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Electric Distribution, Switching and Control Devices

Fuji Electric

Innovating Energy Technology

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Electric Distribution, Switching and Control Devices

Technologies offering a stable and efficient supply of electric energy are attracting greater attention as expectations grow for renewable energy that can replace nuclear power while also protecting the environment from global warming and other hazards. There is an increasing demand for space-saving, energy-saving and highly reliable electric distribution and supply systems for not only factories and production facilities, but also for office buildings and commercial facilities.

Fuji Electric is meeting these needs through extensive development and renewal activities based on cultivated technologies for our energy-saving system equipment, middle-voltage equipment and compact devices optimized for electric distribution and supply systems and structure of various machines. As a result, we have established a reputation for releasing products in a timely manner that match the market needs of both Japan and countries around the world.

In this special issue, we will introduce the latest electric distribution, switching and control technologies and devices that are contributing to secure and efficient power supply while also further advancing Fuji Electric's switching and breaking technologies.

Cover Photo:

Magnetic contactor "SK22," Middle-voltage air load break switch (LBS), Vacuum circuit breaker "MULTI.VCB," Emergency stop pushbutton switch (ϕ22) integrating "Synchro Safe Contact," DC Non-polarity circuit breaker "G-TWIN Series"

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Contents

Electric Distribution, Switching and Control Devices

New Products

Development of Components of Switching, Protection, and Control Equipment to New Electric Power Distribution Systems in Japan

TANAKA, Yasunori *

Throughout the world, the environment surrounding energy and power has changed rapidly in recent years. In the 1990s, a fossil fuel shortage and global warming were the primary concerns, and efforts to reduce greenhouse gas emissions were attracting attention. Subsequently, in Japan, in the aftermath of the Great East Japan Earthquake that occurred in March 2011 and the nuclear disaster at the Fukushima Daiichi Power Station of the Tokyo Electric Power Company, attitudes toward the power environment have changed significantly. In particular, the following issues are being discussed: (1) the large-scale adoption of renewable energy, (2) reduction of energy costs and greenhouse gas emissions, and (3) the stable supply of energy and power, during times of peace and times of crisis.

In June 2014, the Japanese government unveiled its so-called "Growth Strategy." The Cabinet approved a "Fourth Basic Energy Plan" that specifies a new energy policy, and these policies are currently being implemented. For example, Japan's target for reducing emissions of greenhouse gases by FY2020 has been lowered to 3.8% of FY2005 levels, and this target value does not include the greenhouse gas reduction effect that results from the use of nuclear power. On the other hand, the decisive action of "power system reform" has also been clearly shown. In a first stage, the government will revise its "Electric Utility Law" and establish an "Organization Promoting Wide-Area Operations," and in a second stage, the government will advance the overall liberalization of entry to the power retail business. The performance goal for these power system reforms is to complete them by 2020.

To achieve this goal, various measures are about to be undertaken. One such measure is to realize an energy supply that is both clean and economical. Specifically, this measure calls for the large-scale adoption of renewable energy, such as wind power and solar power. A basic demonstration test of floating wind turbines is being advanced by positioning one floating wind turbine offshore each of Fukushima and Nagasaki prefectures, and commercialization by 2018 is targeted. In conjunction with this, large-capacity storage batteries also continue to be promoted for wider use. As of March 2014, the number of in-use stationary lithium-ion storage batteries totaled 17,000 units, and Fuji Electric aims to acquire 50% of the global market for these types of large-capacity storage batteries by 2020.

The construction of smart communities that use smart grids to efficiently utilize energy and power is being proposed as an application of energy-saving technology. Currently, four smart community districts in Yokohama City, Toyota City, Keihanna Science City (Kyoto), and Kitakyushu City are undergoing demand response demonstration tests. An aim of these tests is to acquire basic data about the operation of smart grids and smart cities in Japan, and to develop management techniques. Another aim is to create international standards based on the demonstration tests so that new energy technology, energy saving technology, and smart grid and smart city-related technology possessed by Japan can be deployed internationally. Various forms of energy management systems (EMS), including Community EMS (CEMS), building EMS (BEMS), mansion (condominium) EMS (MEMS), home EMS (HEMS), and so on, are being tried with these demonstration tests. During the summer of 2013, the Yokohama Smart City Project conducted demand response demonstration tests for 1,200 households equipped with a solar power generation system and a HEMS, and found that a maximum peak demand reduction rate of 15.2% was realized. It is important for these types of Japanese-style smart grids and smart cities to be established, and then deployed overseas.

Under such circumstances, demand is increasing for the various components used in switching, protection, and control equipment, and there is a growing need to improve the performance of these components. The industry is rapidly developing smart meters, power conditioners, various monitoring systems, and supervisory control systems. As the supporting elements for this equipment, the development of power semiconductors and storage batteries is obviously important, but the realization of improved performance, smaller size and higher reliability of electromagnetic contactors, relays, load break switches that interrupt fault current, and the like, in a form that is competitive overseas, is

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also important. When smart grids and renewable energy are to be used, a DC power supply system becomes important. Presently, DC systems are being put into practical use at data centers, railways and the like. We expect that DC power will be distributed via smart grids in the future, and in consideration of the increase in received power, that higher voltage and larger current of the DC supply system will be required. Accordingly, we must accelerate the development of equipment for high-voltage DC supply systems, and especially the development of switching and protection equipment.

[Translated from the original Japanese text.]

Electric Distribution, Switching and Control Devices: Current Status and Future Outlook

ASAKAWA, Koji *

1. Introduction

The Basic Energy Plan approved by Japan's cabinet in April 2014, on the premise of safety assurance and prioritizing the stable supply of energy, aims to improve economic efficiency to realize the low-cost supply of energy, to implement utmost efforts to realize environmental compliance, and to construct multi-layered, diverse and flexible energy supply-demand structures[(1)].

Fuji Electric's electric distribution, switching and control devices, as key components in electrical equipment, provide the underpinning support for environmentally-friendly energy equipment, and the technical development and product development that reflects these trends is expected to contribute to society.

In addition, Fuji Electric has been selling magnetic starters[*1] for the past 60 years, and our magnetic starters have continued to lead the industry as products that best meet the needs of the market and customers throughout each era, and our magnetic starter production volume reached 300 million units in 2014.

This paper looks back on the history and technical changes in magnetic starter products, and also discusses the current status and future outlook for electric distribution, switching and control devices.

2. Fuji Electric's Evolving Magnetic Starter Series

The changes in Fuji Electric's magnetic starter series over the past 60 years are shown in Fig. 1. Fuji Electric has continued to lead the industry through significant research and development and applying the resultant technology to our products. To date, Fuji Electric has held 556 registered patents in Japan and overseas for magnetic starters, and currently holds the rights to 196 patents, and is in the top class in Japan in this field.

In terms of technology, we have conducted research and development into the mechanical and electrical endurance performance and the connection reliability of contacts, particularly for leading-edge high-efficiency electromagnets. In this regard, we have worked to miniaturize and to lower the power consumption of devices while furthering globalization and improving the length of service life and reliability. In a comparison of current products with those from 1954, for medium-capacity class (220 V, 37 kW) devices, the device volume has been reduced to 2/5, the apparent power at the time of turn-on has been reduced to 1/4, and the maintained apparent power has been reduced to 1/12.

