

Cost-Effective Solutions for Handling Dc Faults in VSC HVDC Transmission

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Abstract

Utilization of voltage-source converters (VSC) in high-voltage direct current (HVDC) transmission systems are increased in recent years. This paper proposes cost-effective solutions for handling dc-side faults in VSC HVDC bipolar transmission. The basic idea of this paper is to replace the existing mechanical neutral bus switch (NBS), which is normally composed of resonance circuit and mechanical breaker, with semiconductor-based dc breakers. Consequently, converter blocked-time can be reduced significantly and ac grid can be supported with reactive power within a short time. The proposed method will improve the stability of the connected ac grid.

Keywords

«Power conversion», «HVDC transmission», «HVDC breaker», «Semiconductor breaker».

Introduction

The application of high-voltage direct current (HVDC) technology in power grids is growing very fast. They were initially introduced based on line-commutated semiconductor technologies (Classic HVDC) and more recently based on self-commutated semiconductor technologies (Voltage-source converter (VSC) HVDC) [1]. Since the breakthrough was made with the first world VSC-HVDC in 1997 (Hellsjön project, Sweden, 3 MW, 10 km distance, ± 10 kV [2]), VSC-HVDC systems represent through developments in the area of dc power transmission technology. Various configurations of HVDC systems can be identified depending on function and location of the converter stations.

In a symmetric monopole configuration, the converters are connected between two pole conductors, and the midpoint of the two poles may be directly or indirectly grounded so as to make a potential reference for the dc-side voltage. For an asymmetric monopole configuration, the converters are connected between one pole and ground, where either an earth return or a dedicated metallic return line can be used. A bipolar configuration can be considered essentially as a combination of two asymmetrical monopole configurations with a common neutral bus. The bipolar configuration is the standard solution in Classic HVDC. Comparing with the symmetrical monopole, the main advantage of a bipolar HVDC system is higher availability since 50% power transfer capability is maintained even if there is one pole fault. Furthermore, the healthy pole will not be subjected to twice the rated dc-side voltage when there is one pole to ground fault. With the increasing of dc-side voltage and power, the bipolar configuration in VSC HVDC will also become dominating.

Among VSC topologies, modular multilevel converter (MMC) is considered as today's VSC-HVDC topology benchmark which facilitates the HVDC main performance criteria such as losses, modularity and power controllability. However, challenges with VSC HVDC in a bipolar configuration are to sustain

the high short-circuit current and to clear dc-side faults by interrupting the fault current. If the dc yard in a VSC HVDC bipolar configuration is designed similarly as in classic HVDC, the dc-side fault current may be cleared by opening ac-side breakers as well as the neutral bus switch (NBS). In this case, the fault clearing time could be longer than the classic HVDC, where the dc-side fault current is suppressed by fast firing angle control.

Faults on the dc-side of VSC-HVDC systems can also be interrupted by using fast dc-breakers e.g. hybrid HVDC breaker [3]. The fault can be cleared shortly by breakers on the same pole. After opening the dc breaker, the faulted line will be isolated from the converters, thus the converter is ready for operating as static synchronous compensator (STATCOM) to provide reactive power support. The voltage rating of such a dc-breaker is directly related to the rated dc-pole voltage. This means that the higher the dc-pole voltage, the higher the cost.

An alternative solution for dc-side fault handling is to use bipolar cells instead of unipolar cells in modular multilevel converter (MMC) topologies. The bipolar cells, such as full-bridge (FB) cell, can be charged in both current directions, therefore, the capacitors can be inserted into the arms with either polarity when the devices are blocked. During the dc-side fault, a voltage with an opposite polarity of the ac-side voltage is inserted into the converter arms by natural commutation of cell diodes and thus limiting the dc-side fault current by creating a counter voltage. If the cell voltages are sufficiently high, the dc-side fault current can be blocked. Although the faulted dc-line is not isolated from the converters, the converter can still provide the reactive power support by blocking positive arms and operating the negative arms. Although the solution based on bipolar and asymmetric cells offers the dc-side fault blocking capability, it results in fairly high cost and losses penalties. In addition to the steady state rating, FB-MMC based VSC-HVDC are normally designed in order to withstand the severe transients due to the specific system stability requirements [4].

