A fast LVDC vacuum hybrid circuit breaker: Dielectric recovery and design consideration

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Abstract
Aiming at the fast protection requirements of electrical ships LVDC distribution system, this paper studies a topology of unidirectional vacuum hybrid circuit breaker. The hybrid circuit breaker is an improved current injection LVDC breaker based on precharged capacitor, which improves the dielectric recovery capability of vacuum interrupter after artificial current zero by using a freewheel diode. A synthetic test platform is built to study the dielectric strength recovery characteristics of a 45 mm diameter CuCr50 butt contact vacuum interrupter (driven by Thomson coil actuator, average opening speed of about 3 m/s) under high current (about 20 kA) and small gap (about 1 mm). The experimental results indicate that the dielectric strength of the contact can recover at a very fast speed within the arc time of 100 µs; when the arc time is increased to 320 µs, the dielectric strength of the contact cannot recover for a long time. Therefore, the design principle of the circuit breaker is obtained: within the arc time of 100 µs, by increasing the arc time can increase the contact distance, so the transient interruption voltage tolerance margin of the circuit breaker can be improved. Based on the results of the test, this paper also proposes a calculation method of forced commutation circuit parameters, which is verified by the simulation. The research results show that the DC circuit breaker can realise the rapid breaking of 20 kA fault current within 2 ms, and has a good application prospect in the LVDC distribution system.

1 INTRODUCTION

In recent years, DC distribution grid has been applied in many fields such as rail transmission system, urban power distribution network, electric propulsion system and so on. The main limit to the large-scale application of DC grids is their protection devices, which still have several unresolved issues. First of all, the DC fault current does not have zero crossing which makes DC interruption more difficult. Furthermore, because the small impedance of the DC distribution system results in high rise rate and large peak of short-circuit current and a large number of power electronic devices (such as IGBT, diode etc.) have weak ability to withstand the overcurrent. Thus, DC short-circuit fault must be quickly removed, usually within a few milliseconds[1, 2].

The protection method based on the fast DCCBs can effectively limit the spread of fault, and guarantee the system have better power supply continuity. As one of the key protection devices for DC distribution system, DCCBs have attracted much attention [3, 4]. At present, solid-state DC circuit breakers (SSDCCBs) and hybrid DC circuit breakers (HDCCBs) based on solid-state switch technology are two important development directions of fast DCCBs. The SSDCCBs use high-power semiconductor devices to realise current interruption. Thanks to the power electronic device’s breaking time which is as short as microseconds, the breaking speed of the SSDCCBs is extremely fast and current limiting effect is excellent as well [5, 6]. However, the on-state losses of solid-state switch is high, which requires cooling system to ensure the heat balance of the CB [7, 8]. This would result in large volume of CB, making it unsuitable for applications with small volume requirements in electrical ships LVDC distribution system. The HDCCBs combine the advantages of mechanical switch (MS) and solid-state switch, which has both advantages of low on-state losses and short breaking time [9].
The current injection vacuum HCB adopted Thomson actuator has the advantages of strong current interruption ability, high speed and long electrical life, which has become a research hot spot in the field of DCCB \cite{10, 11}. Its typical topology is shown in Figure 1. When the short circuit fault is detected, the VI opens, and an arc is generated between the contacts. Then, a high frequency reverse current is injected into the interrupter to create the crossing point of the current, by which the current is commutated to the LC path. Then the MOV is finally turned on to dissipate the fault energy, and the fault current is interrupted. The key to the success of breaking is that VI should withstand the TIV after arc extinction \cite{12, 13}. If the VI fails to withstand the overvoltage and a breakdown occurs between the contact, the short circuit current would rise again, which leads to a failed interruption. Since the short circuit current of the electrical ships LVDC distribution system rises very quickly, which can reach 20 A/μs \cite{14}, the breakers have to act as fast as possible to limit the fault current, there is a very short duration from the time of arc occurrence to the arc extinction, which puts forward strict requirements for the dielectric recovery capability of the VI. Therefore, in order to improve the dielectric strength of the VI, the typical current injection HCB usually needs to trigger the FCC after the contact reaches the rated distance to realise reliable breaking \cite{15, 16}. For example, \cite{17} requires that the vacuum switch’s contact distance must reach 8 mm, assuming the contact moving speed is 2 m/s, then it takes about 4 ms, the Short circuit current will increase by 80 kA if the rise rate d/dt is 20 A/μs, which is unfavourable for fast breaking and current limiting. Reference \cite{15} investigates the influence of the electrode separation, arc time and frequency of the reverse current on the breaking capability of vacuum breakers in a DC interrupting process, the shortest arc time is 1 ms and the minimum contact gap is 2 mm in the experimental conditions described in the literature. In \cite{18}, an experimental circuit is designed to measure the dielectric recovery strength of VI in MVDC circuit breaker, the test method is worth learning. Ref. \cite{19} studies the dielectric strength recovery characteristics of the improved current injection breaker under the condition of small gap and low current, and obtains the law of the dynamic recovery of the dielectric strength of the contact, but it is not suitable for the situation when the CB breaking high current.

