Interruption Technology of Breakers for High-voltage Direct Current

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ABSTRACT

Applications for direct current (DC) electric distribution have been spreading along with the increase of data centers and renewable energy facilities such as photovoltaic power generation. Fuji Electric has been expanding the application scope of DC circuit specified breakers to meet such market trend. This time, we developed breakers for high-voltage DC (750 V DC, 1,000 V DC) used in the power conditioners of photovoltaic power facilities. By verifying the arc voltage using interruption simulation and interruption testing, and by verifying the magnetic arc drive using magnetic field analysis and interruption testing, we optimized the structure of the arc-extinguishing chamber and achieved a better level of interruption stability at higher voltage than existing products.

1. Introduction

In recent years, as a result of a heightened awareness of energy issues and as a step toward reducing CO_2 emissions to prevent global warming, solar power has been attracting attention as a renewable energy source. With release of the G-TWIN Series of global twin breakers in 2009, Fuji Electric has expanded the application range of breakers including switches for DC circuits. In industrial-use solar power facility, according to system capacity increase, system voltage is getting higher in order to improve the energy utilization efficiency and reduce cost. In response to such requests toward higher voltage, DC high-voltage breakers (750 V DC, 1,000 V DC) have been developed.

This paper presents an example application of a DC breaker to a photovoltaic power plant and describes the main specifications, features, product lineup and elemental technology of DC high-voltage breakers.

2. Application of Breaker to Photovoltaic Power Plant

Figure 1 shows a typical photovoltaic power facility. From a photovoltaic cell array, a junction box, power conditioner (PCS) and a distribution panel are connected sequentially to configure the facility. The use of a breaker and switch in each block is described below.

2.1 Junction box

As shown in Fig. 2, DC power generated by the photovoltaic cell array is collected in the junction box, and sent to the power conditioner. The junction box minimizes the area affected by failure of the photovoltaic cell array, and isolates and insulates circuitry in order to ensure worker safety at the time of maintenance and inspection. The junction box uses a breaker or switch that has the capability to disconnect the DC voltage of the photovoltaic cell and interrupt the operating current and short-circuit current.

2.2 Power conditioner

The power conditioner receives the DC power from the junction box, and converts the power into AC power with its inverter. A grid-connected power conditioner uses a DC breaker at the junction box side (input side) and an AC breaker at the distribution panel side (output side). According to IEC 60364-7-712, the installation of a switch at the input side is required in order to ensure worker safety at the time of maintenance and inspection, and in Japan, a DC breaker is typically

