International Journal of Control and Automation
Vol. 9, No. 4 (2016), pp. 381-394
http://dx.doi.org/10.14257/ijca.2016.9.4.37

A Comparison of Different Hybrid Direct Current Circuit Breakers for Application in HVDC System

Anh-Duc Nguyen, Thai-Thanh Nguyen and Hak-Man Kim*

Incheon National University
hmkim@inu.ac.kr

Abstract

This paper presents the comparison between two topologies of hybrid direct current circuit breaker (HDCCB) that are designed by ABB and Alstom Grid. The main difference between two topologies is the use of the semiconductor in each topology. ABB used IGBT cells whereas Alstom Grid used IGBT cells and thyristors. The working principles of each topology are presented and their advantages and disadvantages are shown in this study. Two HDCCB topologies are implemented in MATLAB / Simulink to clarify the comparison. The effect of the time delay in the topology of Alstom Grid is also discussed in this study.

Keywords*: Hybrid direct current circuit breaker (HDCCB), high voltage direct current (HVDC), ABB DCCB, Alstom Grid DCCB, modeling & analysis*

1. Introduction

The high voltage direct current (HVDC) system uses direct current (DC) for high power transmission. Unlike the high voltage alternative current (HVAC) system, the transmitted current in HVDC system does not change the direction. Besides, a long-distance HVDC transmission system introduces lower investment cost and lower losses than an equivalent HVAC system [1, 2]. Hence, the HVDC system has become realized and interested as new technology.

Nonetheless, the constant DC current, which is one of the advantages of the HVDC transmission system, is an inevitable challenge for fault current interruption. Alternative current circuit breakers (ACCBs) operate basing on the zero-crossing principle but there is no natural zero crossings obtained in the DC current. The issue of identifying suitable circuit breaker topologies for HVDC grid remains controversial. For decades, a variety of topologies of DC circuit breakers have been proposed [3-5]. Among of them, the hybrid DC circuit breaker (HDCCB) that consists of the mechanical switch and the semiconductors has become the leading technology. In general, HDCCB consists of three essential branches: a main branch with a mechanical switch, an auxiliary branch with semiconductor devices and a metal oxide varistor (MOV) [6-8].

The fault current interruption in the HDCCB includes three steps in general. First of all, the load current flows through the main branch in normal condition. When the fault occurs, the open command is delivered to the mechanical switch and fault current is commutated into the auxiliary branch. Later, this branch carries the fault current until the mechanical switch completely opens. Finally, the semiconductors in the auxiliary branch turn off and commutate the fault current here into the surge arrester whose function is to force the current to zero. For enhancement, a power electronic switch formed by a stack of semiconductors is added in series with the mechanical switch to support the switch during commutation [9].

As an improvement, ABB and Alstom Grid introduced their new HDCCB topologies

---

[*] Corresponding Author

with same working principles but different components included [10, 11]. It is noticed that these two HDCCB schemes both interrupt fault currents very quickly and there is low energy loss during normal operation. Each topology has its own advantages and disadvantages. However, the comparison between two topologies still has not been explored. This paper provides an overview and test results of their performance in order to consider the application of the HDCCB topologies of ABB and Alstom Grid.

The paper is divided into four sections as follows. In Section 2, two HDDCB topologies of ABB and Alstom Grid are theoretically investigated according to their working principles. The simulation results of the two topologies are presented in Section 3. Section 4 presents the comparison between the ABB and Alstom Grid HDCCB topologies. Finally, the conclusions and future works are summarized in Section 5.

2. Operation Principle of the Hybrid DC Circuit-Breakers

2.1. The ABB's Hybrid DC Circuit Breaker

The scheme in Figure 1 introduces the simplified ABB's HDCCB topology which consists of three branches as follows:

Main branch or load current path includes an ultra-fast mechanical disconnector (UFD) and a load commutation switch (LCS) connected in series. These two components together build the low-loss load current path of the HDCCB. The LCS contains a small number of IGBTs adequate to commutate fault current to the auxiliary branch. These IGBTs should be installed anti-series in order for bidirectional interruption.

Auxiliary branch contains IGBT cells installed parallel with a surge arrester [12]. Each cell includes IGBTs modules connected in anti-series. The number of cells increases when the voltage level is higher. The function of this branch is to carry the large fault current while the mechanical switch UFD is in opening process.

The surge arrester not only reduces fault current to zero by eliminating energy, but also serves as over-voltage protection of the IGBTs in the auxiliary branch. Total protective level of the arresters is selected to be approximately 1.5 times of the rated DC voltage.

