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# A Clamping Type DC Circuit Breaker with Short Fault Isolation Time and Low Energy Dissipation

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**Abstract-** The development of DC grids faces challenges from DC fault protection. The conventional DC circuit breaker (DCCB) employs metal-oxide varistor (MOV) to isolate the faulted line, in which the fault isolation process is coupled with the energy dissipation process. In this study, a clamping type DCCB (CTCB) uses internal capacitors to clamp the converter voltage is proposed. Thanks to the proposed configuration, fault isolation and energy dissipation are decoupled, resulting in a fast fault isolation and low energy dissipation compared to the conventional DCCB. The working principle of the proposed CTCB is presented and verified in a DC grid simulation model. A comparison is made with the traditional DCCB. The fault isolation time can be reduced by 34.5 %. The dissipated energy can be reduced by 17.4 %. The energy dissipation power can be reduced by 76.2 %.<sup>1</sup>

**Index Terms-** MMC; HVDC grid; DC fault; DC circuit breaker; DC protection.

## NOMENCLATURE

DCCB	Direct current circuit breaker
LCS	Load commutation switch
UFD	Ultra-fast disconnecter
MB	Main breaker
MOV	Metal-oxide varistor
MVC	Main voltage clamper
EAB	Energy absorption branch
CLR	Current limiting reactor
RCB	Residual current breaker

## I. INTRODUCTION

The high voltage direct current (HVDC) grid based on the modular multilevel converter (MMC) is considered to be an effective solution for transferring renewable energy and AC grid interconnection [1]-[3]. The DC fault protection is one of the most challenging obstacles limits the wide application of DC grids. Therefore, significant attention has been paid to DC fault clearance methods from the industry and academia [4]-[5]. Due to the small circuit impedance of DC grid, DC fault currents grow rapidly and the DC fault propagates very fast.

Therefore, the fault current should be interrupted within a short period, e.g. 5 ms, to protect the converters from blocking.

The large fault current will also challenge the power rating of the energy dissipation devices, which require to dissipate the residual energy within a few milliseconds to ensure a fast post-fault restoration. Thus, the applied energy dissipation devices may face risks under this high power transient process. For instance, some modules may be damaged due to the unbalanced voltage-current sharing or overheating [6]-[7]. Therefore, the DC grid fault clearing method must meet two basic requirements: 1) fast fault current isolation and 2) low energy dissipation.

DC circuit breaker (DCCB) has been considered as one of the essential equipment to protect DC grids [8]-[9], which can achieve a fully selective protection compared to methods based on converters with fault blocking capability [10]-[11]. Although solid-state DCCBs can complete a fast fault current interruption, their high on-state losses are the main demerits limit their applications. Hybrid DCCBs use the current commutation branch to realize a tradeoff between low conduction losses and fast interruption speed. ABB firstly proposed the concept of hybrid DCCB, which can interrupt 9 kA fault current in 3 ms. It uses hybrid branch to conduct load current, and anti-series IGBTs are used to achieve bidirectional protection capability [8]. Alstom has developed its hybrid DCCB with 15 kA/3 ms fault interruption capability, in which thyristors are used to reduce the total cost [12]-[13]. China State Grid has installed the first three engineering operating hybrid DCCBs with a capacity of 15 kA/3 ms in the Zhoushan 5-terminal 200 kV MMC-HVDC project [14]-[15], in which full-bridge sub-modules are used to block the DC fault. In 2020, the 500 kV diode bridge based hybrid DCCB with 25 kA capacity had been operated in the Zhangbei DC grid [16].

Despite different topologies of the existing DCCBs, their core purpose is to force the fault current flow into the metal-oxide varistor (MOV). The MOV will insert a counter voltage into the fault circuit, and then the fault current will decrease by dissipating the fault energy [17-18]. A large MOV resistance can dissipate the fault energy fast. However, it needs a high energy dissipation power rating, which may result in a large dimension and high cost. An MOV with low resistance will reduce its requirement for power rating, but will slow the fault isolation speed and enlarge the total dissipated energy. Moreover, the high power rating or high

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energy dissipation of the MOV will both reduce its service life. In this case, it is of great significance to find an optimal solution which can balance the requirements of fault clearing speed and energy dissipation capacity.

In this study, a clamping type DCCB (CTCB) with decoupled fault current decreasing and energy dissipation process is proposed. Capacitor modules are used to withstand the voltage difference between the DC bus and the faulted line. The faulted line can be isolated first once the capacitor is fully charged at a zero current. The energy stored in the capacitor modules is then dissipated by its resistance-capacitor (RC) circuit rather than MOV. Moreover, a line-side bypass branch is also designed to help achieve the fast fault isolation and low energy dissipation.

An introduction of the conventional hybrid DCCB is given in Section II. The topology, working principle and parameter analysis of the proposed CTCB are presented in Section III. In Section IV, the performance of the proposed CTCB is verified in a four-terminal DC grid through simulations conducted in PSCAD/EMTDC. The comparisons of the proposed CTCB with the traditional DCCBs are provided in Section V. The conclusion is drawn in Section VI.

## II. PRINCIPLE OF THE TRADITIONAL HYBRID DCCB

The conventional hybrid DCCB is shown in Fig. 1, which is composed of a load commutation switch (LCS), an ultra-fast disconnector (UFD), a main breaker (MB) and an MOV [8]. RCD snubber circuits are equipped for protecting the insulated-gate bipolar transistors (IGBTs). Moreover, a current limiting reactor (CLR) is used to limit the rate-of-rise of the fault current. A residual current breaker (RCB) is used to isolate the faulted line from the healthy circuit.

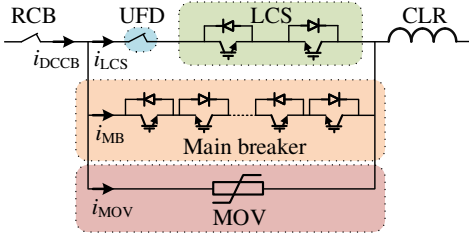


Fig. 1. Topology of the conventional hybrid DCCB.

The operation process of DCCB can be divided into four stages: Before the fault is detected, the DC current flows through the LCS branch in stage I. Once a fault is detected, the MB is conducted, and the LCS will be blocked immediately. In stage II, the fault current commutates to the MB, and the UFD starts to open. The fault current will keep rising in stage II. From the beginning of stage III, the UFD is in open position, the MB is turned off to break the current. The fault current is forced to the MOV branch and fault energy absorbed in MOV. The fault current reaches zero at the end of stage III. At last, the RCB is used to isolate the faulted line from the healthy grid in stage IV, see Fig. 2.

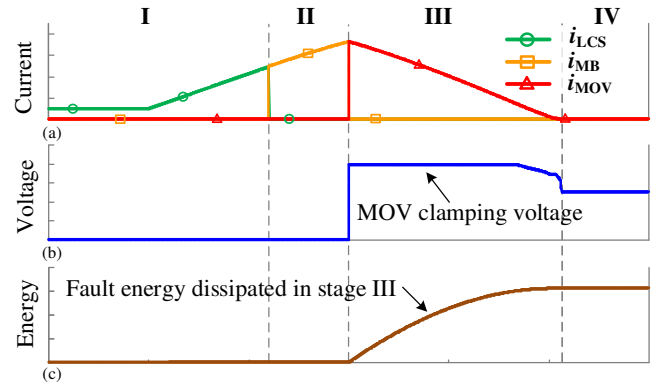


Fig. 2. Operation process of DCCB. (a) Current; (b) Voltage; (c) Energy.

