A Zero Crossing Hybrid Bidirectional DC Circuit Breaker for HVDC Transmission Systems

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Article

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Abstract: With the increasing demand for renewable energy power generation systems, high-power DC transmission technology is drawing considerable attention. As a result, stability issues associated with high power DC transmission have been highlighted. One of these problems is the fault current that appears when a fault occurs in the transmission line. If the fault current flows in the transmission line, it has a serious adverse effect on the rectifier stage, inverter stage and transmission line load. This makes the transmission technology less reliable and can lead to secondary problems such as fire. Therefore, fault current must be managed safely. DC circuit breaker technology has been proposed to solve this problem. However, conventional technologies generally do not take into account the effects of fault current on the transmission line, and their efficiency is relatively low. The purpose of this study is to introduce an improved DC circuit breaker that uses a blocking inductor to minimize the effect of fault current on the transmission line. It also uses a ground inductor to efficiently manage the LC resonant current and dissipate residual current. DC circuit breakers minimize adverse effects on external elements and transmission lines because the use of elements placed on each is distinct. All of these processes are precisely verified by conducting simulation under 200 MVA (±100 kV) conditions based on the VSC-based HVDC transmission link. In addition, the mechanism was explained by analyzing the simulation results to increase the reliability of the circuit in this paper.

Keywords: DC circuit breaker; ±230 kV MMC-HVDC; zero-crossing DCCB; DC transmission line; fault current; hybrid DCCB; bidirectional DCCB; external elements; energy dissipation

1. Introduction

Modern society needs much more electric power than in the past [1]. Therefore, the power generation sector is focused on power generation and transmission [2]. As a result, the instability of high-power direct current (DC) transmission technology was emphasized [3].

High voltage direct current (HVDC) transmission systems can be divided into voltage source converter (VSC) and current source converter (CSC) HVDC systems according to the switching element of the converter [4]. VSC HVDCs using insulated gate bipolar transistor (IGBT) have a small installation area and does not require reactive power compensation facilities [5]. It can also be used in a variety of ways because it has free bidirectional transmission and does not require an alternating current (AC) voltage source [6].

If a problem occurs in the transmission line of the VSC HVDC, a fault current is generated by the fast waveform [7]. This can cause the entire grid of multi-terminal HVDC to be blocked or severely adversely affect the power elements connected to the transmission line [8,9]. Therefore, DC circuit breaker technology that can safely manage fault current has been proposed [10].

DC circuit breaker technology can be divided several ways, of which the zero-crossing breaking method safely manages fault current by generating zero current in the main transmission line and turning off the switch [11,12]. The performance of a DC circuit breaker is an indicator of the breaking time of the main transmission line and the amount...
of leakage current to the outside [13–15]. Therefore, it is very important to manage electric current on the transmission line elements during high-power transmission [16].

DC circuit breakers (DCCBs) are generally classified by switch type into mechanical DCCB, semiconductor DCCB, and hybrid DCCB [17]. Hybrid DCCB is considered the most suitable type of DC circuit breakers for HVDC because it solves the problem of slow operation speed, the disadvantage of mechanical DCCB, and power loss, the disadvantage of semiconductor DCCB [18]. In general, hybrid DCCB places a mechanical switch on the main transmission line through steady-state current, so the current does not pass through the semiconductor switch in the on-state [19].

The breaking direction of the DC circuit breaker can be either unidirectional or bidirectional [20]. In a bidirectional DCCB, the breaker can operate normally regardless of the location of the main transmission line, which facilitates mass production and reduces manufacturing costs [10]. In this paper, we simulated a hybrid bidirectional HVDC DCCB using a zero-crossing method assuming VSC-based HVDC transmission.

Section 2 describes the mechanism of current flow through the circuit operation process and how it is used as a bidirectional DCCB. Section 3 describes the simulation results and analysis. Initially, detailed simulation conditions are specified, and the reverse charging process, blocking inductor and ground inductor are analyzed in order from Sections 3.1–3.3. In Section 3.4 we will analyze the use of switching elements and energy dissipation to increase the reliability of the DCCB and conclude in Section 4.

