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Hybrid HVDC Breaker for Grid Energization

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***Abstract*—Utilization of high-voltage direct current (HVDC) technology and, specifically, voltage source converters (VSC) in power transmission systems is increasing rapidly in recent years. In order to enable reliable operation of HVDC grids, a dc fault current interrupting equipment, i.e. Hybrid HVDC breaker (HHB) is required. HHB can temporarily/permanently isolate the dc fault in the system. Moreover, a smart sequential logic together with the modularized design of HHB can facilitate restart at dc faults, also avoid sudden inrush currents during energization thereby eliminate the need for pre-insertion resistor at the dc side. This paper presents the modular design of HHB and the sequences to energize a VSC converter. The simulation study performed employing PSCAD demonstrates that the converter energization takes place smoothly by suitable logic implementation for sequential closing of the HHB. Thus, this method can result in efficient and cost-effective operation of HVDC grids in practice.**

Keywords—HVDC grids, Energizations, Pre-Insertion Resistor (PIR), Hybrid HVDC Breaker (HHB), Sequential closing sequence

I. INTRODUCTION

Ever since the world's first commercial high voltage direct current (HVDC) transmission system (Gotland link [1]), the HVDC market has grown and is becoming an important part of many transmission networks worldwide. With its excellent control capability and high efficiency of transmission, HVDC technology has become the primary choice of plenty of transmission applications such as subsea electrical transmission, interconnection of asynchronous ac grids, and long-distance bulk power transmissions. In the evolvement of HVDC technology, line commutated converters (LCC) was primarily dominant. With the development of Voltage Source Converter (VSC) HVDC technology in recent years, some of its advantageous features like reactive power support, black start capability, independent control of real and reactive power, and power quality control are favoring HVDC grids in its operation [2]-[4].

Current application of HVDC is mostly limited to point-to-point transmission links. But the future trend shows the potential of interconnecting several point-to-point links at dc side and build-up an HVDC grid. In order to enable the development of HVDC grids, a dc fault current interrupting equipment i.e. Hybrid HVDC breaker (HHB) is required [5]-[6]. An HHB can temporarily/permanently isolate the dc fault in the system, to avoid system shut-down. Moreover, smart sequential control logic for the operation of HHB can bring ancillary functionalities to the system with no additional cost [7]. One such possible functionality of the HHB is to improve the system performance during HVDC converter energization. The energization issue of a five-terminal VSC HVDC system was discussed in [8] which shows the energization of VSC converter and dc line will cause high inrush current and, consequently, severe voltage drops at both ac and dc side. This problem could be overcome by utilizing pre-inserted resistors (PIR) at ac and dc side [8].

This paper demonstrates that the modular design of the HHB is very much conducive that with appropriate control sequence for the operation of HHB modules, HHB can serve as replacement for PIR at dc side. The simulation results show that the converter can be energized without any inrush current in charging of cell capacitors by suitably designed sequential closing logic for HHB.

This paper is divided into the following sections. First, the requirements of an HVDC grid and possible problems during energization are described in Section II. Then, the operating principle and proposed method of sequential closing of HHB are discussed in Section III. Performance of the proposed sequential closing is studied on a 4-terminal HVDC grid which is modeled in PSCAD/EMTDC and the results of the simulation study are presented in Section IV. Finally, the observations from the simulation study are presented in Section V.

II. HVDC GRID REQUIREMENTS AND PROBLEM STATEMENT

A. *Requirement on HVDC grids*

Extensive studies and investigations on HVDC grids have been performed in academia and industries during the past years. As a result, many requirements are established on control logics, converter stations and equipment. Expectedly, the first 4-terminal HVDC grid was announced by state grid corporation of China (SGCC) in 2018 i.e. Zhangbei VSC dc grid demonstration project [9]-[10]. It is a ±500kV VSC grid with ring topology shown in Figure 1 where HHB is introduced as key components for dc fault current interruption. References [11] and [12] have analyzed the dc line fault clearance performance of HHB and the effect of HHB on system stability.

Considering a dc grid, energization and startup of each converter station is a common practice. This practice will affect the total system and corresponding equipment in the grid. From the grid point of view, the energization of a converter should not cause significant disturbance to the dc grid under operation. Since the grid operation point depends on converter dc-side voltage, the dc-side voltage dip should be stable enough, with no significant fluctuation. This is defined as a key requirement for dc grid operation. On the other hand, from the converter point of view, the energization of a converter should not result in significant disturbances to the converters in operation. So, converter arm currents and cell voltages on energized converters should not be disturbed by the energization of other converters.

