The Transitions and Trends of Core Technology for Electric Distribution and Control Devices

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ABSTRACT

Demands are increasing for miniaturization, higher voltage direct current (DC) equipment that handles clean energy power sources. Interrupting and switching of DC requires a wider contact gap when equipment is miniaturized so that arc voltage rises over power-supply voltage instantaneously and stabilized; thus insulation quality can be ensured. This paper rearranged the transitions and trends of basic technology common to various types of equipment and unique inherent technology to solve this challenge regarding the core technology of electric distribution and control equipment, which until now has stored alternating current (AC) from the perspective of a product and manufacturing. By pioneering a contact-device technology field that is not constrained by methods for the interruption and switching of electric current in the air, Fuji Electric aims for device brand integrating AC/DC technology with high reliability.

1. Introduction

Fuji Electric began electric distribution and control devices business in the 1950s with the full-scale manufacture of ultra compact magnetic switches, and has subsequently expanded its control device line. In the 1960s, with the start of manufacture of molded-case circuit breakers and earth leakage circuit breakers as well as the commercialization of distribution equipment line-up applicable up to 36 kV, Fuji Electric expanded its business operations for all products in both areas. In recent years, an extensive product group that includes a line of products from French company Schneider Electric, a joint partner company, has been spread out.

Previously, the majority of products were used in AC applications, but recently, DC applications have been increasing. This increase is caused by the expansion of use of renewable clean energy sources such as photovoltaic power and wind power as stable power supplies based on the keywords of “energy” and the “environment.”

This paper describes the main products in the field of electric distribution and control devices, the evolution of their core technologies, and discusses the outlook for incorporation of novel products and technologies into new fields brought from the surrounding environment changes.

2. Market and Technology Trends[1]

2.1 Product development and the evolution of technology

Fuji Electric’s core products of electric distribution and control devices can broadly classified into three categories: electromagnetic switches, distribution equipment and command switches (operation switches/displays).

The first category of core products is electromagnetic switches that were launched as the “RC Series” in 1954 based on introduced technology from the German company Siemens. Subsequently, by releasing “SRC Series” and “SC Series”, the compact and highly reliable brands were established, and Fuji Electric has been retaining the top market share to the present day (see Fig. 1). In these series, high reliability was realized with a simple configuration in which the main circuit contacts are controlled by electromagnetic driving, and opening and closing is performed remotely. Additionally, as in the SC Series of the 1980s, electronic control was introduced to drive electromagnets, and new technologies have been actively incorporated, such as optimal control of the contact function that makes outstanding reduce of contact wear. Fuji Electric has also developed solid-state contactors that use power semiconductors to realize non mechanical contact operation. Additionally, utilizing the highly

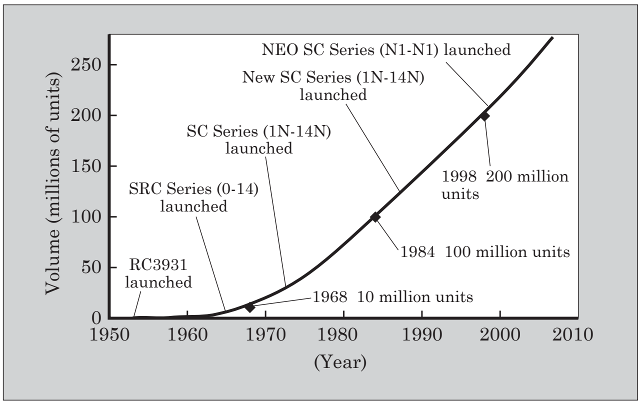

Fig.1 Changes in cumulative production volume of electromagnetic switches

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reliable technology that has been cultivated in these types of industrial fields, the product lineup in the consumer field has been expanded with the "FMC Series" and the like, and the cumulative production quantity to date is approaching 300 million units.

