A No-Arc DC Circuit Breaker Based on Zero-Current Interruption

Xuewei Xiang, Jianyun Chai and Xudong Sun
Tsinghua University, Beijing, 100084, China
xxw15@mails.tsinghua.edu.cn

Abstract. A dc system has no natural current zero-crossing point, so a dc arc is more difficult to extinguish than an ac arc. In order to effectively solve the problem of the dc arc, this paper proposes a dc circuit breaker (DCCB) capable of implementing a no-arc interruption. The proposed DCCB includes a main branch consisting of a mechanical switch, a diode and a current-limiting inductor, a semi-period resonance circuit consisting of a diode, an inductor and a capacitor, and a buffer branch consisting of a capacitor, a thyristor and a resistor. The mechanical switch is opened in a zero-current state, and the overvoltage caused by the counter electromotive force of the inductor does not exist. Meanwhile, the capacitor has a buffering effect on the voltage. The rising of the voltage of the mechanical switch is slower than the rising of the insulating strength of a contact gap of the mechanical switch, resulting in the contact gap not able to be broken down. Thus, the arc cannot be generated. The simulation results show that the proposed DCCB does not generate the arc in the interruption process, the rise rate of the short circuit current can be effectively limited, and the short circuit fault point can be rapidly isolated from the dc power supply.

1. Introduction
Compared with an ac system, the dc system has various and additional advantages and applications. Thus, the dc system is more widely applied on aspects of high-voltage dc power transmission, rail transit, ships and the like. In order to improve reliability, the dc system requires a circuit breaker to interrupt the fault current. A two-terminal dc power transmission system can be protected by using an ac circuit breaker at the ac side, or using a dc circuit breaker (DCCB) at the dc side [1]. However, a multi-terminal system needs to be protected by the DCCB at the dc side [2], and thus, the DCCB is the key piece of equipment within the dc system. The dc system has no natural current zero-crossing point, so the dc arc is more difficult to extinguish than the ac arc. In order to reliably interrupt the short circuit current, the DCCB needs to meet the following requirements: manufacturing a current zero-crossing point; consuming energy stored by the inductor in the system; and withstanding the overvoltage of interruption [3].

DCCBs are mainly divided into mechanical breakers, solid-state breakers and hybrid breakers, combined with mechanical and solid-state breakers. The self-excited oscillation mechanical DCCB utilizes the negative resistance characteristic of a dc arc, to enable the LC oscillation branch and the main current branch to carry out self-excited oscillation to generate the current zero-crossing points. However, the generation of the oscillating current depends on the arc characteristics and if interruption time is too long, the fault current is difficult to interrupt. Reference [4] proposed a super conducting DCCB. A super conducting current limiting module is added into the main branch, which is used for
limiting current rising after a short circuit occurs, and reducing an interruption pressure of the circuit breaker. The pre-charging capacitor oscillation DCCB can rapidly transfer the fault current and generate the zero-crossing point, but it additionally requires a pre-charging circuit and a transfer branch auxiliary switch. The solid-state DCCB utilizes a fully controlled power semiconductor device of the main branch to interrupt a current, it does not require a mechanical switch [5-7]. However, a solid-state DCCB is limited to the capacity of the power semiconductor devices, it requires a great amount of devices to be connected in series and in parallel when being applied to the field of a high voltage, so as to cause a complex structure and control. Meanwhile, it has defects such as high conduction loss, and high cost. The natural commutation hybrid DCCB utilizes the difference of an arc voltage and a turn-on voltage of transfer branch power devices to transfer the fault current [8]. The power devices of the transfer branch are mainly insulated gate bipolar transistors (IGBTs) and integrated gate commutated thyristors (IGCTs). The power devices are connected in series in high-voltage applications, so that the amount of their turn-on voltages is greater than the arc voltage. As a result, the fault current cannot be transferred. The forced commutation hybrid DCCB implements a rapid transfer of the current by auxiliary power devices connected in series of the main branch. The auxiliary power devices do not need to withstand the total system voltage, so that the number of the auxiliary power devices connected in series is small. Thus, relative to the solid-state DCCB, conduction loss of the forced commutation type hybrid DCCB is obviously reduced. However, the transfer branch of the forced commutation hybrid DCCB, requires a great amount of fully controlled devices, so that the cost is high. The ABB Company presented a 320 kV/2.6 kA forced commutation hybrid DCCB, with an interruption capacity of 9 kA and interruption time of 5 ms in 2012 [9]. For another forced commutation hybrid DCCB, an arc generator based on the liquid metal magnetic matrix pinch effect is connected in series into the main branch. A reliable transfer of the current of the main branch and no-arc interruption of the mechanical switch is implemented by regulating the arc voltage of the generator [10]. But the integrated system is complex to control and still needs to utilize the arc generator, in order to generate the arc, and it cannot implement a complete no-arc interruption.