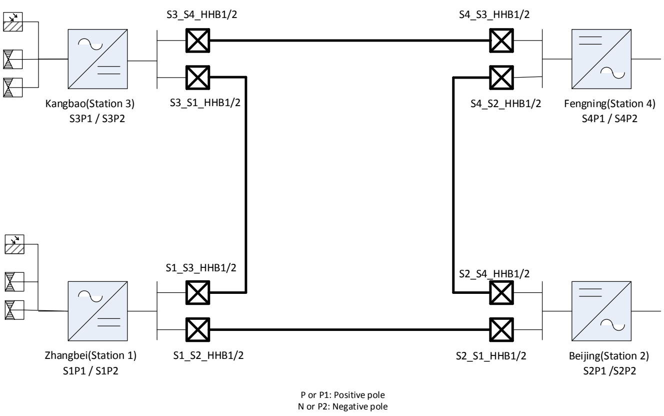

Figure 1 Single-line diagram of 4-terminal Zhangbei VSC dc grid

B. Problem Statement

Energization of a VSC converter and interconnecting links at dc-side consumes energy from the connected ac and dc systems. Generally, this energy is used to charge up the cell capacitors and results in high inrush current through the converter arms. Consequently, the corresponding ac and dc systems will face significant disturbances in their voltage profile. These disturbances are usually smoothed out by utilizing pre-insertion resistors (PIR) on either ac or dc side. In traditional point-to-point VSC-HVDC links, energization of converter from ac side is achieved by ac side PIR. For converters connected to islanded load, wind and photovoltaic energy sources, it is often required to charge and start the converter from dc side, since ac sources are not started initially. So, dc side PIR is necessary to handle such cases. This requirement of dc side PIR is equally essential for HVDC grid applications. Charging of VSC stations from dc side enables black start of the islanded converter and connected grid, which will highly increase the flexibility of grid operation. This paper motivates the utilization of HHB instead of dc side PIR which is an efficient way to energize the system.

III. Methodology

A. The HHB topology and operation principle

This section introduces the topology of the modularized HHB introduced in [5], and its operation principle during fault clearing process. As depicted in Figure 2, the HHB is composed of three main functional units:

- Ultra-fast Disconnector (UFD)
- Load Commutation Switch (LCS)
- Main Breaker (MB)

UFD and LCS are in series, with a comparatively lower resistance, serves as a normal current path. MB branch consists of several identical MB modules, where each MB module has a semiconductor-based branch and a parallel arrester branch. During normal operation, the load current flows through the UFD and LCS branch and during fault clearing process, the current is firstly commutated to the MB branch by turning off of the LCS. Later the MB modules turned off and the fault current is commutated to the MB arrester branch. Following this sequence, the energy will be dissipated through the arresters.

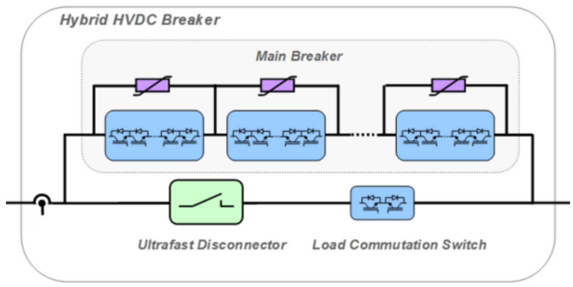

Figure 2 Schematic of Hybrid HVDC Breaker (HHB)

B. Sequential operation of the HHB for system energization

The modular design of the HHB can be utilized in different way to facilitate the operation of the HHB in different modes. For example, [7] introduces a sequential auto-reclosing to support reclosing of the HHB on permanent/temporary fault. Accordingly, a new sequential operation of the HHB is introduced in this section to enable the utilization of the HHB as PIR in dc side. Figure 3 illustrates the detailed stages as follow:

Stage 1: Pre-energization, the MB arresters are determining the current-flow. (Figure 3-1);

Stage 2: when the HHB module one is closed, current in HHB module one is commutated to MB branch, while current in other modules still flow through arrester branches (Figure 3-2);

Stage 3: similar operation and process for HHB module two once MB module two is closed with a time delay (Figure 3-3);

Stage 4: remaining HHB modules are sequentially closed with a time delay. Once the last module is closed, the converter energization is then completed (Figure 3-4);

Stage 5: Finally the converter is deblocked and the current in MB branch is commutated to LCS branch when UFD and LCS are closed (Figure 3-5).