Concerning the second category of core products as molded-case circuit breakers, the fundamental product among distribution devices, following the development of the "L Series" that is based on proprietary current-limiting breaking technology in the latter half of the 1960s, an earth-leakage circuit breaker was released onto the market for the first time in Japan. Since then, Fuji Electric has expanded its variety of products to air circuit breakers rated at 3,200 A. In particular, in the 1990s, due to advances in technology for achieving miniaturization and higher breaking capacity through arc control, twin breakers featuring the same external dimensions for both molded-case circuit breakers and earth-leakage circuit breakers, which had ever been impossible, were developed and subsequently became the industry standard. Additionally, for medium-voltage circuit breakers rated higher than the 600 V AC class, a technology shift from T-type circuit breaker (minimum oil circuit breaker) to compact vacuum circuit breaker (VCB) that handles the high-voltage breaking region was completed through the use of a vacuum valve method in which the contact electrode area is covered with vacuum-insulated tubing.

For command switches, the third category of core products, Fuji Electric developed the "Rca470 Series" first-generation products applied to ϕ30 mm mounting holes, then miniaturized these products to a product with a proprietary ϕ25 mm hole size, and subsequently expanded the lineup to include products that satisfy the international standard of ϕ22 mm. Assembly and mass-production technology based on parts manufacturing technology of highly accurate metal processing and resin molding is used in the production of these products.

Besides these stand-alone devices, in response to the needs of equipment for monitoring and protecting the charged state of the main components that make up the main circuit system ranging from the main trunk to branches, and in distribution panels and control panels, in 1997 Fuji Electric launched the "F-MPC60 Series" of 6.6 kV-class digital-type multi-function relays for high-voltage distribution. This series performed microprocessor-based sampling control, and integrated a protective relay, an electric indicator, a display and operating switch functions. The series was also provided with self-diagnostic and communication functions, which had not been available in the electromagnetic and static type relays, and the need for power monitoring was commercialized in advance as distribution devices. So that detailed power monitoring of low-voltage distribution panels and distribution switch gears could be carried out efficiently, Fuji Electric's lineup was additionally expanded to include the "F-MPC04 Series" of single-circuit and multi-circuit types of monitoring units. Fuji Electric has responded flexibly to the needs for energy savings through energy monitoring and for the systematization of electric distribution and control devices.

2.2 Market needs and technical trends

The main uses, thus far, for low-voltage electric distribution and control devices have been in AC applications of up to 600 V, and there has been little demand for DC applications of up to 750 V. Recently, however, for electrical facilities and equipment that use green energy power sources, such as the power conditioner at a large-scale photovoltaic power generation facility, there has been increasing need for 1,000 V-class DC high-voltage applications. Industrial needs for 600 V AC and lower voltage applications have been met so far, but high-voltage DC applications for residential-use and commercial facilities have been increasing (see Fig. 2).

As specific examples of DC applications, as well as the previously mentioned green energy, building and facilities in Japan are also considering transitioning from the 200 V AC class to the 400 V DC class used in data centers and the like. Also in residential use, an evolution can be seen from the 100 V AC class to smart house applications that use photovoltaic cells and other high-voltage DC sources.

Moreover, from the experience of the Great East Japan Earthquake of 2011, the risk of dependence solely upon commercial power sources has become apparent, the need for countermeasures to handle long-term power outages is recognized, and there is increased interest in installing residential-use storage battery systems including photovoltaic cells. There is a concept of smart communities where the batteries installed in electric vehicles (EV) are interconnected to the system as a storage battery; therefore, the need for inexpensive electric circuit switches and protective devices that can be used in high-voltage DC applications is expected to increase rapidly.