As shown in Fig. 2, the fault current decreasing process and MOV energy dissipation is coupled in the conventional DCCB. The fault energy all concentrate in the MOV in several milliseconds, which increases the burden of MOVs, and limits a further reduction of the fault isolation speed. In this study, a new type of DCCB with decoupled fault isolation and energy dissipation is proposed, and the peak MOV power is also reduced by prolonging the energy dissipation process.

## III. THE PROPOSED CLAMPING TYPE DCCB

### A. Topology and Working Principle

The proposed CTCB is shown in Fig. 3. It consists of the UFD and LCS, the main voltage clamper (MVC) and the line-side energy absorption branch (EAB). It should be mentioned that the topology shown in Fig. 3 is unidirectional for the purpose of easy presenting. The bidirectional topology will be discussed in Section III-B.

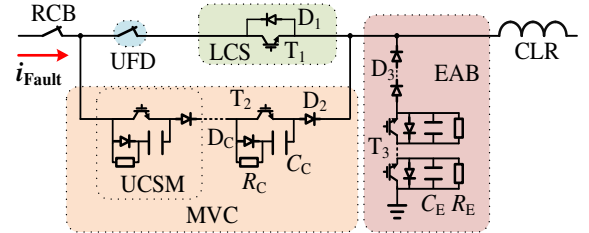


Fig. 3. Topology of the proposed CTCB.

The MVC consists of numbers series-connected unidirectional clamping sub-modules (UCSMs), which can force the fault current to charge the capacitors in one direction. The resistance  $R_C$ , diode  $D_C$ , and capacitor  $C_C$  form the RCD circuit which will dissipate the energy stored in  $C_C$ . The EAB provides a free-wheeling current path for the residual fault current in the faulted line. The diodes ( $D_3$ ) in EAB are used to withstand the DC voltage in the normal state.  $C_E$  and  $R_E$  are employed to dissipate the fault energy stored in the CLR and fault current path once the IGBTs ( $T_3$ ) are blocked.

Compared to the traditional DCCB, the proposed CTCB uses  $C_C$  to achieve DC fault isolation. The capacitor also acts as an energy storage station to absorb the fault energy. Then, the fault energy on the converter-side and line-side is dissipated separately, which can reduce the CB's overall

requirements. However, the capacitor based DCCB [19-20] only uses capacitors to assist the fault current transfer to the MOV, and the energy dissipation process is similar to the conventional DCCB.

There are four operation states of the proposed CTCB: normal operation, current commutation, voltage clamping and energy dissipation.

1) **Normal operation** ( $t_0 \rightarrow t_1$ ): Assuming that the DC fault occurs at  $t_0$ , and the fault will not be detected until  $t_1$ . Only  $T_1$  is conducted during the normal operation, the current flows through the LCS branch, as shown in Fig. 4 (a).

2) **Current commutation** ( $t_1 \rightarrow t_2$ ):  $T_2$  will be triggered and the LCS will be turned off once a DC fault is detected at  $t_1$ . Then, as shown in Fig. 4 (b), the current commutates to the MVC, and the UFD starts to open.

3) **Voltage clamping** ( $t_2 \rightarrow t_4$ ): The UFD is fully opened at  $t_2$ . Then,  $T_2$  will be turned off to charge  $C_C$ . At the same time,  $T_3$  is triggered to create a free-wheeling circuit to transfer the fault current, as shown in Fig. 5 (a). There are two sub-states with the variation of the clamber capacitor voltage  $u_C$ .

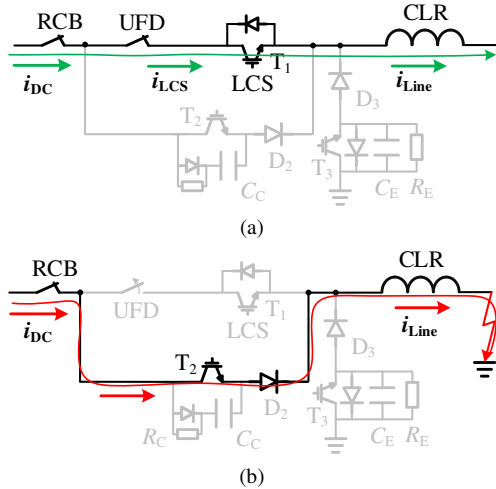


Fig. 4. Operation states of the proposed CTCB. (a) Normal operation  $t_0 \rightarrow t_1$ ; (b) Current commutation  $t_1 \rightarrow t_2$ .

①  $u_C < u_S$  ( $t_2 \rightarrow t_3$ ):  $u_C$  starts to raise from  $t_2$ . The DC line voltage  $u_{Line}$  equals to  $u_S$  minus  $u_C$ , thus it will keep decreasing.  $u_{Line}$  is also the voltage on the CLR, so the fault current will still keep rising, but the rate of rise will become slowly with the  $u_{Line}$  decreasing. It should be mentioned that, during this period, there is no current in the free-wheeling circuit due to the line voltage  $u_{Line}$  is still over zero.

②  $u_C = u_S$  ( $t_3 \rightarrow t_4$ ): The line voltage  $u_{Line}$  will become zero when  $u_C = u_S$  at  $t_3$ . Then, the free-wheeling current  $i_E$  starts to flow through the EAB, as shown in Fig. 5(a). Because of the system inductance, the capacitor current  $i_C$  may not decay to zero immediately. Therefore,  $u_C$  will keep raising for a while.  $i_{Line}$  will totally transfer to the EAB once  $i_C$  becomes zero at  $t_4$ .

4) **Energy dissipation** ( $t_4 \rightarrow t_6$ ): The RCB starts to open at zero current after  $t_4$ . The faulted line will be isolated from the healthy circuit once the RCB is fully opened at  $t_5$ . Then, the fault energy is separately dissipated, as shown in Fig. 5(b).  $T_2$

will be turned on to dissipate the energy stored in  $C_C$  until  $t_6$ .  $T_3$  is turned off to dissipate the residual energy stored in the CLR and DC line until  $t_6$ .

Based on the above analysis, the energy dissipation process is decoupled with the process of isolating the faulted line from the healthy circuit. The fault current from the healthy system is isolated firstly at  $t_4$ , then the healthy circuit can start to recover from  $t_5$ , leaving the CTCB to gradually dissipate the fault energy. This affords a long-time energy dissipation, which helps reduce the power rating of the RC circuit. Moreover, the electric process of the CTCB is also drawn in Fig. 6, in which it shows the fault current is isolated at  $t_4$ , and then the fault energy is dissipated at  $t_6$ .