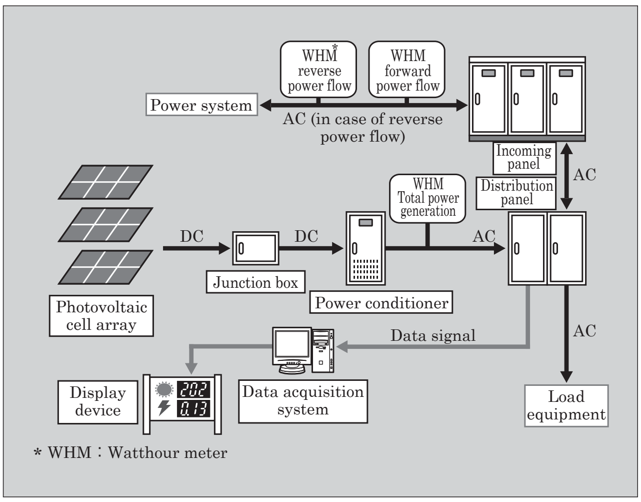

Fig.1 Block diagram of photovoltaic power facility

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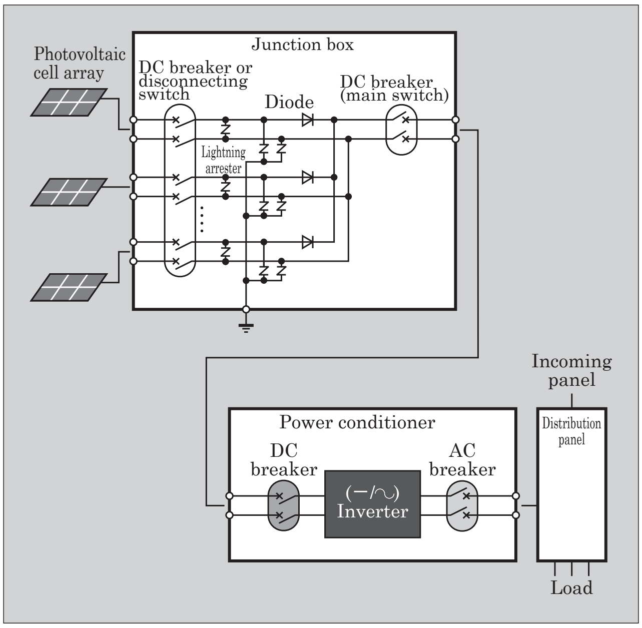

Fig.2 Circuit diagram of junction box and power conditioner

used for this purpose. As a result of the capacity increase of photovoltaic power systems, DC breakers capable of handling higher voltages and larger currents (750 V DC, 1,000 V DC) than ever before are being requested.

2.3 Distribution panel

The distribution panel receives the power that has been converted into AC power by the power conditioner, and distributes it to various electrical loads in a building. The distribution panel also forms a coupling point between the photovoltaic power system and the commercial power supply system from the incoming panel. An earth leakage breaker installed at the input from the power conditioner for photovoltaic power generation can be connected by either a connection method A (see Fig. 3(a)) to the primary side of the distribution panel, or a connection method B (see Fig. 3(b)) to the load side. The connection method is determined as follows, in accordance with the grid interconnection code and indoor wiring regulations.

(a) Connection method A

- ○ Earth leakage breaker for photovoltaic power generation-use: Earth leakage breaker with overcurrent protection, model 3P3E or 3P2E, compatible with reverse connections, equipped with neutral line phase loss protection
- ○ Main earth leakage circuit breaker: Earth leak-

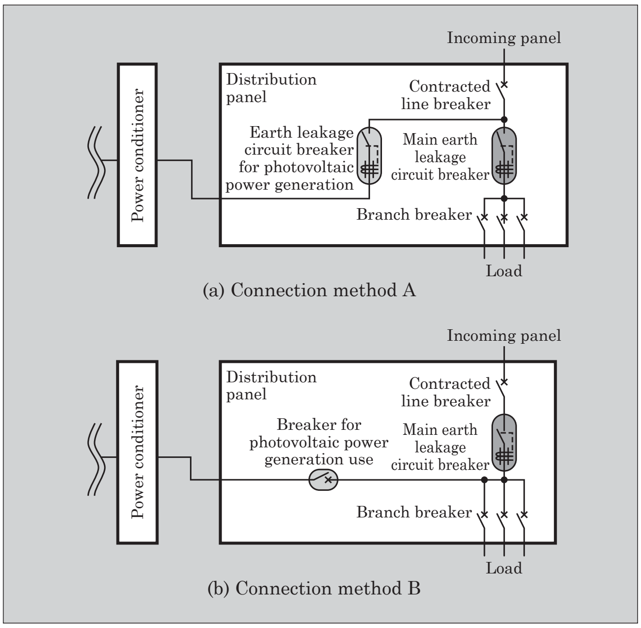

Fig.3 Distribution panel connection methods

Table 1 Breaker and switch specifications

(1) Breaker specifications

Frame size (AF)			400		630		800	
Basic type			BW400RAG		BW630RAG		BW800RAG	
No. of poles			3P	4P	3P	4P	3P	4P
Rated insulation voltage Ui (DC V)			750	1,000	750	1,000	750	1,000
Rated impulse withstand voltage Uimp (kV)			8					
Rated current (A)			250, 300, 350, 400		500, 600, 630		700, 800	
Rated breaking (kA) I_{cu} / I_{cs}	JIS IEC/EN	DC1,000 V	–	5/5	–	5/5	–	5/5
		DC750 V	10/5	10/5	10/5	10/5	10/5	10/5
Overcurrent tripping device			Thermal-magnetic type					