As shown in Fig. 2, AC and DC applications for

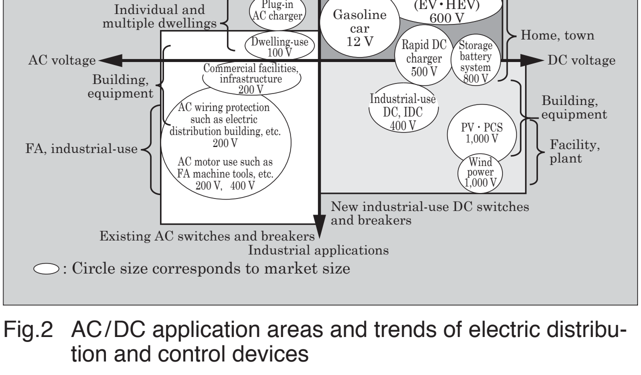


Fig.2 AC/DC application areas and trends of electric distribution and control devices

electric distribution and control devices are expected to expand from the AC low-voltage industrial applications at the lower left region to the following two regions. The first expansion is toward the right, to the new industrial field of DC high-voltage applications, which includes data centers and new energy plants. The other expansion is toward the upper right, to new consumer applications in which the batteries of EVs, HEVs and other types of eco-cars are used as power supplies

3. Technology Development in Electric Distribution and Control Devices

Table 1 arranges the list of the various elemental technologies that organize the technology development in electric distribution and control devices. The core technologies have been extracted from the following three groups. The first is electric distribution devices consisting mainly of molded-case circuit breakers for protecting electric circuits in low-voltage distribution systems from overcurrents due to short circuits and overloading. The second is earth leakage circuit breakers for protecting these circuits from ground faults and earth leakage. The third is a group of control devices consisting mainly of electromagnetic switches used to start and stop, preventing overloading and open-phase operation of electric motors. As the major component common among these devices, a central mechanism detects overload current in the main circuit and, based on the output signal thereof, drives the opening and closing of the contacts. This mechanism is followed by the technology including the opening and closing contacts and a breaking and insulating function by the extinguishing part for the arc generated when the contacts are open. In addition to technology development for product development, the development of new technologies is also being pursued to improve design, production and quality assurance.

With this common fundamental technology established as a platform for all electric distribution and control devices, Fuji Electric has developed and put into practice applied proprietary technology for each model.

3.1 Fundamental technologies

(1) Outer casing of the electric distribution and control devices

As technology development that forms a foundation for product development, the changes in the material of the outer casing of electric distribution and control devices are shown in Fig. 3 as the example of the SC Series electromagnetic contactor. Initially, a ceramic case that covered the arc-extinguishing part was used as an upper case to ensure heat resistance against arc plasma generated while contacts were opening as characteristic of electrical switching devices. Thereafter, by applying arc-suppression technology and the like, thermosetting resin molding material came to be usable, and the shape design became more flexible. In recent years, the casing material has changed to thermoplastic resin molding material in

Table 1 Elemental technologies that configure electric distribution and control devices

Product development technology	Electromagnetic field technology	
	Contact opening and closing technology	
	Breaking/insulating technology	
	Light irradiation display technology	
	Safety technology	
	Environmental technology	
	Materials technology	Material properties and engineering technology Materials analysis technology
	Mechanical engineering technology	Mechanical elements Structure and configuration technology Packaging Mechanism technology Noise and vibration technology Tribology Heating and cooling
	Information processing technology	Embedded software System software Language programming Web, OSS, ASP Communication network, protocol
	Electrical and electronic technology	Digital-analog circuit technology Microcomputer application technology EMC technology Sensing technology
	Simulation technology	Phenomenon analysis technology CAE application technology
Manufacturing and production technology	Precision metal processing technology	Press processing technology Laser processing technology Bending and drawing processing technology
	Precision resin molding technology	Injection molding technology Thermosetting molding technology Insert molding technology Inline molding technology
	Mass-production die technology	Single press processing technology Progressive press processing technology
	Fastening and bonding technology	Brazing and bonding technology Welding technology Adhesive technology
	Surface treatment technology	Plating technology Painting technology
	Mass production assembly technology	Automated assembly technology Jigs, custom machines Anti-pollution technology
	Production line management technology	Parts and materials supply technology Optimal inventory technology Product supply technology
	Facility maintenance technology	
Design management technology	2-3D/CAD technology	CAD, CAM, CAT
	Design drafting	Drawing management Tolerance design
	Development management	
Quality evaluation technology	Line inspection technology	
	Traceability technology	