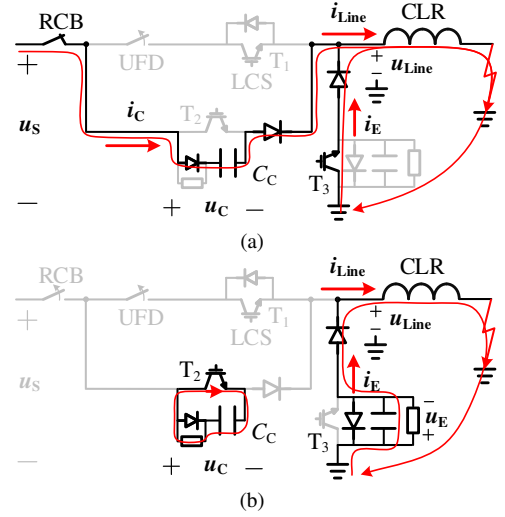


Fig. 5. Operation states of the proposed CTCB. (a) Voltage clamping state  $t_2 \rightarrow t_4$ ; (b) Energy dissipation  $t_4 \rightarrow t_6$ .

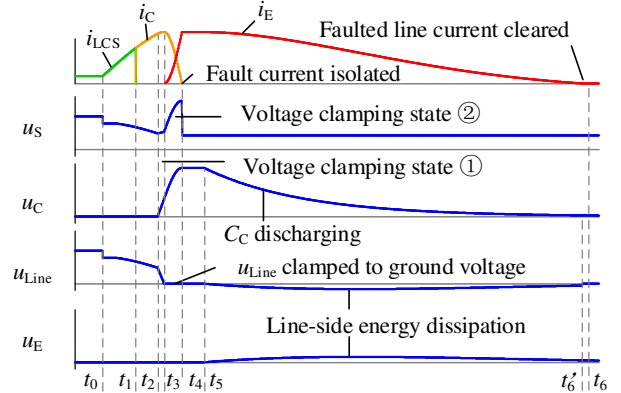


Fig. 6. Electric process of the proposed CTCB.

### B. Bidirectional CTCB and its Backup Protection

The backup protection capability is also demand for protection equipment. A part of DC grid is shown in Fig. A3, the fault current will always flow from the health system to the fault point in the DC grid. The DCCB is usually installed on the two ends of over-head line, and the positive direction of  $CB_{12}$  is used for the primary protection of its transmission lines, see Fig. 7 (a). The DCCB is usually designed as bidirectional equipment, and its backup protection is realized by the reverse direction of the adjacent  $CB_{13}$ , see Fig. 7 (b). In

some study, unidirectional DCCBs are designed to reduce cost [21-22]. Their backup protection can also be realized by the  $CB_{31}$  of the adjacent lines, but the speed and sensitivity of such a protection method are limited, see Fig. 7 (c). As the near backup protection has more technical advantages, it is adopted by the existing projects.

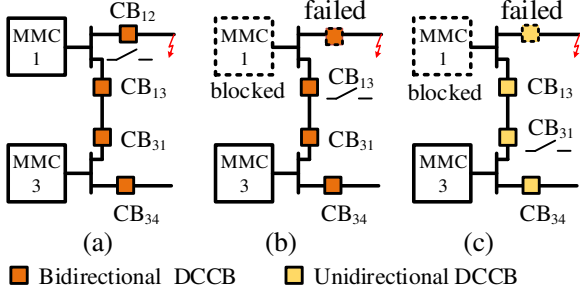


Fig. 7. Protection scheme. (a) Primary protection; (b) Bidirectional DCCB Backup protection; (c) Unidirectional DCCB Backup protection.

The CTCB can use the same backup protection method in Fig. 7 (c), but a bidirectional topology will enhance its performance, see Fig. 8 (a). A diode H-bridge is employed to cooperate with the MVC to achieve the bidirectional current breaking capability. Thanks to this configuration, only unidirectional clamping sub-modules are needed, which can reduce the use of power electronics devices. The EAB is unidirectional due to the direction of  $D_3$ . However, the backup protection can still be realized by the proper coordination with other CTCBs, as illustrated in Fig. 8 (b).

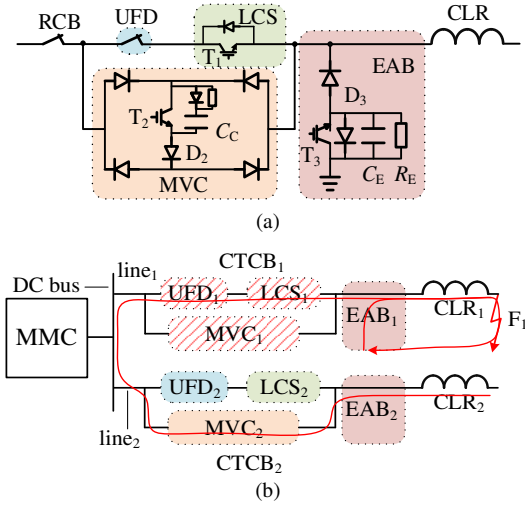


Fig. 8. Topology and back protection of the proposed CTCB. (a) Bidirectional CTCB; (b) Backup protection scheme.

Deployment of the proposed CTCBs at the terminal of an MMC with two DC lines is shown in Fig. 8(b). If CTCB<sub>1</sub> suffers a failure in case of a fault  $F_1$ , CTCB<sub>2</sub> will be ready to protect the system. It should be mentioned that as EAB<sub>2</sub> can only provide a bypassing path for the faults in line<sub>2</sub>, the proposed backup protection still needs the participation of EAB<sub>1</sub>. As illustrated in Fig. 8 (b), the MVC<sub>2</sub> in CTCB<sub>2</sub> will

coordinate with EAB<sub>1</sub> to achieve the backup protection. Considering that the EAB has a low failure rate due to the limited use of semiconductors, it is reliable to ensure a secure backup protection. The CTCB only needs four additional diodes to achieve bidirectional protection, while DCCB often needs twice as many devices. Therefore, the investment of bidirectional CTCB is lower.

In the primary and backup protection, the proposed CTCB can also use the main breaker instead of the main clammer. The fault clearing process will be similar, but the peak energy dissipation power is the same, and the fault isolation and energy dissipation is still coupled in the main breaker. However, the proposed CTCB will benefit the reclosing process, but the main breaker cannot achieve a similar effect.

### C. Reclosing Method of CTCB

After sufficient time for the fault line deionization, the CTCB can be reclosed by first closing the RCB. If the fault disappears, the DC line will be isolated by  $C_c$ . Then, the LCS and UFD are closed, and the system recovers to its initial state. If the fault still exists, a natural charging path is established, and the surge current will automatically charge  $C_c$ , see Fig. 9. Then the CTCB can repeat the process  $t_2-t_6$  presented in Fig 5 for a second-time breaking.

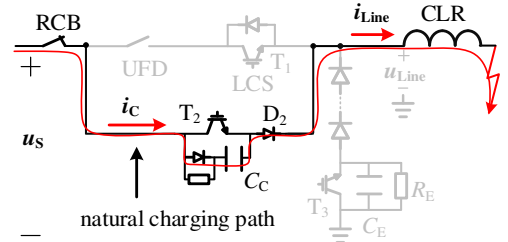


Fig. 9 Natural charging path of reclosing process

Compared with traditional DCCB, the CTCB does not need any further action before the capacitor charging current disappears, thereby allowing enough time for fault detection. However, in the DCCB reclosing process, the protection detection must be quick enough to prevent the IGBT from overcurrent. The use of a capacitor ensures that  $T_2$  does not need a second-time turn-off within a short time, enabling the IGBTs to avoid the reclosing surge current; thus, their service life is extended.

