DC High-Speed Circuit Breaker for Rolling Stock

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Abstract

Rolling stock powered by direct current are equipped with DC high-speed circuit breakers to protect electrical equipment from short-circuit faults and overcurrent. Based on the DC high-speed circuit breaking technology using air circuit breakers cultivated for DC high-speed circuit breakers[1][2] for railway substations developed in fiscal 2016, Mitsubishi Electric has developed and commercialized on-board DC high-speed circuit breakers for rolling stock that achieve excellent high-speed breaking performance and maintenance performance, as well as weight reduction.

1. Introduction

Either AC or DC is used for the current that serves as the power source for rolling stock, depending on the power supply system. Compared to AC, DC requires higher construction costs due to installation of more substations, but it can reduce rolling stock costs thanks to simplified on-board power equipment. Therefore, DC power supply systems have been widely adopted in urban areas where there are many railcars per area. On the other hand, most of the power grid outside of railways consists of AC, and one reason for this is that DC current breaking is difficult. When faults such as short circuits occur in DC circuits, the current increases over time and the current zero point necessary for breaking does not naturally occur, making current breaking increasingly difficult as time passes. Therefore, it is important to break DC at high speed, and DC high-speed circuit breakers (hereinafter referred to as "HB") that forcibly create a current zero point through current-limiting effects play this role. Mitsubishi Electric developed DC high-speed circuit breakers for railway substations (maximum breaking capacity 100kA) in fiscal 2016[1][2], and recently has developed on-board DC high-speed circuit breakers for rolling stock (hereinafter referred to as "TC-type HB", maximum breaking capacity 30kA) that operate in the same power system. Due to the release of these two circuit breakers as products, it is now possible to provide fault current protection for the entire railway DC circuit. The TC-type HB product concept is shown in Fig. 1.

Reliability	Improved current breaking performance · Short-circuit current cut-off current reduced through high-speed current-limiting technology · Critical current arc time reduced through arc drive technology
Maintainability	Reduced maintenance time · Minimization of lubrication points. Disassembly is unnecessary for lubrication work · No use of parts requiring periodic replacement such as dampers
Light weight	Breaker weight reduction · Product volume and weight reduced through structure optimization of arc chute

Fig. 1 TC-type HB product concept

The TC-type HB product was developed based on the concept of improving reliability and maintainability, and lightening weight. Since short-circuit current in DC circuits increases over time, it is crucial to quickly break the current before it increases in order to reduce the burden on electrically connected equipment. With high-speed breaking performance achieved, the TC-type HB keeps the cutoff current (current peak value) of short-circuit current low, making it a highly reliable circuit breaker. Also, the number of lubrication points during maintenance has been reduced through structural optimization and adoption of oilless bearings, and the structural design enables lubrication without requiring disassembly, thereby improving maintainability. Furthermore, product volume and weight have been reduced by optimizing the structure of the arc chute that extinguishes arcs in air during current breaking.

This paper describes the features and applied technologies of the TC-type HB, focusing primarily on high-speed breaking technology.

2. Ratings and Structure

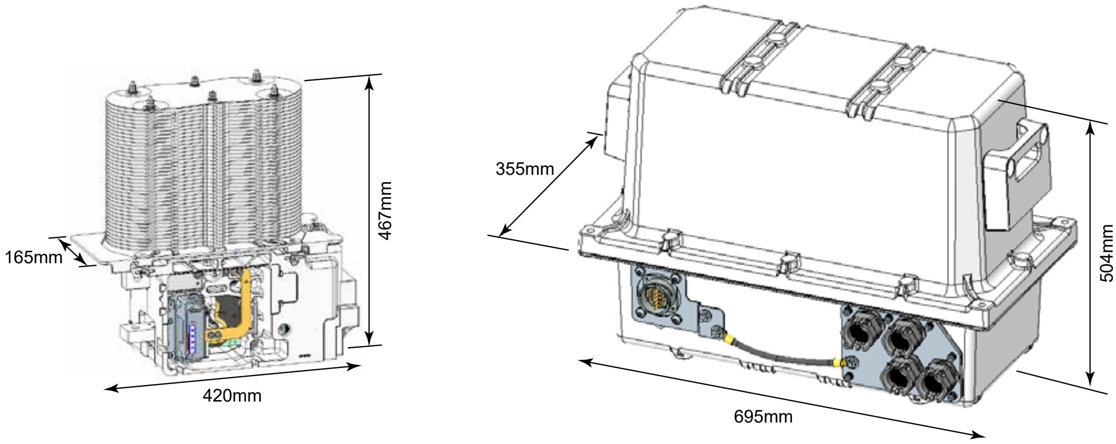
Ratings of the TC-type HB are shown in Table 1. The rated operational voltage is DC 1,800V. The rated operational current is 1,000A. The rated short-circuit making and breaking capacity can handle up to a maximum of 30kA. The over-current release mechanism, which opens the main contacts to initiate current breaking when overcurrent flows in the main circuit, enables free setting of overcurrent setting values in the range of 600 to 3,200A, even after product shipment, by making the return load variable.

