Arcless Current Interruption of DC 150A using a Hybrid DC Circuit Breaker Consisting of SiC-MOSFET and Metal Contacts

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Abstract. DC circuit breakers (DCCBs) have received considerable attention due to the increasing demand for DC power transmission and distributed generation. Hybrid DCCBs that consist of mechanical switches, semiconductor devices, and metal-oxide varistor elements offer fast interruption and a low contact resistance when the mechanical contact is closed. Although semiconductor devices in conventional hybrid DCCBs are turned on by arc voltage between the metal contacts, the contact voltage with a high melting-point material can turn on power devices without generating an arc discharge. The magnitude of the molten-bridge voltage of tungsten is sufficient to turn on metal-oxide-semiconductor field-effect transistor devices under specific conditions. In this report, an arcless commutation of DC current is described by using two-pole tungsten contacts connected in series. Finally, we performed DC current (300 V–150 A) interruption and succeeded in obtaining arcless current interruption with a probability of 100%. No erosion was observed after several interruptions of DC 150A.

Key words

Hybrid DC circuit breaker; Molten metal bridge; SiC-MOSFET; Arcless commutation.

1. Introduction

The advantages of DC systems include a small number of required conductors, lower insulation strength, small reactive losses, transient stability, no skin effects, and higher transmission efficiency, compared to AC systems. As for the HVDC system, the DC power distribution is the preferred topology for the DC micro-grid in ships, aircraft, PV systems, and wind farms. However, present electro-mechanical and solid-state circuit breakers do not satisfy

Fig. 1. Schematic diagram of current waveforms for AC and DC current interruption.

the requirements for control, switching, and protective actions. Therefore, a strong demand for DC micro-grids has accelerated the intensive study of DC circuit breakers (DCCBs) [1].

Because the AC current has a zero point (Fig. 1), its interruption is much easier than DC. The DC arc discharge persists after opening the contacts because of the absence of a zero-current point. Figure 2 shows the typical current and voltage waveforms of DCCBs. After opening the contacts, a magnetic force or an airflow is applied to the arc discharge to increase the arc voltage. The arc extinguishes after its voltage exceeds the circuit voltage. The arc voltage and duration are over one hundred volts and around a few hundred milliseconds, respectively. Thus, the arc causes severe damage to the contact surface.

In medium-voltage distribution systems, all solid-state circuit breakers without contacts for DC distribution are commercially available. Although the solid-state circuit breakers can interrupt the DC rapidly without mechanical contact, the continuous power loss during the operation is one of drawbacks.

Fig. 2. Schematic of current and voltage waveforms during DC current interruption.

The hybrid DCCB that consists of mechanical contacts and a semiconductor power device is a solution and has been intensively studied in accordance with the development of power semiconductor devices. The key device of hybrid DCCB for HVDC systems [2-4] is the load commutation switch (LCS), which builds up the voltage required to turn-on more than one hundred power

devices connected in series. For the medium-voltage systems in the voltage range of several kilovolts, a few power devices are used in hybrid DCCBs [5]. The corresponding circuit and current flow paths are shown in Fig. 3.

By opening the contacts, an arc discharge is initiated between them. The arc voltage is 10–20 V, which is sufficient to turn on the power device. The arc is extinguished after the current is commutated from the contacts to the power device, because the contact voltage is below the minimum sustaining voltage of the arc discharge. The mechanical contacts have no need to extinguish the arc as the duration is limited by the commutating time. The advantage of this system is that it has very low on-state losses, and the current can be turned off independently from the zero-current point.

Fig. 3. Basic operation of the hybrid DCCB: Steady-state operation (a), current commutation from contact S to MOSFET (b), circuit energy dissipation at varistor (c).

The equivalent circuit during short circuit fault is shown as a series connection of a DC source, line resistor, inductance, and arc resistance. Because of the low line inductance of DC grid, the fault current increases much faster than that of the AC grid [6]. The total time for DC current interruption is the sum of opening time of mechanical contacts and the deionization time of the arc between the contacts.

A new topology for DC breakers has been proposed to avoid the arc generation between the contacts [6, 7]. A forced commutation circuit, which contains a capacitor and a power device, is added to reduce the contact current to zero before opening the contacts.