(2) Switch specifications

Frame size (AF)	400		630		800	
Basic type	BW400RAS		BW630RAS		BW800RAS	
No. of poles	3P	4P	3P	4P	3P	4P
Rated insulation voltage Ui (DC V)	750	1,000	750	1,000	750	1,000
Rated impulse withstand voltage Uimp (kV)	8					
Rated current (A)	400		630		800	
Rated short-time withstand current I_{cw}	5 kA・0.3 s		10 kA・0.3 s		10 kA・0.3 s	

age breaker with overcurrent protection, model 3P3E, with neutral line phase loss protection

(b) Connection method B

○ Breaker for photovoltaic power generation use: Molded-case circuit breaker, model 3P3E or 3P2E, compatible with reverse connections, equipped with neutral line phase loss protection

○ Main earth leakage circuit breaker: Earth leakage breaker with overcurrent protection, model 3P3E, compatible with reverse connection, equipped with neutral line phase loss protection

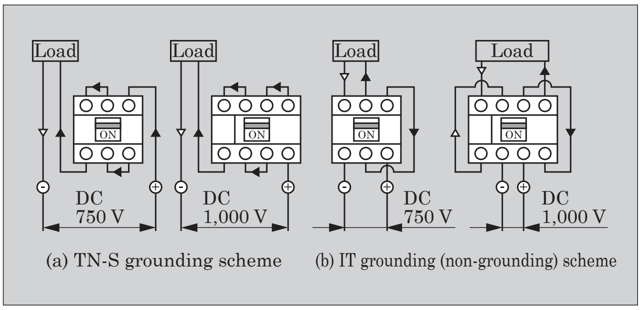

Fig.4 Grounding scheme and connection

3. Specifications, Features and Lineup of DC High-Voltage Breakers

(1) Specification and features

Table 1 lists specifications of the 750 V DC and 1,000 V DC breakers and switches required for use in the power conditioners at photovoltaic power generating facilities.

The main features are as follows.

(a) In consideration of using environments of the breakers, tropical and cold climate specifications were developed for standard products.

(b) The same basic structure was shared with that of the G-TWIN 400 AF, 630 AF and 800 AF, with common options (auxiliary switch, alarm switch, shunt trip device, undervoltage trip device, etc.)

(c) Supports Japanese and foreign standards (JIS, IEC, EN (CE marking))

(d) Product series consists of 4 types of breakers for 750 V DC-use and 1,000V DC-use, supports a TN-S grounding scheme and an IT grounding (non-grounding) scheme (see Fig. 4).

(2) Lineup

Fuji Electric has continuously responded to user requests by developing a series of 30 to 800 AF switches and by expanding its lineup of 650 V DC small switches and parallel connection breakers for use in photovoltaic power generating equipment to contribute to higher applicable voltages and smaller panel sizes.

The lineup of 750 V DC and 1,000 V DC breakers, which are required for use in power conditioners, has been added to the series as a result of the development described herein. The expanded applicability of breakers is as shown in Table 2.

4. Elemental Technologies

4.1 DC breaker technology

If short-circuit current flows through a breaker as

Table 2 List of breaker and switch models

(1) List of breaker models (DC250 to 1,000 V)

Rated DC voltage (V)	Connection method	Rated current (A)																					Breaking capacity I_{cu} (kA)
		5	10	15	32	40	50	63	80	100	125	160	200	250	300	350	400	500	600	630	700	800	
250	2 poles	BW32□AG-BW800□AG C2																					2.5 to 40
400	3 poles	BW32□AG-BW100□AG C4									2.5 to 5												2.5 to 5
500	3 poles	BW50SAG, BW100EAG (–02014, –02025), BW125□AG-BW800□AG-C5																					6 to 40
600	4 poles			BW125RAG C6 to BW800□AG-C6																			25 to 40
750*	3 poles													BW400RAG to BW800RAG C8, D8									10
1,000*	4 poles													BW400RAG to BW800RAG C9, D9									5

＊: Expanded range

(2) List of switches (DC250 to 1,000 V)