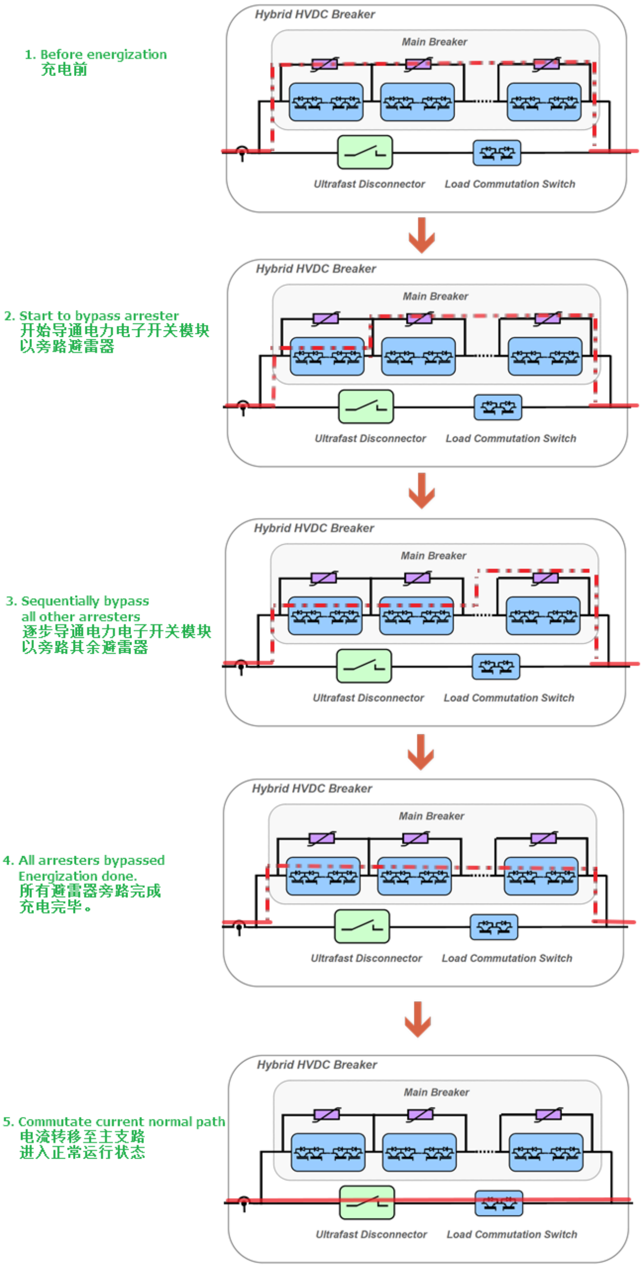

Figure 3. Sequential closing process of HHB

C. System topology for simulation cases

To validate the effectiveness of the concept of using HHB to support converter dc energization, the 4-terminal HVDC grid system described in Figure 1 is employed for the study purpose in this paper. A 4-terminal dc test system with identical topology and system parameters as Zhangbei HVDC grid is built employing PSCAD/EMTDC.

At initial state, it is assumed that all HHB at Zhangbei Station is open and the rest of the system is operating under normal conditions as shown in Figure 4. Zhangbei is isolated on the ac side and is in blocked state initially. Fengning is set to dc voltage control mode. Two cases are considered for simulation study, with and without HHB sequentially closing feature for energization of Zhangbei converter from dc side.

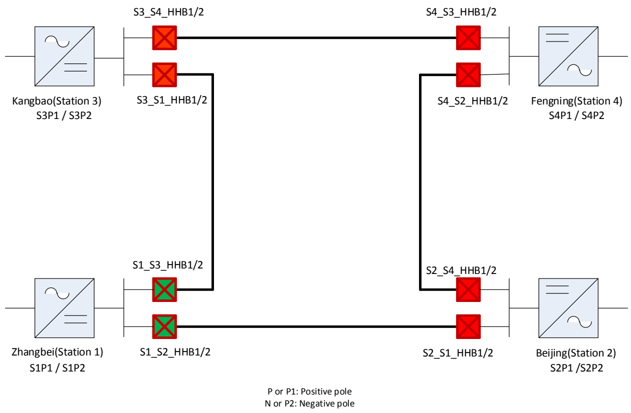

Figure 4 Test System considered for simulation study

IV. STUDY RESULTS

Two different case studies are performed to illustrate the inrush current problem and the performance of the propose method. Results are presented in following sub-sections.