### D. Mathematical Analysis of the Proposed CTCB

Fig. 10 shows the equivalent circuit during the voltage clamping state, wherein the converter is represented as an  $RLC$  circuit [23].

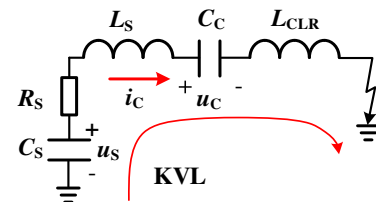


Fig. 10. Equivalent circuit of the voltage clamping state.

As shown in Fig. 10,  $C_S$ ,  $L_S$  and  $R_S$  are the equivalent circuit parameters of the converter. During  $t_2$  to  $t_3$ , the circuit can be expressed as:

$$u_S - u_C - (L_S + L_{CLR}) \frac{di_C}{dt} - R_S i_C = 0, \quad (1)$$

$$-C_S \frac{du_S}{dt} = C_C \frac{du_C}{dt} = i_C. \quad (2)$$

The equation of  $i_C$  is obtained by substituting (2) into (1):

$$-(L_S + L_{CLR}) \frac{d^2 i_C}{dt^2} - R_S \frac{di_C}{dt} - \left(\frac{1}{C_S} + \frac{1}{C_C}\right) i_C = 0. \quad (3)$$

The expression of  $i_C$  is obtained by arranging (3):

$$i_C = C_{11} e^{\alpha_1 t} \cos(\beta_1 t) + C_{12} e^{\alpha_1 t} \sin(\beta_1 t). \quad (4)$$

The initial condition of equation (4) is:

$$i_C(t_{2+}) = i_C(t_{2-}), \quad i'_C(t_{2+}) = \frac{u_S(t_{2-})}{L_S + L_{CLR}}. \quad (5)$$

Thus,

$$\left\{ \begin{array}{l} C_{11} = i_C(t_{2-}), \quad C_{12} = \frac{u_S(t_{2-}) - C_{11} \alpha_1}{\beta} \\ \alpha_1 = -\frac{R_S}{2(L_S + L_{CLR})}, \quad \beta_1 = \sqrt{\frac{4(L_S + L_{CLR})\left(\frac{1}{C_S} + \frac{1}{C_C}\right) - R_S^2}{2(L_S + L_{CLR})}} \end{array} \right. \quad (6)$$

The  $u_C$  can be written as:

$$u_C = \frac{\int_{t_2}^t i_C dt}{C_C} = \frac{1}{C_C(\alpha^2 + \beta^2)} [(C_{11}\alpha - C_{12}\beta)e^{\alpha_1 t} \cos \beta_1 t + (C_{12}\alpha + C_{11}\beta)e^{\alpha_1 t} \sin \beta_1 t - (C_{11}\alpha - C_{12}\beta)e^{\alpha_1 t_2} \cos \beta_1 t_2] \quad (7)$$

The CTCB will change to the voltage clamping state ②, when  $u_C$  equals to  $u_S$ . Then, the  $L_{CLR}$  will be bypassed from the circuit once the EAB is conducted, but other parts of the equations are similar. Therefore, state ② will not studied further due to only small differences exist in the equations.

For the energy dissipation state, the discharging circuit of  $C_C$  in Fig. 5 (b) is an  $RC$  circuit which has been well discussed in [24]. For the EAB, a single direction circuit can be obtained after turning off  $T_3$ , as shown in Fig. 11.

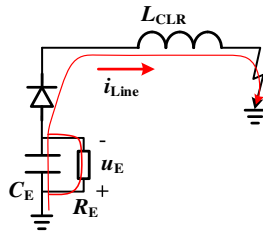


Fig. 11. Equivalent circuit of the energy absorption state.

Based on KVL and KCL, this process can be expressed as:

$$\begin{bmatrix} \frac{di_{Line}}{dt} \\ \frac{du_E}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ \frac{1}{C_E} & -\frac{1}{R_E C_E} \end{bmatrix} \begin{bmatrix} i_{Line} \\ u_E \end{bmatrix}. \quad (8)$$

The equation of  $i_{Line}$  is obtained by arranging (7):

$$\frac{d^2 i_{Line}}{dt^2} + \frac{1}{C_E R_E} \frac{di_{Line}}{dt} - \frac{i_{Line}}{L_{CLR} C_E} = 0. \quad (9)$$

The expression of  $i_{Line}$  is obtained:

$$i_{Line} = C_{21} e^{\alpha_2 t} \cos(\beta_2 t) + C_{22} e^{\alpha_2 t} \sin(\beta_2 t). \quad (10)$$

The initial condition of equation (10) is:

$$i_{Line}(t_{5+}) = i_{Line}(t_{5-}), \quad i'_{Line}(t_{5+}) = 0, \quad (11)$$

where

$$\left\{ \begin{array}{l} C_{21} = i_{Line}(t_{5-}), \quad C_{22} = -\frac{C_{21} \alpha_2}{\beta_2} \\ \alpha_2 = \frac{-1}{2R_E C_E}, \quad \beta_2 = \sqrt{\frac{4}{L_{CLR} C_E} - \left(\frac{1}{R_E C_E}\right)^2} \end{array} \right. \quad (12)$$

The  $u_E$  can be written as:

$$u_E = C_{31} e^{\alpha_3 t} \cos(\beta_3 t) + C_{32} e^{\alpha_3 t} \sin(\beta_3 t). \quad (13)$$

The initial condition of equation (13) is:

$$u_E(t_{5+}) = 0, \quad u'_E(t_{5+}) = \frac{i_{Line}(t_{5-})}{\beta_3}, \quad (14)$$

where

$$\left\{ \begin{array}{l} C_1 = 0, \quad C_2 = \frac{i_{dc}(0)}{\beta} \\ \alpha = \frac{-1}{2R_B C_B}, \quad \beta = \sqrt{\left(\frac{1}{R_B C_B}\right)^2 + \frac{4}{L_B C_B}} \end{array} \right. \quad (15)$$

The mathematical analysis can help understanding the inner principle of the proposed CTCB. The correctness of math equations is verified in the MATLAB, but not shown in the paper due to over length

## IV. CASE STUDY

### A. Test System

The performance of the CTCB is verified in the Zhangbei four-terminal bipolar DC grid [16], as shown in Fig. 12. The converter control modes and system parameters are listed in the Appendix. All models are built in PSCAD/EMTDC V4.6 with a simulation time step of 10  $\mu$ s.