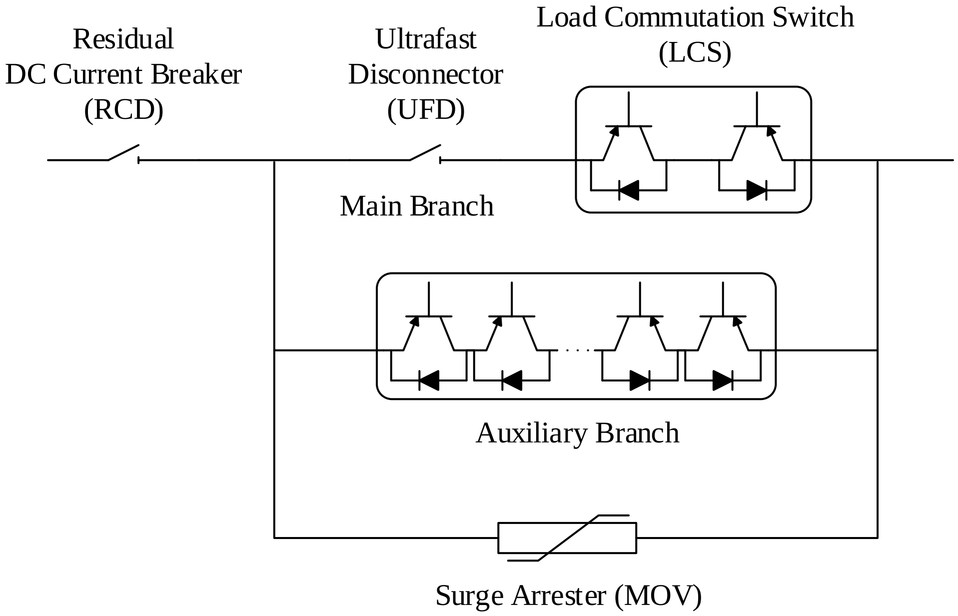
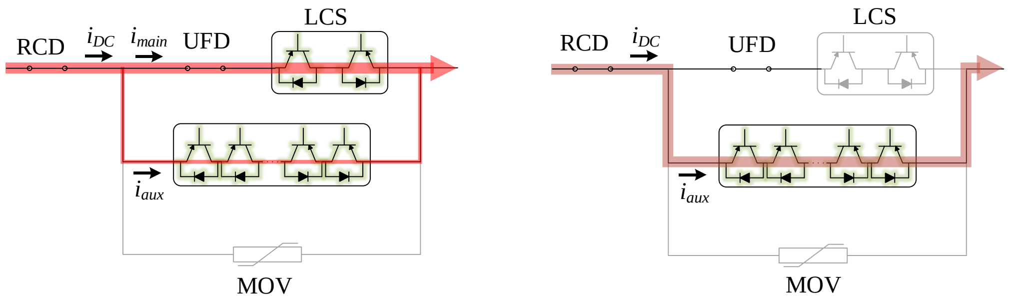
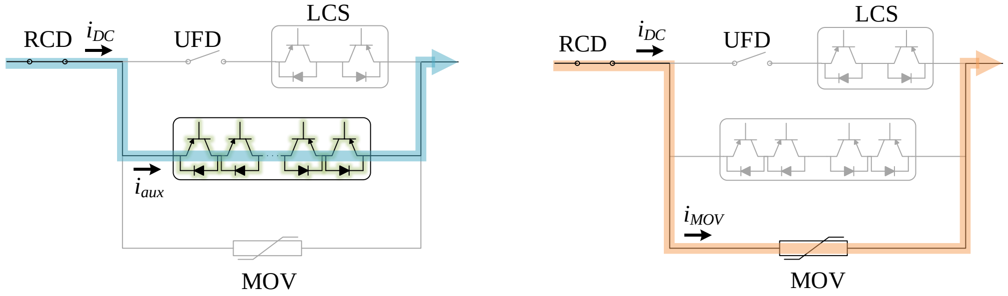


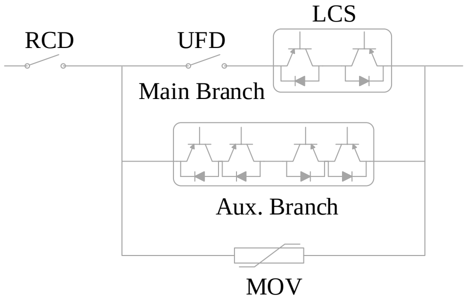
Figure 1. Structure of the ABB's HDCCB



a) Step 1: $0 < t < t_2$ b) Step 2: $t_2 < t < t_3$



c) Step 3: $t_2 < t < t_3$ d) Step 4: $t_3 < t < t_4$



e) Fault Completely Cleared

Figure 2. Working Principle of ABB's HDCCB

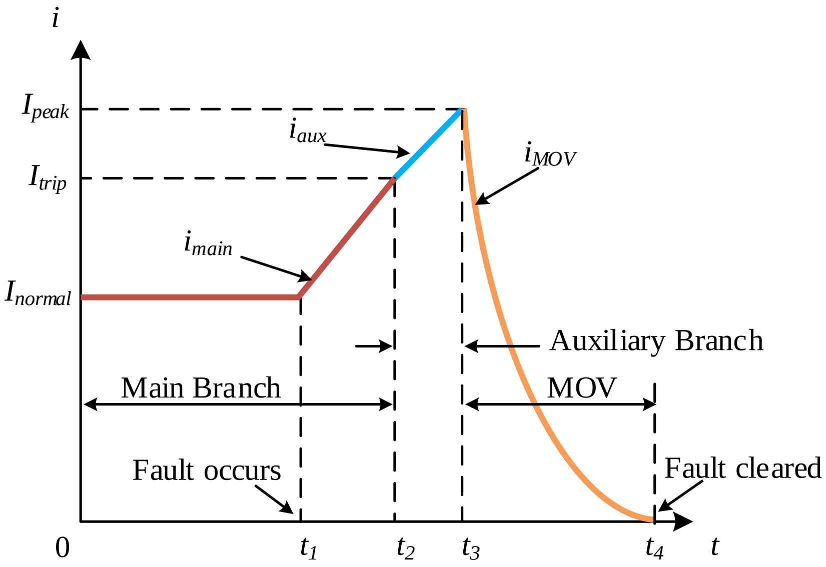


Figure 3. Fault Current Interruption of ABB's HDCCB

The working principle of the ABB's HDCCB described in Figure 2 includes four steps as follows:

Step 1: During normal operation of the system, most of load current passes through the main branch because of the low impedance of the IGBT-based LCS. Meantime, a relatively low amount of current flows in the auxiliary branch due to high impedance of the IGBT cells, as shown in Figure 2a.

Step 2: When a fault occurs, the current increases extremely quickly to a certain fault current level which is called tripping value. When this value is reached, the turn-off signal will be sent to the IGBTs in LCS. This leads to the commutation of fault current from the load current path into the auxiliary branch, as shown in Figure 2b.

Step 3: At time of tripping value, the UFD opens in less than 2 ms. Thus, the function of IGBT cells in auxiliary branch is to withstand the large amount of fault current which is still increasing during the 2 ms period. The IGBT cells in auxiliary branch is provided self-protection in case fault current exceeding the maximum breaking current limit of the IGBTs so that damage from this event can be avoided. Figure 2c describes the current behavior during this step. After the UFD is completely opened, the turn-off command will be sent to the IGBT cells and the fault current commutates into the arrester path.

Step 4: After the IGBT cells in auxiliary branch turn off, fault current is forced to commutate into the nonlinear resistor path with a surge arrester, as shown in Figure 2d. The fault current reduces to zero because of the energy elimination caused by the arrester. After fault clearance, the RCD shall open in 1 s to protect the surge arrester from thermal overload caused by residual current, as in Figure 2e.