Rated DC voltage (V)	Connection method	Rated current (A)										Breaking capacity I_{cu} (kA)
		30	40	50	63	100	125	250	400	630	800	
250	2 poles	BW32□AS to-BW800□AS										–
400	3 poles	BW32□AS to-BW100□AS										–
500	3 poles			BW50SAS		BW100EAS	BW125□AS to BW800□AS C5					–
600	4 poles						BW125RAS to BW800RAS C6					–
650	3 poles			BW50SAS								–
750*	3 poles								BW400RAS to BW800RAS C8, D8			–
1,000*	4 poles								BW400RAS to BW800RAS C9, D9			–

＊: Expanded range

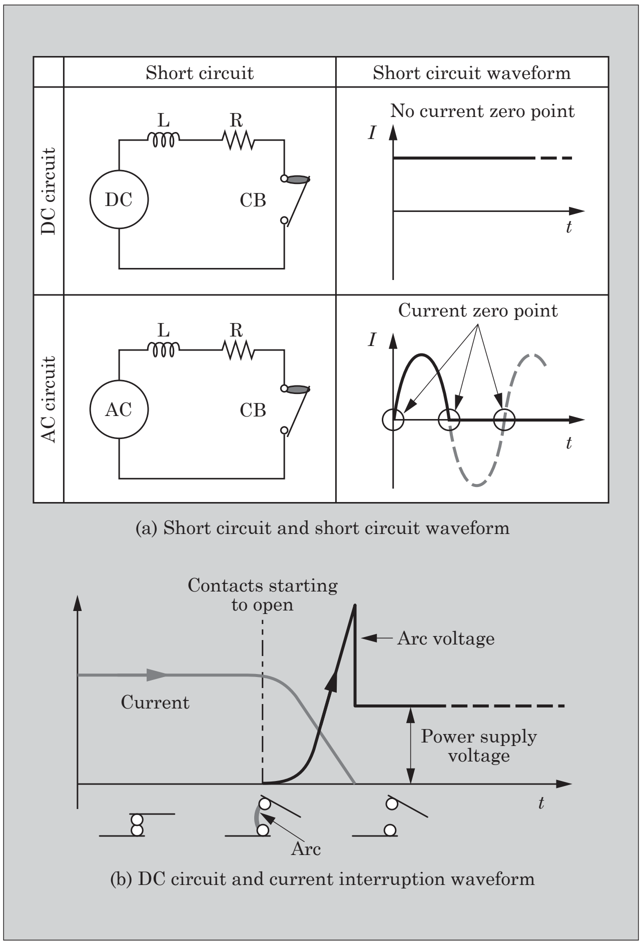

Fig.5 Current breaking and arc voltage

a result of a short-circuit accident, an internal current sensing device activates the switching mechanism of the breaker, the moving conductor moves to its open position, and a current breaking arc is generated between the movable and the fixed contacts. By driving the arc to an extinguishing grid, the arc voltage between the movable contact and fixed contact increases, then it makes the circuit impedance high instantaneously, and the short-circuit current is interrupted.

Generally, in an AC circuit, a current zero point exists periodically, and if the internal insulation can be ensured at the zero point, the current can be interrupted. With a DC circuit, however, the aforementioned zero point does not exist. Thus, for breakers used in DC circuits, technology is needed to interrupt the current (create a zero point) by making the arc voltage between contacts higher than the power supply voltage (see Fig. 5)[1].

4.2 Verification of arc voltage

The main factors that determine the arc voltage are the opening speed of the moving conductor, the contact opening distance, ablation effect, number of grids, and the arc driving force. To achieve both economic efficiency and good breaking performance, use of the existing structure for the opening mechanism, as well as optimization of the number of grids and enhancement of the arc driving force were targeted. In conventional DC breakers, the maximum value of rated voltage had been 500 V DC for a 3-pole device and 600 V DC for a 4-pole device, and then it reveals an arc voltage of about 170 V or higher per pole by a simple calculation. However, to provide breaking performance of 750 V DC with a 3-pole device and 1,000 V DC with a 4-pole device, an arc voltage of at least 250 V per pole is necessary.