The difficulty of the DCCB is the dc arc. The dc arc has no natural zero crossing point and is more difficult to extinguish than the ac arc. Arc erosion of the contact points causes the circuit breaker to need to have frequent repairs, in order to guarantee system reliability. This paper presents a DCCB capable of no-arc interruption to solve the problems of the dc arc. The structural arrangement of this paper is as follows: section II provides the topology of the DCCB, illustrates the working process of the DCCB in detail, and provides a parameter calculation method; the simulation results of the DCCB and the detailed analysis thereof are provided in section III; and section IV summarizes the work of this paper.

2. Proposed DCCB

2.1. Topology

The topology of the proposed DCCB is shown in figure. 1. An equivalent dc system consists of a dc power supply $U_{DC}$, a power supply side equivalent inductor $L_S$, an equivalent resistor $R_S$, a DCCB, a load inductor $L_L$ and a load resistor $R_L$. The DCCB is the proposed dc circuit breaker. The mechanical switch S, the diode $D_1$, the current-limiting inductor $L_1$, the dc power supply $U_{DC}$, the inductor $L_S$, the resistor $R_S$, the inductor $L_L$ and the resistor $R_L$ constitute the main branch for conducting the current when the dc system works normally. The current-limiting inductor $L_1$ is used for limiting rising of the short circuit current, the diode $D_1$ is used for preventing the counter current, and the mechanical switch S is used for interrupting the main branch and providing sufficient insulating strength. The diode $D_2$, the inductor $L_2$ and the capacitor $C$ constitute the semi-period resonance circuit for carrying out resonance charging on the capacitor $C$. The capacitor $C$, the thyristor $T$ and the resistor $R$ constitute the buffer branch. The buffer branch provides a short circuit current for the load side, meanwhile, it has a buffering effect on the voltage. The thyristor $T$ controls turning-on of the buffer...
branch, the diode D3 can avoid the case that the capacitor C withstands the counter voltage, and the resistor R is used for consuming energy stored by the inductor L2.

Generation of the arc requests that the strength of the electric field acted on the insulating medium is higher than the breakdown field strength of the arc. The breakdown electric field strength of air is 30 kV/cm. The mechanical switch is opened in a zero-current state, with the overvoltage caused by the counter electromotive force of the inductor no longer existing. Meanwhile, the capacitor C has a buffering effect on the voltage, with the rising of the voltages of the mechanical switch S slower than the rising of the insulating strength of the contact gap of the mechanical switch S. As such, the contact gap cannot be broken down, and the arc cannot be generated.

2.2. Working process

When the dc system works normally, the equivalent circuit is as shown in figure 2. After the mechanical switch is closed, as demonstrated in figure 2(a), the conducted diode D2 is neglected, the inductor L2 and the capacitor C start to oscillate from a zero state. In the resonance process, the capacitor voltage $u_c$, and the inductor current $i_{L2}$ are respectively as shown in equation (1) and equation (2). Under the action of the current-limiting inductor $L_1$ and the load inductor $L_L$, the current of the main branch gradually rises to the system rated current $I_n$. By half period of resonance, the inductor current starts to reverse, the diode D2 turns off, the resonance process ends, the capacitor C keeps the peak voltage, which is twice of the voltage of the dc power supply. Only the current of the main branch exists in the dc system, with the equivalent circuit shown in figure 2(b).

$$u_c = U_{dc} (1 - \cos \omega_1 t), \ t \leq T/2$$  \hspace{1cm} (1)

$$i_{L2} = \frac{du_c}{dt} = \frac{U_{dc}}{L_2} \sin \omega_1 t, \ t \leq T/2$$  \hspace{1cm} (2)

where $\omega_1 = \sqrt{\frac{1}{L_2 C}}, \ T = 2\pi \sqrt{L_2 C}$.

