Real-time simulation with an industrial DCCB controller in a HVDC grid

P. Rault, M. Yazdani, S. Dennetière, C. Wikström, H. Saad, N. Johannesson

Abstract— **DC breakers and their associated control are seen as important lever for the DC grid expansion. In complement to dynamic studies, as intermediate step towards on-site implementation, factory tests using real control and protection hardware enable to fine tune control sequences, to check the software implementation and then test the coordination and interaction between different devices connected to the same grid.**

This article presents a hardware-in-the-loop setup for testing industrial DCCB controllers and their interoperability with converter controllers. A hybrid DCCB model suitable for real-time simulation has been developed and then validated against offline model. Industrial DCCB controller functions are described. A set-up of three-terminal DC grid with physical controllers for one MMC converter station and 12 DCCBs is described. The results of one application case corresponding to fault clearance is presented and discussed.

Keywords: **HVDC, MMC, DCCBs, HIL**

I. INTRODUCTION

DC networks are seen as an important solution for increasing renewable generation in the energy mix as they increase the capacity of the transmission system and its flexibility. Currently, point to point HVDC links are already common for both onshore and offshore projects, converter stations are provided by one single manufacturer and in case of DC fault the whole system trip. However, looking forward, dealing with DC grid to exchange more energy, two additional aspects has to be considered: the VSC-HVDC multivendor interoperability and handling DC faults [1]. Clearing a DC fault in a DC grid is challenging, since the faulty part must be isolated in a few milliseconds to avoid the whole DC grid collapsing. Due to recent innovation in DC circuit breaker (DCCB) technology, Hybrid HVDC Breaker (HHB) makes isolation of faulty parts in a DC grid possible, since this device is able to interrupt DC current in less than 5 ms with acceptable losses [2]. This kind of DCCB is a good trade-off between loss efficiency which are too large with pure semiconductor based DCCB and speed which are two slow with pure mechanical DCCB.

A fast circuit breaking device is definitely an important aspect of the fault handling in DC grids but will be useless without efficient detection of faults with DC protections. In fact the protection system, is utmost importance, since it must selectively detect the eventual fault and then send triggering signal to relevant DCCBs within few milliseconds. In literature a lot of attention where put in one of these aspects, for instance, [3] discusses the fault current limiting, [4] exhibits the pole to ground DC fault characteristics in monopolar and bipolar configurations, while [5] and [6] investigate different fault detection strategies.

In addition, most of the studies dealing with simulation of DC grid protection raise the attention on the DC system modeling, some general recommendations are providing in [7], some other discussed DC breaker modeling [8]. [9] justifies the need of frequency dependent cable model to get relevant results.

Some relevant works which include the full chain of protection system using offline simulation are available in literature [10].In real HVDC projects, such EMT offline studies constitute the first step, to perform control tuning and preliminary studies of the upcoming project. After such preliminary study, the second step involves real time simulation using Hardware In the Loop (HIL) setup with the physical control cubicles. The aim of such HIL simulation are:

- to validate and/or correct initial control tuning
- to validate the full process chain of the control and protection cubicles (i.e. acquisition, processing time, HMI etc.)
- to cover a wider range of dynamic performance that are not possible to perform in EMT offline study: either due to the long computation time either due to the simplification made in the control system of the offline model

The aim of this work is to perform a HIL simulation of a three-terminal DC grid, which is an essential stage in an innovative industrial context. Therefore, physical C&P cubicles for ABB DCCBs and converter station are used in this project. High Voltage equipment data and topology come from actual manufacturer design. C&P hardware and software, for converter station and DCCB, have been provided by the manufacturer and correspond to their latest technology. This set-up was first developed to test VSC-HVDC multivendor interoperability in the European founded project called Best Paths DEMO#2 [11]. To the authors' best knowledge this final setup is one of the most detailed platform ever that has been setup to analyze industrial interoperability issues and coordination between HVDC converters and DCCB controls. This paper contributes in the description of the test setup for

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HIL simulation. The objective of the paper is also to illustrate various applications of the DCCB.