A pole-to-pole fault  $f_1$  is used to demonstrate the protection process of the proposed CTCB. Moreover, a high resistance pole-to-ground fault  $f_2$  is used to verify CTCB's performance under high impedance faults. The fault resistance  $R_f$  is set as 100  $\Omega$  and 200  $\Omega$ . Both  $f_1$  and  $f_2$  are initiated at  $t = 1$  s. The measurements of  $u_S$ ,  $i_{DC}$  and  $i_{Line}$  are shown in Fig. 12. Other

measurements of the CTCB are shown in Figs. 4 and 5. The CTCB needs numerous components in series to withstand the fault voltage, but the equivalent value of  $C_C$ ,  $R_C$ ,  $C_E$ ,  $R_E$  are set as  $30 \mu\text{F}$ ,  $250 \Omega$ ,  $1000 \mu\text{F}$ , and  $10 \Omega$ , respectively. The used  $30 \mu\text{F}$  capacitor equals the equivalent capacitance of one arm in station 1 (250 cascade HBSMs with  $7500 \mu\text{F}$  capacitor), so it is realistic in the project. The fault detection time is set as 3 ms after the fault wave arrives the CTCB, and the operation time of UFD is 2 ms. Thus,  $C_C$  will not be charged within the initial 5 ms after the fault.

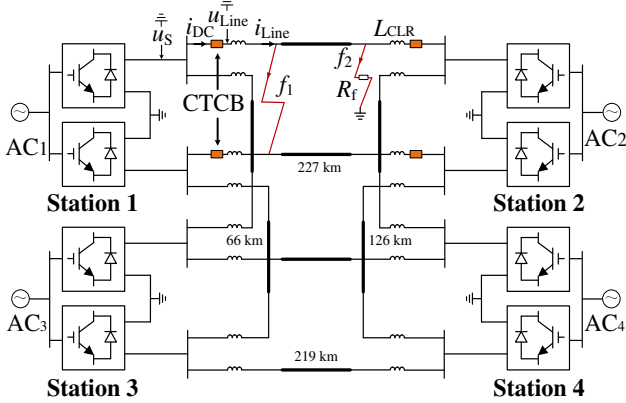


Fig. 12. Topology of four-terminal DC grid.

### B. Pole-to-pole Large Current Interruption

The performance of interrupting large currents of the CTCB is verified by the pole-to-pole fault  $f_1$ . Currents and voltages of the CTCB are shown in Figs. 13 (a) and (b). Fig. 13 (c) shows the operating status of CTCB's components, wherein the high and low levels mean that the switch is ON and OFF. The definition of the time sequences is the same as Section III-A.

In Fig. 13, the fault occurs at  $t_0 = 1 \text{ s}$  and is detected at  $t_1 = 1.003 \text{ s}$ .  $T_1$  is turned off at  $t_1$  and the fault current commutates to the MVC. At  $t_2 = 1.005 \text{ s}$ , IGBT  $T_2$  is turned off, then the fault current starts to charge  $C_C$ .  $u_C$  raises from zero voltage and the fault current keeps raising during  $t_2$ - $t_3$ . At  $t_3 = 1.0053 \text{ s}$ ,  $u_C$  equals to  $u_s$  and  $i_C$  starts to decrease. EAB provides a free-wheeling path for the current in CLR, so  $i_E$  increases while  $i_C$  decreases. At  $t_4 = 1.0072 \text{ s}$ ,  $i_C$  reaches zero and RCB operates to isolate the faulted line. At  $t_5 = 1.0092 \text{ s}$ , RCB opens successfully. Then,  $T_2$  is triggered and  $T_3$  is turned off and the energy stored in  $C_C$  and CLR starts to be dissipated by  $R_C$  and  $R_E$ . At last, the whole process ends at  $t_6 = 1.0434 \text{ s}$  when  $i_E$  becomes zero.

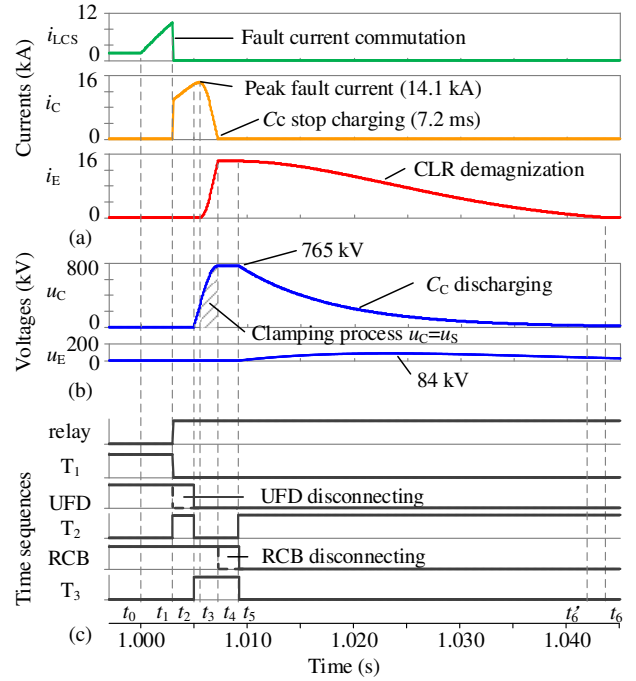


Fig. 13. Operating process of CTCB under large current. (a) Currents; (b) Voltages; (c) Time sequences.

The currents and voltages of the DC grid are shown in Fig. 14. It can be seen that the isolation of the faulted line is decoupled with the decay of the residual fault current. As isolating the faulted circuit is the top priority of protection a DC grid, the proposed CTCB provides such a solution achieving a fast fault isolation. The following energy dissipation process helps reduce the power rating of  $R_C$  and  $R_E$ . During  $t_3$ - $t_4$ , the DC bus voltage  $u_s$  follows the change of  $u_C$ , which is clamped by  $C_C$ , instead of collapsing a lot after the fault. This will be beneficial to the post-fault restoration. The healthy system starts to recover after the clamping process. Although the DC line current  $i_{Line}$  keeps decaying until  $t_6$ , the faulted line has already been isolated from the DC system and therefore, it won't affect the healthy circuits. The line-side elements all have high surge capability, so a long tail energy dissipation process is acceptable.

Based on the above results, the following features of the proposed CTCB can be found: 1) The DC voltage is clamped by the internal capacitor of the CTCB, which helps the post-fault restoration; 2) The isolation of the faulted line and its energy dissipation are decoupled, which achieves a fast isolation and low energy dissipation. 3) There are no sudden changes of fault current and IGBT voltages, which can mitigate the transient rate-of-change of the IGBT's voltage and therefore, reduce their manufacture difficulty. These advantages will be future discussed in Section V.

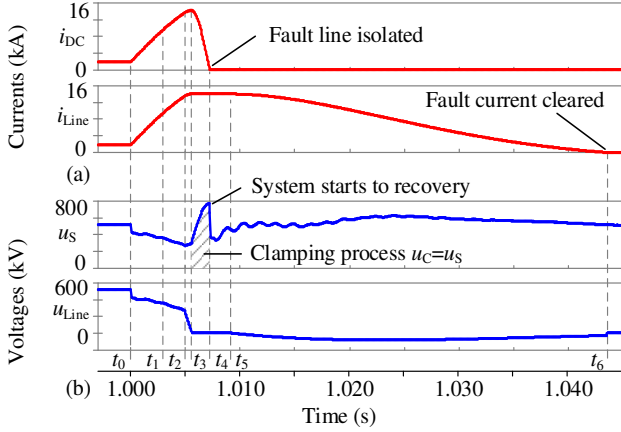


Fig. 14. System dynamics (a) Currents; (b) Voltages.