Table 1 Ratings of the TC-type HB

Item	Specification
Model	18-TC-10
Rated operational voltage (V_{DC})	1,800
Rated operational current (A)	1,000
Mechanical switching service life (times)	200,000
Load switching service life (times)	800
Rated short-circuit making and breaking capacity / time constant (kA/ms)	18/0*1
	30/15
	30/40
	30/100
Current setting value of over-current release mechanism (min. to max.) (A)	600-3,200
Rated impulse withstand voltage (kV)	18

*1 Time constant 0 is the condition where no reactor is connected to the circuit

The TC-type HB has an optional lineup of enclosures that house the circuit breaker. Figure 2(a) shows the structural diagram of specifications without enclosure, and Fig. 2(b) shows specifications with enclosure. The material of the enclosure and main body molded frame is unsaturated polyester. This meets the incombustibility requirements of the rolling stock material combustion test as a flame retardancy as well as European railway standard EN45545-2:2013 R23/HL3. The TC-type HB with enclosure specifications is intended to be mounted under the floor or above the ceiling in rolling stock and connected to electrical circuits, thereby preventing collision and intrusion of foreign objects into the TC-type HB from the outside, and protecting surrounding equipment from arc gas generated during current breaking.



(a) Specifications without enclosure

(b) Specifications with enclosure

Fig. 2 Structure diagram of TC-type HB

3. TC-type HB Circuit Breaking Technology

This section describes the principles and applied technology for the TC-type HB to break DC, and the breaking performance for short-circuit current and critical current.

3.1 DC breaking principle and applied technology

TC-type HB is an air circuit breaker that breaks DC by current-limiting action. To explain the breaking principle, Fig. 3(a) shows a short-circuit test circuit diagram, and Fig. 3(b) shows a current breaking characteristic diagram. A DC 1,800V test voltage is applied to the short-circuit test circuit, and short-circuit current flows when the main contact of the HB closes. When the main contacts of the HB are opened while current is flowing, an arc occurs between the main contacts. The arc generates arc voltage in the opposite direction to the voltage source (direction that attenuates the short-circuit current) between the main contacts of the HB according to the length of the discharge path and the number and physical properties of the discharge electrodes. By maintaining arc voltage higher than the test voltage, DC current can be current-limited and broken. The TC-type HB performs the process from short-circuit occurrence to completion of breaking at high speed, suppressing the maximum value and time span of short-circuit current.

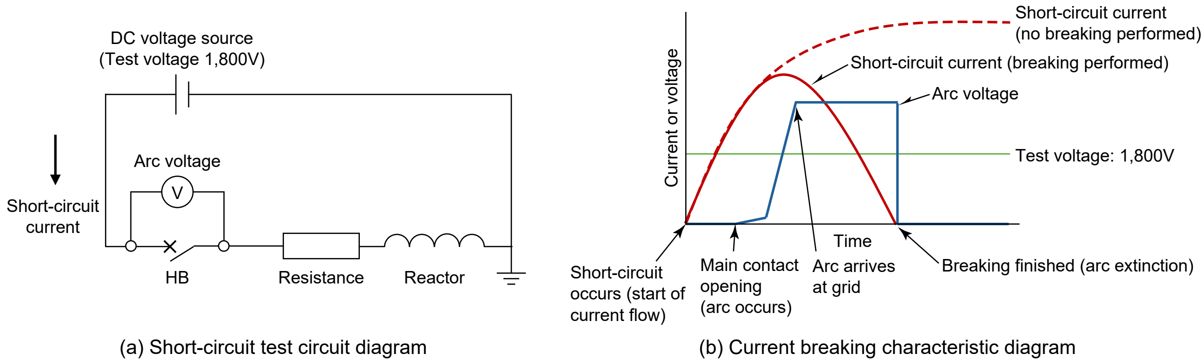


Fig. 3 Diagram of breaking principle of DC breaker

Figure 4(a) is a detailed diagram of the entire TC-type HB. The TC-type HB breaks short-circuit current through four processes: (1) fault detection, (2) main contact opening, (3) arc travel, and (4) arc extinction. This section describes the short-circuit current breaking process and breaking technology.