Consequently, the current performances during the four time intervals together form the fault current interruption procedure, as illustrated in Figure 3. There are generally three stages included in the procedure. The first one is fault detection and next is the current commutation stage. The final stage is fault clearance.

2.2. Alstom Grid’s Hybrid DC Circuit Breaker

The fast turning-off speed of IGBT cells in ABB’s topology is undeniable for fault interruption. However, this characteristic is unsuitable in several situations. For example, the mechanical switch opens too slowly compared to the IGBTs or a longer duration is needed for system protection. Therefore, Alstom Grid introduced their HDCCB topology to overcome this problem.

The Alstom Grid’s HDCCB topology generally contains three branches with functions similar to the ABB’s HDCCB. Nevertheless, the auxiliary branch structure of Alstom Grid’s HDCCB is significantly different from ABB’s one. While the IGBT cells with high turning-off speed are utilized in the ABB’s HDCCB, Alstom Grid alternatively applies series stacks of pulse-power thyristors (PPTs) in the auxiliary branch for time-extension purpose [13], as shown in Figure 4.

The auxiliary branch of Alstom Grid’s HDCCB consists of two “time-delaying” branches and one “arming” branch. Each branch includes thyristor stacks connected in series. These thyristors are extremely difficult to turn off as IGBTs due to their characteristics. As a result, a capacitor bank is installed in series with each stack of thyristors in order to interrupt fault current.

There are at least two “time-delaying” paths in the auxiliary branch of this HDCCB. The first “time-delaying” branch contains a large capacitor bank and a surge arrester with low voltage protection level in parallel. This protection level should not be higher than the voltage rating of the LCS in the main branch. The second one operates similarly but includes a surge arrester with higher voltage rating. The “arming” branch structure is not different from the two branches as mentioned above. However, the capacitor of this branch is selected appropriate to the main surge arrester.

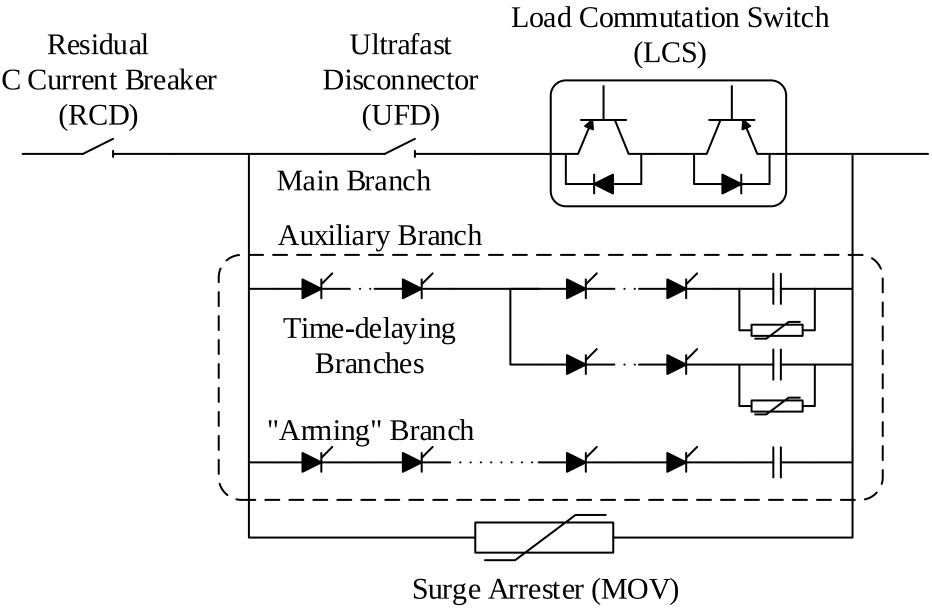


Figure 4. Structure of The Alstom Grid's HDCCB

Figure 5 shows the working principle of the Alstom Grid's HDCCB. There are five steps to be illustrated as follows:

Step 1: During normal operation, all thyristor stacks in auxiliary branch are at turn-off state and load current flows through main branch. This step is described in Figure 5a. When there is a fault occur, the IGBTs in the LCS receive turn-off command and at the same time the thyristor stack in the first "time-delaying" branch is fired.

Step 2: The fault current commutates into the first "time-delaying" branch and the capacitor here begins to be charged, as shown in Figure 5b. Additionally, at LCS turning-off event, the mechanical switch UFD begins opening.

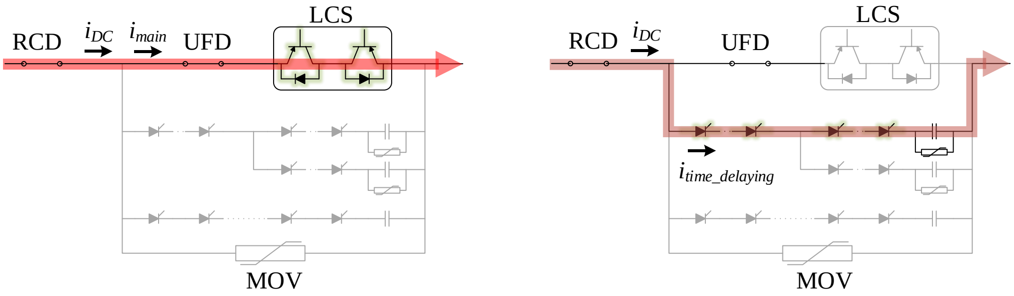
Step 3 includes two minor steps as follows:

> *Step 3.1*: When the contacts of the UFD are apart but remain not fully open, the thyristor stack in second "time-delaying" branch is turned on. The fault current commutates from the first "time-delaying" branch into the second one. Therefore, there shall be two parallel current paths, as illustrated in Figure 5c – Step 3.1.
>
> *Step 3.2:* Once fully charged, the capacitor in the first "time-delaying" branch discharge immediately to the surge arrester in parallel. Thus, the capacitor voltage becomes constant and the fault current in this branch reduces to zero. Consequently, the thyristor stack in the first "time-delaying" branch is automatically turned off according to the characteristics of the thyristor. For that reason, the fault current is completely transferred into the second "time-delaying" branch. When the contacts of the UFD are entirely separated, the thyristor stack in the "arming" branch is triggered so that the fault current starts commutating into this branch, as shown in Figure 5c – Step 3.2.