This paper is organized as follow: in part II the modeling of Hybrid HVDC breaker for real time purpose is discussed. In part III the embedded functionalities of the Hybrid DCCB control are described. In IV, the HIL set-up is described. In part V, a DC fault test is presented. Finally, some conclusions are drawn in part VI.

II. DCCB MODELING FOR EMT SIMULATION

A. Hybrid DCCB topology

The hybrid DCCB shown in Fig. 1, consists in Residual Current Disconnecting Circuit Breaker (RCDCB), an inductor to limit fault current rate of rise, an auxiliary branch for normal operation, a main branch to extinguish DC current. The auxiliary branch has lower conduction losses, it includes an Ultra-Fast Disconnector (UFD) to sustain the DC voltage insulation during the current breaking time and the Load Commutation Switch (LCS) to make the current commute to the main branch. The main branch (MB) is composed by a series of MB cells which are a semiconductor bidirectional switch which commutes the DC current through their parallel varistor in order to decrease the DC current. More information about the hybrid DCCBs design and its operation can be found in [2].

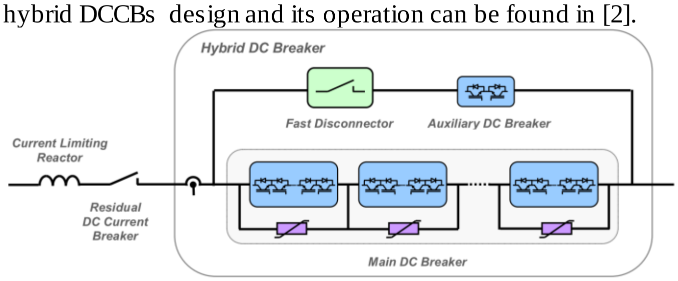

Fig. 1. Hybrid DCCB

B. Detailed model for offline simulation

Because of complexity of hybrid DCCBs, and the significance of DC grid protection, DC grid developers are looking for sufficiently detailed and accurate DCCB models. The models should be able to represent internal components and control system to enable study of failure modes, opening/closing operation limits, repeated operations, exposure to operating conditions beyond design limits, and failures in high-level protection system. The fault current limiting operation is important for grid operators but requires detailed component-level studies in order to understand design trade-offs for DCCBs.

In [8], a hybrid DCCB model is presented. It is suitable for system study of DC grid protection and transient studies involving DC faults. In this paper, the aforementioned model is extended to cope with ABB specific technology: number of cells, varistor data and disconnector. A detailed valve model has been developed to accurately represent switching transients within DCCB. This model takes into account nonlinear characteristics of semiconductors and stray inductances/capacitances as described in Fig. 2.

Varistors have been modeled with their V/I curve in order to accurately represent their nonlinear characteristic. The model has been implemented in EMTP-RV and has been used as a reference to validate the model developed for real-time simulation.

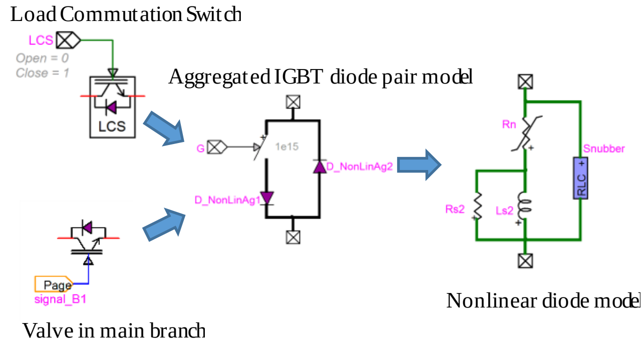

Fig. 2. Detailed valve model in EMTP-RV for offline simulation

C. Detailed model for real-time simulation

The detailed DCCB model developed for offline simulation is presented in the previous section. It is composed of many nonlinear models (varistor and nonlinear diode/IGBT) and many electrical nodes. This sections describes optimizations that have been implemented to get a detailed DCCB model that is suitable for real-time simulation.

First, all devices embedded in the DCCB are modeled with resistors and Norton equivalents. IGBT/diodes and disconnectors are modeled with two-value resistors. Semi-conductors arrangement (number of IGBT in series and in parallel) is used to calculate equivalent resistance of each valve. Varistors are modeled with nonlinear resistor (piecewise nonlinear characteristic). It is assumed that the main branch is composed of n cells that have identical characteristics (semiconductors, valve arrangement, varistor characteristics…). The DCCB model overview is presented in Fig. 3.