A. Case study 1: closing HHB modules at once

In the first instance, the results of a case study with all HHB modules closing at once are presented for energization of Zhangbei converter. The simulation results of this case are presented in Figure 5 to Figure 7 to show the status of the HHB in Zhangbei station and the parameters of Zhangbei and Fengning converter station respectively.

As shown in Figure 5, all S1_S2_HHB1 (Zhangbei to Beijing, pole 1) modules 1-7 are closed at 0.1s to energize the Zhangbei converter S1P1.

As shown in Figure 6, the dc side voltage of Zhangbei station experienced a high transient overshoot before reaches steady-state. The inrush charging currents on valve arm and dc bus are of single half- sinusoidal waveform, with the peak value around 4kA for dc bus charging current.

As shown in Figure 7, operating as the regulating station of dc grid voltage, Fengning station has experienced a large dip on the dc bus voltage to the extent of 60%. This large disturbance can trigger the protection in the other three energized stations of the grid, which is not desirable for reliable operation of HVDC grid.

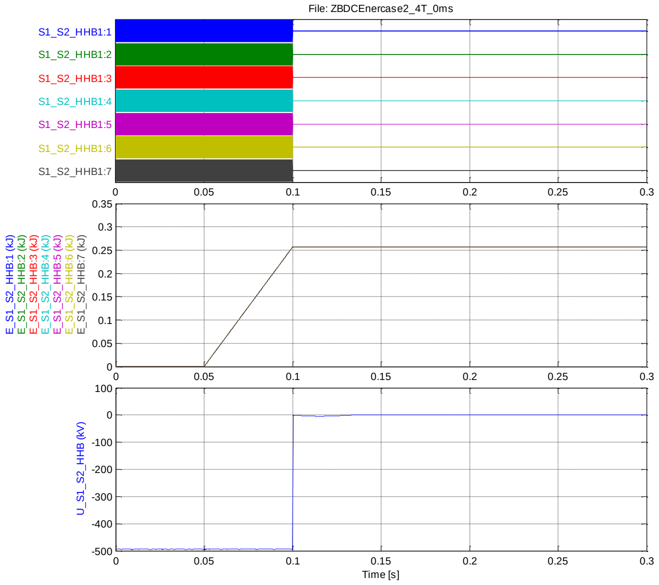

Figure 5: Zhangbei Station S1_S2_HHB1 plot with all HHB modules closing at once– from top to bottom: 1) HHB module 1~7 status 2) HHB module 1~7 energy level 3) Voltage across whole HHB

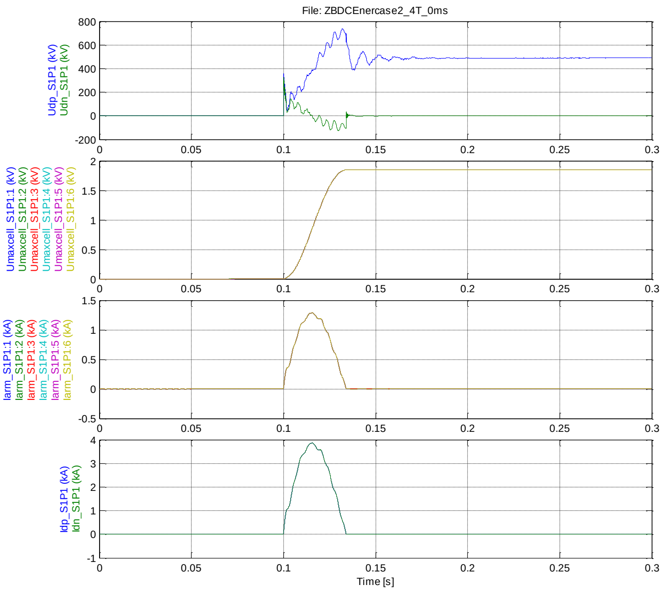

Figure 6: Zhangbei station converter plot with all HHB modules closing at once - from top to bottom: 1) dc bus voltage 2) arm maximum cell voltages 3) arm current 4) converter dc current

