Design and test of a new kind of coupling mechanical HVDC circuit breaker

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Abstract: In this paper, a new kind of coupling mechanical high-voltage direct current (HVDC) circuit breaker topology based on pulse transformer is proposed and its working principle is analysed in detail. On the basis of the requirement of 160 kV rated voltage, and 9 kA breaking current, the varying trend and design principle of parameters are given by the theoretical calculation. The prototype design of 160 kV HVDC circuit breaker is completed and type test passes. Results prove that the prototype of 160 kV HVDC circuit breaker has natural bi-directional breaking capacity. It can interrupt the current below 9 kA and withstand transient interruption voltage 272 kV. The breaking time is <5 ms.

1 Introduction

In recent years, high-voltage direct current (HVDC) transmission has been widely used due to its unique advantages [1]. Compared to AC transmission, HVDC transmission has the advantages of low cost, low loss and high stability, and it is suitable for large-capacity and long-distance transmission [2, 3]. However, the vast majority of DC transmission systems in operation are still point-to-point systems, the main limiting factor is the lack of fast and reliable HVDC circuit breaker [4–11].

DC circuit breakers can be divided into three categories: mechanical DC circuit breaker, hybrid DC circuit breaker and solid-state DC circuit breaker [12–15]. Solid-state DC circuit breaker is composed of the insulated gate bipolar transistor (IGBT) (mostly) and metal oxide varistor (MOV). Since it needs a large number of IGBTs connected in serial to withstand the off-state voltage, on-state loss of IGBTs is quite high which limits its application in the HVDC power grid.

Current-carrying branch of the hybrid DC circuit breaker consists of IGBTs and mechanical switches, both are connected in series to limit the on-state loss [16]. A large number of IGBTs are connected in parallel with the current-carrying branch, as well as the MOV branch. Asea Brown Boveri LTD. (ABB) developed a prototype of 320 kV/2.6 kA hybrid DC circuit breaker in 2012 [17]. Alstom developed a prototype of 120 kV/5.2 kA hybrid DC circuit breaker in 2013 [10]. A 200 kV/15 kA hybrid DC circuit breaker was developed in 2015 in China [18].

Forced zero-type mechanical DC circuit breaker is one of the main research topics because of its sophisticated development, inexpensive cost and low conduction loss. Prototypes of 250 kV/1.2 kA and 250 kV/8 kA were developed in 1984 and 1985 in Japan [19, 20]. Furthermore, with the development of fast mechanical switches (FMSs), the breaking time of mechanical DC circuit breakers has been decreased to 3–5 ms. A 110 kV/12 kA DC circuit breaker was developed in 2016 in China, which could interrupt faults current within 5 ms.

However, whether it is a hybrid DC circuit breaker or traditional mechanical DC circuit breaker, there are some inherent defects [21–23].

For hybrid DC circuit breaker:

(i) Large on-state loss.
(ii) Complex control and power supply.
(iii) Vast volume and poor economy.

For traditional mechanical DC circuit breaker:

(i) Low reliability of breaking because of a large number of serial spark gaps.
(ii) HV levels of trigger switches and commutation capacitor which cause the high insulation requirement.

To overcome these inherent defects in solid-state, hybrid and traditional mechanical DC circuit breakers, a coupling mechanical HVDC circuit breaker topology scheme is presented. The scheme isolates the precharged capacitor and trigger switch on the low-voltage (LV) side by a pulse transformer, while utilising thyristor with the same voltage level as a precharge voltage to ensure the reliability of the trigger switch. Pulse transformer realises voltage isolation between the HV side and LV side. Commutation current is generated on the HV side by the energy transferring.

The equivalent circuit analysis of the breaking process and characteristics analysis of the coupling mechanical DC circuit breaker are elaborated in the following section, which provides guidance for the parameter configuration. Then, the parameters and modular design of the 160 kV HVDC circuit breaker are given. The rated voltage of DC circuit breaker is 160 kV, whereas the rated current is 1 kA. Finally, the breaking test of 160 kV HVDC circuit breaker shows that it can interrupt the current below 9 kA and withstand transient interruption voltage (TIV) 272 kV.