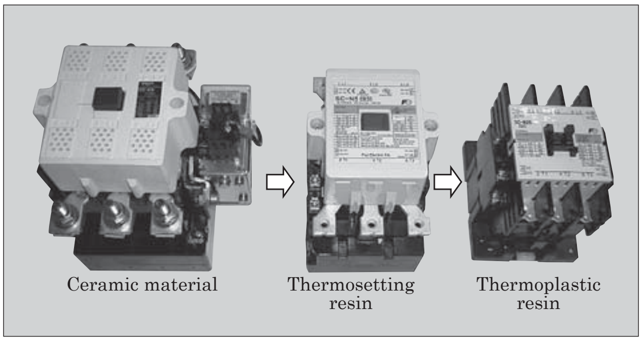


Fig.3 Change in material used for outer casing

consideration of its suitability for recycling; furthermore, an outer casing and components with charged contact parts which having high heat resistance and conforming to the UL standard for non-halogen flame retardant material content have come to be used.

(2) Elemental technologies

Electromagnetic contactors have a long opening-and-closing service life, with electrical and mechanical lives of 2 million times and 10 million times, respectively. In consideration of the tribology to the part where mechanical materials for moving and retaining the contacts are combined, including the lubricative coating of functional parts that retain and support contact sliding, and surface modification of both contacting materials, Fuji Electric has worked to develop friction-lowering elemental technology. Additionally, at the tripping latch and other parts at a high surface pressure in a low-voltage breaker, improvements are needed in the long-term stability of grease and in the balance between the conflicting factors of viscosity and coating uniformity. For this purpose, Fuji Electric has steadily continued to study, improve and accumulate know-how regarding the relationship between component strength and run-time friction through the optimal combination of surface treatment and surface roughness of metal parts.

(3) Design technology

3D CAD software running on a UNIX workstation, which had been popular since before the heyday of PCs in the latter half of the 1980s, was introduced and applied to the development and design of the 1st generation of twin breakers that were launched in 1991. At that time, sheet metal CAD data linked to CAM, which was in its infancy, was directly read-in to wire-cutting machines to shorten the prototype production period, without the use of drawings. Additionally, a rapid prototyping machine was also introduced to shorten significantly the development period for prototyping resin parts. At the same time, Fuji Electric also linked 3D CAD data to CAE, and developed operation analysis software for the contact opening and closing mechanism of a circuit breaker, and applied that analysis software in the development of command switches and the twin breaker series that uses an ultra-compact link mechanism. Figure 4 shows an example analysis of the contact opening and closing mechanism applied to a molded-case circuit breaker, and Fig. 5 shows an example application to the micro-actuator of a command switch. As a result of pioneering analysis methods and design environmental improvements, simulation technology that the designers can professionally use by themselves has been developed.

In terms of compliance with the various standards, priority was first given to Japanese domestic standards during the early stages of a product launch. Subsequently, products were commercialized to support the individual international standards, and at present, Fuji Electric has adopted a policy of global standard conformance so that, as with the "G-TWIN Breakers", nearly all international standards are supported with a single product.

(4) Manufacturing and production technology

With the introduction of wire-cutting machines in the 1980s, in addition to the use of iron core automatic measuring and calking machines, electrostatic coating machines, and the NC processing of sheet metal and machining, the fabrication of complex and precision dies has been sped-up dramatically. Additionally, combined machining technology in which different types of parts are machined simultaneously inside a die was also addressed with the development of an in-die tapping unit.

For treating the surface of components, Fuji Electric independently developed functional plating that applies Ag-C to the copper surfaces of conducting and sliding parts such as the moving contact of a breaker, and miniaturized and enhanced the perfor-

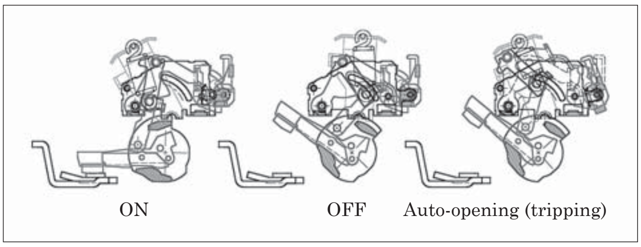


Fig.4 Example analysis of contact opening and closing mechanism used in molded-case circuit breakers