Recently, we have demonstrated an arcless commutation with a hybrid DCCB consisting of vacuum contacts and SiC- metal-oxide-semiconductor field-effect transistor (MOSFET) modules [8]. The required condition is that the contact voltage should exceed the turn-on voltage of the MOSFETs and remain below the boiling voltage of the contacts. Without adding a forced commutation circuit to decrease the contact current to zero, an arcless commutation was achieved at 74 A with a low-inductance connecting line and two SiC-MOSFETs connected in parallel. The probability of arcless commutation, however, decreased to 5.5% at 140 A. In this report, we present DC 300 V–150 A current interruption with a probability of 100% using two-pole tungsten (W) contacts connected in series and one SiC-MOSFET [9].

2. Experimental Setup

Figure 4 shows an experimental circuit for a hybrid DCCB that consists of two-pole tungsten contacts, a SiC-MOSFET device with a SiC Schottky barrier diode, and a metal-oxide varistor (MOV). The maximum voltage and current of the power source were 300 V and 150 A. The inductance (L) and equivalent resistance (R) were 200 μH and 0.32 Ω , respectively. The DC current of the circuit was set at approximately 150 A by applying the voltage of 50 V. A SiC-MOSFET device (Cree, CAS325M12HM2, 1200 V, 444 A, 3.6 m Ω) and MOV (EPCOS, S20K250, 650V) were connected in parallel with the contacts.

Fig. 4. Experimental circuit of hybrid DCCB .

Figure 5 shows the contacts and a piezo actuator placed in atmospheric air. The contact area of one pair was 1 cm². The movable contacts were driven by the piezoelectric actuator (Mechano Transformer, MTKK16S400F170R) that expands by up to 400 μm by applying 150 V. The maximum gap length between the contacts was set to 300 μm , resulting in a contact force of 43 N between them when they were closed.

The piezoelectric actuator acts as a capacitor. The gap length increases by discharging the capacitor associated with the actuator. The opening speed of the contacts was controlled by changing the time constant of the discharging CR circuit switched by the MOSFET device.

Fig. 5. Schematic diagram of fixed and movable contacts driven by a piezoelectric actuator. The maximum gap length and the contact force were 300 μm and 43 N, respectively.

The control sequence of the hybrid DCCB circuit is shown in Fig. 6. The contacts are initially closed. Then, the primary switch S_{DC} turns on to apply a DC voltage to the circuit at t_0 . The contact current increases to 150 A with a time constant of L/R , as indicated in Fig. 4. When the piezoelectric actuator is discharged at t_1 , the contact starts to open and current suddenly decreases and the MOSFET current increases in turn. The duration of this period is the commutation time of the hybrid DCCB. During the commutation period, the contact voltages show the voltage of a molten bridge, then decrease to turn-on voltage of the SiC-MOSFET device. A certain gap length is needed to prevent the arc generation after the commutation. Finally, the SiC-MOSFET device turns off after t_2 , and then the MOSFET current is commutated to the MOV, which dissipates the inductive energy in the circuit. The interrupting time of the hybrid DCCB corresponds to the time from t_1 to t_3 , and its duration could be reduced below a few milliseconds.

Fig. 6. Time control sequence of the hybrid DCCB experiment. The total interrupting time includes the time for energy dissipation by MOV.

3. Results and Discussion

The waveforms of contact voltage, current, and the displacement of the movable electrode with time are shown in Fig. 7.

The capacitance of the piezo actuator was discharged by a MOSFET, which controls the movement of the piezo actuator at $t = 0$. The contact force gradually decreased, and the contact voltage started to increase at 54 μs . The SiC-MOSFET connected in parallel was turned on at 300 μs , thus all the circuit current flowed the contacts before that time. At 230 μs , the contact voltage exceeded two times the Tungsten boiling-voltage, then an arc discharge initiated at around 255 μs . After the SiC-MOSFET was turned on, the circuit current was commutated to the SiC-MOSFET to prevent damage to the contacts. The displacement is almost the same value as the gap length between the contacts. The gap length increased nonlinearly in the initial period.

Fig. 7. Contact voltage, current, and displacement of the movable electrode with time.

Figure 8 shows the waveforms of the circuit and the MOSFET currents and the contact voltage. The circuit current from the power source was constant at 150 A. Initially, the current flowed through the contacts and was then commutated to the MOSFET. During the commutation, the contact current decreased to zero. However, the contact voltage was not detectable because no arc discharge was generated. After turning off the MOSFET, the contact voltage suddenly increased to a peak value over 700 V. The contact voltage was the same as the MOV voltage until the energy dissipation by the MOV completed after approximately 2.2 ms. Finally, the contact voltage recovered to the circuit voltage of 300 V in this case.