Fuji Electric's magnetic starters have evolved by incorporating technical advances while meeting the market needs shown in Fig. 1. These changes are described below.

In 1954, Fuji Electric developed a miniature magnetic starter that was revolutionary at the time. Using molded insulating material in the main structure and moving parts, this was the original form of the current magnetic starter.

Around 1960, the industry demanded improved productivity, factory machinery was moving toward automation, and the foremost need was for longer service life. Fuji Electric's "SRC Series," which was released in 1965, is called the "long-life" "S Series" and realized significantly improved performance as a result of developments in arc[*2] technology and

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***1: Magnetic Starter**

Commonly used in electric motor circuits, magnetic starters are devices capable of circuit switching and electric motor overload protection, and are equipped with magnetic starters and overcurrent relays.

***2: Arc**

Arcing is a type of dielectric breakdown (discharge) that occurs between electrodes as a result of a potential difference created between the electrodes. When gas molecules located between negative and positive electrodes undergo electrolytic dissociation, ionization occurs, creating plasma through which a current flows. As a result, a current flows through what would ordinarily be a non-conductive gas. In this indeterminate space, the gas enters into an excited state, and is accompanied by high temperature and sparking.

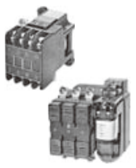
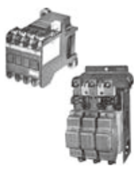
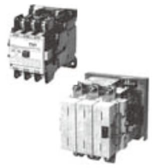
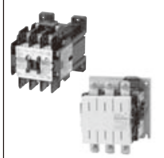
Item	1954 (year)	1965	1978	1984	1988	1999	2011
Market needs	Long life		Miniaturization Higher performance	High reliability Digitalization	International standards Flexibility	Globalization Safety	Microminiaturization Energy savings
Product	RC Series 	SRC Series 	SC Series 	NEW SC Series 	New SC Series SG0G Series 	NEO SC Series SC E Series 	SK Series 
Features	○ Mechanical service life 5 M cycles => 10 M cycles ○ Electrical service life 500 k cycles => 1 M cycles		○ 63% smaller size (volume ratio) ○ Higher voltage of 600 V AC	○ Stable contact ○ Lower noise ○ Lower power consumption	○ International standards ○ Diverse product lineup	○ Standard acquisition of overseas standards ○ Coordination with protection devices ○ Use of environmentally friendly materials	○ Low power consumption with world's smallest size ○ Improved utility
Technology	○ Established basic structure of electromagnet and breaker ○ Developed contact materials and insulating material that support longer service lives		○ Developed UI magnet double-coil type miniature electromagnet	○ Developed electromagnetic super magnet that is installed in electronic circuitry	○ Modularization ○ Development of DC electro-magnet with attached permanent magnet	○ Improved efficiency electromagnetic efficiency ○ Reduced contact bounce	○ Developed high-efficiency DC electromagnet ○ Developed miniature switching technology

Fig. 1 History of magnetic starter series

contact material and insulation material having superior properties, and its electrical service life was extended, to become 500,000 to 1 million times that of the conventional series.

For the "SC Series" that was released in 1978, in response to the need for miniaturization, Fuji Electric developed a UI magnet double coil method that combined a U-shaped fixed core and an I-shaped moving core, and applied magnetic technology to drive the switching contact part directly in medium and large-capacity models.

Around 1980, it became desired for machinery and equipment to be operated for longer durations of time, at higher capacity utilization, and with improved reliability, and magnetic starters were required to provide improved reliability and maintenance-free operation. For the "NEW SC Series" that was released in 1984, Fuji Electric developed a super magnet, an electromagnetic drive system that is integrated with the electronic circuitry. Without any contact bouncing even when voltage fluctuations are large, this series solves a problem relating to electromagnets and contacts, and achieves lower power consumption. Additionally, control has been moved from a relay sequence to a programmable logic controller (PLC) and in response to the need for low-level voltage and current, Fuji Electric has developed an auxiliary contact material and shape to ensure the contact reliability of auxiliary contacts.

Around 1990, as magnetic starters became more popular and their applications increased, the requested specifications and functions became more diverse, and flexible support with a wide variety of products and functions was required. Additionally, there have been remarkable advances in the high-level automation of production systems such as factory automation (FA) and flexible manufacturing systems (FMS). Previously, with the "New SC Series" that was released in 1988, so that the main structure would suitable for the flexible production of magnetic starters, the electromagnet part, contact part and coil part of the main body were modularized, and modules and components were shared commonly among the various models. The functionality and variety of accessories, such as an auxiliary contact unit, were enhanced, and the accessories were designed as customer-detachable structures that are common among an entire series. As control systems became electronic, improved contact reliability was required and so a dual contact structure was adopted as a standard feature for auxiliary contacts. The color of the cover was changed from solid black to a cream color and the design was updated with an arrangement of orange lines, and this design has continued as Fuji Electric's magnetic starter design.

Around 2000, with EU integration, JIS internationalization and the like, the market continued to advance toward becoming borderless, and a response to safety and environmental issues was sought. Fuji Electric realized a response to these issues with the "Neo SC Series" that was released in 1999. At that time, the evolution and widespread use of PCs enabled advanced analysis techniques for transient phenomena, and through simulations of bounce coupled to analyses of the electromagnetic field, mechanism, and vibration, contact bounce was reduced, the efficiency of AC and DC electromagnets was improved, and miniaturization and reduced power consumption were achieved.

The "SK12 Series" of mini-contactors[*3] and thermal relays[*4] that was released in 2011 has the world's smallest micro-miniature size, and satisfies both domestic and overseas specifications and standards, while realizing lower power consumption, and a high-level of safety, utility, and ease of use.

3. Market Trends and Fuji Electric's Efforts[(2)]

In the electric distribution, switching and control device sector, while improving the level of current switching, breaking, detection and measurement technologies in response to market needs, Fuji Electric is also advancing the development of new technologies and incorporating those technologies into products for the global market and emerging markets. Figure 2 shows an overview of the present status and future efforts, and Fig. 3 shows the market and technological trends.

3.1 Machine control panel

Recent market needs in the machine control panel sector include compatibility with changes in motor control systems, and compatibility with IE3 motors that are used for energy savings, and inverters and servos.