Step 4: The capacitor in the second "time-delaying" branch operates similarly to the one in the first branch. This leads to the thyristor turning-off event in the whole "time-delaying" branch. Hence, the "arming" branch carries the fault current, as illustrated in Figure 5d.

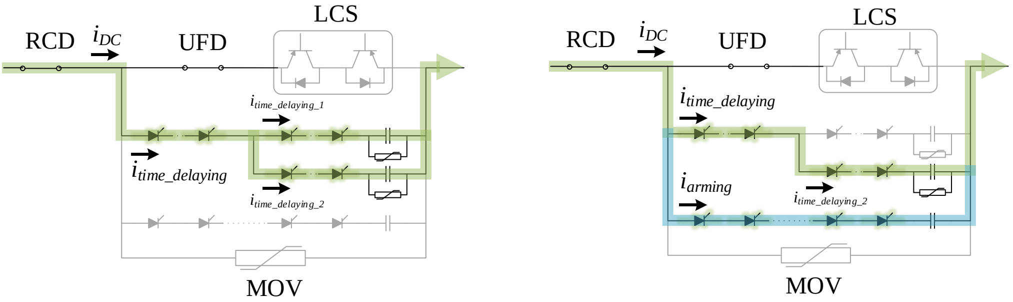
Step 5: The "arming" branch operates with the task to transfer the fault current into the nonlinear resistor path containing the main surge arrester. Ultimately, the fault current is interrupted by the arrester bank and the RCD opens to finish the current breaking process, as illustrated in Figures 5e and 5f, respectively.

As a result, the fault current breaking procedure throughout the five time intervals is represented in Figure 6. In general, the stages presented here are similar to those of the ABB's HDCCB topology.



a) Step 1: $0 < t < t_2$

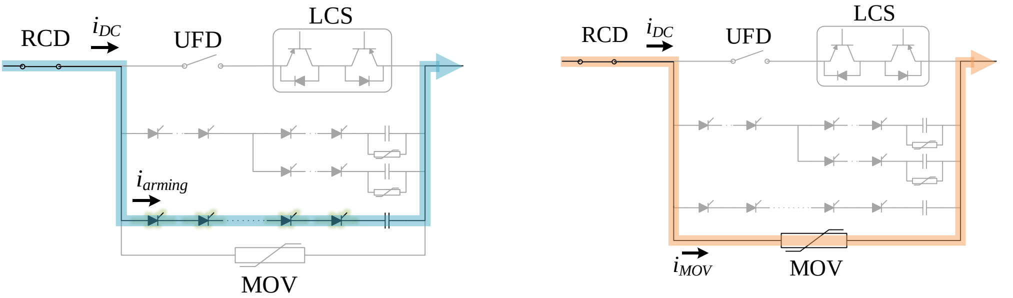
b) Step 2: $t_2 < t < t_3$



Step 3.1

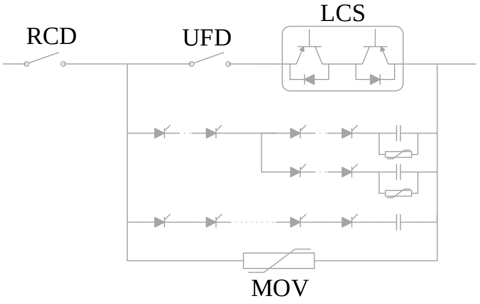
Step 3.2

c) Step 3: $t_2 < t < t_3$



d) Step 4: $t_3 < t < t_4$

e) Step 5: $t_4 < t < t_5$



f) Fault Completely Cleared

Figure 5. Working Principle of the Alstom Grid's HDCCB

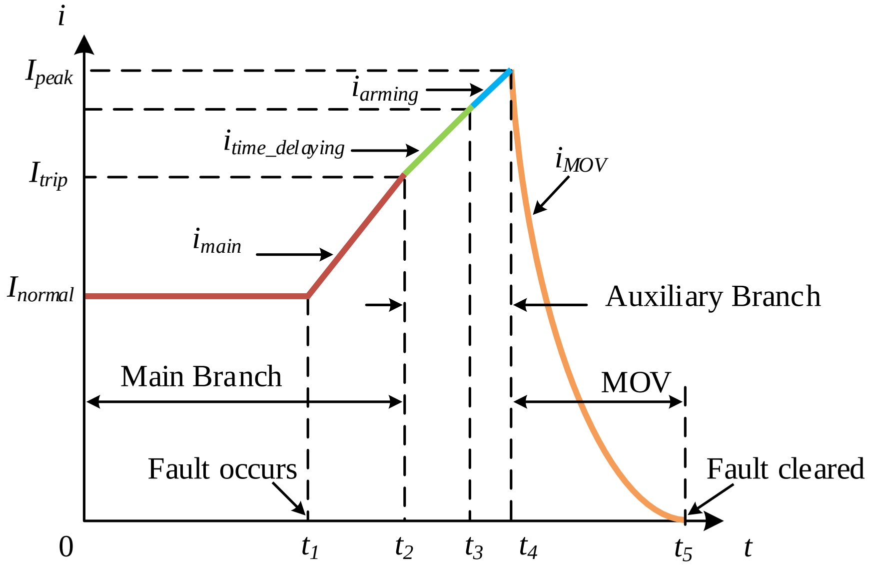


Figure 6. Fault Current Interruption of The Alstom Grid's HDCCB

3. Simulation Results

In order to examine the performances and differences of ABB and Alstom Grid HDCCB topologies, two simulation models have been made. The implementation was executed by MATLAB / Simulink. Figures 7 and 9 illustrate the models of ABB and Alstom Grid HDCCB, respectively.