In the short circuit current interrupting process of the DCCB, the equivalent circuit is shown in figure 3. A short circuit fault occurs to the line outlet of the DCCB at the zero moment, the current-limiting inductor $L_1$ can limit the rise rate of the short circuit current, and a tiny short circuit impedance is omitted. In this stage, the equivalent circuit is as shown in figure 3(a), and the rise rate $a_i$ of the short circuit current is as follows:

$$a_i = \frac{di_{L1}}{dt} = \frac{U_{dc}}{L_1}$$  \hspace{1cm} (3)

As shown in figure 3(b), at the moment $t_1$, the short circuit current rises to the protection value, the protection system actuates, the thyristor T is turned on, and the buffer branch where the capacitor C is positioned provides the short circuit current for the load side. Meanwhile, it is able to take a buffering effect on the voltage. The initial voltage of the capacitor C is higher than the voltage of the dc power supply, and thus, the current of the mechanical switch S is rapidly reduced to zero, and the counter current is avoided resulting in the diode D1. At that moment $t_2$, the mechanical switch S is opened in a zero-current state. The medium between the contacts provides sufficient insulating strength in the interruption process, and the equivalent circuit is as shown in figure 3(c). In this stage, the circuit equation is as follows:

$$L_C \frac{d^2 u_c}{dt^2} + RC \frac{du_c}{dt} + u_c = 0$$  \hspace{1cm} (4)

The initial state is:
\begin{equation}
\begin{aligned}
    u_c(t_c) &= 2U_{dc}, \\
    u'_c(t_c) &= -\frac{i_{21}(t_c)}{C} = -\frac{I_s + a \cdot t_s}{C}
\end{aligned}
\end{equation}

In the stage, the voltage of the capacitor \( C \) is:
\begin{equation}
    u_c = A_1 \cdot \exp[r_1(t-t_s)] + A_2 \cdot \exp[r_2(t-t_s)]
\end{equation}

The current of the inductor \( L_1 \) is:
\begin{equation}
    i_{l1} = -C \frac{du_c}{dt}
\end{equation}

where \( \alpha_1 = R/(2L_1) \), \( \omega_1 = 1/\sqrt{LC} \), \( r_1 = -\alpha_2 + \sqrt{\alpha_2^2 - \omega_1^2} \), \( r_2 = -\alpha_2 - \sqrt{\alpha_2^2 - \omega_1^2} \), \( A_1 = i_{l1}(t_c)/[C(t_c-t_s)] \), \( A_2 = A_1 \cdot r_1 - A_3 \).

As shown in figure 3(d), at the moment \( t_3 \), discharge of the capacitor \( C \) is completed, the diode \( D_3 \) turns on, the capacitor avoids withstanding the counter voltage; the current of the inductor \( L_1 \) reaches the peak \( i_p \), the voltage of the mechanical switch \( S \) reaches the peak \( u_p \), which is calculated by equation (8). In this stage, the current expression of the inductor \( L_1 \) is as shown in equation (9). At the moment \( t_4 \), energy of the inductor \( L_1 \) is consumed up by the resistor \( R \), the thyristor \( T \) turns off, and the interruption process ends.

\begin{equation}
    u_p = U_{dc} + i_p \cdot R
\end{equation}

\begin{equation}
    i_{l1} = i_p \cdot \exp[-(t-t_s)/\tau]
\end{equation}

where \( \tau = L_1/R \).

2.3. Parameter calculation

The parameters of the proposed DCCB needs to be reasonably designed, including the current-limiting inductor \( L_1 \), the energy consumption resistor \( R \) and the buffer capacitor \( C \), so as to implement a no-arc interruption.

The inductor \( L_1 \) is used for limiting the rise rate of the short circuit current, and for the given rise rate \( a_i \), the calculation formula of the inductor is as follows:
\begin{equation}
    L_1 = U_{dc}/a_i
\end{equation}

The resistor \( R \) is used for consuming energy stored by the inductor \( L_1 \) in the final stage of the short circuit current interruption process, so the value of the resistor \( R \) is expected to be greater. However, when the capacitor \( C \) discharges, the excessive resistance value causes a large voltage drop of the buffer branch, so as to cause the case that the voltage at the intersection point of the buffer branch and the main branch is lower than the voltage of the power supply, and thus, the current of the mechanical switch cannot be reduced to zero. The maximum resistance value is as follows:
\begin{equation}
    R_{max} = U_{dc}/[I_n + a_i \cdot t_s]
\end{equation}

The reduction of the capacitor voltage corresponds to the rising of the voltage of the mechanical switch, and in order to implement a no-arc interruption, the rising of the voltage of the mechanical switch needs to be slower than the rising of the insulating voltage of the mechanical switch. At the moment \( t_3 \), when the capacitor voltage is zero, the reduction rate of the capacitor voltage reaches the maximum. And as long as the insulating voltage \( u_i \) provided by the contact gap of the mechanical switch is guaranteed to be greater than the actual voltage \( u_p \) of the mechanical switch, as shown in equation (12), the condition of no-arc in the entire interruption process is met.
\[ u_i = E_T \cdot V_s (t_3 - t_2) \geq u_p \] (12)

Where, \( E_T \) is non-breakdown electric field strength, and can be obtained by taking a certain safety allowance according to air breakdown field strength.