(a) Changes in motor control systems as a result of globalization[(3)]

As globalization progresses, the alignment of each country's individual standards with IEC standards is a trend not only in Japan but is common throughout the world, and as a result, electric motor control systems are changing. As shown in scheme A of Fig. 4, the mainstream electric motor control method used in Japan is one in which over-current protection devices[*5] are not installed in the branch circuits. According to indoor wiring regulations[*6], a dedicated branch circuit must be provided for each electric motor unit, but with a 20 A molded-case circuit-breaker (MCCB)[*7], if the total electric motor capacity is 2.2 kW, individual over-current protection devices will be unnecessary. Meanwhile, overseas, scheme B and scheme C that provide an over-

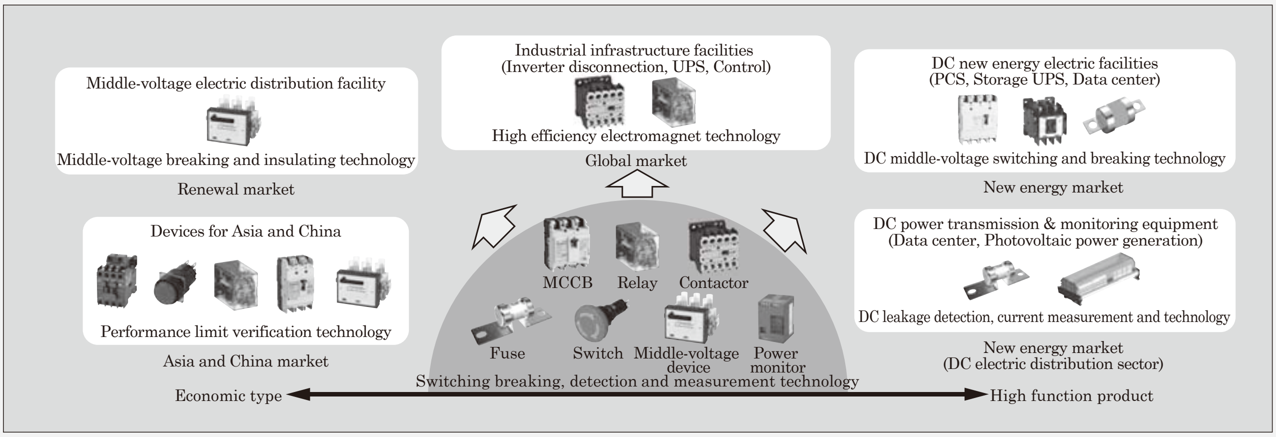


Fig. 2 Efforts for electric distribution, switching and control devices

***3: Magnetic contactor**

An magnetic contactor is a device that is operated directly with an electromagnet, and is characterized as being able to switch overcurrent and to switch electric circuits frequently. The magnetic contactor is also known as a contactor.

***4: Over-current relay (thermal relay)**

An over-current relay is a device that detects overload currents and is typically used to prevent motor burnout. Used in combination with an magnetic contactor, an over-current relay is also referred to as a thermal relay.

***5: Over-current protection device**

An over-current protection device breaks and protects an electric circuit in the case where an overload or short-circuit current flows, and this device refers to molded-case circuit-breakers and manual motor starters.

***6: Indoor wiring regulations**

Indoor wiring regulations are a commercial standard for the design, construction, maintenance and management of electrical structures at the site of demand. These regulations are intended to be supplements that further interpret the various laws and technical standards for electrical installations. Power companies use these regulations as a reference when inspecting and examining electrical construction work, and they are applied to general electrical structures and residential-use electrical structures (excluding special middle-voltage equipment).

***7: Molded-case circuit-breaker (MCCB)**

Molded-case circuit-breakers are devices that have the capability to perform current switching at or below the rated current value in a low-voltage circuit, to detect overcurrents, to break large currents such as short-circuit current, and are mainly used to protect wiring. A molded-case circuit-breaker is also referred to as a MCCB.