2 Working principle of the coupling mechanical HVDC circuit breaker

As presented in Fig. 1, the coupling mechanical HVDC circuit breaker can be divided into HV side and LV side. The HV side includes commutation branch in parallel with the main branch, as well as energy absorbing branch. The main branch is made up of serial-connected FMSs. The commutation branch is composed of \(L_2\) and \(C_2\), which are also connected in series. \(L_2\) is the secondary inductance of the pulse transformer. The energy absorbing branch includes the zinc oxide arrester which consists of MOV.

The LV side consists of precharged capacitor \(C_1\), the primary inductance of the pulse transformer \(L_1\) and a trigger switch module composed of thyristors Silicon Controlled Rectifier (SCR) and anti-parallel diodes (D).

The trigger switch module is used to replace spark gaps. As a half-controlled device, thyristors (SCR) are more controllable than...
When a fault occurs, thyristors (SCR) are triggered to turn on and the energy stored in precharged capacitor $C_1$ is transferred to the secondary side by pulse transformer. The commutation current depends on the energy stored on the LV side and energy transfer. Not only the amplitude and frequency of the commutation current need to be designed but also the process of energy transfer needs to be considered. Thus, the commutation process is analysed here. The equivalent circuit of the primary and secondary sides of the pulse transformer in the commutation process is shown in Fig. 4.

In this period, there is an arc in the FMS, and thyristors are in on-state. Vacuum interrupters are selected as the arc-extinguishing unit of 160 kV HVDC circuit breaker. On the basis of past research results, the range of vacuum arc voltage is $<100$ V [24–26]. The arc voltage can be ignored here compared with the voltage of the capacitor and inductor up to tens of kilovolts and the effect on the breaking process is not obvious. In Fig. 4, $U_0$ is the precharge voltage of $C_1$ and $M$ is the mutual inductance of the pulse transformer. To simplify the analysis, spurious parameters of the pulse transformer and line are also ignored. When thyristors are turned on, an oscillation current $i_1$ is generated in the LV side and a high-frequency oscillation current $i_2$ is generated in the commutation branch.

The circuit equation of LV side and commutation branch can be written as the equation below:

$$\begin{align*}
L_1 \frac{di_1}{dt} + C_1 \int_{t_2}^{t} i_1 dt - M \frac{di_2}{dt} &= U_0 \\
L_2 \frac{di_2}{dt} + C_2 \int_{t_2}^{t} i_2 dt - M \frac{di_1}{dt} &\approx 0
\end{align*}$$

Assuming that the coupling coefficient of pulse transformer is $k$. From (1), currents $i_1$ and $i_2$ can be shown in the equations below, respectively:

$$i_1(t) = \frac{U_0}{L_1 P} \left[ a_1 \sin P_1 t - P_1 \sin P_1 t \right]$$

$$i_2(t) = k \frac{U_0}{P \sqrt{L_1 L_2}} \left[ P_2 \sin(P_2 t) - P_1 \sin(P_1 t) \right]$$

where

$$k = \frac{M}{\sqrt{L_1 L_2}} a_1 = \frac{1}{L_1 C_1}, \quad a_2 = \frac{1}{L_2 C_2}$$

$$P = \sqrt{a_1^2 + a_2^2 - (1 - 2k) a_1 a_2}, \quad P_1 = \frac{a_1^2 + a_2^2 - P}{2(1 - k)}$$

$$P_2 = \frac{a_1^2 + a_2^2 + P}{2(1 - k)}$$

### 3.1 Parameters design

In the process of current breaking, $di/dt$ at current zero crossing and TIV are related to the design of the commutation parameters. The $di/dt$ at current zero crossing will be greater with the increase of amplitude and frequency of the commutation current $i_2$. TIV can be written as the equations below:

$$U = L_1 \frac{di}{dt} + C_1 \int i dt$$

$$\frac{di}{dt} = L_1 \frac{d^2 i}{dt^2} + \frac{i}{C}$$

$L_1$ and $C_1$ are equivalent capacitance and the equivalent inductance of commutation branch, whereas $i$ represents commutation current. When the commutation current is constant, the characteristics of breaking parameters under different breaking current $I$ are shown in Fig. 5.

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![Fig. 1 Topology of coupling mechanical HVDC circuit breaker](image1.png)

![Fig. 2 Waveforms of multiple current zero crossings](image2.png)
As shown in Fig. 5, with the increase of breaking current \( I \), the characteristics of breaking parameters will have different changes. The value of \( \frac{dI}{dt} \) will increase with the breaking current decreases, so that \( U \) and \( \frac{du}{dt} \) of the anti-peak will be greater. In the case of high current, the value of \( \frac{dI}{dt} \) reduces but \( i \) and energy increases resulting in the largest \( U \) and \( \frac{du}{dt} \) of the positive peak. It is difficult for the mechanical HVDC circuit breaker to interrupt current successfully at the first current zero crossing.