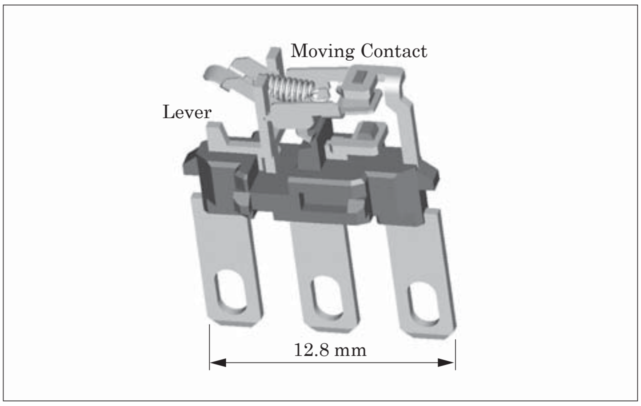


Fig.5 Example application to micro-actuator in command switch

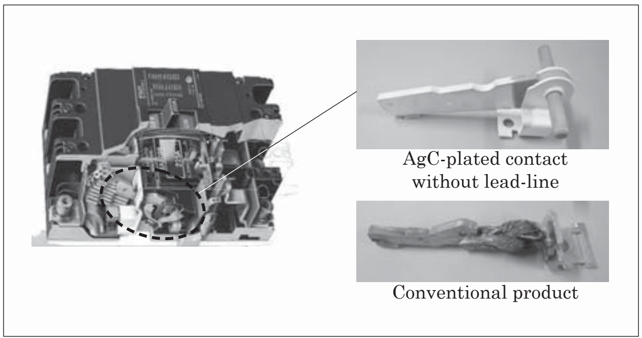


Fig.6 Example of AgC plating used in twin breaker series

mance of the conducting and sliding parts (see Fig. 6).

Technology such as CO_2 laser cutting and NC bending were also introduced along with wire-cutting machines in the 1980s as a pioneer in the industry. In terms of production, the start-up of an automated line for compact electromagnetic switches, the introduction of just-in-time production, the online availability of daily production plans and received orders, the implementation of a cellular production system for electromagnetic switch manual assembly and the like have formed the basis for the variable-mix variable-volume production of today.

3.2 Original technology

(1) Miniature actuator technology for electromagnetic switches

Electromagnetic switches have met the needs for smaller size and higher performance with each successive model change. In particular, the DC operating-type had larger outer dimensions due to its higher coil volume than the AC operating-type. For this reason, Fuji Electric paired an electromagnetic switch with permanent magnets on either side of the coil as shown in Fig. 7(a) to launch the “SK Series,” a new series of the world’s smallest mini contactors that features the same dimensions as the AC-operating type and ultra-low power consumption of 1.2 W for the 2.2 kW-class.

In the development of an actuator that combines permanent magnets and a coil, which contributes to miniaturization of the electromagnetic switch, the power consumption was reduced so that closing operation occurs at 50% of the rated driving voltage of the coil, and release operation occurs at 20% of that rated value so as not to overlap with the polygonal line of contact load force shown in Fig. 7(b). For this purpose, electromagnetic analysis was used actively in 3D CAD, as is shown in Fig. 7(c).

(2) Current-limiting and breaking technology for twin breakers

The twin breaker series that established the industry standard of uniform external dimensions for molded-case circuit breakers and earth leakage circuit breakers was the result of accumulated technology development for smaller size and higher breaking capacity. By way of the L type, the first to be released onto the market, through the “EA and SA Series” that incorporate the current-limiting and breaking characteristics shown in Fig. 8 into a compact size, Fuji Electric has developed a moving contact turn-over mechanism at breaking time, a blowout magnet, and a method of arc driving control with an opening with 2 contacts subsequent to the twin breaker series. Furthermore, Fuji Electric has additionally developed advanced breaking technology such as arc gas flow control and a fork-type dual contact breaking (see Fig. 9). These technology developments are paying dividends and have led to the commercialization of the latest G-TWIN Breakers.