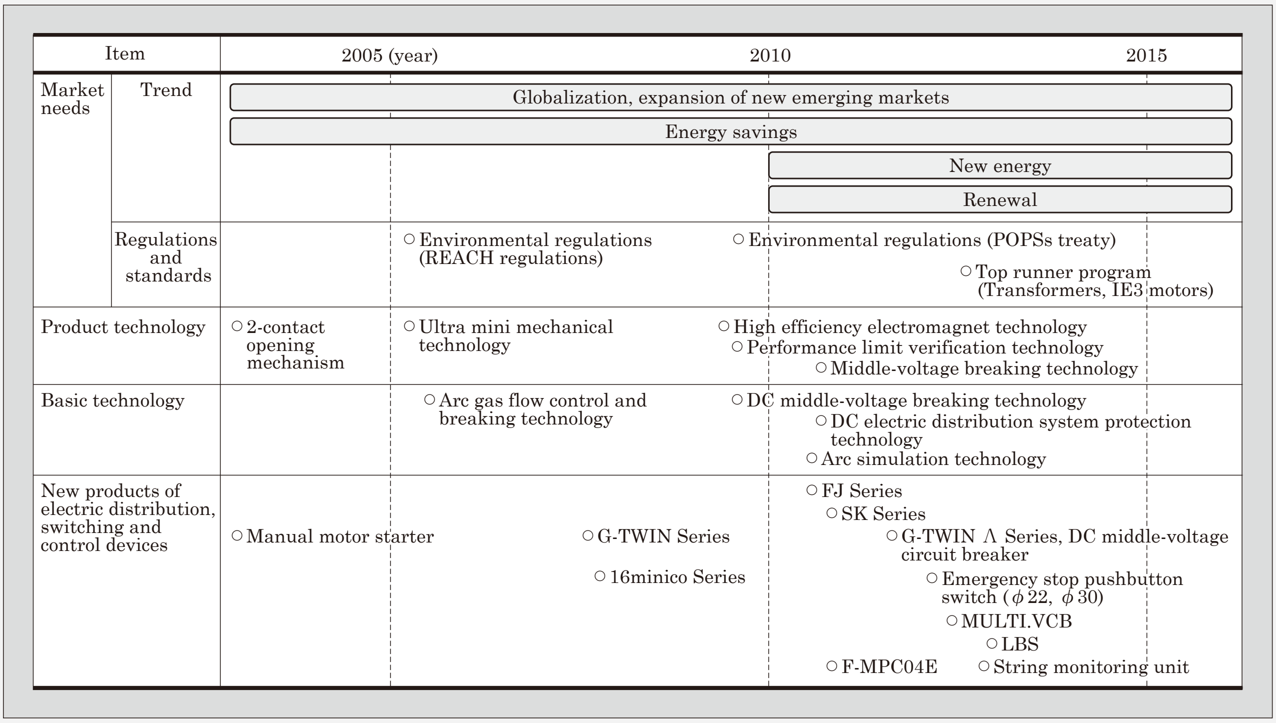


Fig.3 Trends of electric distribution, switching and control devices

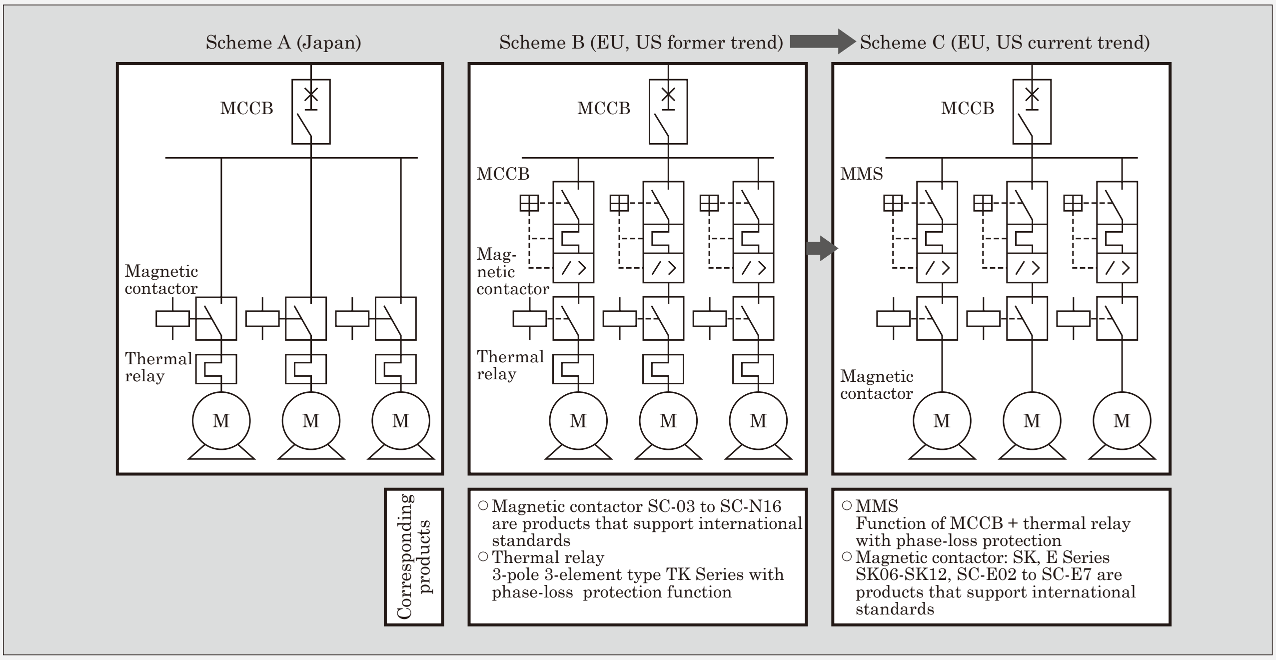


Fig.4 Change in electric motor control methods

current protection device for each electric motor circuit are required. Recently, in consideration of control panel safety, further expansion of the short-circuit current rating (SCCR) is requested, and in order to attain breaking coordination with an magnetic contactor, protection devices that have a high current-limiting capability during short-circuit current breaking are required.

With such an electric motor protection circuit, the application of a manual motor starter (MMS) or a combination starter results in an electric motor control system that is highly efficiency and that realizes "space savings," "wire savings" and "high-level short-circuit protection coordination." An MMS is an integrated MCCB and thermal relay, and a combination starter is an MMS further combined with an magnetic contactor. Combining electromagnetic contact technology developed over many years with the switching and breaking technology of MCCBs, the MMS employs a dual-contact breaking (double break) mechanism, and has the features of excellent contact wear during contact switching and excellent current limiting and cut-off performance. In 2002, Fuji Electric commercialized Japan's first MMS and combination starter. Additionally, Fuji Electric also plans to provide a lineup of combination starters that incorporate the "SK Series," which are introduced in this special issue.

(b) Support of top runner motors (IE3 motors)

In Japan, industrial motors will be added to the top runner program*8 as of April 2015. Industrial motors have been estimated to account for 75% of the annual power consumption of the industrial sector. At present, 97% of the motors used in Japan are IE1 (standard efficiency) level motors, and if all motors were to be replaced with IE3 (premium efficiency) level motors, the energy savings effect is estimated to be 1.5% of the total power consumption in Japan, corresponding to 15.5 billion kWh/year. According to a survey by The Japan Electrical Manufacturers' Association (JEMA) of the motors of various companies, compared to IE1 motors, IE3 motors draw higher average startup current but limit the maximum value. For this reason, they do not have a significant effect on the performance of magnetic starters (magnetic contactors and thermal relays).

(c) Application to inverter and servo primary-side switching

Historically, magnetic starters have been developed for, and used in, motor switching applications. Until around 2000, the majority of applications had been in motor direct on-line applications, but as power saving and control technology advances, inverters and servos have come into widespread use, and their application in primary-side switching applications is increasing rapidly, and account for 50% of the applications at present. Figure 5 shows the findings of a survey by Fuji Electric about the changes in magnetic starter applications.

When using inverter and servo systems, at the time when an magnetic starter is switched on, due to the charging current from an internal smoothing capacitor, the inrush current may be greater than that of the starting current of a conventional motor, and therefore the contact welding resistance must be improved. Table 1 shows the results of a survey (as estimated from customer interviews) of the electrical switching endurance required of magnetic starters. Essentially, a switching endurance of 1 million times will satisfy the needs of the majority of applications, and the number of switching operations in a drive device is assumed to be about 100,000 times. Under these circumstances, the "SK18" and "SK22" were developed as the optimal SK Series devices for primary-side switching applications (for low-frequency switching, current switching, and disconnection). Further details are described in section 4.1.

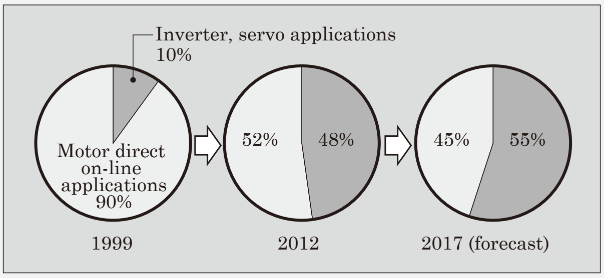


Fig.5 Changes in magnetic starter applications

Table 1 Electrical endurance required of magnetic starter for switching and circuit breaking use

Application	Max. number of switching operations per day (number of times)	Max. number of switching operations per day (number of times)	Max. number of switching operations over 10 years (tens of thousands of times)
UPS	–	1	Up to 0.365
Inverter, servo primary side	1	20	Up to 7.3
Air conditioning, compressor	3	60	Up to 21.9
Power supply switching	10	200	Up to 73
Transportation (Direct on line)	20	400	Up to 146

3.2 Electric distribution equipment

(a) Renewable energy and smart grids

With the expanded use of renewable energy such as photovoltaic power generation, the popularization of electric vehicles, and the establishment of middle-voltage DC power supply systems for data centers, smart grids, and the like, DC distribution systems that differ from conventional distribution systems are continuing to expand. The establishment of DC protection technology to ensure safe operation has become necessary, and research and development of failure modes, such as short-circuits and ground faults, is being advanced (refer to "Technology of Estimating Short Circuit Current and Ground Fault for Direct

***8: Top runner program**

Based on Japan's "Act on the Rational Use of Energy" (Energy Saving Act), for each target device, the top runner method sets standards that are higher than those of the (top runner) device having the best energy efficiency, determines a target fiscal year, and promotes the widespread use of energy-saving products.

Current Distribution Systems" on page 179).

After the Great East Japan Earthquake that occurred in FY2011, a system of "Feed-in Tariff Scheme for renewable energy" (FIT) has been adopted, and photovoltaic power generation facilities, for which construction work can be carried out relatively easily, are increasingly being installed. Until 2011, the majority of installations were for residential use, but following the enforcement of FIT, the introduction of power-generation business facilities for non-residential use has been increasing rapidly. On the other hand, for photovoltaic cells, which had been called maintenance-free, in the ten years after installation, there is a greater than 10% incidence of photovoltaic cell panel failure due to hot spots caused by shadows on the panel surface, Potential Induced Degradation (PID) phenomena that degrades output, solder defects during production, and the like, and higher efficiency and reliability are demanded. Moreover, in order to reduce the power generation cost, the trend toward the higher voltage of 1,000 V DC is progressing.