In this paper, an unidirectional vacuum HCB is studied to satisfy the demand to remove the fault in 5 ms in an electrical ships LVDC distribution system. In order to improve the dielectric recovery capability of the VI after rapid interruption of large current, a freewheeling diode is used in parallel with the vacuum switch. The topology proposed in this paper has these following advantages: (1) Compared with solid-state DC circuit breakers, no high conduction losses in normal operation, no cooling system is required, therefore, the cost and volume are better. (2) Compared with the HCB using solid-state switch as the main breaker \cite{20, 21}, it has a stronger breaking capacity and lower cost, no need to connect power electronic devices in parallel when breaking large currents. (3) Compared with traditional current injection hybrid circuit breaker (Figure 1), the freewheeling diode makes the vacuum switch withstand the TIV time backward, which provide the dielectric recovery time of the VI and improves the breaking reliability of the contact within small gap. Because the system has extremely high requirements for fast breaking, the gap of the contacts is quite small (about 1 mm) during the fault current interruption process. The dielectric recovery strength of a vacuum interrupter after the current crossing point is critical to the LVDC breaker, so an experimental circuit was designed and built and an experimental study was carried out on the dielectric strength recovery characteristics of a 45 mm diameter CuCr50 butt contact VI under high current (about 20 kA) and small gap (about 1 mm). Then the dielectric strength recovery characteristics at different arcing times of the contacts were initially obtained. Finally, according to the experimental results, the design method to reduce the capacitor energy in the LC path of the LVDC breaker is discussed. The rest of this paper is organised as follows. The principle and operation process of the LVDC breaker will be presented in Section 2. The dielectric strength recovery characteristics of the VI under a small gap and high current are necessary reference for optimising the design of the CB, and its experimental research will be presented in Section 3. Then, the optimal design of the CB is discussed in Section 4. Finally, conclusions are drawn in Section 5.

2 | DCCB SCHEME AND OPERATION

2.1 | Configuration of LVDC breaker

The improved topology of HCB based on current injection breaker principle is composed of a vacuum switch based on electromagnetic repulsion mechanism (the VI in the Figure 2),

\[ \text{FIGURE 1} \quad \text{Typical topology of current injection breaker} \]

\[ \text{FIGURE 2} \quad \text{Improved topology of current injection breaker} \]
FCC, freewheeling diode D and metal oxide varistor MOV as shown in Figure 2. The commutation capacitor C is charged to prescribed values.

2.2 Details of breaking sequence

In normal operation, the VI carries the rated current with low on-state losses. The control time sequences and waveforms of fault current breaking for improved topology are shown in Figure 3. The operation process includes the following intervals.

1) When the sensor detects the fault at \( t_1 \), the controller sends the opening signal to VI immediately. After a period of mechanical delay, the contact starts to separate and produce arcs.
2) The T of the commutation branch is conducted at \( t_2 \) to inject reverse current forcing the \( i_{VI} \) to transfer to the commutation branch.
3) While the \( i_{VI} \) is crossing zero at \( t_3 \), the freewheeling diode D is on, and the \( i_C \) will flow through the branch of D. At this time, the voltage across the VI is very low, and the vacuum dielectric strength can recover rapidly, interval \( t_3 \sim t_4 \) is called zero voltage time denoted by \( T_q \) in this paper.
4) At \( t_4 \), the \( i_C \) is equal to \( i_m \) again, the freewheeling diode D cuts off, and the voltage across the VI increases gradually.
5) The voltage is greater than the threshold voltage of MOV at \( t_5 \), then the MOV starts to absorb the energy and \( i_m \) begins to transfer to the MOV branch.
6) At \( t_6 \), all currents are transferred to the MOV branch. Finally, the residual energy is absorbed by the C and MOV. The fault current drops to zero at the \( t_7 \) and the whole breaking process is completed.