This paper proposes a cost-effective solution for handling dc-side faults in VSC HVDC bipolar Transmission. The basic idea of this paper is to replace the existing neutral bus switch (NBS), which is normally composed of resonance circuit and mechanical breaker, with fast semiconductor-based breakers e.g. [3, 5]. Independent of rated pole voltage, the neutral bus voltage is normally not changed very much, and the level is very low. Thus very robust solution with relatively low cost and losses can be realized. The capability of fast breaking high current makes it possible to achieve comparable performance as classic HVDC, with added function of supplying reactive power to connected ac grid after fast dc-side fault interruption.

Description of A VSC HVDC Bipolar System under Dc-side Fault

A typical point-to-point HVDC bi-pole configuration is schematically shown in Fig. 1. Each station consists of two converter poles. Several switches are available on dc-side to enable different operation modes i.e. bi-pole and mono-pole. These switches are labeled as:

- GRTS (ground return transfer switch) which is used to transfer the direct current from metallic return path to the ground return path,
- HSS (high speed switch) which can be used to isolate the dc-line from the converter quickly,
- MRTB (metallic return transfer breaker) which is used to transfer the direct current from ground return path to the metallic return path through the pole conductor of a stopped and isolated pole,
- NBS (neutral bus switch) which is normally used to isolate the neutral bus of a stopped converter from the operating pole,
- NBGS (neutral bus grounding switch) which is used to provide a temporary local ground for the DC neutral bus inside the DC station.

Table I: Typical operation time delay for different switches and processes in the system under study

Item	Operation time delay
Mechanical breakers open	28 ms
Mechanical breakers close	65 ms
Semiconductor-based breakers open/close	2.5 ms
Deionization time	300 ms
Power ramp up	150 ms

During both bi-pole and monopole operation, the voltage on the neutral bus may be only a few percentage of the rated pole voltage. So, the NBS is exposed to lower voltage stresses in comparison to the breakers at the pole, if it only operates after the opening of ac-side breakers.

In the case of dc-side ground fault in any of poles, the converter of that faulty pole can be blocked while the whole system continues running in mono-pole operation mode, after fault current interruption. In order to interrupt the fault current, the ac-side breakers should open first, see t_1 in Fig. 3(a). After the operation of ac-side breakers, the fault current will decay, depending on fault impedance. The residual fault current in dc-side will be interrupted by NBS when the fault current is reaching the NBS current interruption capability at t_2 . Later, the converter pole disconnecter (HSS) isolates the faulty line. At this stage, the ac-side breakers can reconnect the converter pole again, in order to support ac-grid with reactive power. Fig. 3(a) illustrates a typical timeline for aforementioned procedure. In the case of temporary fault, the HSS can be re-closed again after deionization time of the fault-arc path. The deionization time depends on many factors such as line voltage, conductor type, atmosphere at fault location, fault current, etc [6, 7]. A typical time of 300 ms is assumed in this study. Table I shows assumed deionization time and also typical operation time for different switches.

Fast Semiconductor-Based Dc Breaker Utilized as Neutral Bus Switch (SNBS)

A drawback with conventional NBS is low current interruption capability of the switch which is typically bellow 2 kA. So, the fault current can not be interrupted unless it is below a certain level. Utilizing semiconductor-based dc breakers (hybrid HVDC breaker or pure semiconductor breaker [3]) enables high current interruption in typically 2 ms. Consequently, the lengthy time interval for fault current decay (t_1 to t_2 in Fig. 3(a)) can be reduced significantly. As shown in Fig. 3(b), SNBS can be immediately triggered after ac-side breaker is opened. The SNBS will commutate the fault current to arrester path at t_2 while HSS can isolate the dc-line at t_3 . The converter can be de-blocked and support the ac-side after SNBS and ac breakers are closed at t_6 . Note that fault energy needs to be dissipated in SNBS arresters before operation of HSS. So, the time interval $[t_2-t_3]$ depends on fault energy i.e. fault location and impedance in the loop. So, the total blocking time of the converter is dependent to the fault location and