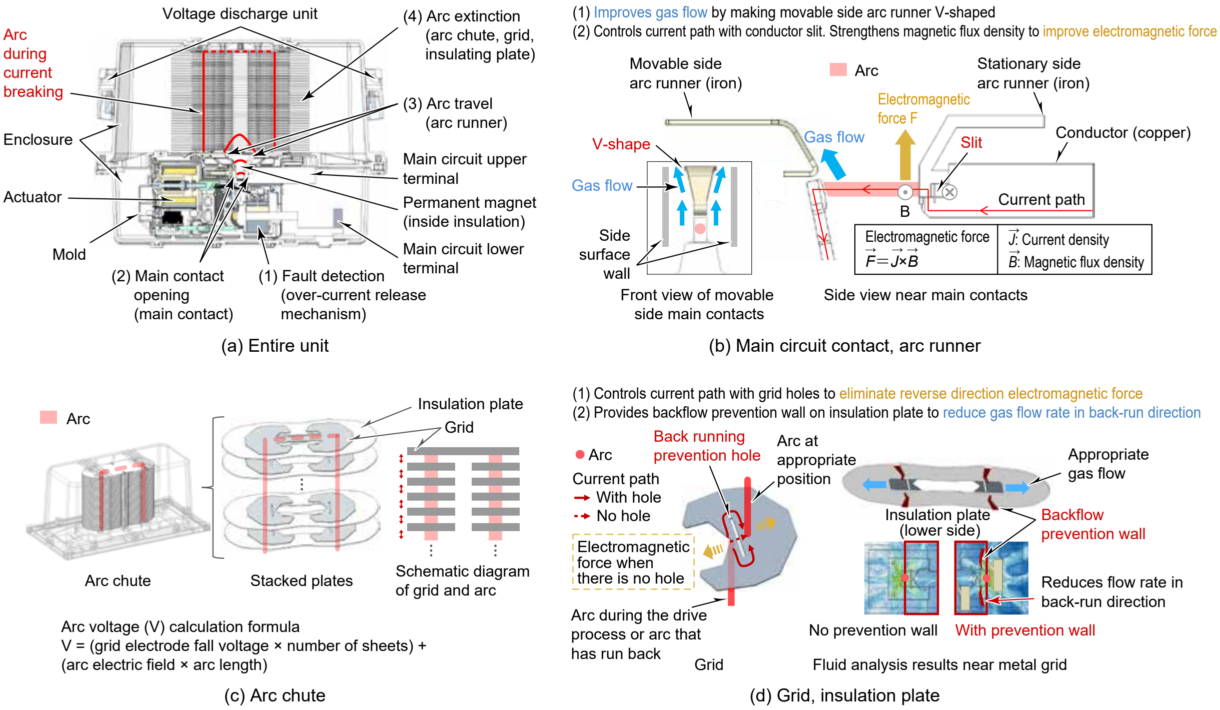


Fig. 4 Detailed diagram of TC-type HB

(1) Fault detection

The HB has a built-in over-current release mechanism, and when the main circuit current exceeds a preset current value, a release device configured as an electromagnet operates to transition the circuit breaker to the open state. In the TC-type HB, high-speed opening operation was achieved by optimizing the magnetic driving force of the electromagnet and reducing the weight of moving parts.

(2) Main contact opening

When opening and closing in the state where main circuit voltage is applied, there is a risk that main contacts fuse due to arcing between them. For the TC-type HB, we have demonstrated that fusing can be prevented by using different contact materials for the movable and stationary sides of the main contacts, and we have thereby achieved a shorter opening time by preventing fusing.