2. Circuit Operation Process

Figure 1 shows the current flow in the DCCB proposed in this paper is in a steady-state. If the DC steady-state persists, the blocking inductor has no effect. It does not cause any additional power loss. The steady-state current charges the reverse charge capacitor, so no further action is required when operating later. Even in this case, there is no power loss when the reverse charge thyristor is fully charged. The proposed DCCB works well even if there is a fault current anywhere in the transmission line.

![Figure 1. The overall circuit diagram of the DCCB proposed in this paper and the steady-state current flow.](image)

Figure 2 shows the flow of the fault current from the rectifier stage to the DCCB and the emitted the inductor and the capacitor (LC) resonant current. When a fault current is detected, it sends a signal to the gate terminal of the reverse charge thyristor and proceeds with the reverse charging process. At this time, some of the fault currents are used in the reverse charging process to create a larger resonant current. Immediately after that, the
LC resonant current is emitted by turning of the left or right thyristors according to the direction of the fault current [21]. When the fault current and LC resonant current are zero-crossed, the mechanical switch on the main transmission line turns off to eliminate the effect of fault current.

Figure 2. Current flow of LC resonant emission current and fault current from the rectifier stage to the DCCB.

The DCCB in this paper can break in both directions, as described above. Unlike the example in Figure 2 where there is a fault current in the rectifier stage, when the fault current flows from the inverter stage to the DCCB, the reverse charging process is the same, and when the right thyristor is turned on, the LC resonant current is emitted to generate a zero crossing point and the right mechanical switch is turned off.

Figure 3 shows the flow of residual current after zero-crossing of the DCCB main switch. To minimize the effect of residual current on the rectifier and inverter stages, the current is returned to the DCCB through parallel diodes and bypass diodes. At this time, the reverse charge thyristor is turned on continuously, dissipating the energy in the DCCB to the ground. When the residual current is removed to the ground, it resonates through the ground inductor passing through, leaving a small amount of energy in the DCCB but with little effect.

Figure 3a shows the current flow after breaking the fault current passing from the rectifier stage to the DCCB, and Figure 3b shows the current flow after breaking the fault current passing from the inverter stage to the DCCB. The mechanism for directing current flow through a diode connected in parallel to the mechanical switch, which is usually the main switch, is the same. Depending on the direction of the fault current according to the placement of the DCCB, the flow of residual current is symmetrical and the process of dissipating energy through the ground is the same.
3. Simulation Results and Analysis

Figure 4a schematically shows the simulated VSC-based transmission circuit to test the DCCB proposed in this paper. The simulation was performed assuming that a fault occurs in 230 kV, 50 Hz, and 200 MVA transmission between the DCCB and a 30 km cable [22,23]. Assuming the fault current flowing to the DCCB in the rectifier stage in the schematic, the DCCB in this paper can break the fault current in both directions, so in the example, the DCCB could be placed on the adjacent stage of the modular multilevel converter (MMC) on the right.

Figure 4b is a graph showing the magnitude of the fault current when a fault occurs within 3 s under a given simulation condition. Simulations performed under these conditions show that the current increases rapidly in 3 s and then gradually decreases [24].

The basic parameters used in the simulation are summarized in Tables 1–3. These parameters are default values. Optimized values are identified by analyzing the results as described later. Also, the current limiting reactors in Table 2, not shown in the schematic diagram of Figure 2, refer to the inductors used at both ends of the transmission line of a general DCCB.
Figure 5 is a graph comparing the reverse-charge method and the normal-charge method used in the proposed DCCB. The resonant current signals the switch's gate (in this case, the left thyristor), assuming that it is emitted within 0 s when turned on. In general, the larger the value of the resonant current emitted, the faster the same amount of fault current
can be zero-crossed. However, as the amount of generated resonant current increases, more energy remains, making it difficult to eliminate residual current.