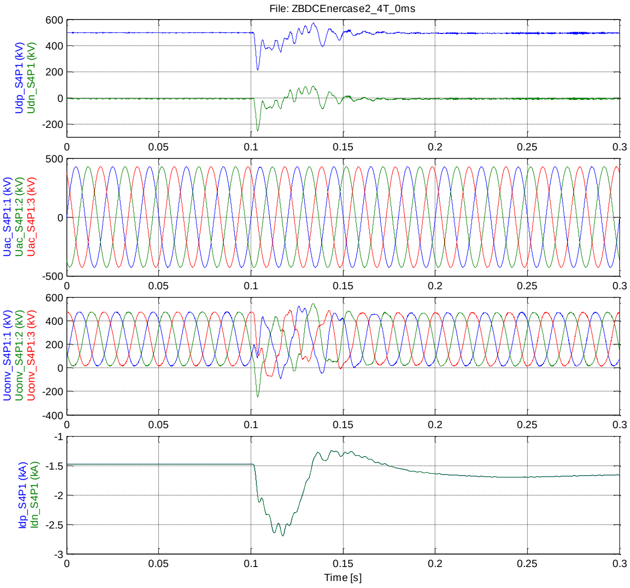

Figure 7: Fengning station converter plot with all HHB modules closing at once - from top to bottom: 1) dc bus voltage 2) PCC bus voltage 3) converter bus voltage 4) converter dc current

B. *Case study 2: sequential closing of HHB*

In this section, the results of a case study with HHB modules sequentially closed are presented. The simulation results of this case are presented in Figure 8 to

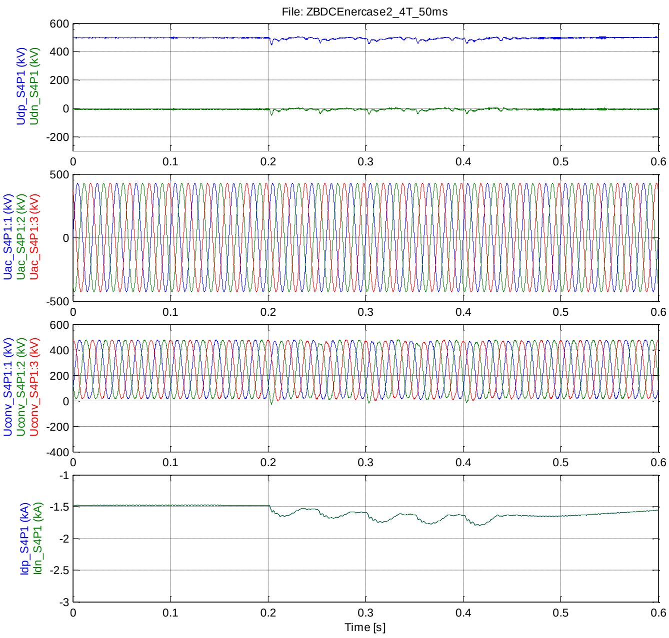

Figure 10 which show the status of HHB and respective converter station parameters.

As shown in Figure 8, at 0.1s, all S1_S2_HHB1 modules are closed in sequence with time delay between the modules closing, to energize the Zhangbei converter S1P1. Trials have been made with the selection of different time delays. It is found that the time delay between the closing of the HHB modules has significant influence on the system performance, and requires accurate tuning as per specific project parameters and requirements. For the case study in this paper, it is observed that 50 ms time delay will cause acceptable voltage fluctuation. The dip on dc bus voltage will be less than 10% as shown in Figure 9 and