It can be seen from the above analysis that, the freewheeling diode makes the vacuum switch withstand the TIV time backward, which provide the dielectric recovery time of the VI and improves the breaking reliability of the contact within small gap. The setting of arc time and \( T_q \) must be considered in the design of circuit breaker, which must be determined by the dielectric recovery characteristics of VI. The experimental tests will be presented in the next section.

3 DIELECTRIC STRENGTH RECOVERY CHARACTERISTICS OF THE DCCB

3.1 Experimental circuit

In order to analyse the dielectric strength recovery characteristics of VI after fast DC interruption and determine the reliable dielectric recovery time of the CB, a synthetic experimental circuit is designed and built. The experimental test circuit consists of a capacitor discharge circuit (CDC) composed of \( C_1-T_1-L_1-VD_1 \), a FCC composed of \( C_2-L_2-T_2 \), a high voltage circuit (HVC) composed of \( C_3-T_3-R_1 \), a freewheeling diode \( VD_2 \) and a fast recovery diode \( VD_3 \), as shown in Figure 4. The parameters of experimental circuit are as follows: \( C_1=120 \text{ mF}, L_1=15 \mu \text{H}, C_2=2 \text{ mF}, L_2=4 \mu \text{H}, C_3=80 \mu \text{F}, R_1=80 \Omega \).

Thomson coil actuator is used in this hybrid circuit breaker as the operating mechanism due to its fast response [22–24]. The structure diagram and physical diagram of the high-speed mechanism are shown in Figure 5. The displacement curve of the contact is shown in the Figure 6, the time 0 of the curve is the time when the contact opening signal is sent out. The opening time of the contact is about 100 \( \mu \text{s} \), and the average opening speed can reach 3 m/s.

The test process is as follows: as an initial state, the VI is closed, and the thyristors \( T_1, T_2 \) and \( T_3 \) are off. Furthermore, the current source \( C_1, C_2 \) and the voltage source \( C_3 \) are charged to prescribed values before the experiment starts. Then \( T_1 \) is triggered to supply a DC current to the VI at the start of the experiment. While the current arrives at a given value (about 20 kA), the VI is separated to produce arcs. After a period of arcing, \( T_2 \) is conducted to inject the high frequency (1779 Hz)
reverse current which superimposes the short-circuit current to zero, different arc time can be obtained by controlling the trigger moment of $T_2$. At the moment of current-zero, the arc of the VI is extinguished, then the current of the FCC would flow through the diode $VD_2$, and the voltage across VI is approximately equal to 0 V until a high voltage pulse with $\frac{dv}{dt}$ approximately 400 V/µs generated by HVC is imposed on it, so that the vacuum dielectric strength can be recovered quickly during this period. If the VI successfully withstands the overvoltage, it means that the electric field strength of the VI is greater than the electric field strength imposed on it under this test condition, and the current is successfully disconnected; on the contrary, if the VI is broken down, it means that electric field strength of the VI is less than the electric field strength imposed on it, the current will rise again. According to the requirements of the electrical ships LVDC distribution system, the amplitude of the overvoltage generally does not exceed twice the rated voltage of the power system. In the test, the high voltage capacitor in HVC can charged up to 5.5 kV, that is, the amplitude of the high voltage pulse can reach 5.5 kV, which can meet the dielectric recovery test requirements of the LVDC circuit breaker. The currents in the circuit are measured with Rogowski current transducer, the arc voltage is measured by a low voltage probe and the high voltage imposed on the VI is measured by a high voltage probe. Electrical signals are recorded with oscilloscope.