Figure 5. Comparison of the magnitude of resonant current between the reverse-charge method and the normal-charge method in the DCCB in the proposed DCCB.

When comparing the reverse-charge method and the normal-charge method used in the proposed DCCB, the reverse-charge method generates a peak resonant current that is 7.03 times larger than that of the normal-charge method. The slope of the current before peaking is also steeper when using the reverse-charge method than the normal-charge method [25]. This means that when using the reverse-charge method, zero-crossing can be performed faster on the mechanical switch of the main current branch. However, a corresponding problem arises, more energy must be dissipated. This issue will be addressed in Section 3.4.2, but in the case of the DCCB in this paper, energy can be dissipated efficiently due to the path of current to ground.

3.2. Blocking Inductor

Figure 6 shows the peak current in the inverter and rectifier stages depending on the blocking inductor. Regardless of the value of the two DCCB inductors, the impedance of the transmission line increases as the value of the blocking inductor increases. Therefore, the amount of current flow in the inverter stage is reduced. The graph does not clearly show the effect of the inductor when the blocking inductor is less than $10^{-4}$ H. However, when it exceeds $10^{-3}$ H, the peak current is greatly improved. When the value of the blocking inductor exceeds $10^{-3}$ H, the peak current in the inverter stage decreases rapidly.
The peak current in the rectifier stage decreases significantly after passing the bifurcation point. This bifurcation point occurs at 4 mH ($4 \times 10^{-3}$ H) when the sum of current limiting reactor values is 0.2 mH ($2 \times 10^{-4}$ H), and at 2 mH ($2 \times 10^{-3}$ H) when the sum of current limiting reactor values is 2 mH ($2 \times 10^{-3}$ H). This kind of bifurcation point occurs when the value of the blocking inductor is greater than the value of current limiting reactors and the sum of the inductors of the main current branch exceeds 3 mH ($3 \times 10^{-3}$ H). Increasing the value of the blocking inductor and exceeding the aforementioned bifurcation point can rapidly reduce the peak current in the rectifier stage.

However, since the blocking inductor is located in the transmission line, if an excessively large value is used, the time from initial transmission to steady-state may be extended. Therefore, the optimized value of the blocking inductors must cross the bifurcation point to rapidly reduce the peak current in the rectifier stage so as not to be excessive.

### 3.3. Ground Inductor

Figure 7 shows the peak current, zero crossing time (ZCT), and rectifier current stable time (RST) depending on the ground inductor. ZCT is the time the main switch is turned off at the main current branch. The fault current is equal to the LC resonant current, so this generates a current zero. RST is the time until the current in the rectifier stage is stabilized (usually less than the steady-state current).

Increasing the ground inductor causes less LC resonant current to flow to ground and more LC resonant current to emit to the main switch. Therefore, ZCT is shortened because more resonant current is emitted. However, the larger ground inductor, the less the current returned to the DCCB by increasing its own impedance after the main switch breaks. As a result, the ground current decreases and the rectifier stage takes a long time to stabilize.

In the graph, when the value of the ground inductor is small, the characteristic change in characteristics is very small, but when it is greater than $10^{-3}$ H, the effect is remarkable, so the value of the ground inductor has a trade-off relationship between ZCT and RST. Since ZCT and RST cannot be designed well at the same time, the trade-off characteristics must be considered in the DCCB design procedure.
The ground inductor has the same characteristics when changed to a resistive element. Even in the case of the resistors, there is no significant power loss when the reverse charge capacitor is fully charged. Likewise, the larger the resistance, the more LC resonant current is emitted to the main switch, but less current is returned to the DCCB after the main switch break. However, when using an inductor on the ground, the more the current changes over time, the higher the impedance and the less current flow. Therefore, less current flows to the ground than when using a resistor, and conversely, more resonant current can be effectively emitted to the main switch. Because of these characteristics, in this paper, we use a ground inductor for the DCCB with better characteristics.

