No-Polarity Interruption Technology of Circuit Breakers for High-Voltage Direct Current

SATO, Yutaka*

ABSTRACT

With photovoltaic power generation facilities for applications other than residential use, the voltage is being increased along with the increase in system capacity, and there is a demand for non-polarity circuit breakers that are capable of safely interrupting currents in the opposite direction and handling high voltages. In order to realize such a circuit breaker, Fuji Electric has improved the structure of the arc extinguishing chamber. We made two structural designs and then conducted a magnetic field analysis and an interrupting test for their verification. We have thereby achieved the improved structure that realizes stable interruption performance from small to large current. This has allowed us to realize the non-polarity of middle-voltage direct current circuit breakers while ensuring compatibility with the conventional devices by maintaining the same rated operational voltage, breaking capacity and dimensions.

1. Introduction

Recently, use of photovoltaic energy, a type of renewable energy, for power generation has been attracting attention as a solution to global environmental and energy issues as well as a way to reduce CO_2 emissions and help prevent global warming. Photovoltaic power generation facilities other than those for residential use are proceeding to increase voltage to achieve a generated voltage of 1,000 V. The aim is to improve energy utilization efficiency along with the increase in system capacity. Fuji Electric has expanded the scope of application of the DC circuit breakers and switches of the global twin breaker "G-TWIN Series," released in 2009, in response to the market demands. In 2010, we developed DC middle-voltage circuit breakers and switches (750 V DC and 1,000 V DC). While these DC middle-voltage circuit breakers had polarity with the positive and negative poles specified, non-polarity types are desired in the market in view of increasing demands for safety.

This paper describes the non-polarity interruption technology applied to the DC non-polarity circuit breakers and switches of the G-TWIN Series released in April 2014.

2. Background of Development and Specifications of DC Non-Polarity Circuit Breakers

Figure 1 outlines typical photovoltaic power generation facilities. From a photovoltaic cell array side, it consists of a junction box, power conditioner (PCS) and a distribution panel. Conventional 750 V DC and 1,000 V DC circuit breakers with polarity had the positive and negative polarities indicated and used by specifying the wire to connect. However, a current in the reverse direction flows through the circuit breaker when a reverse connection is made inadvertently or a short circuit occurs as shown in Fig. 2. Non-polarity circuit breakers capable of safe interruption even in these

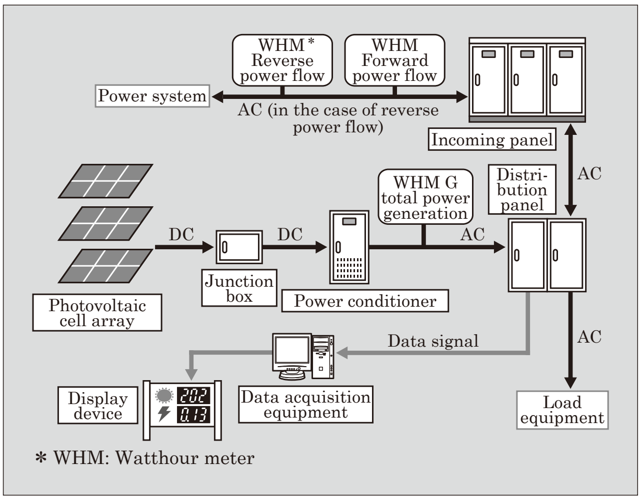

Fig.1 Overview of photovoltaic power generation facilities

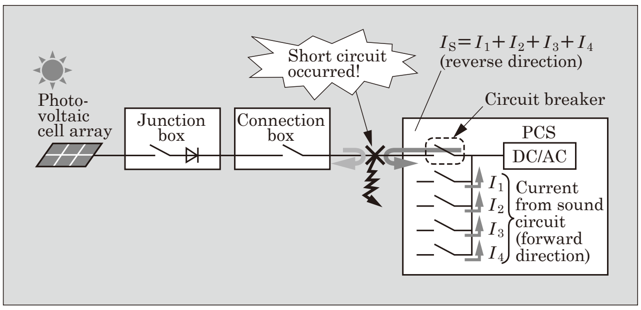

Fig.2 Flow of current in short circuit accident

* Technology & Manufacturing Group, Fuji Electric FAComponents & Systems Co., Ltd.