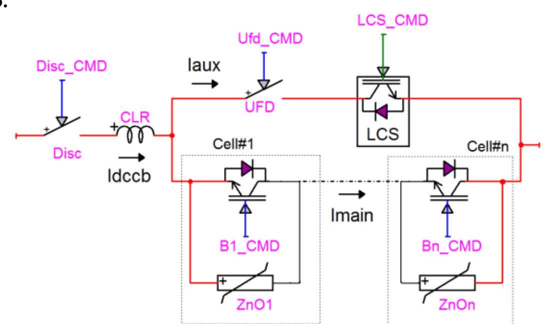

Fig. 3. DCCB model overview

The discretized version of this circuit is provided in Fig. 4. Resistances R_Ufd, R_LCS, R_Disc, R_B1..n are the equivalent switching devices resistance. They are calculated from command signals. As cells are connected in series, the following logic is implemented in order to calculate Norton equivalent of varistors: for each cell which valve is closed, the varistor is represented by a resistor which resistance corresponds to the first segment of the nonlinear characteristic; for each cell which valve is open, the Norton equivalent is calculated from Imain current and the nonlinear characteristic. This logic is very efficient to limit the calculation time of the DCCB model and to keep the execution time practically independent from the number of cells and number of segments of the varistor (ZnO) nonlinear characteristic. The same approach is applicable to bi-directional DCCB.

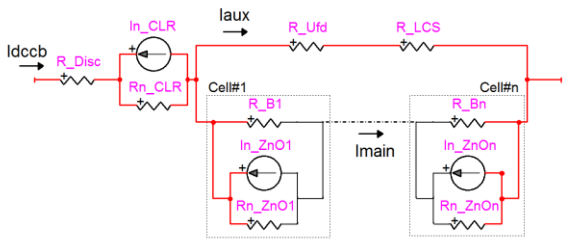

Fig. 4. Discretized version of the DCCB model

To validate the DCCB model implemented for real-time simulation, 2 test cases are illustrated in this section. Simulation results obtained with the offline model described in Section II. B. are compared with the results obtained with the real-time simulation model. The difference between Test case#1 and #2 is the insertion of a 70km long DC cable. A frequency dependent cable model [12] is used in Test case#2.

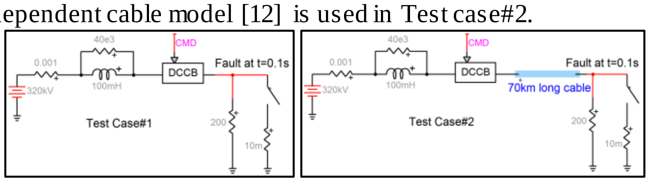

Fig. 5. DCCB model test cases

DCCB current (Idccb) from offline and real-time simulations are superimposed in Fig. 6. Simulation results match very well. Several other test cases have been used to validate the real-time implementation. Time step for offline and real-time simulation is 30µs.

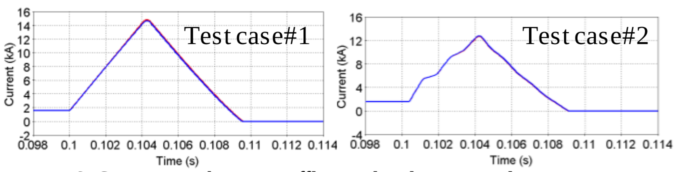

Fig. 6. Comparison between offline and real-time simulation

III. DCCB STATION CONTROL FUNCTIONS

A. DCCB control

The control interface of the modular Hybrid DCCB sections allows fault breaking, current limitation, normal load current transfer and back-up breaker functionality. Several sub sequences are the building blocks of different control functions, and operating sequences. The block/deblock subsequences of main branch prioritize switching of individual cell based on the stored energy of corresponding varistor. And blocking of individual cell is inhibited if corresponding varistor is overloaded.