### C. Pole-to-ground Small Current Interruption

A pole-to-ground fault  $f_2$  with different fault resistance  $R_f$  (100 and 200  $\Omega$ ) has been tested. Fig. 15 shows the simulation results under  $R_f = 100 \Omega$ . The fault current increases slowly with large fault resistance, and the fault resistance can also help dissipate the line-side energy. The fault is detected 3 ms after the transmission wave reaches the relay, at  $t_1 = 1.0037$  s.  $C_C$  starts to be charged at  $t_2 = 1.0057$  s. However, due to the small current, the voltage clamping process of charging  $C_C$  is long. The faulted line is isolated until  $t_4 = 1.0124$  s. Then, the residual fault energy is dissipated by both  $R_E$  and  $R_f$  from  $t_5 = 1.0145$  s to  $t_6 = 1.0437$  s. The CTCB needs 12.4 ms to isolate the faulted line. It can be acceptable considering that the small fault current may cause less damage to the system. As shown in Fig. 15 (b), the peak voltages of  $u_C$  and  $u_E$  are also reduced under the high resistance fault.

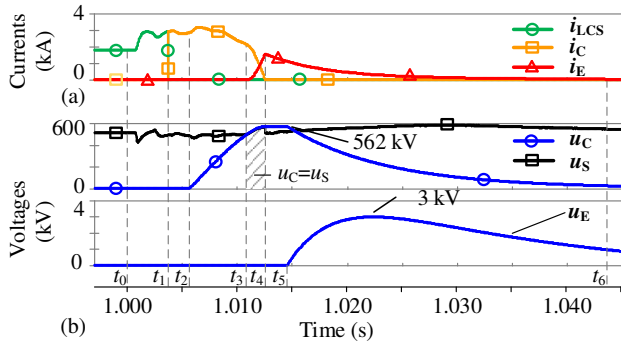


Fig. 15. CTCB performance under  $R_f = 100 \Omega$ . (a) Currents; (b) Voltages.

The CTCB has a different performance under a higher fault resistance, e.g.  $R_f = 200 \Omega$ . Fault current rises less than the last case, as shown in Fig. 16. The high fault resistance results in less voltage drop of  $u_s$ . Therefore, the voltage clamping process is longer compared to the last case until  $t_3 = 1.027$  s. The fault energy is mainly dissipated by fault resistance. Therefore, the magnitudes of  $i_E$  and  $u_E$  are low. Although the fault clearing process needs long time under a high resistance fault, it still can be acceptable. This scenario has less challenge to the system than large current fault, thus the system can afford more time for the fault clearing.

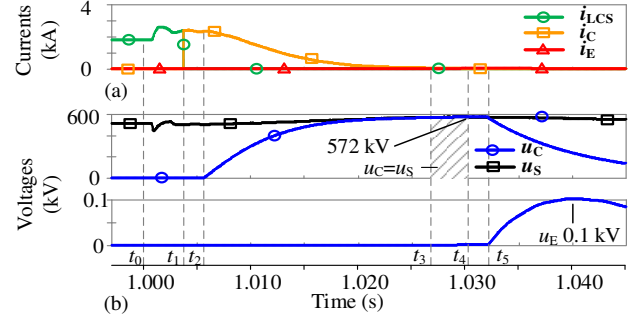


Fig. 16. CTCB performance under  $R_f = 200 \Omega$ . (a) Currents; (b) Voltages.

## V. ENERGY STORAGE AND DISSIPATION ANALYSIS

### A. Capacitor Storage Demand Analysis

As a core component of the proposed CTCB, the  $C_C$  and  $C_E$  have significant influences on the performance of the CTCB. A smaller capacitance of  $C_C$  can be charged fast, which will benefit for the quick fault isolation and system recovery. However, a small capacitor may need to face a high overvoltage. Considering the difficulty of manufacture, the capacitance of  $C_C$  is chosen as 30  $\mu\text{F}$ . the same value as the equivalent capacitance within one upper or lower arm in the Zhangbei project (250 cascade HBSMs with 7500  $\mu\text{F}$  capacitor), which is practical for industrial realization.

The EAB also affects the voltage clamping process. A large capacitor will be needed if no EAB [25]. In the following studies,  $i_{DC}$  and  $u_C$  under four cases are compared to show the influence from the capacitors and EAB: 1) small capacitor (30  $\mu\text{F}$ ) with EAB; 2) small capacitor without EAB; 3) large capacitor (100  $\mu\text{F}$ ) with EAB and 4) large capacitor without EAB, as shown in Fig. 17.

It can be seen from Fig.17 that a small capacitor can achieve a fast fault isolation. Comparing the Cases 1 and 3, 2.7 ms can be reduced by the small capacitor.  $u_C = 765$  kV in Case 1 is higher than  $u_C = 523$  kV in Case 2. However, both cases can be acceptable if the converter can keep operating under 810 kV [16]. Comparing the Cases 1 and 2, 2 ms can be reduced for the isolation thanks to the deployment of the EAB. Both Cases 2 and 4 need a large  $C_C$  which may be impractical for real applications and the fault isolation time is too long.

The above analysis shows that Case 1 with a small capacitor and EAB has the fastest fault isolation time and the second highest capacitor voltage. However, the capital cost of the capacitor is major about its capacity, as listed in TABLE I. Case 1 is preferred due to it has the lowest energy storage requirement among the four cases, so the proposed scheme of CTCB is able to achieve a fast isolation and low requirements of the internal capacitor.



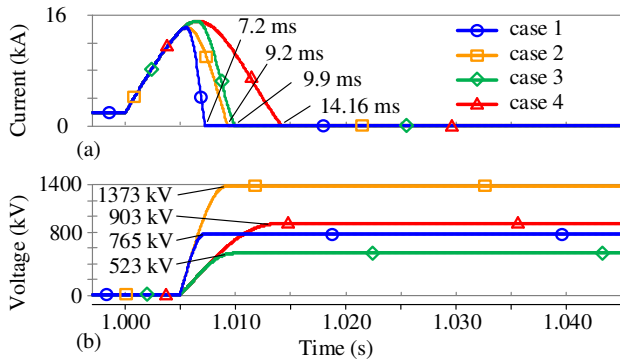


Fig. 17. Comparisons of  $i_{DC}$  and  $u_C$  under four cases. (a) Currents; (b) Voltages.

TABLE I  
COMPARISONS OF  $C_C$

Items	Equivalent capacitance	Voltage	Total energy
Case 1	30 $\mu$ F	765 kV	8.77 MJ
Case 2	30 $\mu$ F	1373 kV	28.27 MJ
Case 3	100 $\mu$ F	523 kV	13.67 MJ
Case 4	100 $\mu$ F	903 kV	40.77 MJ

### B. Comparison with the Conventional Hybrid DCCB

As a well-known HVDC switchgear, the hybrid DCCB proposed by ABB is selected to compare with the CTCB in terms of: 1) electrical processes during the fault protection; 2) rate-of-change of IGBT's voltage; 3) total dissipation energy and its power rating.

The studied DCCBs is the same as shown in Section II, the total clamping voltage of DCCB is 800 kV. The DC fault is detected at  $t = 1.003$  s. The operation delay of the UFD is set as 2 ms. Therefore, the MOV will be inserted at 1.005 s, which is the same as the  $C_C$  of CTCB.