Table 1 Circuit breaker and switch specifications

(1) Circuit Breaker specifications

Item			Specifications					
Frame size (AF)			400		630		800	
Basic type			BW400RAG		BW630RAG		BW800RAG	
Number of poles			3P	4P	3P	4P	3P	4P
Rated insulation voltage U_i (V DC)			800	1,150	800	1,150	800	1,150
Rated impulse withstand voltage U_{imp} (kV)			8					
Rated current (A)			250, 300, 350, 400		500, 600, 630		700, 800	
Rated breaking capacity (kA) I_{cu} / I_{cs}	JIS IEC/EN	1,000 V DC	-	5/5	-	5/5	-	5/5
		750 V DC	10/5	10/5	10/5	10/5	10/5	10/5
Overcurrent tripping system			Thermal-magnetic type					

(2) Switch specifications

Item	Specifications					
Frame size (AF)	400		630		800	
Basic type	BW400RAS		BW630RAS		BW800RAS	
Number of poles	3P	4P	3P	4P	3P	4P
Rated insulation voltage U_i (DC V)	800	1,150	800	1,150	800	1,150
Rated impulse withstand voltage U_{imp} (kV)	8					
Rated current (A)	400		630		800	
Rated short -time withstand current I_{cw}	5 kA・0.3s		10 kA・0.3s		10 kA・0.3s	

cases were required and we developed DC non-polarity circuit breakers.

Table 1 shows the specifications of the 750 V DC and 1,000 V DC cricuit breakers and switches developed.

Major features are as described below:

(a) Compatible with reverse connection.

(b) Standard models accommodate tropical and cold regions.

(c) Their basic structures are the same as the G-TWIN 400 AF, 630 AF and 800 AF, enabling to share optional parts (auxiliary switches, alarm switches, shunt trip devices, under-voltage trip devices, etc.).

(d) Conformance to domestic and overseas standards (JIS, IEC, EN (CE marking)) has been achieved.

(e) In view of outdoor use, the upper limit of the operational ambient temperature has been increased from 50 to 70°C.

3. Non-Polarity Breaking Technology for DC Current

3.1 Conventional breaking technology

When a short circuit current flows through the circuit breaker, the internal current detector activates the switching mechanism of the circuit breaker, thereby opening the moving conductor and generating an arc between the moving and fixed contacts. Driving the arc to the extinguishing grid increases the arc voltage between the moving and fixed contacts, which instantaneously increases the circuit impedance to interrupt the short circuit current.

In an AC circuit, a current zero point occurs periodically, which means that the current can be interrupted as long as the internal insulation is ensured at a zero point. In a DC circuit, however, no zero point exists as it is. Therefore, a technology is required that interrupts the current by boosting the arc voltage generated between the contacts to be higher than or equal