Fuji Electric has focused its efforts on technical development that addresses this need for improved reliability and higher voltage, and has commercialized a string monitoring unit that measures and continuously monitors the generated current and voltage for each DC middle-voltage circuit breaker and string, and that is capable of breaking operation even when a reverse current is flowing. In commercializing this device, Fuji Electric researched arc simulation technology, and used its DC middle-voltage circuit breaking technology (refer to "Arc Simulation Technology" on page 195).

(b) Longer service live and renewal demand for infrastructure

Partially in response to the Sasago Tunnel ceiling collapse on the Chuo Expressway in December 2012, the Japanese Ministry of Land, Infrastructure and Transport enacted an action plan for extending the service life of infrastructure in May 2014.

With this action plan, ensuring public safety and security, total cost reduction and budget leveling for medium- and long-term maintenance and updating, and ensuring competitiveness of the maintenance industry are necessary. Furthermore, the action plan does not stop at so-called lifecycle prolongation, i.e., extending the service life from new construction through demolition, and is also linked to establishment of a maintenance cycle and continuous development through various initiatives, including renewal, so that essential infrastructure functions will continue to be exhibited into the future.

For middle-voltage electric distribution devices, through using the latest middle-voltage circuit breaking and insulating materials and pursuing lower lifecycle cost and greater ease-of-use, Fuji Electric is working to develop new products from which the customer will derive an immediate benefit at the time of renewal. In recent years, Fuji Electric has developed the "MULTI.VCB," "Auto.V" and middle-voltage AC load break switches (LBS) equipped with striker tripping-type current-limiting power fuses. Further details are described in section 4.4.

3.3 Overseas markets

For Asian markets, there is brisk investment in infrastructure despite the risks; Japanese companies are expected to continue to make investments, and products that meet market needs (specifications and price) are needed. For this region, Fuji Electric is working to expand its lineup of switches, such as magnetic starters, and low-voltage electric distribution devices, such as circuit breakers for wiring. High-frequency switching operations are not required for air-conditioning equipment and the like, and so Fuji Electric has released the "FJ Series" of low-cost and durable magnetic starters for the Asian and Chinese markets. Fuji Electric's product lineup, which had previously been compatible with currents of up to 32 A, has been expanded to handle currents of 40 to 95 A.

Additionally, centered around Fuji Tusco in Thailand, Fuji Electric is prioritizing the expansion of its Asian business for substation equipment. Middle-voltage electric distribution devices used in middle-voltage electric distribution panels are required to be 7.2 kV JIS-compliant for use in Japan, but in Southeast Asia, the devices must be 24 kV IEC-compliant. For this reason, 24 kV vacuum valves, small and strongly insulated structures, interlocked structures and the like are required. In the future, Fuji Electric intends to advance its efforts for product development in this field.

4. Fuji Electric's Efforts Involving the Latest Devices

4.1 Switching devices*9

The "SK Series" of magnetic contactors was released in 2012 and with a rating of up to 12 A is classified as being within the miniature range, and

***9: Switching device**
Switching devices are used with low-voltage circuits to switch motors and other electric circuits frequently. In this special issue, switching devices are referred to as magnetic contactors and magnetic starters.

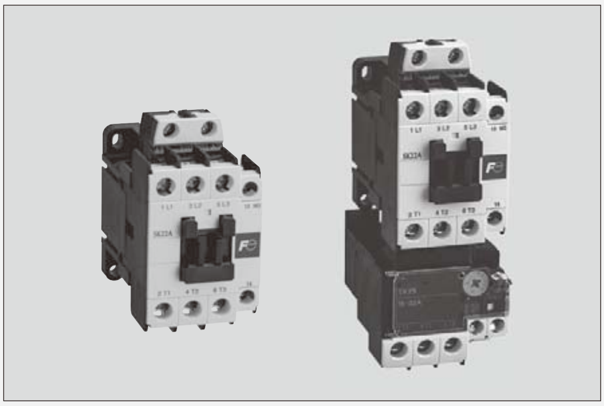


Fig.6 Magnetic contactors and starters “SK18” and “SK22”

Fig.7 Emergency stop pushbutton switch (ϕ22) with “Synchro Safe Contacts”

is receiving good reviews as an magnetic contactor having the world’s smallest size and low-power consumption. Additionally, the SK Series was expanded in June 2014 with 18 A and 22 A rated models, the “SK18” and “SK22” (see Fig. 6). In this development work, we improved high-efficiency electromagnetic technology and succeeded in developing a miniature-size, low-power consumption DC electromagnet.

The SK18 and SK22 inherit the basic features of the “SK12” and are products well suited for inverter and servo primary-side switching applications (for low-frequency switching, current switching, and disconnection). Their main features are listed below.

(a) Miniaturization

A 15% reduction in width and a 13% reduction in depth, compared to conventional devices, were realized. As DC operating types, these are the world’s smallest size devices for this rating class.

(b) Lower coil power consumption

A 66% reduction in power consumption, compared to conventional devices, was realized. As DC operating types, these are the world’s smallest size devices for this rating class.

(c) Improvement of welding current limit

Improvement by a factor of 2.5 times, compared to conventional devices, was realized.

Further details are described in “Magnetic Contactor ‘FJ Series’ and ‘SK Series’ Line Expansion” on page 163.

4.2 Control devices*[10]

A representative control device is the operating switch. An emergency stop pushbutton switch is an important operation switch used to prevent injury to humans and damage to machinery, and safety and reliability of the switch is absolutely essential. In recent years, international standards relating to safety of machinery have been codified, and based on those standards, improved product safety is sought. Through an exhaustive pursuit of reliability and safety, Fuji Electric has developed emergency stop pushbutton switches (ϕ22 and ϕ30) which are integrated with “Synchro Safe Contacts” and that support various safety solutions. In this development work, Fuji Electric improved the technology of miniature switch mechanisms that use molded parts, and has developed a mechanism whereby the NC contact must be in the open state while the trigger action or the operating element and the contact block are separated.

The appearance of the ϕ22 emergency stop pushbutton is shown in Fig. 7, and main features are listed below.

(a) Proprietary “Synchro Safe Contact”

(b) Side indicator that improves visibility of contact operation status

(c) Safety trigger action mechanism

(d) Easily removable operating element and contact block

Further details are described in “Emergency Stop Pushbutton Switches (ϕ22 and ϕ30) Integrating ‘Synchro Safe Contact’” on page 169.

4.3 Low-voltage circuit breakers*[11]

In photovoltaic power generating systems for non-residential applications in Japan, in order to reduce the power generation cost, there is a trend toward higher voltages, from 600 V and 750 V to 1,000 V DC, and there is increasing demand for safety at the time of an accident. Because direct current has no current zero point, the arc voltage must be forcibly boosted to a level greater than the power

***10: Control device**

Control devices are used in low-voltage control circuits to control machines and systems. In this special issue, control devices are referred to as operating switches, relays, sensors and timers.