The sequence to open the DCCB is as below:

1. The LCS is blocked.
2. The UFD is ordered to open when the auxiliary current is low enough.
3. Wait for UFD to reach mid position to ensure that it can withstand the expected voltage.
5. The MB cells are blocked.

The sequence to close the DCCB is as below:

1. The RCDCBs, Residual Current Disconnecting Circuit Breaker, are ordered to close.
2. Receiving the close indication of RCDCB, the MB cells are deblocked.
3. The UFD is ordered to close.
4. Receiving the close indication of UFD, the LCS is deblocked.

A. Soft start

The soft start is a function that is used to energize part of the main circuit. The function can be used for testing of the insulation of a cable or overhead line with reduced voltage. The soft start procedure is simply an individual deblocking of the MB cells with delays in between, which will slow down the buildup of voltage and reducing the inrush current.

During the procedure a switch on to fault protection is active while the other protection configurations are the same as in normal operation.

B. Current limiting functionality

The current limitation function is normally used in a DC grid when there is an earth fault and a need of current limitation until the fault is disconnected. The hybrid DCCB can start the current limiting functionality for self-protection to avoid damage caused by fault current, if no breaking order is received from the external control system.

When initiating current limitation, the load commutation switch is blocked and the UFD is opened, commutating the current to the main branch. Thereafter, tuning off the MB cell switches (IGBTs or BIGTs), the current is commutated to the MB cell varistors.

The current limitation continues as long as the fault current persists when the main branch is deblocked. The thermal capacity of the varistors allow for a predefined number of successive blockings of the MB cells before the DCCB is opened and the current interrupted.

C. DC chopper controls

In some topologies such as bipole configurations pole to ground faults in one pole will not generate overvoltages in the healthy pole. However this is not the case with a symmetric monopole configuration where a pole to ground fault will lead to overvoltage in the healthy pole.

Since long term overvoltage in the healthy pole might lead to breakdown of that pole, a DC voltage chopper is used to quickly reduce the overvoltage. A chopper is a semiconductor device that will ground the pole through a resistor when it is turned on.

The control of the chopper is designed to balance the DC voltages by reducing individual pole to ground overvoltage or pole to pole overvoltage.

D. HVDC grid protection algorithm

Because the DC grid is equipped with multiple DCCBs, multiple protection zones exist throughout the grid and the fault detection must therefore be able to differentiate between different fault locations to achieve selectivity. As the DC grid consist of three stations, the DC line protections are implemented on three separate pieces of hardware, each one receiving the simulated voltages and currents belonging to that particular station (as seen in Fig. 7).

In each station, each of the two incoming feeders have the same set of protections. However, because the three stations are connected by two sets of cables with different lengths and one overhead line, different settings are used for each of these.

The DC line protection consist of two different algorithms operating in parallel, one based solely on local measurements and one using telecommunication. The locally based protection measure and compare the steepness of the incident wave to achieve selective detection. Because the principle is insensitive to the network conditions in the backward direction, the same settings can be used for both ends of the same cable or overhead line. The principle is thoroughly described in [6].

The telecommunication-based protection algorithm is the traveling wave differential protection as described in [13]. The communication between the stations occur via a pair of optical fibers. For simulating the additional telecommunication delay due to the geographical distance in a real application, the transmitted data is delayed by an amount of time equal to the propagation delay plus an additional 0.5 ms for representation of other equipment that might be required in a long-distance communication channel, e.g. power boosters or multiplexing equipment. For synchronization of the data being transmitted between stations, the method based on signal-processing from [14] is used, thereby not requiring an absolute time reference such as GPS.

Another feature of the DC line protection system is that it also use the proactive mode of the hybrid DCCB. The incident wave protection is very fast and react to the very first transient of a fault. Therefore, it is used for ordering the DCCB to prepare for current interruption. The protection system takes advantage of the additional time while the DCCB is preparing for interruption in order to confirm the existence of a fault within the network, and only then will order a trip of the DCCB. Furthermore, by the time the breaker is ready to interrupt the current, the telecommunication-based differential protection has also had enough time to detect the fault. This approach increase the security of the protection as it does not trip solely due to transients.