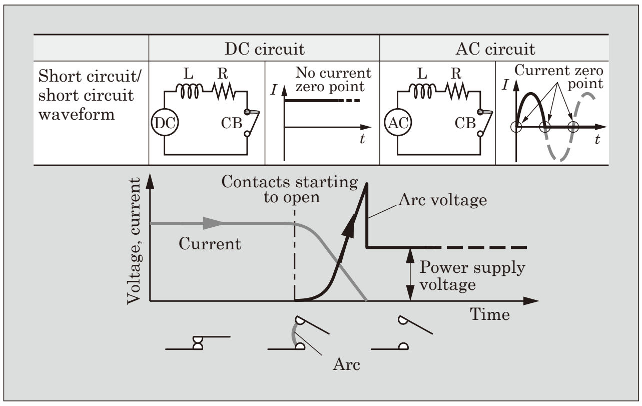

Fig.3 Current interruption and arc voltage

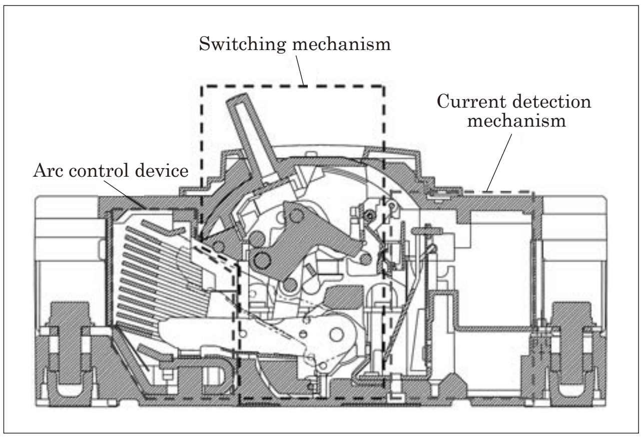

Fig.4 Overall structure of circuit breaker

to the power supply voltage and causing a decrease in the arc current (creating a zero point)[1] (see Fig. 3).

Figure 4 shows the overall structure of the circuit breaker. The circuit breaker is equipped with a current detection mechanism for detecting overcurrent, switching mechanism to open and close the contacts and extinguishing chamber for extinguishing arcs.

The main factors that determine the arc voltage are the opening speed of the moving conductor, the contact opening distance, ablation effect of the arc control device, number of grid plates and arc driving force. With DC circuit breakers, in particular, ensuring the arc driving force was a challenge. Figure 5 shows the structure of a conventional circuit breaker including the extinguishing grid, moving conductor, moving contact and fixed contact and the state of arc between the contacts.

With the conventional structure shown in Fig. 5, the magnetic flux generated by the arc flows through the extinguishing grid and the Lorentz force generated in the process is used for driving the arc. As shown in Fig. 6, the arc driving force increases as the current increases. However, in the small current region of about 1 to 10 A, an arc driving force is insufficient to guide the arc to the extinguishing grid and the arc voltage does not rise sufficiently, resulting in long and unstable break time. The JIS and IEC do not require circuit breakers of 400 to 800 AF to provide interruption in such a small current region that is less than the rated current, but Fuji Electric has verified stable switching and interruption over the entire region.

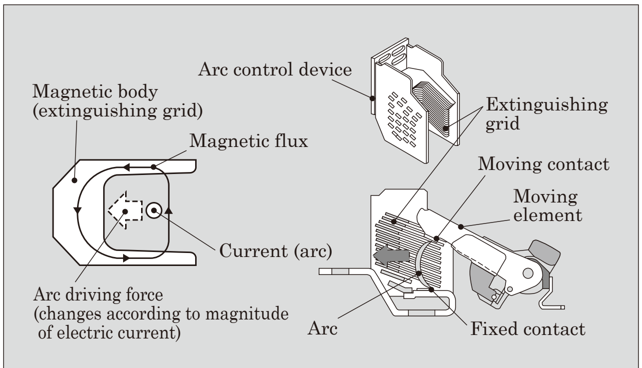

Fig.5 Basic principle of arc driving

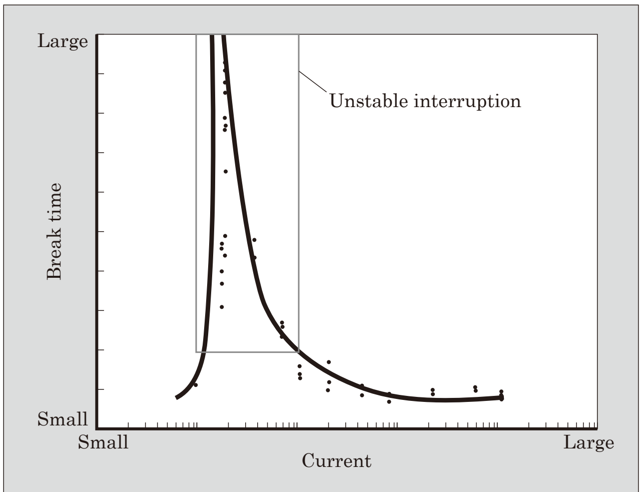

Fig.6 Relationship between current value and break time of DC circuit breaker

3.2 Improvement of arc driving force in small current region

With the conventional structure, arc driving is forced by the magnetic field of the permanent magnets mounted inside the main unit of the DC circuit breaker in order to improve the arc driving force in the small current region[2] (see Fig. 7). However, when the current flows in the reverse direction, the direction of the Lorentz force that acts on the arc is also reversed to obstruct arc driving, and thus could not interrupt. For that reason, it was necessary to specify the polarity of the circuit breaker.