(3) Original technology in manufacturing and production

Fuji Electric has exercised its ingenuity to focus on the bonding of dissimilar metal materials. For example, the development of brazing technology using a press to crimp a thin copper plate while being heated and a technology for diffusion bonding have resulted in reduced silver usage and increased the reliability of metal bonding (see Fig. 10). In particular, as a result of the new diffusion bonding technology, instead of the former method in which brazing filler was placed between the silver alloy contact of an electromagnetic switch or the like and a contact plate made of copper material and then these two components were bonded

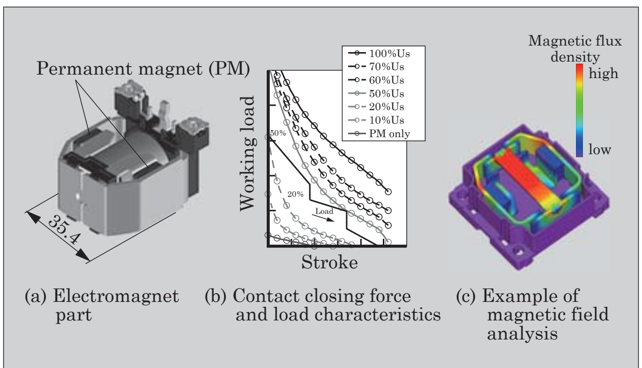


Fig.7 Miniaturization of electromagnet part of electromagnetic switch

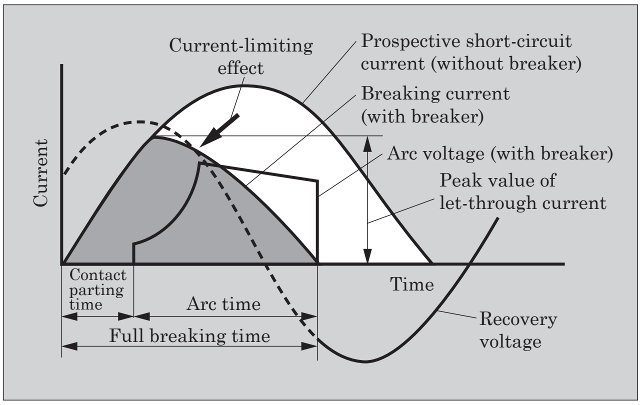


Fig.8 Current-limiting breaking characteristics for high breaking capacity

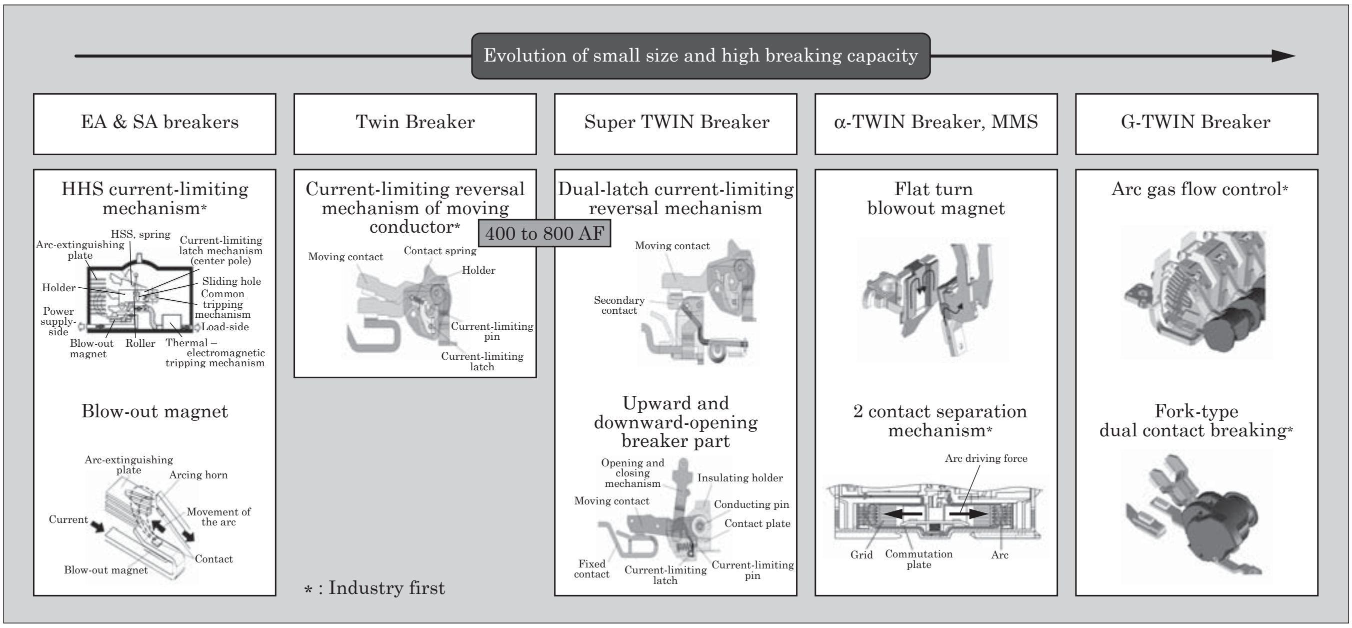
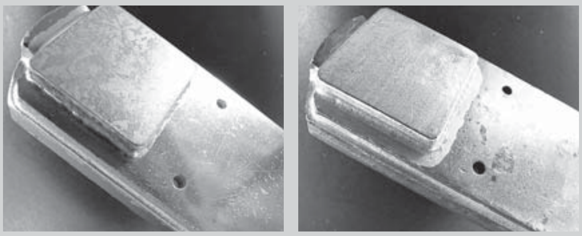


Fig.9 Technical development for higher breaking capacity of molded-case circuit breakers



(a) Proprietary diffusion bonding technology (b) Gas brazing bonding technology

Fig.10 Examples of contact bonding in electromagnetic switch

together by gas brazing, the two components are now bonded together directly by applying the eutectic reaction of Ag and C, without using brazing filler.