IV. HVDC GRID TEST SYSTEM

A. Description of the DC grid benchmark

The DC grid benchmark presented in Fig. 7. Overview of the three-terminal DC grid

Fig. 7 is considered as a test case to assess performances of DCCB. It consists of a three-terminal HVDC grid composed of converters in symmetrical monopolar configuration. AC/DC converter stations are Half Bridge Modular Multilevel (HB-MMC) type, with a rating of 1000 MW each and a ±320 kV DC voltage. On DC side, each AC/DC converter station is connected by two conductor pairs, which are either underground/undersea cables (200 km and 64 km) or overhead line (40 km). DCCBs with their associated current rising limiting inductor are installed at each conductor end, to isolate the cable/line from the network, in case of DC fault.

All DCCBs are bidirectional, they include a 70 mH inductor and four main breakers (MB) cells with a rated voltage of 80 kV each, data are derived from [15].

Since this DC grid is based on symmetrical monopolar configuration with no strong reference to ground, there is inherent large DC voltage deviation in the healthy pole in case of pole to ground faults. To quickly balance DC voltages after fault clearing, DC choppers have been integrated to the test case.

In Fig. 7 all DCCBs, all choppers and the converter in Station 1 are ABB system while Station 2&3 converters are generic. All ABB equipment are controlled by ABB control hardware.

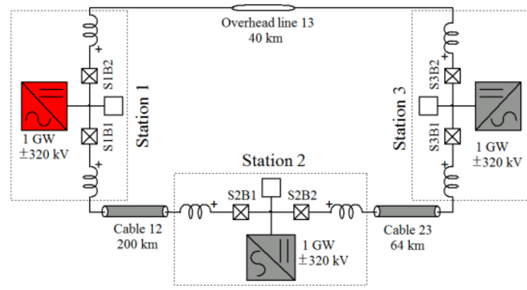

Fig. 7. Overview of the three-terminal DC grid

B. HIL test platform

1) Overview of the set-up

The set-up is composed of four ABB MACH3 industrial C&P cubicles and an HYPERSIM real time simulator. The four C&P cubicles include:

- PCP – Pole Control and Protection:
  - High level controls,
  - Converter protection (harmonics, balancing, Umax, Imax)
- SCM – Station Control and Monitoring:
  - Operator workstation (OWS),
  - Engineering network server (ENS),
  - Antivirus server, Firewall,
  - GPS, TFR, debugging tools, compilers
- MCP – Multiterminal Control and Protection:
  - Control for 12 Hybrid HVDC Breakers,
  - DC grid line protections
  - DC voltage choppers
- SI – Simulator Interface:
  - Virtual I/O interface,
  - Valve control interface (firing pulses), including valve control algorithm

2) Real-time MMC models

The hardware and software setup of the HIL simulation are shown in Fig. 8. The same principle are used for the modeling of the 3 converter stations.

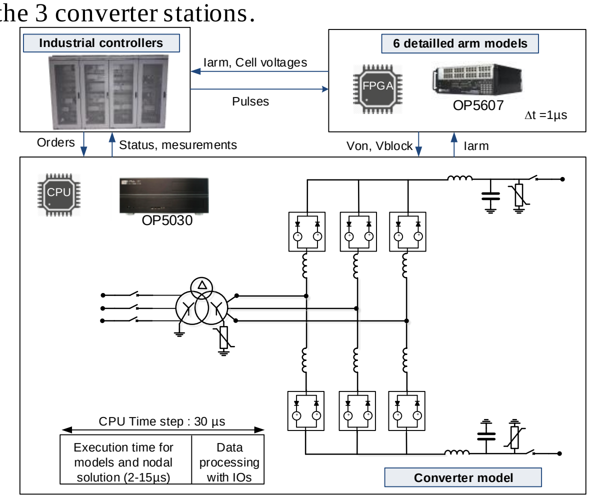

Fig. 8. Hardware setup for the HIL simulation

The only difference is the interface with the physical control that are only included for the ABB converter station. The valve model of this MMC runs on an FPGA board with a smaller time step of 1 µs to represent each sub-module (SM) individually [16]. They are directly commanded by a valve controller which receives arm currents and all SM voltages through 6 optical fibers. Other information exchanged between the converter controllers and the simulated hardware equipment are directly transferred through a digital interface [17] instead of analog signal.