Taking limits of the breaking time (5 ms in the 160 kV DC transmission system) and breaking reliability into consideration, multiple current zero crossings need to be created while \( \frac{dI}{dt} \) cannot be so large, so that 400 \( \mu \)s is chosen as the oscillation periodic time of \( i_2 \). Owing to the maximum breaking current 9 kA, the peak of commutation current \( i_2 \) is selected as 10 kA. Therefore, under the premise of known frequency and amplitude of commutation current \( i_2 \), the specific parameters of the commutation circuit need to be designed.

According to the analysis based on the following conditions (i)-(v) and formulae (1)-(3), the larger the coupling coefficient \( k \) of pulse transformer is, the higher the energy conversion rate and the smaller the required capacity of the capacitor is. The curve of \( C_1 \) with different values of \( k \) is shown in Fig. 6.

The input conditions are assumed as follows:

(i) The oscillation periodic time of \( i_2 \) is 400 \( \mu \)s.
(ii) The first peak amplitude of \( i_2 \) is 10 kA.
(iii) The tuning degree \( \chi = \frac{\omega_1}{\omega_2} = 0.97 \).
(iv) \( U_0 = 45 \text{ kV} \).
(v) \( C_2 = 10 \mu \text{F} \).

As shown in Fig. 6, the economics of HVDC circuit breaker increases with the increase of \( k \). Pulse transformers rely on the tight coupling of primary and secondary coils to transfer energy. The higher the coupling coefficient, the higher the energy transfer efficiency. Therefore, the energy required to generate the same current is reduced and \( C_1 \) will decrease. As shown in (1), in order to reduce \( U_0 \) (precharge voltage of \( C_1 \)), the coupling coefficient \( k \) should be as large as possible. However, according to the actual situation:

(i) The coupling coefficient \( k \) of pulse transformer is difficult to reach 0.9 or above because of the manufacturing process.
(ii) The higher the voltage level is, the more stringent the insulation requirements are and it is more difficult to reach the same coupling coefficient $k$ of the pulse transformer.

(iii) The volume of the pulse transformer is limited by the overall volume of the 160 kV DC circuit breaker.

In summary, taking into account the volume, 160 kV voltage level, the difficulty of design and manufacturing of the pulse transformer, the value of $k$ is chosen to be 0.8.

3.1.1 Selections of $C_1$ and $C_2$: To get the variations of $C_1$ and $C_2$, the input conditions are assumed as follows:

(i) The oscillation periodic time of $i_2$ is 400 μs.
(ii) The first peak amplitude of $i_2$ is 10 kA.
(iii) The tuning degree $\chi = \omega_1 / \omega_2 = 0.97$.
(iv) $U_0 = 45 \text{kV}$.
(v) $k = 0.8$.

On the basis of the choice of the value of $k$ (0.8), the overall capacities of the capacitors with different values of $C_2$ are shown in Fig. 7 and the trend of $C_1$ varies with capacitor $C_2$ is shown in Fig. 8.

It can be seen from Fig. 7 that the overall capacity of the capacitors $C_1$ and $C_2$ has the minimum value when $C_2$ is 10 μF. When $C_2$ increases, the capacity of $C_2$ will increase linearly because the voltage level of $C_2$ is the system voltage (160 kV). Moreover, when $C_2$ decreases, more energy will be needed to generate enough commutation current. As shown in Fig. 8, $C_1$ decreases with the increasing of $C_2$. To reduce the overall capacities and cost, the value of $C_2$ is selected as 10 μF under the condition of $k$ (0.8). Moreover, in order to retain a certain margin, the value of $C_1$ is selected as 135 μF.

Combined with stray parameters and over-voltage after breaking, the final design of key parameters of the breaker is shown in Table 1.

On the basis of the results of parameters design, the power systems computer-aided design (PSCAD) model of DC circuit breaker was established. The simulation result is shown in Fig. 9.