After the inductor \( L_1 \) and the resistor \( R \) are determined, time \( t_3 \) is only related to the capacitor \( C \), and has a proportional relation with the capacitor \( C \), and thus, the minimum capacitor value \( C_{\text{min}} \) can be obtained by equation (12). The value of the buffer capacitor \( C \) is negatively correlated with the speed of the mechanical switch \( V_s \). The higher the speed of the mechanical switch is, the lower the required value of buffer capacitor is, and vice versa. After the capacitor is determined, the resonant inductor \( L_2 \) is selected so as to obtain the suitable oscillation period and resonance peak current.

\[ + \quad + \quad + \quad + \]
\[ \text{DCCB} \]
\[ U_{\text{DC}} \]
\[ L_S \quad R_S \quad S \quad D_2 \quad D_1 \quad R \quad L_1 \quad L_L \]
\[ C \]
\[ - \quad - \quad - \quad - \]

**Figure 1.** Topology of no-arc DCCB.

\[ - \quad - \quad - \quad - \]
\[ \text{DCCB} \]
\[ U_{\text{DC}} \]
\[ L_1 \]
\[ \text{C} \]
\[ R \]
\[ R \]
\[ U_{\text{DC}} \]

**Figure 2.** Equivalent circuits when the dc system normally works.

\[ + \quad - \quad + \quad - \]
\[ \text{DCCB} \]
\[ U_{\text{DC}} \]
\[ L_1 \]
\[ \text{C} \]
\[ R \]
\[ R \]
\[ U_{\text{DC}} \]

**Figure 3.** Equivalent circuits in the short circuit current interrupting process.

### 3. Simulation Results

In order to verify the effectiveness of the proposed no-arc DCCB, a 10 kV/1 kA DCCB is applied to simulation analysis in MATLAB/Simulink. Simulation parameters are as shown in table 1.

| Symbol | Quantity | Value (Unit) |
|--------|----------|--------------|
| \( U_{\text{DC}} \) | dc power supply | 10 kV |
| \( I_n \) | rated current | 1 kA |
| \( L_S \) | equivalent inductor | 1 \( \mu \)H |
| \( R_S \) | equivalent resistor | 2 m\( \Omega \) |
| \( L_L \) | load inductor | 20 mH |
| \( R_L \) | load resistor | 10 \( \Omega \) |
| \( C \) | buffer capacitor | 300 \( \mu \)F |
| \( L_1 \) | current-limiting inductor | 10 mH |
| \( L_2 \) | resonance inductor | 1 mH |
| \( R \) | energy consuming resistor | 3 \( \Omega \) |
In the resonance charging process, waveforms of the current and voltage of the capacitor are as shown in figure 4. The voltage of the capacitor $C$ reaches 20 kV, which is twice voltage of the dc power supply, the resonance peak current is 5.5 kA. After the current crosses zero, the diode $D_2$ turns off, the capacitor voltage keeps at 20 kV, and the resonant period is 3.44 ms.

In the short circuit current interrupting process, waveforms of currents of the mechanical switch, the buffer branch and the inductor $L_1$ are as shown in figure 5. At the moment of 10 ms, a short circuit fault occurs and the current of the inductor $L_1$ starts to rise from the rated current 1 kA. At the moment of 11 ms, the short circuit current rises to 2 kA, the protection system actuates, the thyristor $T$ is turned on, the current of the capacitor buffer branch is rapidly risen, and the current of the mechanical switch is rapidly reduced. The mechanical switch is opened when the current is reduced to zero, the buffer branch separately provides the short circuit current, and the value of the provided short circuit current is equal to the current of the inductor $L_1$. The inductor $L_1$ withstands a forward voltage, the current of the inductor $L_1$ rises continuously and reaches a peak of 2.7 kA after the capacitor voltage is equal to zero. Later the diode $D_3$ turns on, the inductor $L_1$ discharges by the resistor $R$, the current is continuously reduced, and until the moment of 11 ms, energy of the inductor $L_1$ is attenuated up, and the interruption process ends.