3) DC grid simulation and network modeling

DC cables and DC overhead lines are represented by frequency dependent cable models optimized for real time simulation [12]. Electrical and geometrical data have been used to derive the time domain model. AC grids are represented by Thevenin equivalent.

The interface between DCCB real time models and their controllers is achieved through the same digital IO channel as the converter, which is very convenient for this kind of R&D activities since it provides flexibility and save a lot a wiring connection. In total, 220 analog outputs, 128 digital outputs, and 224 digital inputs are transferred in the same cable.

The DC grid simulation takes the opportunity of the inherent propagation delays through the DC cables/OHL to split the station and cables tasks on different CPUs. However the four DCCBs and their associated converter station must be in the same task. A lot of efforts were put in the task mapping strategy to make the full system, including the IOs, running with a 30 µs time step without overrun [18]. The simulation real time performance of was duly tested for many possible configurations and fault situations, which make the authors confident in the relevance of the results.

V. HVDC Grid System performances with DCCB

Due to space restriction, only one test results is shown in this article. Results are recorded from the ABB TFR (Transient Fault Recorder) or directly from the real time simulator during event acquisition.

The following test case aims to demonstrate the capability of a DC grid to ride through a DC fault thanks to DCCBs using industrial C&P systems. Initial conditions considered in this example are shown in Fig. 9. Converter station°1 and 2 are in Power-Voltage droop control mode with a dead-band of 10 kV while the converter station 3 is in DC voltage control mode. In the figure, the DCCBs status are represented by a filled black box, when there are closed and white when there are opened. The cable 12 and cable 23 are connected, while the overhead line is disconnected. Setpoints of all converter stations are set to get the power flow displayed in Fig. 9. A pole to ground fault on the positive pole of cable 23 at station 2 terminal is applied.

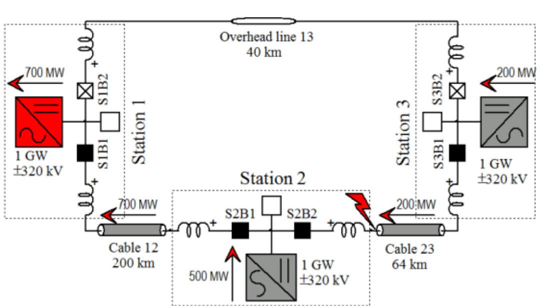

Fig. 9. Scenario considered for the DC fault test case

Fault location is identified by the traveling wave protection algorithms and trip signals are sent to DCCB on both sides of cable 23 (S2B2 and S3B1). When fault is cleared by the DCCBs, Station°3 is isolated from the DC grid and is in STATCOM mode. Thanks to the droop control station 1 and 2 remain operating, exchanging almost 500 MW between each other.