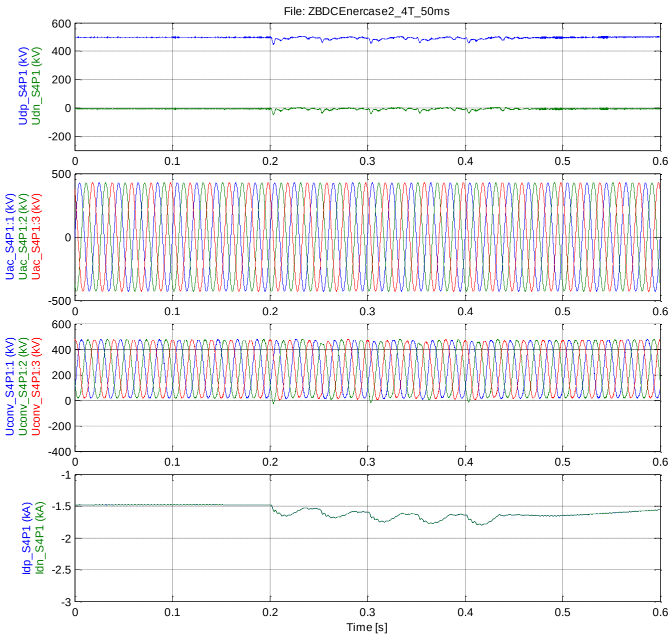

Figure 10. Furthermore, it is also observed when the time delay between the closing of the HHB modules is greater than 30 ms, the arrester energy of the HHB module could stabilize at certain level before the close of next module as current through the arrestor has reduced to zero before the closing of the next module. Thus the current through the HHB modules is discontinuous and the arrestor will not subject to current stress for the entire duration of soft closing, as can be observed from the fourth plot in Figure 9.

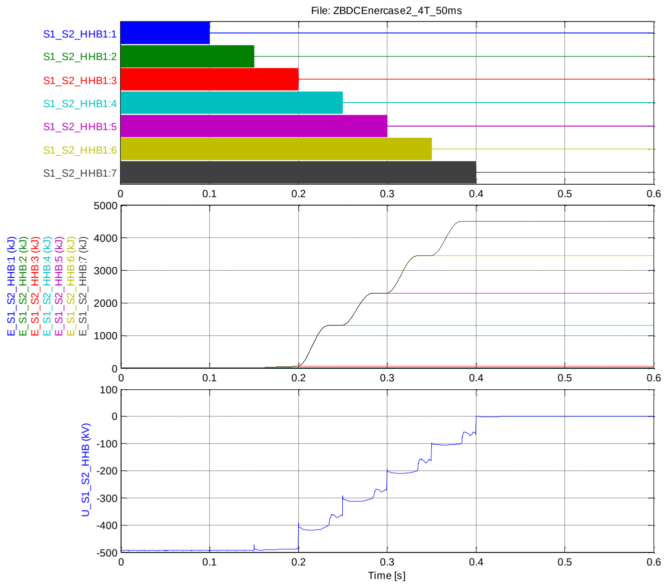

Figure 8: Zhangbei Station S1_S2_HHB1 plot with a delay of 50 ms between the closing of HHB modules – from top to bottom: 1) HHB module 1~7 status 2) HHB module 1~7 energy level 3) Voltage across whole HHB

C. Discussion

The time delay between the closing of HHB modules will influence the system performance, and requires accurate tuning based on specific project requirements. In this paper, a fixed time delay of 50ms is used between the closing of each HHB module, which would ensure the maximum voltage dip exposed on dc bus below 10% of the nominal voltage.

The study results can be evaluated from different perspectives as follow.

1) System-level disturbance

As shown in case study 1, if the converter is energized without HHB as PIR, the dc voltage dip can be larger than 60% of nominal voltage, which is not acceptable from system operation point of view. Moreover, the generated inrush current can trigger the overcurrent protection for converter arm.

On the other hand, as shown in case B, if the converter is energized with HHB as PIR, a sequential closing function will energize the converter step by step and significantly reduce dc voltage dip. Meanwhile the converter arm is not experiencing high stresses.

As conclusion, the HHB as PIR will reduce both disturbances to connected system and equipment.

2) The HHB internal stresses

Based on simulation and analysis, conclusion is that the HHB can smoothly charge the converter with a minimal influence on the connected dc grid.

However, the component stresses on HHB modules during the sequential closing operation needs be evaluated. In general, following parameters are decisive for the component design of MB modules: module current, module voltage, and module energy level. During the closing process, as the voltage on MB modules is decided by the parallel arrester, meanwhile no overvoltage is generated across HHB, thus the voltage stress is not a major issue for the component selection.