Fig. 18 shows the currents and voltages of the proposed CTCB and ABB's DCCB under the same fault  $f_1$ . It can be seen that the peak fault current of the CTCB is slightly higher than that of ABB's DCCB. This is because the  $C_C$  within CTCB needs a charging process before the decrease of the fault current. The fault current  $i_{DC}$  of CTCB decreases to zero at  $t = 1.0072$  s, which is 3.8 ms (34.5 %) faster than ABB's

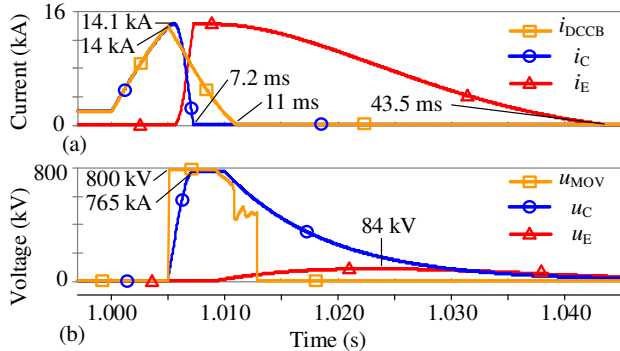


Fig. 18. Electrical processes of CTCB and ABB's DCCB. (a) Currents; (b) Voltages.

DCCB whose fault current  $i_{DCCB}$  decreases to zero at  $t = 1.011$  s. Therefore, the proposed CTCB can isolate the faulted line from the healthy circuit faster than ABB's DCCB.

The dissipated energy and power are shown in Fig. 19. In Fig. 19 (a), the dissipated energy of the MOV of ABB's DCCB is  $E_{MOV} = 28.7$  MJ. The dissipated energy by CTCB's  $C_C$  and  $C_E$  is 8.8 MJ and 3.5 MJ. Fig. 19 (b) shows the energy stored in the CLR. The peak energy of  $E_{CLR\_DCCB}$  is 14.5 MJ, but the total energy dissipation in the MOV is 28.7 MJ due to the coupled fault isolation and energy dissipation. The peak energy of  $E_{CLR\_CTCB}$  is 14.9 MJ. Therefore, the dissipated energy in the CTCB is 23.7 MJ (8.8+14.9 MJ) which is 17.4% lower than ABB's DCCB. ABB's DCCB needs to dissipate bulk power in several milliseconds. In this case, its peak power is 11000 MW, while the CTCB has much lower peak power of 2610 MW (1900+710 MW), as shown in Fig. 19(c).

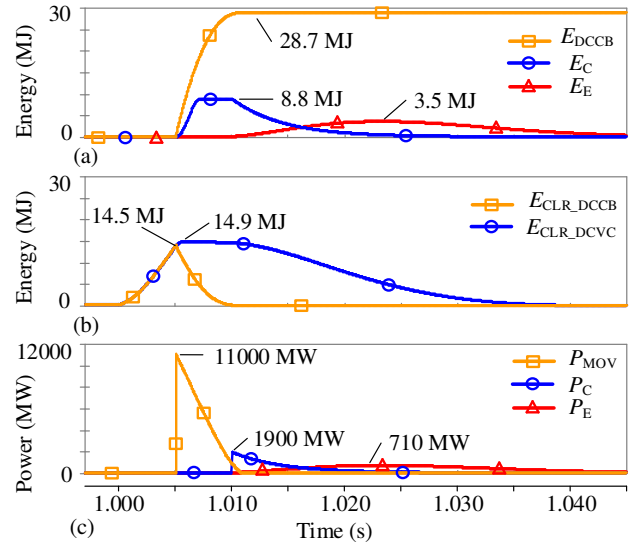


Fig. 19. Energy and power dissipation of CTCB and ABB's DCCB. (a) Dissipated energy; (b) CLR energy; (c) Energy dissipation power.

Thanks to the decoupled fault isolation and energy dissipation processes, the CTCB can significantly reduce the total dissipation energy and power, which is helpful to reduce the volume of equipment. As shown in Table II, the total dissipation energy, the peak and average power of CTCB has been reduced by 17.4 %, 76.2 %, and 87.6 % compared to its ABB counterpart. Less fault energy indicates the system suffers less disturbance during the fault, and a lower power will reduce the volume for the resistors.

TABLE II  
COMPARISONS OF ENERGY AND POWER DISSIPATION

Items	DCCB	CTCB	Reduced by
Total energy	28.7 MJ	23.7 MJ	17.4 %
Peak power	11000 MW	2610 MW	76.2 %
Average power	4783 MW	592 MW	87.6 %

### C. Semiconductors Requirements Comparison

The comparison of the energy storage element has been given in Section V. B, the requirements for semiconductors are given in this sub-section.

Assuming that all used semiconductors are 4.5 kV devices in 500 kV DC grid, and redundant devices are not considered, CTCB and DCCB's semiconductor requirements are shown in TABLE III. The DCCB's main breaker needs 178 series-connected IGBTs and diodes in one direction. The CTCB needs 170 IGBTs and 340 diodes in series for its MVC, and 19 IGBTs and 112 diodes in series for its EAB. Further considering the bidirectional design, the semiconductor requirements for DCCB doubled, but the CTCB only need four more diodes. Therefore, the use of high price IGBTs is reduced in CTCB.

TABLE III  
SEMI-CONDUCTOR COST CALCULATION

Items	ABB DCCB	CTCB
IGBTs	356	189
diodes	356	456
Total cost (p.u.)	391.6	234.6

At the same voltage level, diodes are much cheaper than IGBTs [24]. Suppose the cost of diodes is 10% of IGBTs, the per-unit cost of DCCB and CTCB are also given in TABLE III. It shows that by using fewer IGBTs, the total cost reduced by around 40 % compared to ABB DCCB, making CTCB a promising solution for future DC protection equipment.

## VI. CONCLUSIONS

This paper proposes a clamping type DCCB (CTCB) with short fault isolation time and low energy dissipation. The proposed CTCB utilizes a branch of capacitors to isolate the DC current, and achieve the fast isolation of the faulted line. An energy absorption branch is used to provide a free-wheeling current path to achieve low energy dissipation. Thanks to the proposed configuration, the processes of the fault isolation and energy dissipation are decoupled. Therefore, a fast post-fault restoration can be realized by quickly restarting the safely protected converter station. The primary protection, backup protection and reclosing logic of CTCB is discussed, and its performance is verified in the DC grid simulation.

In this study, the proposed CTCB can isolate the faulted line within 7.2 ms, 34.5 % less than ABB's DCCB. The energy dissipation of IGBTs and its peak power also reduced by 17.4 % and 76.2 %, respectively. By comparing the requirements for semiconductors, the proposed CTCB can save 40 % cost on IGBTs and diodes, making the proposed CTCB a potential solution for DC protection.

The proposed CTCB still has some protentional drawbacks. The EAB needs to withstand DC rating voltage under normal state, but the long-term insulation ability of series-connected diodes still needs more consideration. Moreover, if EAB fails, the near backup protection cannot be achieved. Therefore, the performance of EAB may affect the protection performance of CTCB.