In terms of original bonding technology, Fuji Electric has continued to advance technology development over a significantly long time, and has increased long-term reliability by improving its technology. For example, at the isolation valve where a contact electrode, which is an essential part of a vacuum breaker, is in a vacuum, ceramic and metal materials that have different rates of thermal expansion are bonded together using brazing technology through a metallization layer.

In terms of high-precision manufacturing and production technology, a method of tie bar processing was adopted for the contacts in an operation display device, and this advanced processing method has been continued through to the present. At the processing stage, metal strips for precision parts such as precision mechanisms that require micron-level dimensional accuracy are continuously tied together and then cut off just prior to assembly stage to realize automated assembly with a high level of positional accuracy.

4. The Cultivation of New Fields and New Markets, and Innovative Technology for the Future

In a "3-year rolling plan" that aims to cultivate new markets, Fuji Electric has announced its intention to focus development on DC high-voltage devices for use in new energy applications and in the field of data centers (see Fig. 11).

As a precursor, circuit breakers for DC high-voltage circuits in large-scale photovoltaic power generation equipment (mega solar) have been developed (see Fig. 12). Despite having the same external shape as the 400 to 800 AF "G-TWIN Series," as well as supporting JIS, global standards such as IEC are also supported. Previously, the 600 V DC class was the upper limit, but with Fuji Electric's newly developed products, applications of up to 750 V DC are supported with 3-pole products, and the high voltage region of up to