***11: Low-voltage circuit breaker**

Low-voltage circuit breakers are circuit breakers used in low-voltage circuit to protect against bodily harm, and damage to wires and devices. In this special issue, they are referred to as molded-case circuit-breakers, earth leakage breakers, and manual motor starters.

supply voltage. Moreover, it has been indicated that a reverse current flows when a short circuit exists between the connection box and the junction box, and a device that can ensure safety is required. On the basis of such market trends, Fuji Electric is researching and developing DC middle-voltage circuit breaking technology, and based on 1,000 V DC non-polar circuit breaking technology, has recently developed a reversibly connectable circuit breaker (400 to 800 AF) for DC middle-voltage circuits. The main features of this circuit breaker are listed below.

(a) External dimensions: Same as “G-TWIN Series” 400 to 800 AF
(b) Rated operating voltage: 750 V DC (3-pole device), 1,000 V DC (4-pole device)
(c) Internal and external accessories: Common for all devices in the G-TWIN Series
(d) Can be connected in reverse (no polarity)
(e) Lineup of non-trip switches (load switches)

Further details are described in “No-Polarity Interruption Technology of Circuit Breakers for High-Voltage Direct Current” on page 174.

4.4 Middle-voltage electric distribution devices*[12]

Amidst advances in information technology, middle-voltage electric distribution devices are increasingly being requested to provide a stable supply of electric power and to have higher reliability. Such equipment has also been used in photovoltaic power generation facilities in recent years, and its applications are expanding. Products are sought that incorporate such market trends as miniaturization, improved ease of use, and improved environmental durability, and that also lower the lifecycle cost, including maintenance, installation and renewal.

Under these circumstances, Fuji Electric implemented a model change of its basic series of general-use high-vacuum circuit breakers and load switches that our customers have continued to use over several decades, and developed the “MULTI.VCB,” “Auto.V” and middle-voltage AC load break switches (LBS) equipped with striker tripping-type current-limiting power fuses. Figure 8 shows the appearance of a MULTI.VCB and Fig. 9 shows the appearance of a LBS.

(1) Features of “MULTI.VCB” and “Auto.V”

(a) Lower lifecycle cost

The lubrication cycle has been extended from 3 years to 6 years, and the device can be accessed from its front panel for servicing.

(b) Improved environmental durability of insulation performance

The anti-tracking performance has been improved.

(c) Improved ease-of-use

Panel cutting has been streamlined, and a terminal block is provided as standard equipment.

(2) Features of the middle-voltage AC load break switches (LBS) equipped with striker tripping-type current-limiting power fuses

(a) Miniature size (10% reduction in volume compared to conventional products)

(b) Improved ease of use

For the task of fuse replacement, workability and safety have been improved, and a one-touch isolation barrier has been realized.

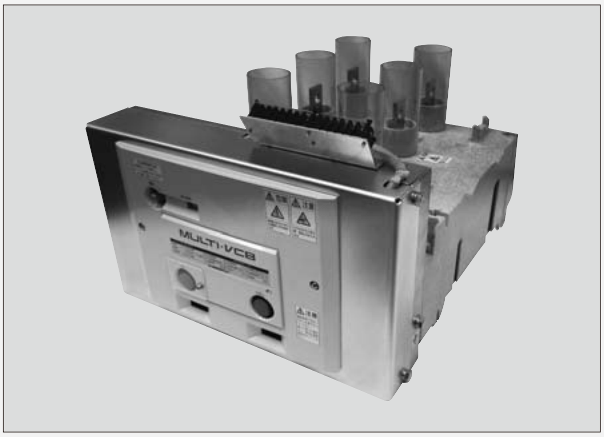


Fig.8 Middle-voltage vacuum circuit breakers “MULTI.VCB”

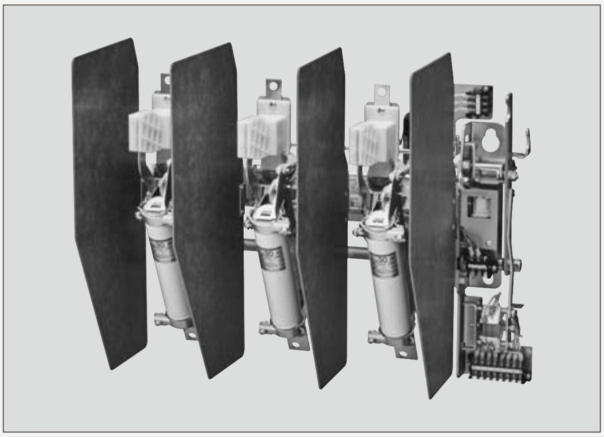


Fig.9 Middle-voltage air load break switch (LBS)

4.5 Power monitoring devices

Amidst the expanding use of renewable energy, as a photovoltaic-related device that supports high

***12: Middle-voltage electric distribution devices**

Middle-voltage electric distribution devices are essential for middle-voltage electric distribution facilities. In this special issue, middle-voltage electric distribution devices refer to middle-voltage circuit breakers, middle-voltage load switches, middle-voltage fuses, middle-voltage magnetic contactors, and protection relays.

DC voltage (1,000 V DC), Fuji Electric has developed a "F-MPC PV" string monitoring unit that enables the generated current and generated voltage of each string to be measured and continuously monitored. The features of this device are listed below.

(a) Measurement of high DC voltage up to 1,000 V DC max
(b) Measurement of up to 12 strings
(c) Collective monitoring of temperature and digital input information necessary for monitoring interior of the connection box
(d) High-precision measurement based on shunt resistance method
(e) Integrated collective management with upper-level monitoring system

Market trends in this sector include miniaturization, compatibility with existing facilities, and the movement to eliminate control power supplies and communication wiring. In response to these trends, Fuji Electric is carrying out technical development of such topics as a current detection method that uses a Hall current transformer, the acquisition of control power from photovoltaic power generation, conversion to wireless technology, and the like, and plans to improve its lineup of models.

5. Postscript

This paper has reflected on the historical and technological changes in magnetic starters for Fuji Electric's electric distribution, switching and control devices, and has also described recent market trends and Fuji Electric's related efforts.

Fuji Electric intends to continue to promote research and technical development in response to societal and market changes, and to continue to contribute to society by providing reliable products that satisfy our customers in Japan and overseas.

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Magnetic Contactor “FJ Series” and “SK Series” Line Expansion

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ABSTRACT

A magnetic contactor is a control device that mainly starts and stops motors, and demand for them is increasing in the Chinese and Southeast Asian markets. Fuji Electric has expanded the economical magnetic contactor “FJ Series” product line intended for the markets and the compact-sized magnetic contactor “SK Series” product line ideal for inverters and servo amplifiers. To the FJ Series, we have added products with 40 to 95 A ratings and optimized the support sliding-portion design to ensure a small size and high reliability. For the SK Series, we have developed 18 A and 22 A products, which are higher ratings than the existing 6 to 12 A, to successfully improve the limit performance of contact welding resistance for inrush current by 2.5 times that of the existing products.

1. Introduction

Magnetic contactors are switches for industrial use installed in control panels of production facilities and machinery mainly as control devices for starting and stopping motors. Their demand is increasing in the Southeast Asian and Chinese markets. In these markets, magnetic contactors that combine high durability and low prices achieved by limiting applications are desired. Meanwhile, as motor control in Japan and other advanced countries, high-efficiency/high-precision inverter/servo control is common in addition to motor direct starting. On the primary side of these drive control devices, magnetic contactors are often installed. As described above, magnetic contactors for different applications are desired that provide limited functions to meet requirements for the regions of use or particular usage.