3.4. Elements
3.4.1. Switching Element Verification

Figure 8 shows the peak current in the inverter and rectifier stages when different cases. In case 1, all elements are in normal conditions in the DCCB. In case 2, the left and right parallel diodes are removed. In case 3, the reverse charging process, which is one of the use of the left and right bypass diodes, proceeds the same as in case 1, except that residual current flows in the DCCB after the main switch breaks. Case 4 assumes that both the left and right thyristors are both turned on and the LC resonant current is emitted without specifying the direction.

In case 2, the load on the parallel diodes disappears. Therefore, the influence of the residual current increases in the rectifier stage. In the DCCB in this paper, the peak current in the rectifier stage can be reduced by about 28% using parallel diodes. This can significantly reduce the adverse effects on the elements of the rectifier stage. There doesn’t seem to be a significant difference in the result value for case 3 compared to case 1, but there is a problem with energy dissipation. This is described in Section 3.4.2. By using of the bypass diode, the residual energy caused by the LC resonant current can be efficiently dissipated. In case 4, the direction of the LC resonant current cannot be specified, since both thyristors are turned on. Therefore, part of the LC resonant current affects the inverter stage and creates a high load on the transmission line. In this paper, specifying the emission direction of the LC resonant current in the DCCB can reduce peak current in the inverter stage by about 17%. This reduction in current significantly reduces the load on the transmission line, mainly in the inverter stage.
Figure 8. Peak current in the inverter and rectifier stage when different cases; Case 1: All elements are operating under normal conditions; Case 2: Under normal conditions, the parallel diodes are removed; Case 3: Under normal condition, the bypass diode is changed to a thyristor, the mechanical switch is turned off, the changed thyristor is also turned off (The reverse charging process works the same.); Case 4: Under normal conditions, resonant current is emitted without specifying the direction of the thyristor (both the left and right thyristors are turned on).

3.4.2. Energy Dissipation Verification

Figure 9a schematically shows the dissipation process in the proposed DCCB. The use of dissipative thyristors near ground in this DCCB is schematically illustrated in Figure 9c,d. Also, the measured node was expressed to verify the energy dissipation between the DCCB and the transmission line. The voltage measurement in Figure 9c represents the residual energy of the DCCB, and the residual energy of the transmission line is verified by the voltage measurement in Figure 9d.
Figure 9. Simulation of energy dissipation in the DCCB proposed in this paper (a) Schematic illustration of the DCCB diagram in the presence of the dissipative thyristor. (b) Current flow in the presence of the dissipative thyristor. (c) Graph of voltage between the DCCB and ground over time. (d) Graph of voltage between the main current branch and ground over time.

Figure 9b schematically shows the current flow after the main mechanical switch is turned off when there is a dissipative thyristor in Figure 9a. In the absence of a dissipative thyristor in the proposed DCCB, residual current will inevitably flow through the ground inductor to ground, resulting in ripple. As can be seen in Figure 9c,d, the value of this ripple is very small compared to the steady-state voltage. If you need to further reduce the ripple, turn on the dissipative thyristor after the main switch is turned off, so the current will not pass through the ground inductor. As shown in Figure 3b, when the fault current occurs in the opposite direction, as shown in Figure 3b, only the current flow from the DCCB to the ground passes through the dissipative thyristor.

Figure 9c shows the voltage between the DCCB and the ground. In the proposed DCCB, ZCT occurs within 1ms under simulated conditions and RST is less than 2 ms. Therefore, in order to independently analyze the use of the dissipative thyristor in the
energy dissipation process, the dissipative thyristor was turned on after 0.1 s (100 ms). Since the fault current did not occur 3 s ago, the voltage of the DCCB is the same as the voltage charged to the reverse charge capacitor under the normal steady-state. When the main switch is turned off and the energy dissipation process is reached, 99% of the voltage is lost to ground even without the dissipative thyristor, leaving little residual energy in the DCCB. Therefore, even without the surge arrester, the energy dissipation problem rarely occurs when the DCCB proposed in this paper is used. This small ripple can also be made to converge to zero by turning on the dissipative thyristor shown in Figure 9a. Analyzing the current at 4–4.1 s confirms that it converges to zero when the dissipative thyristor is turned on.