To achieve non-polarity of DC middle-voltage circuit breakers, the challenge is to find a way to ensure the arc driving force in the small current region without using permanent magnets. Increasing the Lorentz force, which is the arc driving force, requires a reduction of the magnetic resistance of the magnetic circuit, and an effective way to do this is to decrease the air gap in the magnetic circuit.

From this viewpoint, we studied the following two proposals for the arc control device structure.

(1) Proposed structure 1

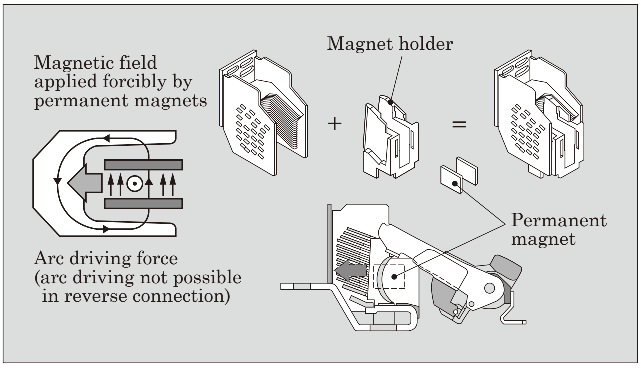

Fig.7 Structure of conventional arc control device

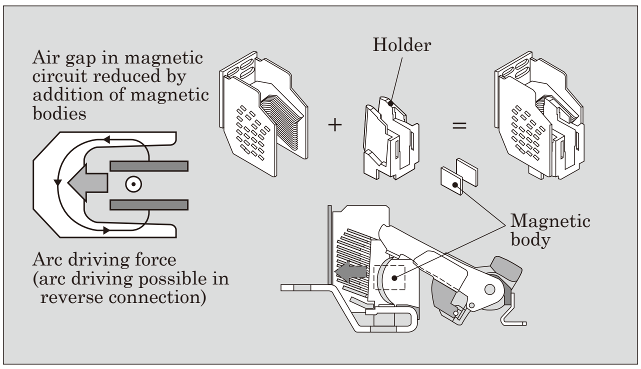

Fig.8 Proposed structure 1

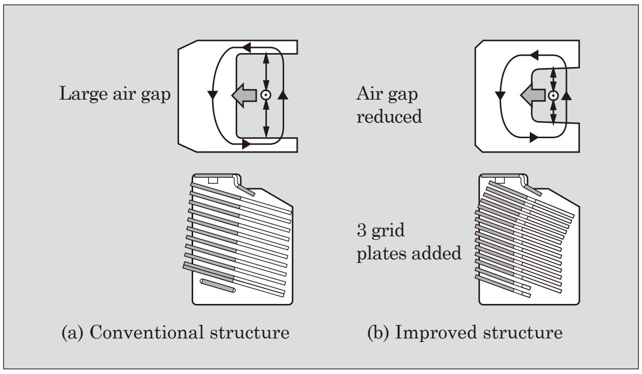

Fig.9 Proposed structure 2

This structure uses magnetic bodies in place of the conventional magnets (see Fig. 8). Placing magnetic bodies between the arc and grid reduces the air gap in the magnetic circuit.

(2) Proposed structure 2

In this structure, the grid is brought closer to the arc to reduce the air gap and the number of grid plates is increased (see Fig. 9). The cross-sectional area of the magnetic body through which the magnetic flux flows is increased by increasing the number of grid plates. We can expect more improvement effect on the arc driving force than the proposed structure 1.

3.3 Study based on magnetic field analysis

For the two proposed structures, we modeled the extinguishing grid, moving conductor, moving and fixed contacts and arc in three dimensions. Magnetic field analysis was used to create a vector diagram of the magnetic flux density and calculate the driving force (Lorentz force) to act on the arc (see Figs. 10 and 11). The result of the analysis showed that proposed structure 1 successfully improved the arc driving force for 400 AF but did not sufficiently increase the driving force from 630 to 800 AF and thus we verified also proposed structure 2. The reason for this is assumed to be that, with 630 to 800 AF, the distance between the grid and the moving conductor is longer than that with 400 AF and the arc driving force differs even by placing the magnetic bodies in the same way as 400 AF. We used proposed structure 1 to prototype the arc control device for 400 AF and proposed structure 2 for 630 to 800 AF, and verified the effect through interruption evaluation test.