The Figure 7 shows the dielectric recovery test typical waveforms in the case of arc time 25 µs, $T_q = 30$ µs. Due to the dispersion of opening time of the mechanical switch, the arcing time of the two pictures has a difference of several microseconds, but it has little effect on the test results. In order to observe the arc voltage, amplify the arc voltage 100 times when processing the waveform. From the Figure 7, we can see that the arc voltage is about 20 V, arc voltage waveform disorder after reverse current injection is caused by the insufficient range of the probe; then after about 105 µs, the contact current crosses zero. After that, the contact successfully withstands the over-voltage and the current is successfully disconnected after 30 µs zero voltage time; but when the high voltage is increased to 4.2 kV, the contact is broken down, leading to the failure of interruption. Repeat the above experiments three times each, it is found that the each test result is consistent (that is, when the amplitude of the high voltage is 3.8 kV, the VI successfully withstands the over-voltage; when the amplitude of the high voltage is 4.2 kV, the VI is broken down leading to breaking failure), therefore, the critical breakdown voltage of the contact can be determined to be between 3.8~4.2 kV, and the overvoltage continues to increase from 3.8 kV until the occurrence of alternating breakdown and withstand phenomenon, at this time, the amplitude of overvoltage is the critical breakdown voltage of the contact, which is about 4 kV. By controlling the trigger moment of $T_3$, different
FIGURE 8 Curves of the critical breakdown voltage

FIGURE 9 Curves of the critical breakdown electric field strength

$T_q$ can be obtained to measure the breakdown voltage in this scenario. Finally, a curve of dielectric strength can be drawn.

### 3.2 Experimental results and discussion

Curves of the critical breakdown voltage have been measured under different arc time of 5, 25, 35 and 320 µs. Each experiment starts from the $T_q$ of 10 µs, increasing $T_q$ in steps of 5 µs to obtain the critical breakdown voltages of 10, 15, 20, 25, 30, 35 and 40 µs respectively, and a series of critical breakdown points are connected. The results are shown in Figure 8. It can be seen from Figure 8, that with the increase of the $T_q$, the residual particles in the contact gap gradually dissipate, and the dielectric strength of the contact gap gradually recovers, so the critical breakdown voltage gradually increases.

The critical breakdown electric field strength curve is obtained by dividing the critical breakdown voltage by the corresponding contact opening distance at each time, as illustrated in the Figure 9.

Due to the limitation of the experimental condition (The rated voltage of $C_2$ is 6 kV, in order to leave a certain safety margin, the maximum charging voltage is 5.5 kV) it is found that when the arc time is increased to 108 µs, the maximum high voltage of 5.5 kV can be successfully withstood within a sufficiently small $T_q$. For the convenience of subsequent analysis, the scenarios that the contact are not broke down are listed in the Table 1.

| Current (kA) | Arc time $T_q$ (µs) | High voltage (kV) | $E$ (kV/mm) |
|-------------|--------------------|------------------|-------------|
| 20          | 108                | 24               | 5.5         | 8.2       |
| 20          | 88                 | 4                | 5.5         | 8.69      |
| 20          | 72                 | 8                | 5.5         | 8.89      |

Based on the Figure 9, and Table 1, it can be seen that the contact’s electric field strength recovery is relatively close within the arc time of 100 µs, both of which can recover at a very short time, and can recover to the static withstand voltage level after about 40 µs of $T_q$. The static withstand voltage level of vacuum interrupter is generally 10 kV. The static withstand voltage of the VI used in this article is 20 kV (1 mm), in order to get sufficient margin for reliable interruption, the static withstand voltage of the VI is 10 kV (1 mm) finally when designing the LVDC circuit breaker. However, when the arc time increases to 320 µs, the dielectric recovery capacity of the contact is greatly reduced compared with that of the contact in the arc time 100 µs, and the electric field strength of the contact cannot be recovered after a long time.