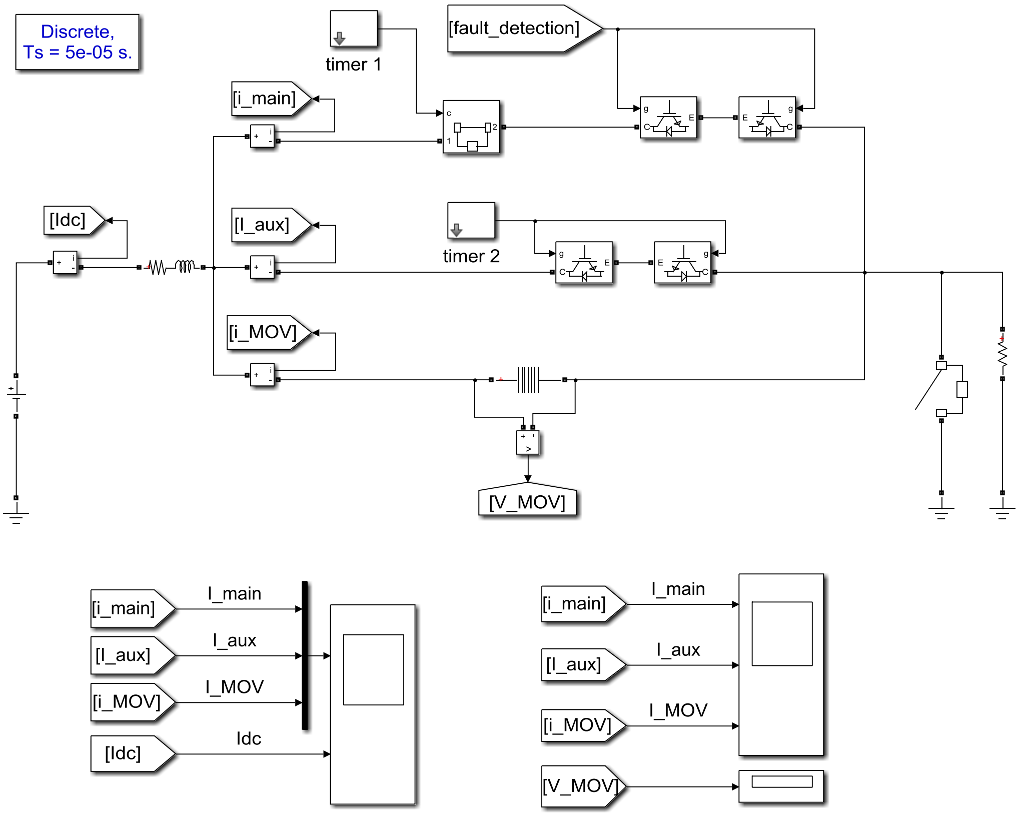
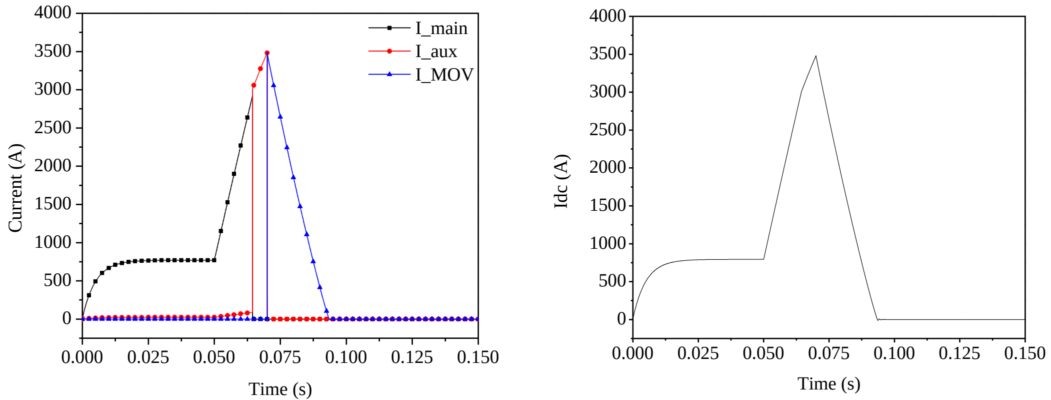


Figure 7. Simulation Model of The ABB's HDCCB

For clear comparison between two models, the interruption procedure is observed during 0.15 s with fault occurring at 0.05 s. Furthermore, the basic parameters of the components in their main branches are selected to be the same so that the main branches operate similarly to each other. Additionally, for simplified testing, the auxiliary branch model of ABB includes only one IGBT cell with two anti-series IGBTs instead of several cells as real application. The Alstom Grid model also consists of single thyristors in each subsidiary branch.

The fault clearance test of the ABB's HDCCB is shown in Figure 8. The performance of the currents *i_main* in the main branch, *i_aux* in the auxiliary branch, *i_MOV* through the surge arrester are examined, as shown in Figure 8a. At tripping value of 3000 A, *i_main* reduces to zero whereas *i_aux* increases to 3000 A and continue rising. After the mechanical switch opens completely, the current *i_aux* becomes zero and *i_MOV* rises, indicating the current commutation from the auxiliary branch into the surge arrester. The testing result of the fault current interruption procedure is shown in Figure 8b.