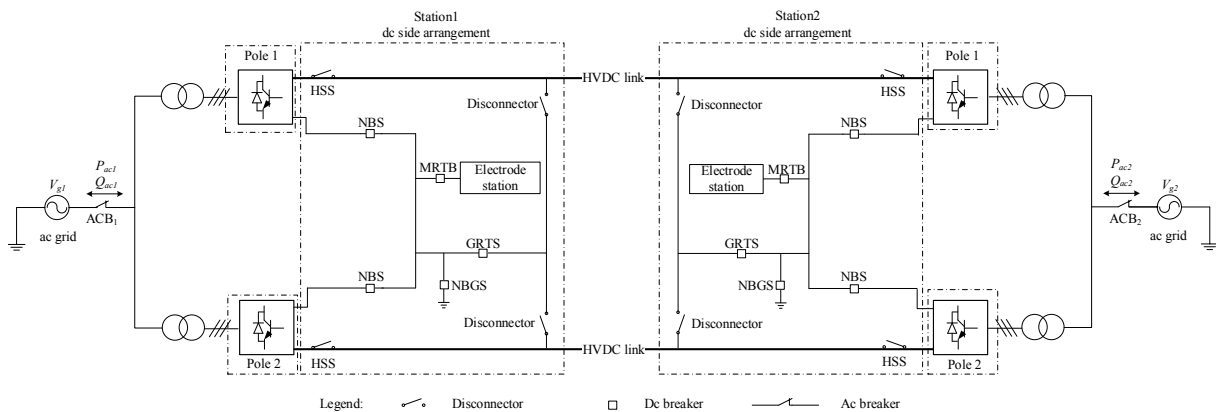


Fig. 1: Schematic diagram of a bipolar VSC HVDC system

fault impedance. However, this time is significantly less than the conventional method, compare Fig. 3(a) and Fig. 3(b). Typically for the 600 km long dc-line the fault clearing time can be reduced from 700 ms to 200 ms.

A point-to-point HVDC system is developed in PSCADTM/EMTDCTM to study the performance of the proposed method. Main circuit parameters are available in Table II. Conventional NBS, see Fig. 1, is replaced with semiconductor-based breaker (SNBS) rated for 16 kA and 80 kV. As a case study, a temporary fault has been created at 300 km away from the converter station and results are shown in Fig. 2. Fault occurs at $t=2.1$ s and converter-block signal and ac-breaker-open signal are triggered after fault detection time. Expectedly, the fault current rises until the ac-side breaker is totally opened after 28 ms delay. At this moment, SNBS will commutate the current to the arrester path and later, the HSS is opened at $t=2.22$ s to isolate the dc-side line. In order to support the ac-side, the SNBS and ac breakers are closed afterwards. The converter is de-blocked at $t=2.29$ s after 2.5 ms and 65 ms time delay for closing SNBS and ac breakers, respectively. Fig. 2 shows that the ac-side outage time is less than 200 ms for this case study. Following the aforementioned sequences, the HSS can be closed after deionization time at $t=2.5$ s and active power ramp up can be started, in the case of temporary fault.

Comparison and Discussion

Ac system stability can be addressed in voltage and frequency terms. The voltage stability is related to reactive power, whereas the frequency stability is related to active power. Thus the performance of an HVDC system during a dc-side fault can be evaluated by the outage duration of active and reactive power. It is very important to evaluate the exact technical index which is directly related to connected ac system stability. The acceptable power outage duration is related to strength of the connected ac grid. The proposed method of SNBS will significantly reduce the power outage duration. So, if the maximum power outage is below the acceptable range, the SNBS is a much cheaper solution in comparison to full-bridge converters and half-bridge converters with hybrid HVDC breakers on pole.