In the short circuit current interrupting process, waveforms of the current, voltage and electric field strength of the mechanical switch are as shown in figure 6. The mechanical switch starts to be opened and the voltage of the mechanical switch starts to rise after the current of the mechanical switch is reduced to zero. When the contact gap is minimal, the electric field strength is extremely high. The rising of the voltage is slower than that of the insulating voltage provided by the contact gap. Along
with the increase of the contact gap, the electric field strength is gradually decreased and is lower than arc generation electric field strength. In the interruption process, the mechanical switch withstands a peak voltage of 21 kV, and after the interruption process ends, the voltage of mechanical switch keeps at 10 kV, which is the voltage of the dc power supply.

Based on the analyses provided above, it can be concluded that the proposed DCCB does not generate the arc in the interruption process. The interruption process of the DCCB lasts for 18 ms, but the short circuit fault point can be rapidly isolated from the dc power supply in 1 ms, and the rise rate of the short circuit current can be effectively limited. Thus, requirements of the dc system have been met.

4. Conclusion

A no-arc DCCB is proposed in this paper. The analyses of the working processes is demonstrated, the parameter calculation methods are given out, and a simulation verification is carried out. The following conclusions are obtained:

- The mechanical switch is opened in a zero-current state, with the overvoltage caused by the counter electromotive force of the inductor no longer existing. Meanwhile, the capacitor has a buffering effect on the voltage, with the rising of the voltages of the mechanical switch slower than the rising of the insulating strength of the contact gap of the mechanical switch. As such, the contact gap cannot be broken down, and the arc cannot be generated.
- The DCCB implements a no-arc interruption, can effectively limit the rise rate of the short circuit current, and rapidly isolates the short circuit fault point from the dc power supply. In demonstrating this, the DCCB can be applied to actual dc power transmission and distribution engineering.
- Prototype production and experiments of the DCCB will be carried out at a later stage.

References

[1] N. Flourentzou, V. G. Agelidis and G. D. Demetriades, “VSC-based HVDC power transmission systems: An overview,” IEEE Transactions on Power Electronics, vol. 24, pp. 592-602, 2009.
[2] L. Tang and B. T. Ooi, “Protection of VSC-multi-terminal HVDC against DC faults,” in Power Electronics Specialists Conference, 2002. Pesc 02. 2002 IEEE, 2002, pp. 719 - 724.
[3] C. M. Franck, “HVDC Circuit Breakers: A Review Identifying Future Research Needs,” IEEE Transactions on Power Delivery, vol. 26, pp. 998-1007, 2011.
[4] B. Xiang, Y. Tan, K. Yang, Z. Liu, Y. Geng, J. Wang, and S. Yanabu, “Quenched Resistance Effects on a Superconducting Current-Limiting-Type DC Breaker,” IEEE Transactions on Applied Superconductivity, vol. 26, pp. 1-5, 2016.
[5] C. Meyer, S. Schroder and R. W. DeDoncker, “Solid-State Circuit Breakers and Current Limiters for Medium-Voltage Systems Having Distributed Power Systems,” IEEE Transactions on Power Delivery, vol. 19, pp. 1333-1340, 2004.
[6] M. M. R. Ahmed, G. A. Putrus, L. Ran, and R. Penlington, “Development of a Prototype Solid-State Fault-Current Limiting and Interrupting Device for Low-Voltage Distribution Networks,” IEEE Transactions on Power Delivery, vol. 21, pp. 1997-2005, 2006.
[7] C. Meyer and R. W. De Doncker, “Solid-state circuit breaker based on active thyristor topologies,” IEEE Transactions on Power Electronics, vol. 21, pp. 450-458, 2006.
[8] J. M. Meyer and A. Rufer, “A DC Hybrid Circuit Breaker With Ultra-Fast Contact Opening and Integrated Gate-Commutated Thyristors (IGCTs),” IEEE Transactions on Power Delivery, vol. 21, pp. 646-651, 2006.
[9] M. CALLAVIK, A. BLOMBE R G, J. HÄFNE R, and A. A, “The hybrid HVDC breaker: An innovation breakthrough enabling reliable HVDC grid,” 2012.
[10] Y. Wu, M. Rong, Y. Wu, F. Yang, M. Li, J. Zhong, G. Han, C. Niu, and Y. Hu, “Investigation of DC hybrid circuit breaker based on high-speed switch and arc generator,” Review of Scientific Instruments, vol. 86, p. 024704, 2015.