For semiconductors and arresters, current stresses on MB modules should still be verified. As shown in the fourth plot of Figure 9, current through dc bus, which is effectively the current through MB modules, has a maximum magnitude of 500A and duration less than 50ms, which is within design capability of semiconductors. As shown in second plot of Figure 8, energy on MB modules has a maximum value of 4.5 MJ which has to be taken into consideration in the design of HHB arrestor along with its various possible operating modes. Thus the outcome of this simulation study provides effective input to component selection and proper design of HHB.

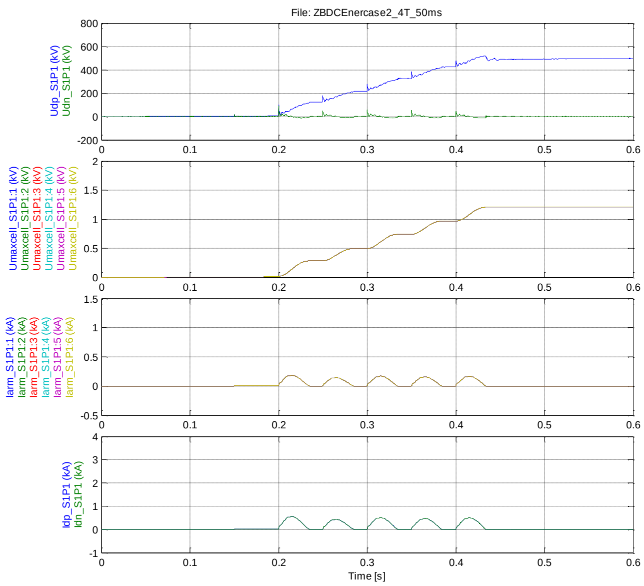

Figure 9: Zhangbei station converter plot with a time delay of 50 ms between the closing of HHB modules - from top to bottom: 1) dc bus voltage 2) arm maximum cell voltages 3) arm current 4) converter dc current

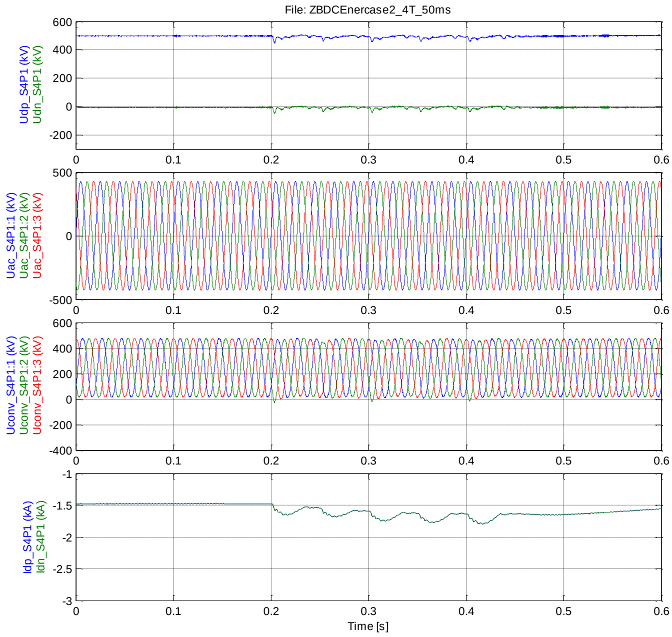

Figure 10: Fengning station converter plot with a time delay of 50 ms between the closing of HHB modules - from top to bottom: 1) dc bus voltage 2) PCC bus voltage 3) converter bus voltage 4) converter dc current

3) *Fault handling strategy and system coordination*

In case there is a fault during sequential closing process, as key components to HVDC grid, coordination with system control and protection is needed. In case of fault occurs during the closing sequence, the fast re-closing protection will be activated and immediately open the all MB modules. According to [7], the fault current and required energy is relatively low. However, in worst case, fault occurs when the HHB is closed, in this case the system Control and Protection is playing an important role to detect the fault quickly and send the open order to the HHB.

V. Conclusion

This paper proposes an innovative method of deploying modular-design HHB to support MMC converters energization from dc side. Operating the modular HHB with proposed sequential closing logic can ensure a smooth energization of the connected converter and dc lines. The study shows how the system parameters are influenced by this method. Two different case studies are done on a 4-terminal dc grid of Zhangbei dc grid as benchmark in PSCAD, which proved the efficient performance of the proposed concept. The outcome of this paper can contribute to a more efficient and cost-effective HVDC grid in practice.

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