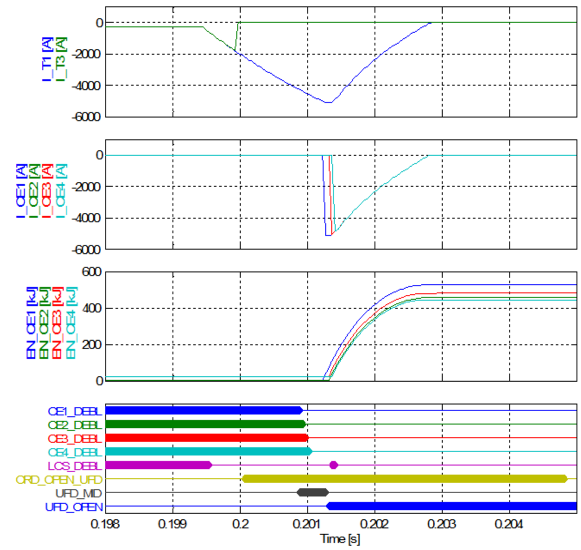

Fig. 10. Station 2 – DCCB 2 positive pole (S2B1) – Fault clearing

Fig. 10 shows the transient waveforms recorded by the S2B1 DCCB located in station 2 which opens due to the DC fault. The first plot corresponds to DCCB current (I_T1) and auxiliary branch current (I_T3), the second plot corresponds to varistor currents of the MB cells, the third plot is the varistor energies. The last plot is the deblock command of MB LCS cells and command and status of the UFD (open order, mid-position and open indication). First stage corresponds to the current rise due to the fault limited by the DCCB inductor, then the second stage is the current extinction by the MB cells. During the first stage, the LCS is blocked in order to commute the fault current to the main branch which explains the auxiliary branch current (I_T3) is going to 0 A. Once this current is zero, UFD open command is released and after few milliseconds the status mid-position and then open position are recorded by the controller. During the second stage, MB cells are blocked one after each other, at that time the fault current is flowing through their parallel varistor. Varistors enable to quickly reduce the DC current amplitude. A 300 µs delay between the command sent by the controller and the effect on the measurements can be noticed. This delay is mainly due to the communication to send the command and then receive feedback status.

Fig. 11 shows the station 2 measurements. The first and second plot displays respectively positive and negative DC voltages at the cable 12 terminals, at converter station 2 bus bar and the cable 23 terminal. The third plot displays the command of the positive and negative DC chopper. The last plot shows the cable current of both cables for the positive pole. The cable 23 DC voltage on the positive pole is clamped to zero due to the fault, the converter bus and cable 12 voltage decreases as well but are slowed down by the DCCB inductor. This explains why cable 12 voltage decreases two time slower than DC bus voltage. At the fault instant, pole to pole voltage is maintained by the converter station. But pole to ground voltage on the healthy pole is limited by the converter station DC surge arresters. Between the fault ignition and the fault clearing, the current rise (i.e. di/dt) change direction which influence the converter bus voltage. When DC voltage on healthy pole is below a threshold, DC chopper is automatically triggered to balance voltage of both poles. If the negative pole voltage is too low, negative DC chopper is activated and if the positive pole voltage is too high positive DC chopper is activated. Thanks to this solution, the healthy part of the DC grid is balanced much faster than if no DC chopper were used. A stable current is flowing through cable 12 after transients is observed.

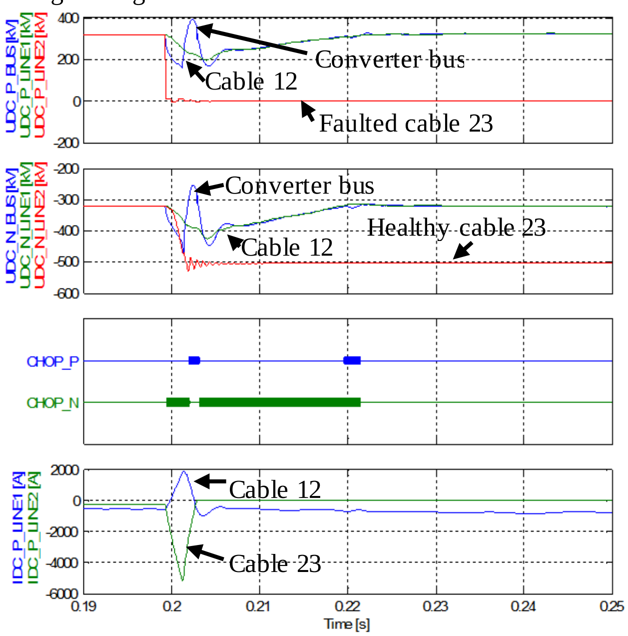

Fig. 11. Station 2 – DC voltages measured at station 2

VI. CONCLUSIONS

A hardware in the loop set-up built-up for testing DC breakers controllers operations and their interoperability in three-terminal DC grid was described in this article. It simulates manufacturers' high voltage equipment and connect several physical controllers corresponding to their latest technology. Modeling and set-up validation was proven over several representative examples.

This set-up is readily available for preforming future R&D activities around DC grid protections and also can be extended to other vendor equipment.

More generally, many other situations, not reported in this article, were performed successfully. It demonstrates the effective operation of DC breaker controllers which are available in manufacturers' shelve, and thus assess the performance of industrial products. Eventually, this set-up provides more confidence for installation of DC breakers for future DC grid development.

VII. ACKNOWLEDGEMENTS

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