## APPENDIX

The DC grid model is based on the Zhangbei project [16]. Parameters of the four stations are given in Table AI. The control modes of the DC grid are given in Table AII.

TABLE AI  
PARAMETERS OF THE MMCS

Items	MMCs 1&2	MMCs 3&4
AC voltage	230 kV	500 kV
Transformer Capacity	1700 MW	3400 MW
Transformer Leakage	0.1 pu	0.15 pu
Arm Inductance	0.06 H	0.1 H
SM Number	250	250
SM Capacity	7500 $\mu$ F	15000 $\mu$ F
CLR Inductance	150 mH	150 mH

TABLE AII  
CONTROL MODES OF THE DC GRID

Station	Control Mode	Parameter
Station 1	active power	$P_N=1500$ MW
	reactive power	$Q_N=150$ Mvar
Station 2	active power	$P_N=1500$ MW
	reactive power	$Q_N=150$ Mvar
Station 3	active power	$P_N=3000$ MW
	reactive power	$Q_N=300$ Mvar
Station 4	DC voltage	$U_{DC}=\pm 500$ kV
	reactive power	$Q_N=300$ Mvar

## REFERENCES

- [1] T. An, X Zhou, C Han Y Wu, Z He, H Pang and G Tang, "A DC grid benchmark model for studies of interconnection of power systems," *CSEE Journal of Power and Energy Systems*, vol.1, no.4, pp.101-109, Dec. 2015.
- [2] X. Zhao, L. Chen, G. Li, J. Xu and J. Yuan, "Coordination method for DC fault current suppression and clearance in DC grids," *CSEE Journal of Power and Energy Systems*. (early access)
- [3] Juan Manuel Carrasco et al., "Power-Electronic System for the Grid Integration of Renewable Energy Sources: A Survey," *IEEE Transactions on Industrial Electronics*, vol. 53, no.4, pp. 1002-1016, Aug. 2006.
- [4] J. Yang, J. E. Fletcher and J. O'Reilly, "Short-Circuit and Ground Fault Analyses and Location in VSC-Based DC Network Cables," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 10, pp. 3827-3837, Oct. 2012.
- [5] X. Han, W. Sima, M. Yang, L. Li, T. Yuan and Y. Si, "Transient Characteristics Under Ground and Short-Circuit Faults in a  $\pm 500$  kV MMC-Based HVDC System With Hybrid DC Circuit Breakers," *IEEE Transactions on Power Delivery*, vol. 33, no. 3, pp. 1378-1387, June 2018.
- [6] N. Tsukamoto, S. Imato, Y. Baba and M. Ishii, "Current distribution in MOV element stressed by 4/10  $\mu$  s impulse current," 2016 33rd International Conference on Lightning Protection (ICLP), Estoril, 2016, pp. 1-4.
- [7] J. Magnusson, R. Saers, L. Liljstrand and G. Engdahl, "Separation of the Energy Absorption and Overvoltage Protection in Solid-State Breakers by the Use of Parallel Varistors," *IEEE Transactions on Power Electronics*, vol. 29, no. 6, pp. 2715-2722, June 2014.
- [8] A. Hassanpoor, J. Häfner and B. Jacobson, "Technical Assessment of Load Commutation Switch in Hybrid HVDC Breaker," *IEEE Transactions on Power Electronics*, vol.30, no.10, pp.5393-5400, Oct. 2015.
- [9] Y. Guo, G. Wang, D. Zeng, H. Li and C. Hong, "A Thyristor Full-Bridge-based DC Circuit Breaker," *IEEE Transactions on Power Electronics*. (early access)

- [10] B. Li, J. He, Y. Li and R. Li, "A Novel Solid-State Circuit Breaker With Self-Adapt Fault Current Limiting Capability for LVDC Distribution Network," *IEEE Transactions on Power Electronics*, vol. 34, no. 4, pp. 3516-3529, April 2019.
- [11] K. Sano and M. Takasaki, "A Surgeless Solid-State DC Circuit Breaker for Voltage-Source-Converter-Based HVDC Systems," *IEEE Transactions on Industry Applications*, vol. 50, no. 4, pp. 2690-2699, July-Aug. 2014.
- [12] W. Grieshaber et al., "Development and Test of a 120kV direct current circuit breaker," in Proc. CIGRE Session, Paris, France, Aug. 2014, pp. 1-11.
- [13] A. Jamshidi Far and D. Jovcic, "Design, Modeling and Control of Hybrid DC Circuit Breaker Based on Fast Thyristors," *IEEE Transactions on Power Delivery*, vol. 33, no. 2, pp. 919-927, April 2018.
- [14] G. Tang, Z. He, H. Pang, X. Huang and X. Zhang, "Basic topology and key devices of the five-terminal DC grid," in *CSEE Journal of Power and Energy Systems*, vol. 1, no. 2, pp. 22-35, June 2015.
- [15] W. Zhou X. Wei S. Zhang et al., "Development and test of a 200kV full-bridge based hybrid HVDC breaker," *2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*, Geneva, 2015, pp. 1-7.
- [16] G Tang, H. Pang and X. Wei, "Research on Key Technology and Equipment for Zhangbei 500kV DC Grid," 2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia), Niigata, 2018, pp. 2343-2351
- [17] D. Jovcic, G. Tang and H. Pang, "Adopting Circuit Breakers for High-Voltage dc Networks: Appropriating the Vast Advantages of dc Transmission Grids," *IEEE Power and Energy Magazine*, vol. 17, no. 3, pp. 82-93, May-June 2019.
- [18] A. Shukla and G. D. Demetriades, "A Survey on Hybrid Circuit-Breaker Topologies," *IEEE Transactions on Power Delivery*, vol. 30, no. 2, pp. 627-641, April 2015.
- [19] M Zhou, W Xiang, W Zuo, W Lin, J Wen "A novel HVDC circuit breaker for HVDC application" *International Journal of Electrical Power & Energy Systems*, vol. 109, Page 685-695, July 2019
- [20] D. Jovcic, "Fast Commutation of DC Current Into a Capacitor Using Moving Contacts," *IEEE Transactions on Power Delivery*, vol. 35, no. 2, pp. 639-646, April 2020.
- [21] G. Chaffey and T. C. Green, "Directional current breaking capacity requirements for HVDC circuit breakers," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, 2015, pp. 5371-5377.
- [22] C. Li, J. Liang and S. Wang, "Interlink Hybrid DC Circuit Breaker," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 11, pp. 8677-8686, Nov. 2018.
- [23] C. Li, C. Zhao, J. Xu, Y. Ji, F. Zhang and T. An, "A Pole-to-Pole Short-Circuit Fault Current Calculation Method for DC Grids," *IEEE Transactions on Power Systems*, vol. 32, no. 6, pp. 4943-4953, Nov. 2017.
- [24] Q. Song X. Li W. Yang et al., "A Modular Multilevel Converter Integrated with DC Circuit Breaker," *IEEE Transactions on Power Delivery*, vol. 33, no. 5, pp. 2502-2512, Oct. 2018.
- [25] Z. Xu, H. Xiao and Y. Xu, "Two basic ways to realise DC circuit breakers," *The Journal of Engineering*, vol. 2019, no. 16, pp. 3098-3105, 2019.



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