Fig. 8. DC 300V–150A current interruption by the hybrid DCCB operated in an arcless commutation.

The detailed changes in current and voltage waveforms are shown in Fig. 9. During the commutation, the current changed nonlinearly, probably because of the nonlinear changes in the contact voltage. The voltage spike shown at $t = 0$ was caused by the voltage applied to the piezoelectric actuator. However, the current changes

during the initial 30 μs , and the contact voltage was almost zero. The change in the current value was caused by decrease in the contact force that affected the contact resistance directly. After 30 μs , the contact voltage gradually increased and small voltage fluctuations were observed at the end of the commutation. The two dotted lines indicate the boiling and melting voltages of W. The maximum value of the contact voltage did not reach the boiling voltage of W.

Fig. 9. Contact and MOSFET current waveforms during the commutation from contacts to MOSFET. The peak value of the contact voltage is below the boiling and melting voltage of tungsten.

The contact voltage is calculated by equation (1), given by Holm [10].

$$T_{\max} = \sqrt{\frac{V_c^2}{4L} + T_0^2} \quad (1)$$

According to the Holm's $\phi\theta$ relation for metal contacts, the contact voltage V_c is a function of the surface temperature of the contacts, as shown in equation (1), where $T_{\max}$ is the maximum temperature on the contact surface, T_0 is the room temperature, and $L [\text{V/K}]^2$ is the Lorenz number: 2.4×10^{-8} for silver. The softening, melting, and boiling voltages of a silver, copper and tungsten electrodes, calculated by equation (1) are listed in Table 1.

Table 1. – Metal temperatures and corresponding contact voltages

Temperature /Voltage	Silver Ag	Copper Cu	Tungsten W
Softening	180°C	190°C	1000°C
Melting	960°C	1083°C	3380°C
Boiling	2193°C	2582°C	5527°C
Softening voltage	0.09 V	0.12 V	0.6 V
Melting voltage	0.37 V	0.43 V	1.1 V
Boiling voltage	0.75 V	0.8 V	2.1 V

During the commutation, the circuit equation is given by equation (2), where $v_c(t)$ is the contact voltage, stray inductance of the loop and MOSFET are L_S and L_{MOS} , turn-on resistance of MOSFET is r_{on} , and the commutation current is $i(t)$. V_b is the boiling voltage of the metal.

$$v_c = r_{\text{on}} i(t) + (L_S + L_{\text{MOS}}) \cdot \frac{di(t)}{dt} \leq V_b \quad (2)$$

If the magnitude of $v_c(t)$ is below the boiling voltage V_b during the commutation, no arc discharge initiates. Thus, the condition of the arcless commutation for the hybrid DCCB can be written as $v_c(t) < V_b$. The circuit current is almost constant during the commutation, as shown in Fig. 8. However, the voltage drop ($r_{\text{on}} \times i(t)$) increases when the circuit current is high. Thus, a higher V_b or lower v_c is required in case of a higher current interruption. The turn-on resistance of power devices should be lower to satisfy equation (2). Figure 10 shows the relationships between the current and voltage of the SiC-MOSFET (1200 V, 300 A) and Si-IGBT (1200 V, 170 A) devices. The turn-on resistance of the SiC-MOSFET is quite low at lower applied voltages. The melting or boiling voltage of the metal contact is small, and thus the lower turn-on voltage is suited for arcless commutation. This is the reason why we are using a SiC-MOSFET.

Fig. 10. Current and voltage relationships of SiC-MOSFET and Si-IGBT devices. Turn-on resistance of SiC-MOSFET is quite low, particularly at small applied voltages.

4. Conclusion

Arcless commutation was successfully demonstrated in a hybrid DCCB consisting of two-pole W contacts, a SiC-MOSFET with low turn-on resistance, and a MOV. The higher boiling voltages of W electrodes satisfied the arcless condition determined by the circuit parameters. The calculated boiling voltage of two-pole W contacts was approximately 4.2 V, which is sufficient to achieve arcless commutation of DC 150 A. The arcless interruption of DC 300 V–150 A current succeeded with a probability of 100%. The total interruption time was 2.2 ms, which was limited by the energy dissipation by the MOV.

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