Acknowledgements

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