As shown in Fig. 9, the first peak of commutation current is 10 kA and the oscillation frequency is 2500 Hz. The commutation current is not completely symmetrical and consists of the current components of two frequencies as shown in (3).

| Parameters | Design |
|------------|--------|
| frequency of commutation | 2500 Hz |
| pulse transformer | $k = 0.8$ |
| $C_2$ | 10 μF |
| $C_1$ | 135 μF |
| MOV residual voltage: | 175% of rating voltage |

Table 1 Design of key parameters

Fig. 5 Characteristics of breaking parameters under different breaking currents

Fig. 6 Curve of $C_1$ with different values of $k$

Fig. 7 Curve of overall capacities of $C_1$ and $C_2$ with different values of $C_2$

Fig. 8 Curve of $C_1$ with different values of $C_2$

Fig. 9 Simulation result of commutation current
3.2 Prototype design of 160 kV HVDC circuit breaker

The topology of 160 kV HVDC circuit breaker is shown in Fig. 10 which is mainly made up of the following parts:

(i) The main branch includes four 40 kV mechanical switch modules in series. Each module consists of a 40.5 kV vacuum interrupter driven by an electromagnetic repulsion mechanism and a resistor–capacitor ($R_jC_j$) snubber and a resistor ($R_x$) voltage balancer in parallel therewith.

(ii) Commutation branch consists of $C_2$ and $L_2$ which are selected according to the breaking time, fault current and reliability of breaking.

(iii) MOV, the residual voltage of which is 280 kV. The maximum absorption energy of MOV is 15 MJ and the characteristics of $V$–$I$ are shown in Fig. 11.

(iv) LV energy storage circuit which is made up of $C_1$, $L_1$ and trigger switch module (thyristor anti-parallel diode).

4 Breaking test

Owing to the capacity limit of the breaking test, there is no DC breaking test circuit for HVDC circuit breaker. What is the most common method is that the AC current generated by the generator or inductor–capacitor oscillation circuit is used to simulate the DC fault current [27–29]. A generator current source test circuit is shown in Fig. 12. The circuit can be divided into three parts:

(a) The current source which is used to produce 0–12 kA/50 Hz AC current. It consists of a generator whose output voltage is 3–12 kV and transformer with the ratios of 12:112, 12:168 and 12:224. FK1 is the auxiliary closing switch and FK2 is the auxiliary opening switch.

(b) The frequency modulation (FM) branch made up of capacitor $C_t$ which is parallel in the circuit breaker at both ends. It is configured to adjust the parameters of TIV such as $du/dt$.

Differences between test circuit and actual DC systems make it different between the value of $du/dt$ in the breaking test and that in the actual DC transmission system. To meet the assessment requirement ($du/dt$ is not <1400 V/μs), the FM should be added in the test circuit.

The specific working principle of ‘FM’ is as follows:

(i) Before the current zero crossing, current $I$ flows through the FMS and commutation branch so that it cannot affect the process of arcing.

(ii) After the current zero crossing, current $I$ flows through the ‘FM’ branch and commutation branch so that it can adjust $du/dt$ of TIV.

(iii) The tested HVDC circuit breaker consists of FMS branch, energy absorbing branch and commutation branch with LV energy storage circuit.

The tested circuit breaker is shown in Fig. 13.

The test makes use of the first 1/4 cycle of the alternating current to simulate the DC current which needs to be interrupted. The time sequence of the test is divided into several stages:
The control system of the HVDC circuit breaker receives the breaking command and sends an opening command to the FMS delayed by $t_1$ after receiving the breaking signal.

(ii) $t = t_1$: FMS receives the opening command and the contacts start to open.

(iii) $t = t_2$: After 3 ms of arcing time, the thyristors are triggered, that is, the commutation current is injected.

The specific action sequence is shown in Fig. 14.

### 4.1 Simulation of breaking test

According to the test circuit of 160 kV HVDC circuit breaker, the simulation model is built based on PSCAD. The simulations of high current (9 kA) and low-current (25 A) breaking are completed. The results are shown in Figs. 15 and 16.

(i) $t = 0$: The control system of the HVDC circuit breaker receives the breaking command and sends an opening command to the FMS delayed by $t_1$ after receiving the breaking signal.

(ii) $t = t_1$: FMS receives the opening command and the contacts start to open.

(iii) $t = t_2$: After 3 ms of arcing time, the thyristors are triggered, that is, the commutation current is injected.