To estimate the actual value of arc voltage per one pole of a DC breaker, the arc voltage was investigated using an interruption simulator. The analysis showed that arc voltage values reached the vicinity of 1,000 V; however, because an arc voltage of at least 250 V per pole was not achieved, the number of extinguishing grids were increased, and the layout and shape were optimized so that the arc could be efficiently guided toward the grid within the limited range of the contact opening distance. The results of interruption testing with an actual device showed that while interruption can be achieved in the short-circuit current region, the arc is not driven to an arc extinguishing chamber grid and the interruption was unstable in the small current region of 100 A and below. Consequently, improvements have been made so that stable interrupting performance can be attained even in the small current region (see Fig. 6).

The results of the investigation with an interruption simulator are as follows.

- ○ Analysis condition: 1,000 V/20 A DC, 2 ms time constant
- ○ Analysis model: BW800RAG-4P (10 extinguishing grids)
- ○ Analysis results:

Arc voltage 241 V/1 pole,
964 V/4 poles < 1,000 V

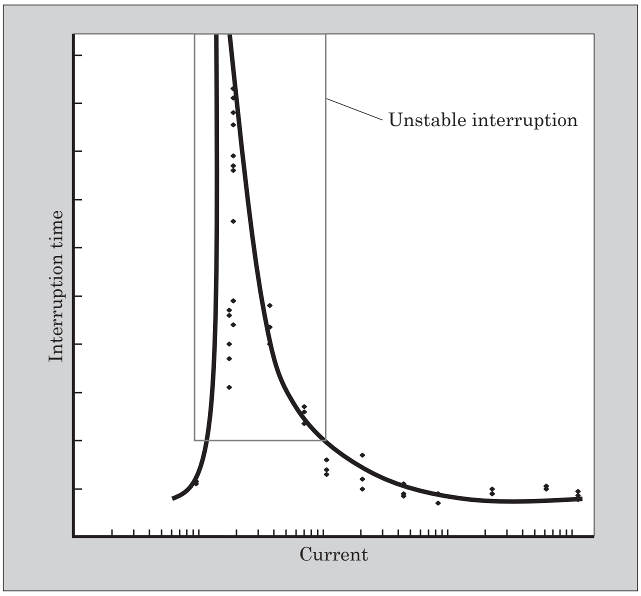

Fig.6 GT800AF DC500 V/2 DC interruption results

4.3 Arc driving in small current region

Figure 7(a) shows the relationship of the arc between contacts with the structure of the extinguishing grid, the moving conductor, the moving contact and fixed contact in a existing breaker.

Generally, as a result of the Lorentz force, the arc driving force increases as the current increases. In the small current region, an arc driving force is insufficient to guide the arc to an extinguishing grid. Accordingly, an arc voltage does not rise sufficiently, thereby causing unstable interruption.

Fuji Electric possesses various elemental technologies for DC current interruption. As one of them, the method in which a permanent magnet is installed inside the DC breaker unit was adopted for the basic structure.

To the existing arc extinguishing chamber, a function forcing a magnetic field using a permanent magnet was added to obtain an arc driving force, and the number of arc extinguishing grids was increased from 10 to 12 grids (see Fig. 7(b)). Using such a basic structure, the magnetic flux density and grid shape, as well as the positional relationship of components such as the permanent magnet were used as variable parameters to pursue optimization.

4.4 Magnetic field analysis

The arc-extinguishing grid, permanent magnet, moving conductor, moving contact, fixed contact and arc were modeled in three dimensions, and a vector diagram of the magnetic flux density and the driving force (Lorentz force) that acts on the arc are calculated by magnetic field analysis. The structure of the arc-extinguishing chamber was determined based on the analysis results, and the interruption effect was verified by an interruption evaluation test. Additionally, the breaker actually used in the interruption test was disassembled, and the wear condition of the arc-extinguishing grid, moving contact and fixed contact, as well as the existence of arc marks were checked, and by providing feedback about the shape and positional relationship to the three-dimensional model for analysis, the structure was optimized while adjusting consistency between the analysis results and the interruption test results (see Fig. 8).