(3) Arc travel

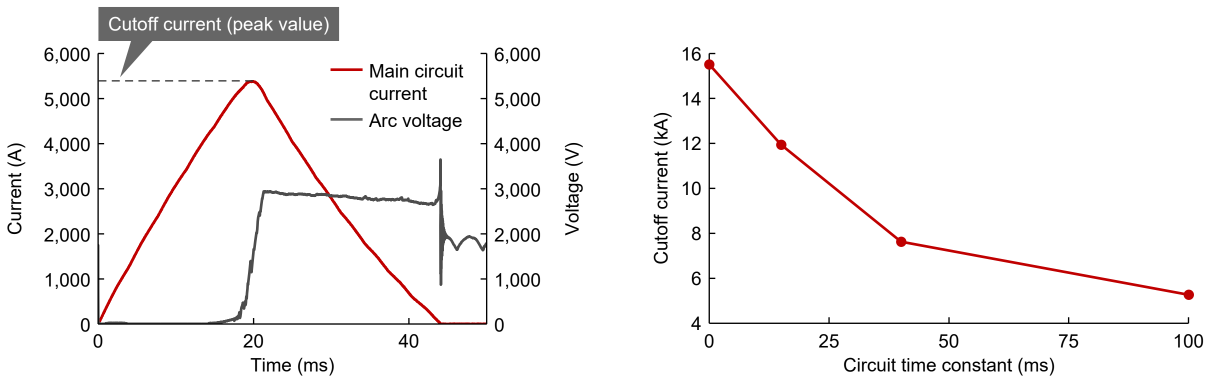
The arc generated between contacts is transferred from the arc initiation point to the arc runner and extends into the arc chute while moving along the arc runner to the tip. For high-speed breaking, it is necessary to quickly guide the arc into the arc chute. The TC-type HB has achieved faster arc drive by increasing electromagnetic force through slitting the main circuit conductor and increasing gas flow with the V-shaped arc runner (Fig. 4(b)).

(4) Arc extinction

The arc that reaches the arc chute is confined to the grid, maximizing the arc voltage and breaking the current through current-limiting action (Fig. 4(c)). In the TC-type HB, backflow prevention holes are provided in the grid to control the current path within the grid, preventing generation of electromagnetic forces that hinder arc extension (Fig. 4(d)). Also, prevention walls are provided on the insulation plates to control gas flow paths, reducing gas flow in directions that hinder arc extension and achieving faster current breaking through arc voltage stabilization.

3.2 Short-circuit current breaking performance

Figure 5(a) shows the breaking current waveform from short-circuit test results of the TC-type HB, and Fig. 5(b) shows cutoff currents extracted from breaking test results under various test conditions. The breaking current waveform demonstrates that the HB's arc voltage rises steeply when the main circuit current increases and the arc voltage is maintained at a level higher than the power source voltage of 1,800V, thus completing the breaking process before the main circuit current reaches the breaking capacity of 30kA. The arc voltage waveform is smooth without sudden voltage drops, and thus the arc is controlled to a state suitable for current breaking, ensuring a stable breaking performance. Furthermore, the cutoff current characteristics show that currents with circuit time constants from 0 to 100ms can be interrupted.



(a) Breaking current waveform (test voltage 1,800V, breaking capacity 30kA, time constant 100ms)

(b) Cutoff current characteristic

Fig. 5 Short-circuit test results for TC-type HB

3.3 Critical current breaking performance

The HB breaks current by extending the arc to raise the arc voltage higher than the power source voltage. The main driving force for arc extension is electromagnetic force, but at critical currents (100 to 1,000A) are weak, so the generated electromagnetic force is also weak, therefore the arc does not extend sufficiently, resulting in breaking difficulties. In the TC-type HB, permanent magnets are installed inside the mold on the contact side surface to secure the electromagnetic force necessary for critical current breaking in the forward direction (current direction from the upper terminal to the lower terminal), thus achieving high-speed breaking for critical current breaking. Figure 6 shows the forward direction critical current breaking test results. Although the permanent magnets act disadvantageously for critical current breaking in the reverse direction (current direction from the lower terminal to the upper terminal), sufficient breaking performance was secured for the reverse direction critical current (600 to 1,000A) of the product specification.