Figure 9d shows the voltage between the main current branch and ground. Figure 9d is very similar to the graph in Figure 9c. The voltage state is normal 3 s ago, when the main switch is turned off, the voltage decreases sharply. At this time, the proposed DCCB rapidly dissipates the energy equivalent to 98% of the energy seen under normal voltage conditions, similar to Figure 9c. This amount of loss doesn’t cause much trouble but using a dissipative thyristor to converge the voltage to zero can completely eliminate the energy dissipation problem.

4. Conclusions

We have designed an improved DC circuit breaker taking into account external elements and the transmission line by expanding the conventional breaker technology. Due to the development of high-power transmission, the influence of the current on the external elements and the transmission line cannot be ignored. The DC circuit breaker in this paper uses a blocking inductor to reduce the load on the transmission line at the inverter stage and significantly reduce the amount of current flow through the rectifier stage based on the bifurcation point to protect the device and circuit. When determining the value of the ground inductor, ZCT and RST were found to have an inverse relationship, and the inductor was selected according to the optimal analysis methodology for the proposed DCCB design. In addition, verification of the individual switching elements was carried out in detail to confirm the use of each element in the DCCB. Moreover, the problem of energy dissipation, which is a concern due to the lack of a reverse charging process or a surge arrester, was solved by analyzing the ground voltage between the DCCB and the transmission line. The current flow mechanism has been analyzed to increase reliability and aid further research in the field of DCCB.

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References

1. Asplund, G. Sustainable energy systems with HVDC transmission. In Proceedings of the Eighth IEEE International Symposium on Spread Spectrum Techniques and Applications—Programme and Book of Abstracts, Sydney, NSW, Australia, 30 August–2 September 2004.
2. Long, W.; Nilsson, S. HVDC transmission: Yesterday and today. IEEE Power Energy Mag. 2007, 5, 22–31. [CrossRef]
3. Rudervall, R.; Charpentier, J.P.; Raghuveer, D. High voltage direct current (HVDC) transmission systems technology review paper. *Energy World* 2000, 2000, 1–19.

4. Flourentzou, N.; Agelidis, V.G.; Demetriades, G.D. VSC-Based HVDC power transmission systems: An overview. *IEEE Trans. Power Electron.* 2009, 24, 592–602. [CrossRef]

5. Nakajima, T.; Irokawa, S. A control system for HVDC transmission by voltage sourced converters. In Proceedings of the 1999 IEEE Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No.99CH36364), Edmonton, AB, Canada, 18–22 July 1999.

6. Schettler, F.; Huang, H.; Christl, N. HVDC transmission systems using voltage sourced converters design and applications. In Proceedings of the 2000 Power Engineering Society Summer Meeting (Cat. No.00CH37134), Seattle, WA, USA, 16–20 July 2000.

7. Elserougi, A.A.; Abdel-Khalik, A.S.; Massoud, A.M.; Ahmed, S. A new protection scheme for HVDC converters against DC-side faults with current suppression capability. *IEEE Trans. Power Deliv.* 2014, 29, 1569–1577. [CrossRef]

8. Mei, J.; Fan, G.; Ge, R.; Wang, B.; Zhu, P.; Yan, L. Research on Coordination and optimal configuration of current limiting devices in HVDC Grids. *IEEE Access* 2019, 7, 106727–106739. [CrossRef]

9. Tzalepis, D.; Blair, S.M.; Dysko, A.; Booth, C. DC busbar protection for HVDC Substations incorporating power restoration control based on dyadic sub-band tree structures. *IEEE Access* 2019, 7, 11464–11473. [CrossRef]

10. Franck, C.M. HVDC circuit breakers: A review identifying future research Needs. *IEEE Trans. Power Deliv.* 2011, 26, 998–1007. [CrossRef]

11. Shukla, A.; Demetriades, G.D. A survey on hybrid circuit-breaker topologies. *IEEE Trans. Power Deliv.* 2015, 30, 627–641. [CrossRef]

12. Van Gelder, P.; Ferreira, J.A. Zero volt switching hybrid DC circuit breakers. In Conference Record of the 2000 IEEE Industry Applications Conference. In Proceedings of the Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No. 00CH37129), Rome, Italy, 8–12 October 2000.