As can be seen, TIV in the positive breaking is not much different from that in the reverse breaking. However, TIV in low-current breaking is quite different from that in high-current breaking.

According to the analysis of TIV in Section 3.1, the anti-peak of TIV is much higher in low-current breaking than that in high-current breaking. As described in (4), the value of $U$ depends on $di/dt$ and $i$. When the commutation current is constant, $di/dt$ under the condition of low-current breaking is much larger than that under the condition of high-current breaking. Moreover, at the moment of current zero crossing, the effect of current $i$ is minimal. So there will be some differences in the anti-peak of TIV.

### 4.2 Result of breaking test

Test results of low-current (−26, 29 A) and high-current (−9.19, 9.2 kA) breaking are shown in Table 2. The current and voltage waveforms of low-current breaking are shown in Fig. 17 and that of high-current breaking are shown in Fig. 18.

Compared Figs. 15 and 16 with Figs. 17 and 18, the test results are basically consistent with the simulation results. However, the test results are still somewhat different.

In Fig. 17, several peaks after 5 ms in the current of (a) are caused by measurement interference because TIV starts to rise after 5 ms. So the current is interrupted at the first current zero crossing. However, since the breaking current is only −26 A which is much smaller than the measurement interference, breaking current waveform is not visualised in Fig. 17a. The first peak in the current of (b) is commutation current because of the reverse breaking and the second peak is also caused by measurement interference.

In Fig. 18, in order to simulate the rising process of the fault current in the actual DC system and ensure that the breaking current reaches 9 kA, the current is interrupted on the rising edge in the half wave of commutating current is opposite to the breaking current.

Test results of low-current (−26, 29 A) and high-current (−9.19, 9.2 kA) breaking are shown in Table 2. The current and voltage waveforms of low-current breaking are shown in Fig. 17 and that of high-current breaking are shown in Fig. 18.
the test of high-current breaking. Therefore, the commutation current is injected when the breaking current has not reached the peak. In Fig. 18a, the initial oscillation is not large enough to create a zero crossing. Owing to the manufacturing process errors of the pulse transformer, there are some differences between the parameters of commutation current in the actual prototype and design. As shown in Fig. 9, the commutation current is not completely symmetrical so that the first current zero crossing is generated in the third oscillation period of the commutation current. Therefore, both the low and high currents are interrupted at the first current zero crossing.

As shown in Figs. 17 and 18, the maximum breaking current reaches 9.2 kA which fully proves the breaking performance of 160 kV HVDC circuit breaker. The minimum breaking current is 26 A due to the limit of the test circuit. The abilities of current bi-directional breaking and low-current breaking are verified.

Compared to the results of Table 2, Fig. 17 and 18, the peak of TIV at low-current breaking test is less than that at high-current breaking but $du/dt$ is far greater than that at high-current breaking. In all of the breaking tests, the circuit breaker successfully breaks current at the first zero crossing. The breaking time is <5 ms. In addition, the maximum voltage of the LV side does not exceed 45 kV, thus the insulation level of the pre-charging part and trigger switch can be substantially reduced.

### 5 Conclusion

To improve the reliability of breaking and reduce the insulation requirements of the pre-charging part and trigger switch, a coupling mechanical HVDC circuit breaker is presented in this paper. According to principal analysis, the 160 kV prototype design and breaking test, the following conclusions are obtained:

(i) The pulse transformer is used to isolate the HV side and LV side. Not only it can achieve the isolation of voltage but also energy can be transferred by the coupling of current. The trigger switch module replaces spark gaps resulting in multiple current zero crossings.

(ii) The relationship between the capacity of the capacitors ($C_1$ and $C_2$) and $k$ is given by the theoretical calculation. Under the condition of a certain precharged voltage level, the amplitude and the rising edge time of the commutation current, the needed capacitance of $C_1$ decreases with the increase of $k$ and the overall capacity of the capacitors has the minimum value when $C_2$ is 10 μF. Taking minimising the capacity of the capacitor as the optimisation target, the optimal key parameters of the coupling HVDC circuit breaker can be obtained by calculation.

(iii) The 160 kV coupling mechanical HVDC circuit breaker has natural bi-directional breaking capacity, and it can break current...
which is not <9 kA within 5 ms while the TIV reaches 272 kV. Thus, the principle of coupling mechanical HVDC circuit breaker is proved feasible and the design of its parameters is reasonable.

6 References

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