Figure 9 shows the state of the arc-extinguishing chamber after the interruption test. The actual arc diameter and path can be estimated based on observation of the arc marks. In the final structure, based

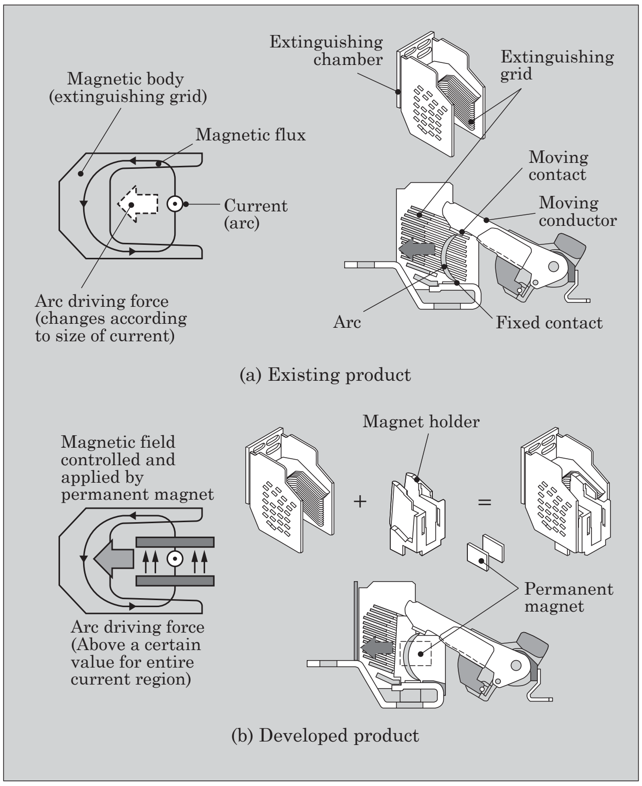

Fig.7 Basic structure of breaker

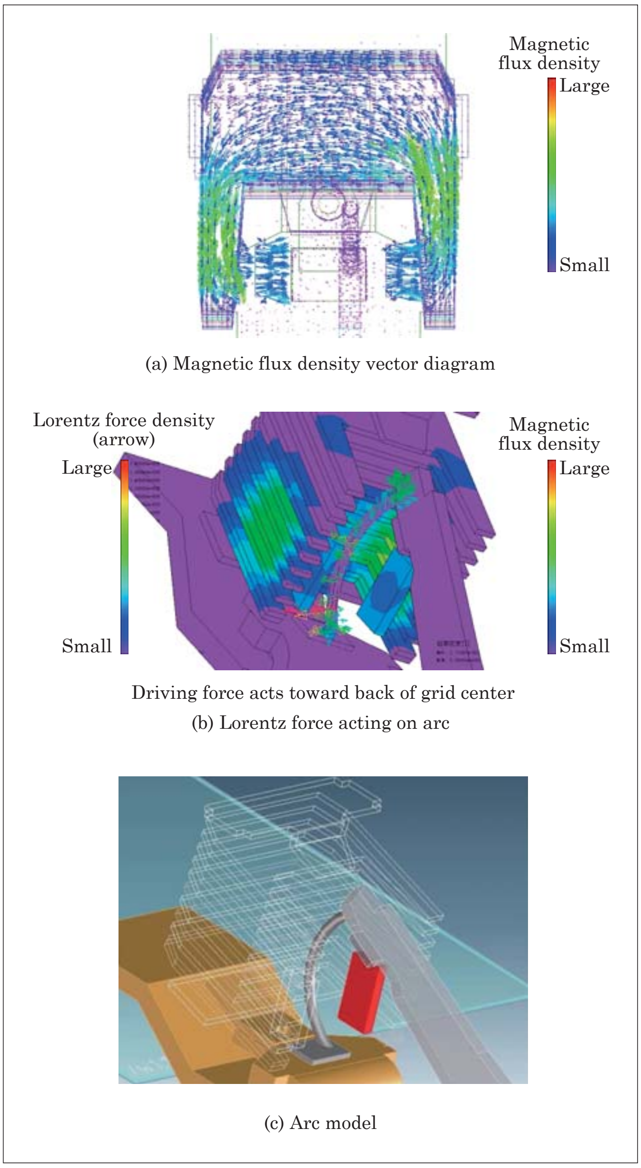

Fig.8 Analysis of magnetic flux density and Lorentz force

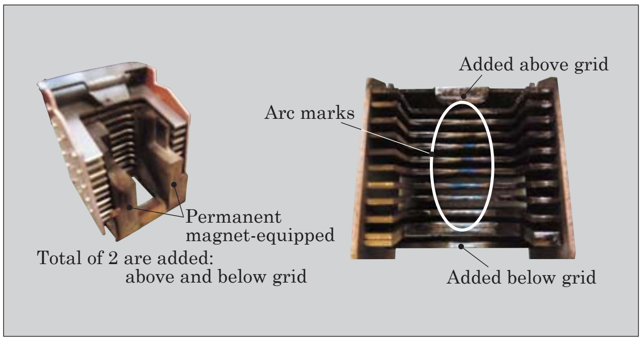

Fig.9 Status of arc-extinguishing chamber after interruption test

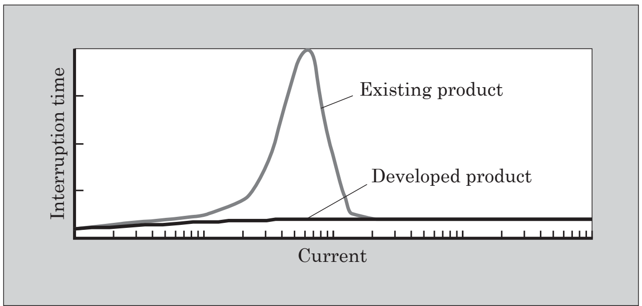

Fig.10 Results of all-area interruption

upon the magnetic field analysis results and the interruption test results, the distance between the arc-extinguishing grid with the magnet holder that holds the permanent magnets and the moving contact with moving conductor after opening were optimized.

4.5 Results of interruption performance verification

With the addition of a permanent magnet to the arc-extinguishing chamber and an increase in the number of arc-extinguishing grids, stable interrupting performing is achieved even in the small current region, where interruption had previously been unstable, and interruption has become possible in the range of several amps to 10 kA, thereby ensuring switching safety (see Fig. 10).

With the addition of a permanent magnet, an arc driving force for guiding the arc to the arc-extinguishing grid can be obtained even in the small current region (see Fig. 11).