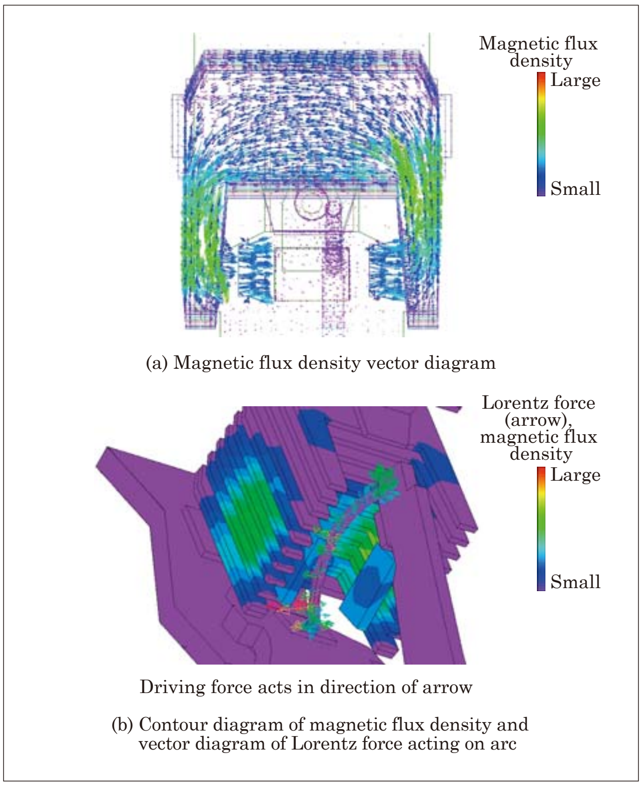

Fig.10 Analysis result of magnetic flux density and Lorentz force

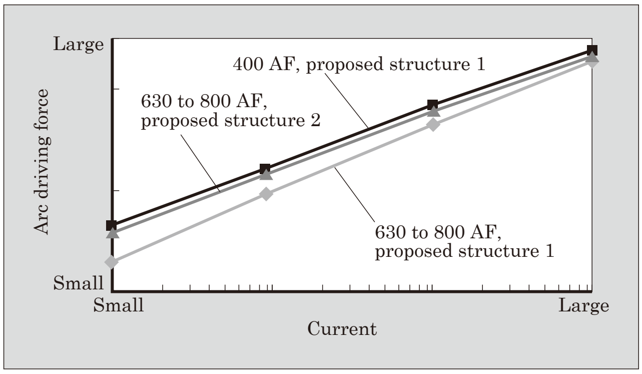

Fig.11 Analysis result of arc driving force

3.4 Result of verification of interruption performance

The interruption test was conducted on the conventional product not using the magnets, proposed structure 1 and proposed structure 2. For 400 AF, proposed structure 1 improved the break time and achieved stable interruption performance over the entire region (see Fig. 12). For 630 to 800 AF, proposed structure 2 showed an improvement in the small current region but did not provide stable interruption in the medium to large current region (see Fig. 13), which indicated the necessity to strengthen insulation on the side of the grid in order to achieve the intended performance.

As a result of examining the arc control device after the interruption, it was found that the arc from the

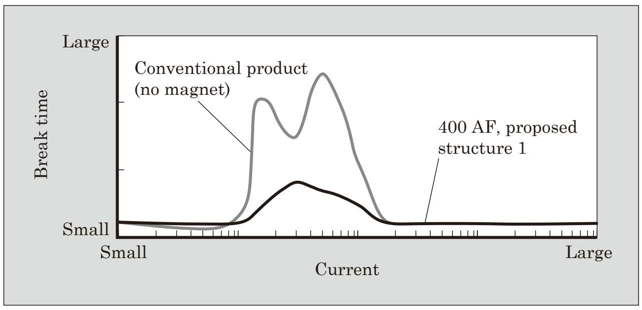

Fig.12 Result of interruption over entire region (400 AF)