a) Current in each Branch b) Current passing through HDCCB

Figure 8. Fault Current Interruption of The ABB's HDCCB

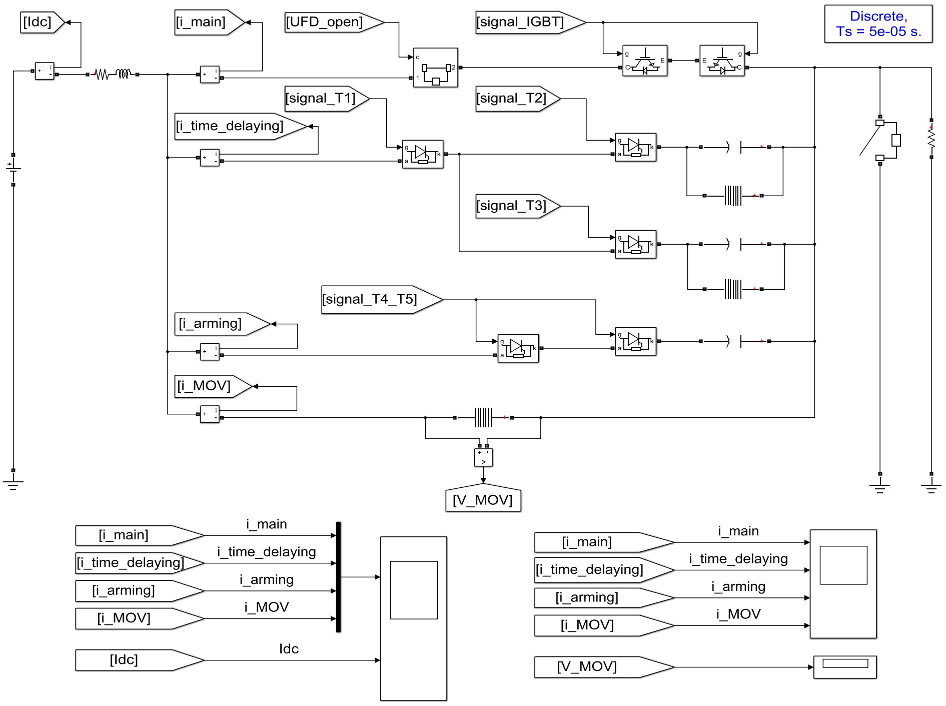
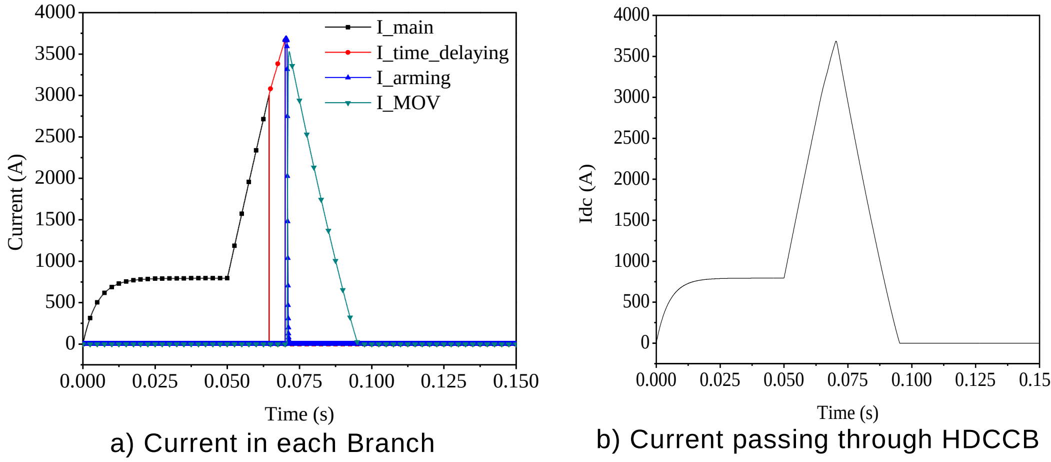


Figure 9. Simulation Model of The Alstom Grid's HDCCB



a) Current in each Branch b) Current passing through HDCCB

Figure 10. Fault Current Interruption of the Alstom Grid's HDCCB

Figure 10 represents the test of the fault current in the Alstom Grid's HDCCB with the currents *i_main* in the main branch, *i_time_delaying* in the "time-delaying" branch, *i_arming* in the "arming" branch and *i_MOV* through the main surge arrester. Although there are four currents to be observed in Figure 10a, the fault current performance in this simulation model is similar to that of ABB design, as shown in Figure 10b. It is observed that the auxiliary branch of Alstom Grid's HDCCB model carries the fault current for a longer period of time than the ABB one.

Furthermore, the fault current interruption procedure in the ABB model finishes sooner than that of the Alstom Grid. Figure 11 describes in detail the zero-crossing points of these two HDCCB designs. It is observed that current zero of the ABB's HDCCB occurs at 0.093 s while this number is approximately 0.095 s in the Alstom Grid's HDCCB, 2 ms later than the former. For examining the case in which longer duration is needed for system protection, a delay time period of 3 ms is selected for the mechanical switch and the implementation is executed again. The zero-crossing point of this model in the new case is nearly 0.1 s, as shown in the dash-dot blue line in Figure 11. It is also observed that for the longer time of interruption, there is higher fault current of nearly 4000 A passing through the auxiliary branch of Alstom Grid's HDCCB. If the IGBT cells of ABB's HDCCB are used in this case, the very high value of the fault current can be a challenge for them. Hence, with the capability of safely withstanding very high fault currents, the thyristors used in Alstom Grid's HDCCB are preferred when the system requires more interruption time. In addition, in case the mechanical switch acts slowly compared to the IGBTs, thyristors are also more interested for application.

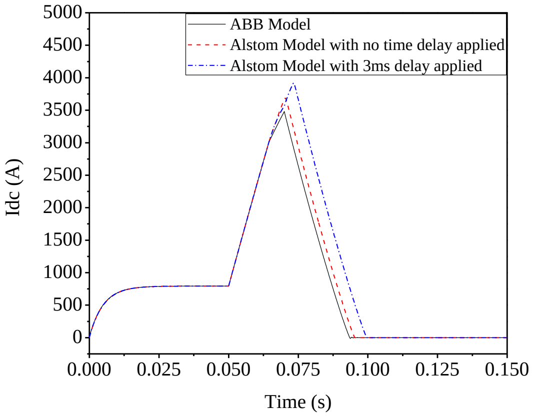


Figure 11. Zero-Crossing Points of Two HDCCB Models

4. Comparison between HDCCB Topologies of ABB and Alstom Grid

As the previous parts introduced and implemented two HDCCB schemes of ABB and Alstom Grid, it can be seen that they have same working principles in general with three substantial branches. The main branch consists of one main mechanical disconnector in series with one power electronic switch whose function is to commutate fault current into auxiliary branch at time of fault detection. Consequently, the auxiliary branch of the two HDCCB schemes carries the fault current not only to postpone for some time, but also to reduce the very high current burden on the mechanical switch while it is opening. The main surge arrester absorbs energy after fault current commutates from the auxiliary branch into this nonlinear resistor path.