Utilization of semiconductor-based breakers as NBS can significantly decrease the power outage, in comparison to the conventional mechanical-based breakers with slightly more cost. Since the SNBS is operated after opening of ac breakers, it is not exposed to high voltage as pole breakers. Interestingly, it is located at neutral bus and small isolation is enough for this solution. However, with the cost of higher isolation level, it is possible to replace the HSS with semiconductor-based breakers (SHSS) and further reduce the power outage duration. In this case, there is no need to operate the NBS at all, while SHSS is operated after opening of ac-side breakers. The SHSS and SNBS will have the same rating since they are operated in the same condition while the ac breakers are opened. The operation sequence for a system with SHSS is shown in Fig. 3(c) for comparison purposes.

In addition, full-bridge converters and also half-bridge converters with hybrid HVDC breakers on pole, enable a fast fault current interruption with no need for ac-side breaker operation. Whether the enhanced performance is justified by the additional cost or not, is an interesting issue. Fig. 3(d) shows a typical timeline for a half-bridge converter with hybrid HVDC breaker on pole under dc-side fault.

Ultimately, comparison between conventional dc-breakers (Fig. 3(a)), SNBS (Fig. 3(b)), SHSS (Fig. 3(c))

Table II: Circuit Parameters for Simulated Model, one pole

Quantity	Notation	Value
Rated active power	P	1 GW
Rated reactive power	Q	300 MVar
Direct voltage	v_{dc}	500 kV
Alternating voltage	v_g	400 kV
Rated frequency	f	50 Hz
Fault inductance	L_{fault}	0.1 mH
Line type/length	$Line_{type}/Line_l$	overhead/600 km