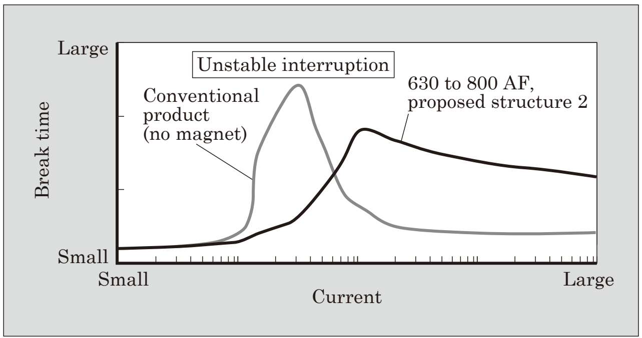

Fig.13 Result of interruption over entire region (630 to 800 AF)

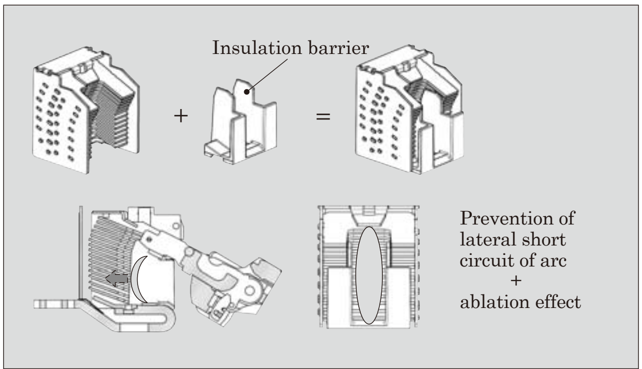

Fig.14 Improved structure

tip of the moving conductor did not extend to the top part of the grid but laterally short-circuited around the middle part of the grid. Accordingly, we added an insulation barrier near the moving conductor without changing the shape of the grid (see Fig. 14). This has the following two aims:

(a) To prevent lateral short-circuiting of the arc by adding an insulation barrier between the arc and the grid

(b) To aim the arc voltage rising effect by ablation effect obtained from use of plastic for the insulation barrier. An ablation effect means rising of the arc voltage by the energy generated when plastic vaporizes.

By making this improvement, we achieved stable

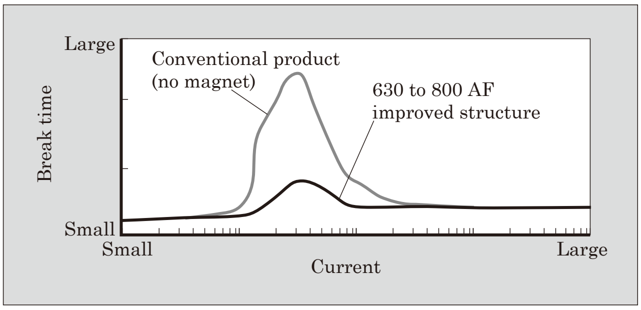

Fig.15 Result of test on improved structure (630 to 800 AF)

interruption performance from small to large currents (see Fig. 15).

The improvement of the structure of the arc control device has allowed stable interruption over a wide range from a few amps to 10 kA with non-polarity specifications and the safety of switching has been verified.

4. Postscript

This paper has described non-polarity breaking technology for DC middle-voltage circuit breakers that can be installed in high-capacity photovoltaic power generation facilities.

In the future, there is likely to be greater demand for reliable and safe power supplies in DC power distribution facilities including facilities related to domestic and overseas new energy power generation and green data center. We intend to accurately capture the various market and customer needs by providing product technologies for higher voltage products and continue to work on research and development.

References

(1) Okamoto, Y. et al. New Technology of the Global Twin Breaker "G-TWIN Series". FUJI ELECTRIC REVIEW. 2010, vol.56, no.3, p.97-102.

(2) Moriai, H. Interruption Technology of Breakers for High-voltage Direct Current. FUJI ELECTRIC REVIEW. 2012, vol.58, no.3, p.127-132.