Table 1 describes the comparison of ABB and Alstom Grid topologies in different aspects. First of all, the similarities of these two topologies are considered. ABB and Alstom Grid both apply the current commutation method with three significant branches for their own design. The main branch in each topology equivalently consists of one mechanical switch and at least a pair of anti-series IGBTs. In addition, the MOV is used in the third branch of the two topologies with equivalent voltage rating for energy dissipation.

Secondly, the main difference of ABB and Alstom Grid topologies locates in the auxiliary branch. ABB uses IGBT cells in series whereas thyristor stacks are preferred by Alstom Grid. There are some advantages and disadvantages of each semiconductor device mentioned above to be considered. The switching speed of the IGBTs is extremely high, which is either the benefit or the drawback of ABB’s HDCCB. It is pointed out that if the mechanical switch is slow or if a longer time is needed for the DC protection, IGBTs can meet the challenge when carrying the very high fault current which is increasing continuously. Accordingly, Alstom Grid uses thyristor stacks to fulfill this problem because they can safely withstand very high fault currents. However, the thyristors in this topology require a capacitor connected in series in order for fault current interruption.

When the two HDCCB topologies are compared with each other, according to the characteristics of the semiconductor devices, it can be noticed that ABB scheme interrupts the fault current more quickly whereas the design of Alstom Grid carries the high fault current more safely than each other. In practice, IGBTs with capability of switching on and off easily are more commercially favored so they might be more high priced than thyristor. Furthermore, in ABB topology, higher voltage level requires higher number of IGBT cells in series, leading to high component cost demand in HVDC system. Nevertheless, each thyristor stack is connected in series with one appropriate capacitor whose price increases depending on its size and voltage rating. Thus, the higher voltage level of the system leads to the higher component price for the Alstom Grid scheme.

Another difference between the two topologies locates in the power losses during normal operation. Because the IGBT cells in the auxiliary branch of ABB’s HDDCB remain turning on at steady state, there is a very small amount of losses when the load current passes through the HDCCB. The transfer losses of ABB’s HDCCB are only a percentage of the losses incurred by a pure semiconductor breaker, for example 0.01% of the transmitted power [10]. The utilization of IGBT cells makes the operation of the ABB’s HDCCB still include higher losses than the Alstom Grid’s HDCCB which uses thyristors. However, the losses in the capacitor banks in the Alstom Grid topology are also increased in case of the high voltage level.

Finally, the application of each topology in HVDC system is also considered. The voltage-source converter (VSC) HVDC system uses semiconductors which can pass current in either directions and can be controlled to turn on or off, for example IGBT-based switches. Meantime, the line-commutated converter (LCC) HVDC system consists of semiconductors which can carry voltage in either polarities and can be controlled to turn on only, for instance thyristor-based devices. Moreover, one of the disadvantages of the IGBT when compared to the thyristor is that the former has lower power capability and weaker overload capability than the latter. Accordingly, the thyristor-based LCC HVDC system can carry greater power and withstand overload more effectively than the IGBT-based VSC one. Hence, the applications of ABB's HDCCB should be included in VSC-HVDC system rather than LCC ones. On the contrary, the LCC-HVDC system is relatively more suitable for Alstom Grid's HDCCB. Furthermore, with economical consideration, the medium voltage DC (MVDC) system is more appropriate for ABB's HDCCB application rather than Alstom Grid one because the IGBT cost is not as high as the capacitor cost in MVDC system. However, the IGBT price increases significantly when IGBTs are applied in HVDC system. It is eventually higher than the capacitor price despite the increasing size and cost of the capacitor bank used in Alstom Grid's HDDCB. Thus, the price of ABB's HDCCB including IGBT cells is quite fairly higher than that of Alstom Grid one consisting of thyristor stacks and capacitors. Consequently, for HVDC system application, it is certain that Alstom Grid's HDCCB is preferred in systems which require longer time delay for system protection and ABB's HDCCB is more appropriate for systems in which fast current interruption is necessary.

Table 1. Comparison between ABB and Alstom Grid HDCCB Topologies

	ABB HDCCB	**Alstom Grid HDCCB**
Current breaking method	Current commutation method.	Current commutation method.
Main branch components	One mechanical disconnector in series with at least two IGBTs connected anti-series.	One mechanical disconnector in series with at least two IGBTs connected anti-series.
Auxiliary branch components	Uses IGBT cells in series.	Uses Thyristor stacks in series with an appropriate capacitor.
Surge arrester	MOV	MOV
Component cost demand	+ Depends on the number of IGBT cells. + The higher voltage level of the system, the more IGBT cells required.	+ Depends on the number of thyristor stacks and capacitor size. + The higher voltage level of the system, the larger size of capacitor required.
Advantages	+ The IGBTs are able to switch on and off very quickly. + IGBTs can be controlled to turn on or off easily.	The thyristors can withstand very high fault currents safely.
Disadvantages	In case of longer time needed for system protection, IGBTs struggles in withstanding high peak current.	Thyristors cannot be turned off easily as IGBTs. They require a capacitor connected in series to reduce fault current to zero in order for automatically turning off.
On-state losses	+ Low losses in the range of several tens of kW only. + Higher losses than Alstom Grid HDCCB.	+ Low on-state losses. + Low enough for the use of liquid coolants
Fault current interruption speed	+ Significantly high. + A few milliseconds higher than Alstom Grid topology.	High although the system protection require long time delay.
Application	Preferred in MVDC system and HVDC system in which the fast fault current interruption is required.	Preferred in HVDC system which requires the more time delay for system protection.

5. Conclusions

In this paper, the HDCCB topologies of ABB and Alstom Grid were compared. The differences between the two topologies locate in the semiconductor components in their auxiliary branch. In ABB topology, the special IGBT is used leading to an increasing total cost of its topology, and the losses in HDCCB is mainly due to the losses in IGBT cells. By comparison, in the Alstom Grid topology, thyristor stacks are used instead of IGBT cells, which require the capacitor banks to interrupt the fault current. Therefore its total cost can be increased due to the size of the capacitor banks. The fault current interruption speeds of both designs were examined and compared to each other. The results showed that the ABB model breaks the fault current more rapidly than the Alstom Grid one. It was also noticed that in case of longer time required for system protection, the Alstom Grid design with thyristor stacks in auxiliary branch can carry the very high fault current safely.