Fuji Electric has continuously provided the market with magnetic contactors that match user needs including the standard type magnetic contactor “SC Series” while pursuing smaller size and higher efficiency as a pioneer of magnetic contactors.

This paper describes line expansion of the economical contactor “FJ Series” for emerging countries and compact magnetic contactors “SK Series” ideal for inverters/servo amplifiers.

2. Economical Magnetic Contactor for Emerging Countries “FJ Series”

There are two major needs concerning magnetic contactors used in Southeast Asia and China:

(a) For facilities focused on safety such as equipment for export and elevating machinery, products featuring high quality and high switching durability, as well as conformity with international standards such as IEC and UL are desired.

(b) For simple control devices and facilities such as air conditioners, products offering the necessary and sufficient durability with low prices are desired.

The FJ Series offers products that meet the needs described in (b) and the line has now been expanded up to 40 to 95 A products in addition to those with 6 to 32 A ratings released in 2011 (see Fig. 1).

2.1 Background to line expansion and product features

(1) Background to line expansion

For high-frequency switching and high-quality applications such as overseas machine tool and elevating machinery applications, we continue to offer the standard SC Series. We recommend economical types for general residential air conditioners and low-frequency switching applications because only products with up to 32 A ratings were available as economical types. Therefore standard types were used to accommodate the needs for higher rating uses. We have now added products with 40 to 95 A ratings, increasing options of economical types and expanding applications of magnetic contactors.

(2) Downsizing

We have achieved a volume reduction of 38% from the standard SC Series while ensuring the performance required for economical magnetic contactors (rated operational voltage, rated operational current and electrical durability) (see Fig. 2).

Product downsizing has been successfully achieved by providing a structure integrating 1A/1B auxiliary

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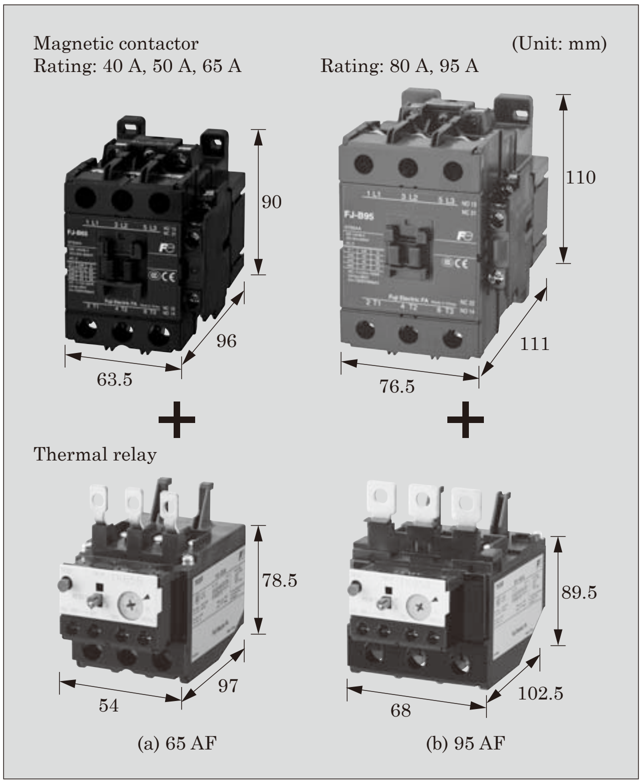


Fig.1 Additions to “FJ Series” (40 to 95 A)

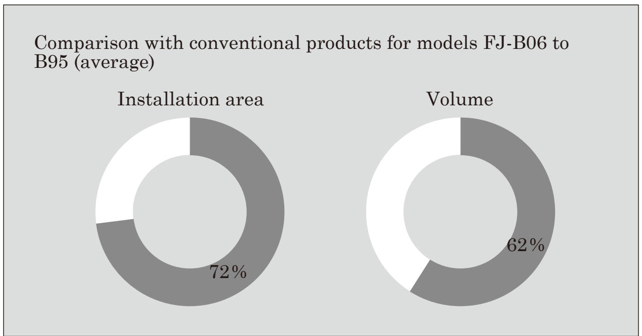
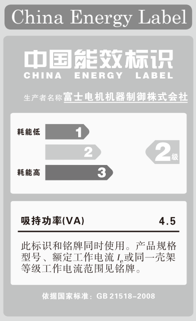


Fig.2 Downsizing of magnetic contactors



Environmental performance

○ Compliant with RoHS Directive*

○ Compliant with Energy Efficiency Label Management Method

Rated current (A)	6	9	12	18	25	32	40	50	65	80	95
Holding VA	4.5	4.5	4.5	9	9	9	12.7	12.7	12.7	13.4	13.4
Class	2	2	2	3	3	3	2	2	2	2	2

* RoHS Directive: European Union (EU) Directive regarding restrictions of the use of certain hazardous substances contained in electrical and electronic equipment

Fig.3 Energy efficiency class (environmental protection performance)

contacts for self-holding and interlocking of the control circuit into the main unit, in addition to limiting the variations such as reversing and mechanical latch types. If there are not enough contacts then they can be optionally added.

To reduce the size, the electromagnets that operate magnetic contactors have also been downsized. The electromagnet power consumption of the developed products with 40 to 95 A ratings satisfies the Class 2 requirements of the energy efficiency classification based on the Energy-Saving Law of China. Figure 3 shows the energy efficiency classes of the FJ Series.

(3) Ensuring safety

While low prices are required of economical types, considering possible electric accidents arising from misuse or at the end of product lifespan, their electric safety must be equivalent to that of the standard types. For the FJ Series, materials with high thermal tolerance equivalent to those of the standard types are used as contact supports, for which the highest thermal performance is required of all conductive part holding components. In this way, we have ensured a safety performance equivalent to that of the standard types including prevention of interphase short-circuit accidents due to excessive energization heating or prevention of electric shocks by providing terminal covers as standard equipment.

2.2 Stabilization of moving part behavior for downsizing

One product downsizing approach is to reduce the depth length, but this reduces the contact moving strokes. To address this problem, it is necessary to stabilize the behavior of the contacts (moving parts) upon making and release so as to suppress the amount of contact bounce upon making, and contact support bounce upon release. A contact support bounce upon release is a phenomenon that occurs when the control coil voltage is turned off, where the iron core is de-excitated and the contact support and moving core are pushed back in the direction of release by the back spring force, which causes the contact support to hit the upper frame and instantaneously bounce back (see Fig. 4).

In particular, as the rated capacity of a magnetic contactor increases to 40 to 95 A, the contact force of the contact inside also increases to cause a significant bounce upon release. To suppress contact bounces upon release for the developed products, structural analysis simulation has been used for evaluating the amount of contact bounce upon electromagnet release. In this way, we have identified the relationship between the component dimensions and amount of bounce.