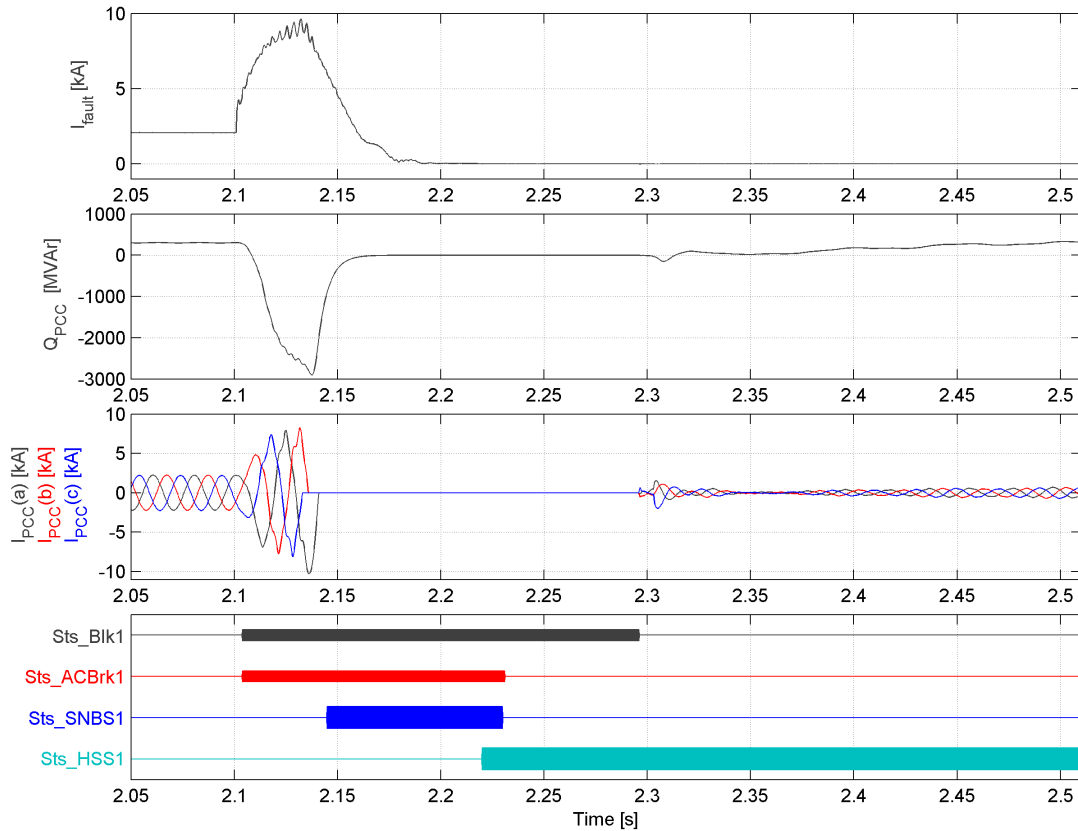


Fig. 2: Simulation results for the case study (I_{fault} : dc-side fault current, Q_{PCC} : reactive power at ac-side, I_{PCC} : ac-side current, Sts_Blkl1 : Converter block signal, Sts_ACBrk1 : ac breaker status signal, Sts_SNBS1 : SNBS status signal, Sts_HSS1 : HSS status signal)

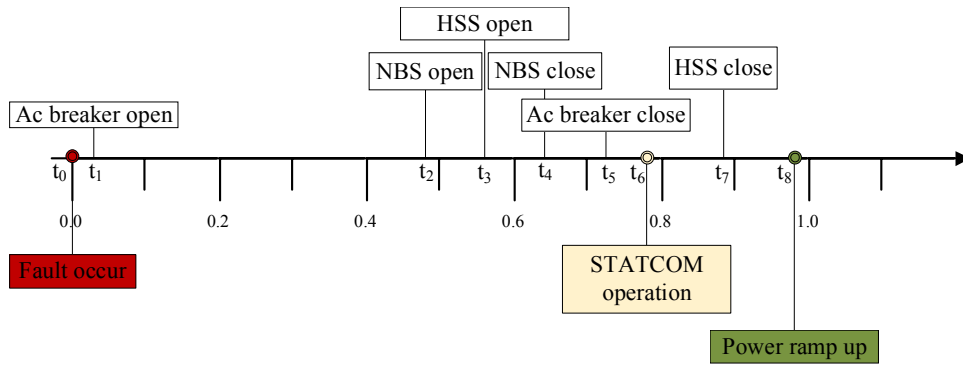
and hybrid HVDC breaker (Fig. 3(d)) indicates that selecting a suitable technology for dc-side fault handling is a trade-off between power outage and cost. The less power outage, the most costly solution.

Conclusion

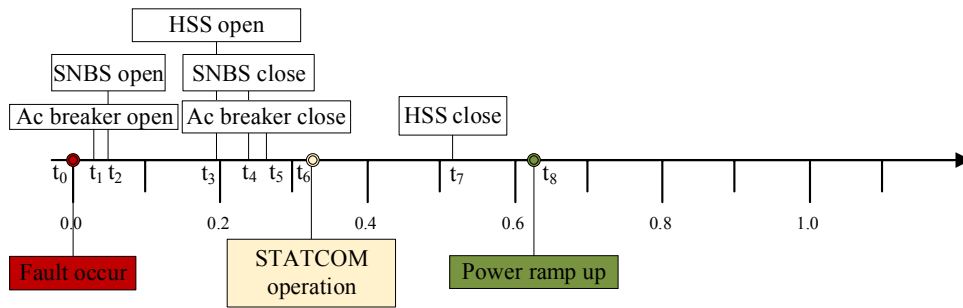
Utilization of semiconductor-based dc breaker as NBS is proposed and investigated in this paper. From active power outage point of view, the proposed solution can achieve a comparable performance as ac line or classic HVDC. From reactive power outage point of view, the proposed solution will give almost similar performance as a stand-alone STATCOM. The total performance of the proposed solution fulfills the ac network stability requirement. Thus, the proposed bipolar VSC HVDC transmission system is the most cost-effect solution. It is also the most robust, secure and environment friendly solution due to significantly lower number of semiconductor switching components and lower losses.