The dielectric recovery ability of the contact is related to the contact opening distance, opening speed of the contact, arc time and other factors. The breaking strategy of improved current injection breaker and traditional current injection breaker is obviously different. In order to withstand the TIV, the traditional current injection breaker generally allows the contacts to reach the rated distance before breaking. The improved current injection breaker contacts are in a moving state during the breaking process. Therefore, as the arc time increases, whether the dielectric recovery ability can be improved depends on the competition between the contact opening distance and the arcing energy. Increasing arc time can increase the contact opening distance when the contact undergoes the TIV, which is conducive to dielectric recovery. Nevertheless, if the arc time is too long, the arc energy will increase, which will increase the residue concentration of the contact clearance and the surface temperature of the contact will be overheated, which is not conducive to dielectric recovery. Therefore, the longer arc time is not the better. By observing the critical breakdown voltage curves of 0, 25 and 35 µs arc time in Figure 8, it is found that the critical breakdown voltage of contact is higher under the condition of longer arc time and the same $T_q$, which indicates that the influence of contact opening distance on dielectric recovery is greater than that of arc time in 0 36 µs, thus increasing the arc time can improve the critical breakdown voltage. In addition, from Figure 9 and Table 1, it can be seen that the critical breakdown electric field strength at the same $T_q$ with the arc time of 320 µs is far less than that in the case of with the arc time of 100 µs. It can be inferred that between the arc time of 36 and 320 µs, there is a certain arc time, which is called the critical arc time. Because when the arc time exceeds this value, the contact opening distance has less influence on the dielectric recovery capability than the arc time, so the dielectric recovery capability of the contact begins to decrease.
4 OPTIMAL DESIGN OF THE DCCB

4.1 Calculation method of the forced commutation circuit

The design of LC path parameters is the key to reliable breaking of the fast DCCB. When designing the forced commutation parameters of circuit breakers, the actual working conditions should be considered, and the size and cost of circuit breakers should be minimised on the premise of meeting the breaking reliability. Based on the above principles, the design of forced commutation branch parameters shall satisfy the following conditions:

1. The peak value of the reverse current should be greater than the current to be interrupted.
2. The reverse current should all flow through the VI branch to reduce the energy of the commutation capacitor.
3. The zero voltage time $T_q$ depends on the period of the reverse current, and its period is related to the parameter design of LC path, the higher the commutation frequency, that is, the smaller the energy of the capacitor, the better the cost, volume and other characteristics of the CB, but on the other hand the higher the commutation frequency means that the zero voltage time $T_q$ becomes smaller, therefore, the frequency of the reverse current should meet the needs of dielectric strength recovery for VI to ensure reliable current interruption. We can learn this from the results of the dielectric recovery test.

The equivalent circuit diagram of the forced commutation process is shown in Figure 10, ignoring the influence of branch resistance and thyristor on-state voltage drop.

According to the KVL

$$L_D \frac{di_D}{dt} + u_D + u_{arc} - L_{arc} \frac{di_c}{dt} = 0 \quad (1)$$

where $i_C$ is reverse current, $i_D$ is current flowing through the freewheeling diode branch, if is reverse current flowing through the VI branch. Thus, the rate ratio of the reverse current flowing to the VI branch and the freewheeling diode branch is obtained by

$$\frac{di_D}{dt} = \frac{I_{arc} - \frac{u_D + u_{arc}}{\frac{di_D}{dt}}}{\frac{di}{dt}} \quad (2)$$

When the rate ratio is less than or equal to 0, the freewheeling diode will not be on, the reverse current will all flow through the VI branch, let the formula (2) be less than or equal to 0 since the $L_D$ is greater than 0, the rate of reverse current flowing to the branch of VI can be obtained by

$$\frac{di}{dt} \leq \frac{u_D + u_{arc}}{I_{arc}} \quad (3)$$

According to engineering experience, the $I_{arc}$ is $0.08 \mu H$, $u_D$ is 1 V, and $u_{arc}$ is 20 V in (3). When $i_D = 0$, then $i_C = i_f$, so a constraint of the $di/dt$ of reverse current can be obtained by

$$\frac{di}{dt} \leq 262 A/\mu s \quad (4)$$

The $di/dt$ of the reverse current in dielectric recovery test is about 220 A/μs less than 262 A/μs. Therefore, the $di/dt$ of the reverse current in FCC can be 220 A/μs. The setting of the precharged voltage value of the commutation capacitor should consider the system parameters. In the process of the fault current interruption, the commutation capacitor is reversely charged by the fault current, and the charging voltage is equal to the TIV. In order to make full use of energy and reduce the volume, the pre-charged voltage of commutation capacitor is generally slightly smaller than the TIV value. What is more, according to the engineering experience, TIV is generally twice of the rated voltage of the system. In addition, according to the requirements of the system, the over-voltage of the system should not exceed 2000 V and considering the power density and cost performance of film capacitor, the pre-charged voltage of the commutation capacitor is set as 1650 V, thus the value of the inductance in FCC can be obtained by