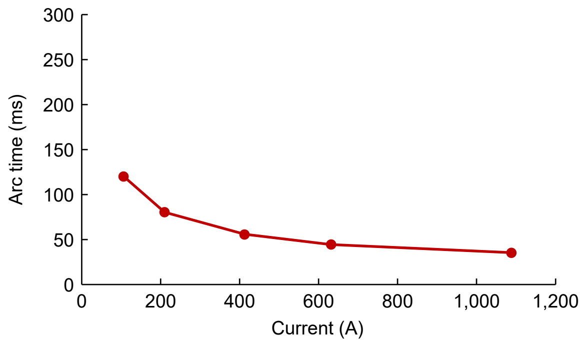


Fig. 6 Critical current breaking test results for TC-type HB (forward direction)

4. Conformity with Market Requirements

This section describes the features of the TC-type HB meeting market requirements.

4.1 Improved maintenance performance

General HBs require lubrication at multiple points during periodic inspections and this involves disassembly work, so a lot of time is required for maintenance. The TC-type HB employs oilless bearings for the mechanism's sliding parts, reducing lubrication points and enabling lubrication without disassembly. Maintenance performance is also improved by not using components that require periodic replacement such as dampers, eliminating replacement work.

4.2 Weight reduction

For the TC-type HB, we succeeded in reducing the weight of the grids and insulation plates that constitute the arc chute by optimizing the structure necessary for current breaking. Figure 7(a) shows the structure diagram of the arc chute stacked plates and arc chute of the TC-type HB, and Fig. 7(b) shows the structure diagram of the arc chute stacked plates and arc chute of a general HB. The TC-type HB reduces the volume of grids and insulation plates compared to general HBs (part indicated in red in the figure). As a result, the TC-type HB weighs 32kg, a 20% weight reduction compared to the development target of 40kg for HB weight (referring to products distributed in the market). Weight reduction of HBs contributes to improved workability and energy saving in rolling stock operation.

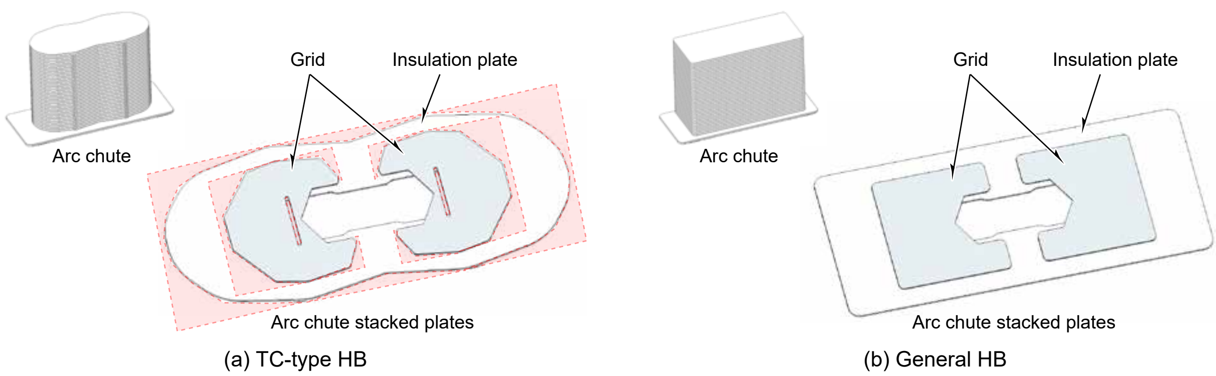


Fig. 7 Structure diagrams of arc chute stacked plates and arc chute

5. Conclusion

We have developed and commercialized on-board DC high-speed circuit breakers for rolling stock that excel in high-speed breaking performance and maintenance performance, and achieve weight reduction. In recent years, high-voltage DC transmission (HVDC), DC microgrids, and similar technologies, which leverage the superior transmission efficiency of DC, have been realized, and the use of DC in power transmission and distribution is expanding. Based on DC breaking technology established in the development of the TC-type HB, we will continue to contribute broadly to society by supplying products suited to the growing need for DC power transmission and distribution.

References

(1) Toya, N., et al.: High Speed Circuit Breaker for Railway Substation, Mitsubishi Denki giho, 91, No. 11, 629–633 (2017)
(2) Sasaki, H., et al.: Development of a High-Speed Circuit Breaker for DC Railway Substations, 2019 IEEE Third International Conference on DC Microgrids, 4-A-4 (2019)