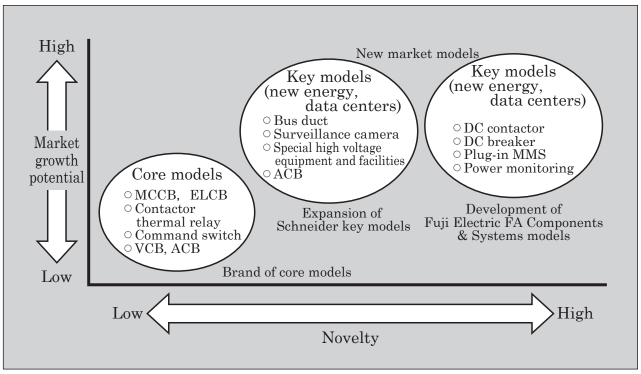
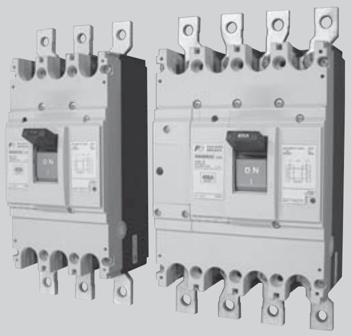


Fig.11 Measures for new fields and new markets (3-year rolling plan)



(a) 3-pole for 750 V DC rated usage (b) 4-pole for 1,000 V DC rated usage

Fig.12 "G-TWIN Series" high-voltage DC breakers

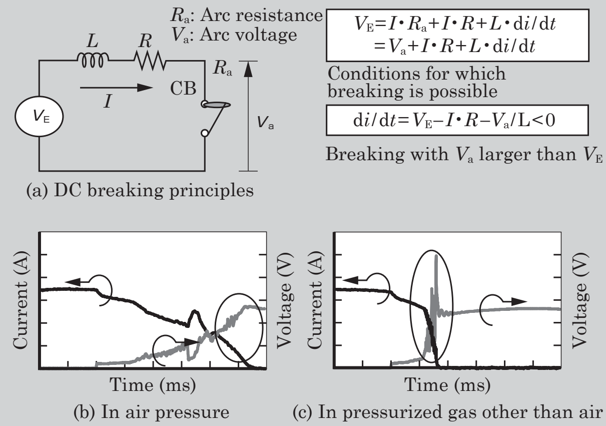


Fig.13 Basic study of high-voltage DC breaking

1,000 V DC is supported with 4-pole products. With a DC high-voltage, because there is no current zero point that is in the case of AC and because arcing is continuous in the case of a short gap, breaking will not be possible, and an arc voltage must be generated greater than the power supply voltage established in consideration of the insulation recovery characteristics. In Fuji Electric's newly developed products, a combined method of arc gas flow control in the aforementioned arc-extinguishing part and the use of a permanent magnet for arc driving were adopted. In order to achieve the contact opening with a short gap in high-voltage DC breaking, the electromagnetic field analysis used in the development of the mini contactor SK Series was applied to control arc driving effectively and realize miniaturization.

In the future, the need for compact electric distribution and control devices that is capable of high-voltage DC breaking at voltages above 1,000 V is expected to increase. One conceivable approach is a configuration of hybrid breaking principles that combines semiconductors and electrical switching devices. Another example is DC breaking with a sealed chamber into which an electrode has been inserted in an airtight container, such as the vacuum valve of a vacuum breaker, that not only has been miniaturized and placed in a vacuum, but in which a gas other than air has been sealed and gas flow control is improved at the time of breaking.

Figure 13 shows the principles of high-voltage DC breaking in a gas-filled environment inside a chamber. The development of technology for an instantaneous arc voltage followed by stable insulation recovery is thought to hold the key for DC applications of the next generation of electric distribution and control devices.

5. Postscript

The history and trends of electric distribution and control devices have been categorized above. General-purpose equipment for industrial applications may lack the flashiness of consumer products such as consumer electronics, but plays an important role in supporting safe and secure public infrastructure. Fuji Electric has a nearly 60-year history of electrical switching device development, and has built a trusted brand. In the future, aiming for the realization of non-contact hybrid electrical switching devices such as arc-free AC switches or breakers, Fuji Electric shall move forward on a firm foundation of fundamental technology while embracing the notion of making dreams become real in future product development. With a renewed vigor for establishing future energy and environmental technology, Fuji Electric intends to push forward with new distinctive technology development and to contribute to the development of an affluent society.

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