Acknowledgment

This work was supported by Incheon National University Research Grant in 2014.

References

[1] M. M. Rahman, M. F. Rabbi, M. K. Islam, and F. M. Mahafugur Rahman, “HVDC over HVAC Power Transmission System: Fault Current Analysis and Effect Comparison”, In Proceeding of the International Conference on Electrical Engineering and Information & Communication Technology (ICEEICT), Dhaka, **(2014)** April 10-12, pp. 1-6.

[2] G. F. Reed, H. A. Al Hassan, M. J. Korytowski, P. T. Lewis, and B. M. Grainger, “Comparison of HVAC and HVDC Solutions for Offshore Wind Farms with A Procedure for System Economic Evaluation”, In Proceeding of the IEEE Conference on Energytech, Cleveland, OH, **(2013)** May 21-23, pp. 1-7.

[3] T. Senda, T. Tamagawa, K. Higuchi, T. Horiuchi, and S. Yanabu, “Development of HVDC Circuit Breaker Based on Hybrid Interruption Scheme”, IEEE Trans. Power Apparatus and Systems, vol. PAS-103, no. 3, **(1984)** March, pp. 545-552.

[4] G. Ge, M. Liao, X. Duan, and J. Zou, “HVDC Hybrid Circuit Breaker Based on SF6 Interrupter and Vacuum Interrupter in Series”, In Proceeding of the 2nd International Conference on Electric Power Equipment – Switching Technology (ICEPE-ST), Matsue, **(2013)** October 20-23, pp. 1-4.

[5] C. Peng, A. Q. Huang, and X. Song, “Current Commutation in A Medium Voltage Hybrid DC Circuit Breaker Using 15 kV Vacuum Switch and SiC Devices”, In Proceeding of the Applied Power Electronics Conference and Exposition (APEC), Charlotte, NC, **(2015)** March 15-19, pp. 2244-2250.

[6] W. Zhou, X. Wei, S. Zhang, G. Tang, Z. He, J. Zheng, Y. Dan, and C. Gao, “Development and Test of A 200kV Full-Bridge Based Hybrid HVDC Breaker” In Proceeding of the IEEE 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), Geneva, **(2015)** September 8-10, pp. 1-7.

[7] O. Cwikowski, M. Barnes, R. Shuttleworth, and B. Chang “Analysis and Simulation of the Proactive Hybrid Circuit Breaker”, In Proceeding of the IEEE 11th International Conference on Power Electronics and Drive Systems (PEDS), Sydney, NSW, **(2015)** June 9-12, pp. 4-11.

[8] U. Amir Khan, J-G. Lee, F. Amir, and B-W. Lee, “A Novel Model of HVDC Hybrid-Type Superconducting Circuit Breaker and Its Performance Analysis for Limiting and Breaking DC Fault Currents”, IEEE Trans. Applied Superconductivity, vol. 25, no. 6, **(2015)** December.

[9] A. Hassanpoor, J. Hafner, and B. Jacobson, “Technical Assessment of Load Commutation Switch in Hybrid HVDC Breaker”, IEEE Trans. Power Electronics, vol. 30, no. 10, **(2015)** October, pp. 5393-5400.

[10] M. Callavik, A. Blomberg, J. Hafner, and B. Jacobson, “The Hybrid HVDC Breaker - An Innovation Breakthrough Enabling Reliable HVDC Grids”, ABB Grid Systems, Technical Paper, **(2012)** November.

[11] W. Grieshaber, J-P. Dupraz, D-L. Penache, and L.Violleau, “Development and Test of A 120kV Direct Current Circuit Breaker”, CIGRÉ Session, Paris, **(2014)**, Paper B4-301.

[12] R. Derakhshanfar, T.U. Jonsson, U. Steiger, and M. Habert, “Hybrid HVDC Breaker – Technology and Applications in Point-to-Point Connections and DC Grids”, CIGRÉ Session, Paris, **(2014)**, pp. 1-11.

[13] C. C. Davidson, R. S. Whitehouse, C. D. Barker, J-P. Dupraz, and W. Grieshaber, “A New Ultra-Fast HVDC Circuit Breaker for Meshed DC Networks”, In Proceeding of the IEEE 11th International Conference on AC and DC Power Transmission, Birmingham, **(2015)** February 10-12, pp. 1-7.

[14] B-C. Kim, Y-H. Chung, H-D. Hwang, and H-S Mok, “Development of HVDC Circuit Breaker with Fast Interruption Speed”, In Proceeding of the IEEE 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), Seoul, **(2015)** June 1-5, pp. 2844-2848.

[15] A. Raza, X. Diangou, S. Xunwen, and L. Weixing, “Appraisal of VSC Based MTDC System Topologies for Offshore Wind Farms”, In Proceeding of the IEEE 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), Seoul, **(2015)** June 1-5, pp. 2141-2147.

Authors

Anh-Duc Nguyen, he received B.S. degree in Electrical Engineering from Hanoi University of Science and Technology, Vietnam in 2014. Currently, he is a combined Master and Ph.D. student in the Department of Electrical Engineering, Incheon National University, Korea. His research interests include HVDC protection and HVDC applications.

Thai-Thanh Nguyen, he received B.S. degree in Electrical Engineering from Hanoi University of Science and Technology, Vietnam in 2013. Currently, he is a combined Master and Ph.D. student in the Department of Electrical Engineering, Incheon National University, Korea. His research interests include power system analysis and FACTS & HVDC modeling and analysis.

Hak-Man Kim, he received his first Ph.D. degree in Electrical Engineering from Sungkyunkwan University, Korea in 1998 and received his second Ph.D. degree in Information Sciences from Tohoku University, Japan, in 2011, respectively. He worked for Korea Electrotechnology Research Institute (KERI), Korea from Oct. 1996 to Feb. 2008. Currently, he is a professor in the Department of Electrical Engineering, Incheon National University. His research interests include Microgrids and DC power systems.