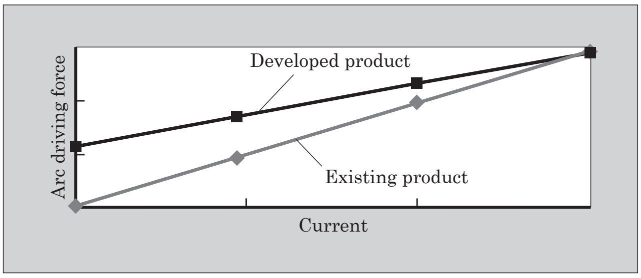

Fig.11 Effect of adding permanent magnet

Moreover, as the effect of adding two arc-extinguishing grids, a stable arc voltage can be kept from the start until the end of interruption, and arc voltages of at least 250 V for 1 pole and at least 1,000 V for 4 poles were attained. As a result, interruption stability, which was a destabilizing factor in previous products, could be achieved.

5. Postscript

This paper has described interruption technology for high-voltage DC breakers suitable for use in large-capacity photovoltaic power generation (mega solar) plants for which future adoption is anticipated.

In the future, requests for a more reliable supply of power and greater safety of DC distribution equipment are expected to increase for new energy generation-related facilities and green data center-related facilities. By accurately assessing marketplace and customer needs, such as for product technologies that support higher voltages and the compliance with and acquisition of international standards and certifications, Fuji Electric intends to advance the research and development of interruption technology for DC breakers.

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.

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