References

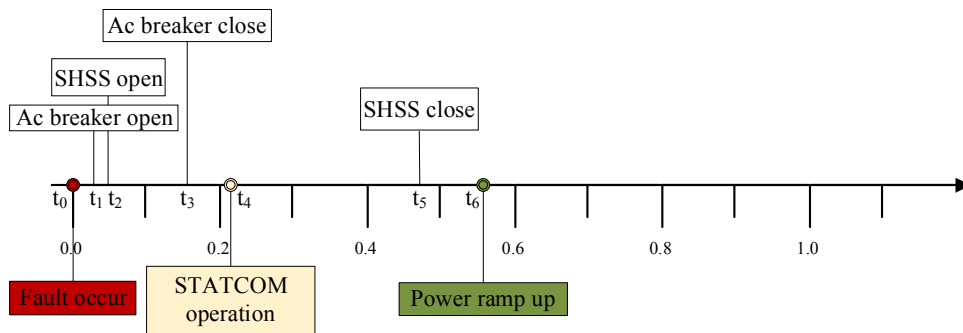
- [1] A. Nami, J. Liang, F. Dijkhuizen, and G. D. Demetriades, "Modular Multilevel Converters for HVDC Applications : Review on Converter Cells and Functionalities," *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 18–36, Jan 2015.
- [2] G. Asplund, K. Svensson, J. Häfner, J. Lindberg, and R. Pålsson, "Dc transmission based on voltage source converters," in *Cigré paper No. 14-302*, Paris, France, 1998.



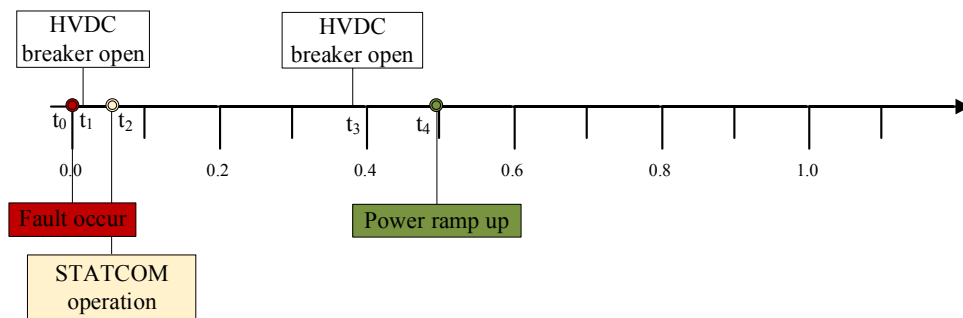
(a)



(b)



(c)



(d)

Fig. 3: Typical operation sequence for system under the fault condition (a) conventional mechanical breaker is used, (b) semiconductor-based breaker is used as NBS, (c) semiconductor-based breaker is used as HSS, (d) semiconductor-based HVDC breaker.

[3] J. Häfner and B. Jacobson, "Proactive hybrid hvdc breakers - a key innovation for reliable hvdc grid," in *Cigrésymposium*, Bologna, Italy, 13-15 September 2011.

- [4] A. Nami, J. Liang, F. Dijkhuizen, and P. Lundberg, "Analysis of modular multilevel converters with dc short circuit fault blocking capability in bipolar hvdc transmission systems," in *EPE proceeding*, Geneva, Switzerland, 8-10 September 2015.
- [5] A. Hassanpoor, J. Hafner, and B. Jacobson, "Technical assessment of load commutation switch in hybrid hvdc breaker," *Power Electronics, IEEE Transactions on*, vol. 30, no. 10, pp. 5393–5400, Oct 2015.
- [6] "Deionization time of fault-arc paths," *Electrical Engineering*, vol. 69, no. 2, pp. 130–130, Feb 1950.
- [7] B. Ravindranath and M. Chander, "*Power system protection and switchgear*". New age international (P) Ltd., 1977.