13. Xu, Z.; Xiao, H.; Xiao, L.; Zhang, Z. DC fault analysis and clearance solutions of MMC-HVDC Systems. *Energies* 2018, 11, 941. [CrossRef]

14. Javed, W.; Chen, D.; Farrag, M.E.; Xu, Y. System configuration, fault detection, location, isolation and restoration: A review on HVDC microgrid protections. *Energies* 2019, 12, 1001. [CrossRef]

15. Li, B.; He, J.; Li, Y.; Wen, W. A novel DCCB reclosing strategy for the flexible HVDC Grid. *IEEE Trans. Power Deliv.* 2019, 35, 244–257. [CrossRef]

16. Meah, K.; Ula, S. Comparative evaluation of HVDC and HVAC transmission systems. In Proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24–28 June 2007; pp. 1–5.

17. Wei, T.; Yu, Z.; Zeng, R.; Chen, Z.; Zhang, X.; Wen, W.; Huang, Y. A novel hybrid DC circuit breaker for nodes in multi-terminal DC system. In Proceedings of the IECON 2017—43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 29 October–1 November 2017.

18. Daibo, A.; Niwa, Y.; Asari, N.; Sakaguchi, W.; Takimoto, K.; Kanaya, K.; Ishiguro, T. High-speed current interruption performance of hybrid DCCB for HVDC transmission system. In Proceedings of the 4th International Conference on Electric Power Equipment—Switching Technology (ICEPE-ST), Xi’an, China, 22–25 October 2017.

19. Peng, C.; Husain, I.; Huang, A.Q.; Lequesne, B.; Briggs, R. A fast mechanical switch for medium voltage hybrid DC and AC circuit breakers. In Proceedings of the 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, Canada, 20–24 September 2015.

20. Ray, A.; Rajashekar, K.; Banavath, S.N. Bidirectional coupled inductor based hybrid circuit breaker topologies for DC System Protection. In Proceedings of the 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 17–21 March 2019; pp. 1138–1145.

21. Sima, W.; Fu, Z.; Yang, M.; Yuan, T.; Sun, P.; Han, X.; Si, Y. A novel active mechanical HVDC Breaker with consecutive interruption capability for fault clearances in MMC-HVDC systems. *IEEE Trans. Ind. Electron.* 2018, 66, 6979–6989. [CrossRef]

22. Li, J.; Zhao, X.; Song, Q.; Rao, H.; Xu, S.; Chen, M. Loss calculation method and loss characteristic analysis of MMC based VSC-HVDC system. In Proceedings of the 2013 IEEE International Symposium on Industrial Electronics, Taipei, Taiwan, 29–31 May 2013; pp. 1–6.

23. Amin, M.; Molinas, M.; Lyu, J.; Mohammad, A. Oscillatory phenomena between wind farms and HVDC systems: The impact of control. In Proceedings of the 2015 IEEE 16th Workshop on Control and Modeling for Power Electronics (COMPEL), Vancouver, BC, Canada, 12–15 July 2015.

24. Jia, H.; Yin, J.; Wei, T.; Huo, Q.; Li, J.; Wu, L. Short-circuit fault current calculation method for the multi-terminal DC Grid considering the dc circuit breaker. *Energies* 2020, 13, 1347. [CrossRef]

25. Guo, Y.; Wang, G.; Zeng, D.; Li, H.; Chao, H. A thyristor full-bridge-based dc circuit breaker. *IEEE Trans. Power Electron.* 2019, 35, 1111–1123. [CrossRef]