$$L = \frac{U_{i_f}}{\frac{di}{dt}} = \frac{1650}{220} = 7.5 \mu H \quad (5)$$

The arc time of the CB can be set as 35 μs on the basis of the analysis in Section 3. Considering that the dispersion of opening time of the high-speed VI yet, the actual arc time is taken as 5 μs. From Figure 8, it can be concluded that the $T_q$ required for the VI to withstand 2000 V is 16 μs (since the $T_q$ required to withstand 1500 V is not obtained in the experiment, the $T_q$ to withstand 2000 V is taken). To ensure sufficient margin, the $T_q$ required to be twice as long as 32 μs. In order to make the $T_q$ greater than 32 μs, the freewheeling diode $D_2$ of the force commutation branch will turn on when the reverse current drops, so the reverse current will decrease far faster than the rising speed. Therefore, we can ignore the $T_q$ provided by the down section of the reverse current and let the $T_q$ provided by the rising section of the reverse current be greater than 32 μs.
The expression of the reverse current is as follows:

$$i_C = i_{\text{max}} \cos \omega t \quad (6)$$

where $i_{\text{max}}$ is the peak value of the reverse current, $\omega$ is the angular frequency of the reverse current. When $t = 32 \, \mu s$, $i_C = 20 \, kA$, the commutation capacitor value $C$ can be solved by the following formula hence

$$CU_0 = L^2_{\text{max}} \quad (7)$$

$$\omega = \frac{1}{\sqrt{LC}} \quad (8)$$

### 4.2 Simulation of the DCCB breaking fault current

The process of the DCCB’s fault current interruption is simulated according to the obtained parameters. For simulating the practical short-circuit conditions in the system, when the controller detects that the fault current reaches 20 kA, it sends an opening signal to the CB. After a mechanical delay of the CB (100 µs), the contact opens to generate a vacuum arc voltage of 20 V. The simulation results are shown in the Figure 11. It can be seen from the Figure 11 that the peak value of the reverse current is about 24 kA, the initial drop rate of the current flowing through the VI is about 220 A/µs, the peak value of the TIV is about 2 kV, and $T_q$ is about 35 µs, which can meet the needs of dielectric recovery of the CB. The short-circuit breaking time of the CB does not exceed 2.5 ms. The Figure 12 shows the voltage waveform of the commutation capacitor during the interruption process. It can be seen that the final capacitor voltage is charged to about 2 kV by the main current, which meets the insulation requirements of the system. The Figure 13 shows the simulation waveform diagram of the freewheeling diode and voltage across the vacuum switch during the short-circuit breaking process. It can be seen from the Figure 13 that the voltage across the freewheeling diode $u_D$ is equal to the voltage across the vacuum switch $u_0$, and the peak value is about 2 kV. The current flowing through the freewheeling diode $i_D$ is the part where the reverse current is greater than the short-circuit current, and the amplitude is about 1.1 kA. The simulation results can instruct the design of the rated parameters of the device.

### 5 CONCLUSION

In this paper, an improved current injection breaker is studied to meet the demand of fast protection in electrical ships LVDC distribution system. In order to obtain the reliable dielectric recovery time of the CB in fault current interruption, the dielectric recovery test of the VI under small gap and high current is carried out, and the influence of the arc time on dielectric recovery ability is preliminarily obtained

1) In 100 µs of arc time, the dielectric strength of the contact can be recovered to the static withstand voltage level quickly;
2) When the arc time is increased to 320 µs, the dielectric strength of the contact cannot be recovered for a long time.

It provides a basis for the design of vacuum circuit breakers used in the electrical ships LVDC distribution system. From this we can obtain the design principle of the CB: within the arc time of 100 µs, increasing the arc time can increase the contact distance to improve the transient interruption voltage (TIV) tolerance margin of the CB.

Nevertheless, the test only meets design requirements of the CB, which needs further study. Then, a calculation method of forced commutation circuit parameters based on the minimum constraint of capacitor energy is proposed to design the CB. Finally, simulations are carried out to verify the improved
topology and calculation method. The simulation results show that the CB can quickly remove the fault in 2.5 ms, which provides a reference for the subsequent development of engineering prototype. The research results show that the DCCB has a good application prospect in the LVDC distribution system.

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