Figure 5 illustrates the contact support bounce phenomenon that occurs when a contact support is released. When the contact support moves from the

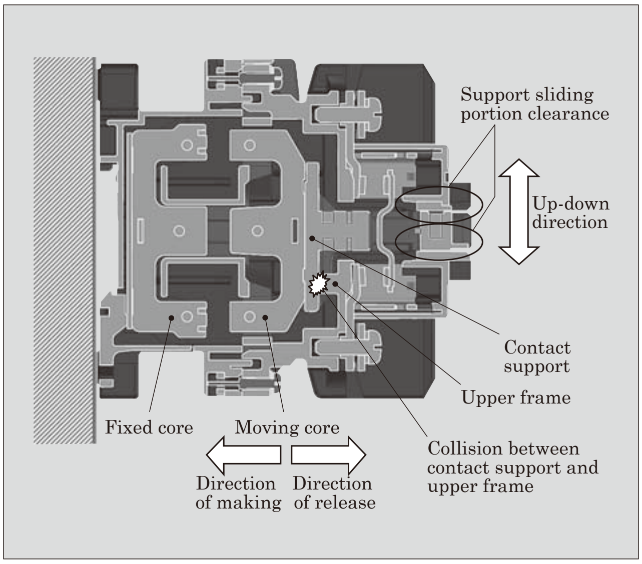


Fig.4 Structure of magnetic contactor

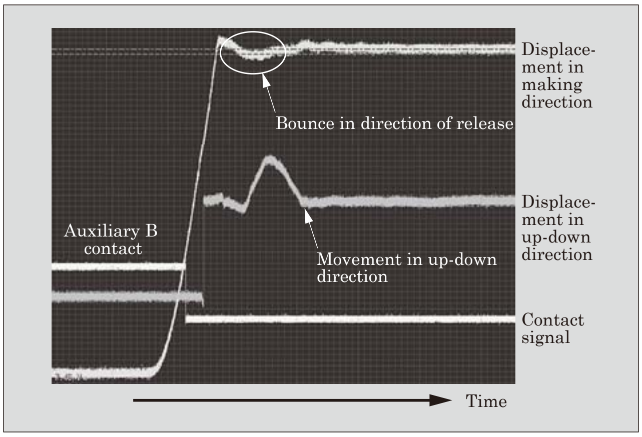


Fig.5 Contact support bounce upon release (observed displacement waveforms)

making position to the release position as the coil is turned off, a bounce in the opposite direction turned out to occur. Large bounces may cause the auxiliary B contact to turn on and off repeatedly a few times when released. In order to prevent this malfunction, the amount of bounce must be kept small by absorbing the collision energy of the contact support.

Structural analysis simulation has revealed that dispersing the collision energy generated upon release on the sliding surface that guides the contact support (see the up-down direction in Fig. 4) allows bouncing to be suppressed. Specifically, movement of the contact support in the up-down direction can be controlled by the support sliding portion clearance with which the support comes into contact, as shown in Fig. 4. We have evaluated and verified the relationship between the support sliding portion clearance and the amounts of bounce and wear, as shown in Fig. 6. This clearance also influences abrasion of the support sliding portion, and the optimum clearance dimensions (see the arrow in Fig. 6) that keep a balance between the amounts of

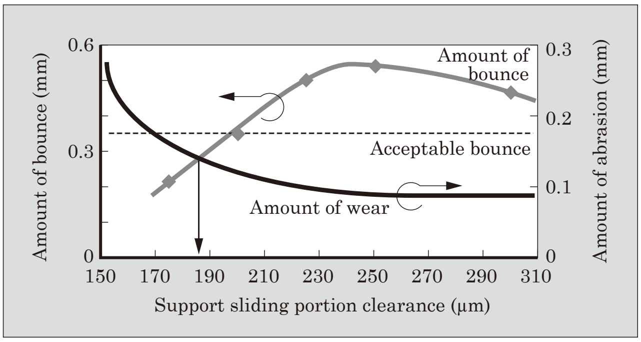


Fig.6 Support sliding portion clearance vs. amounts of bounce and wear

bounce and abrasion has been reflected in the product design.

For products with 40 to 95 A ratings, we have optimized the design of the support sliding portion clearance to achieve a small size and ensure high reliability.

3. Compact Size Magnetic Contactor "SK Series[1]"

In 2011, we launched a range classified as miniature with a rating of 12 A or smaller by the AC-3 standard, which has been received favorably as the world's smallest low-power-consumption range of magnetic contactors. We now have developed products with larger ratings than 12 A, "SK18" of the 18 A and "SK22" of 22 A, to expand the line. Their appearance is shown in Fig. 7 and features in Fig. 8.

3.1 Background of development and product features

(1) Background of development

DC-operated products of the SK Series allow low-power-consumption driving and can also be directly driven by PLCs, which makes them a popular choice for the primary side of inverters and servo amplifiers. Many of these applications use products of 30 A or smaller and products with ratings of over 12 A have been in demand.

For SK18 and SK22, we have pursued user friend-

Fig. 7 "SK18" and "SK22"

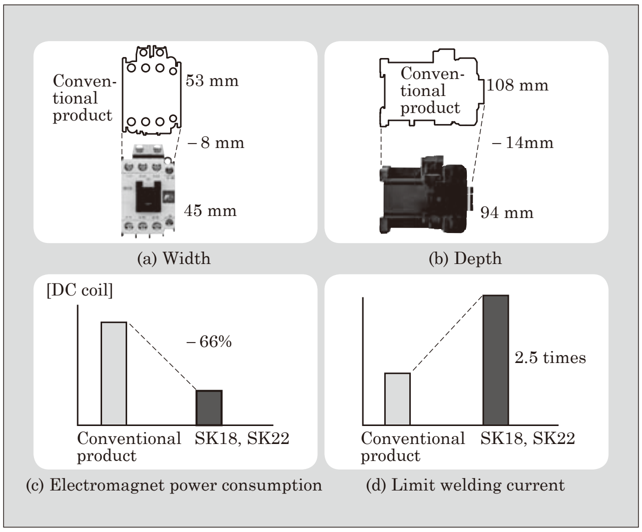


Fig. 8 Features of “SK18” and “SK22”

liness in applications used for inverters and servo amplifiers. For this reason, the SK Series offers products for specialized applications, a different line from the SC Series which provides standard magnetic contactors. Specifically, the limit performance of contact welding resistance has been improved to 2.5 times the conventional products.

Inverters and servo amplifiers has a built-in capacitor for rectifying and smoothing circuit, and an inrush current flows into the capacitor in a few ms when the contactor is closed. This inrush current may cause a risk of slight welding of the magnetic contactor. With the SK Series, the improved limit performance of contact welding resistance has reduced this risk. In view of inverter and servo amplifier applications and general market applications, the electric lifespan of AC-3, which relates to motor direct starting, has been specified to be the necessary and sufficient amount of 1 million switching actions.

(2) Improved limit performance of contact welding resistance

Limit performance of contact welding resistance for inrush current upon contact closing of a magnetic contactor is determined by factors including contact bounces upon closing and contact materials. For SK18 and SK22, bounces upon contact closing have been successfully reduced by optimizing the wipe amount of contact and pressure, and new environment-friendly Cd-free contacts providing improved contact welding resistance have been adopted. In this way, we have achieved a limit performance that withstands an inrush current 2.5 times larger than the conventional SC Series.

3.2 Downsizing technology

In order to fit three poles of the main circuit including one pole for the auxiliary contact into the product width of 45 mm, performance is required that allows turnon and cutoff of a current that is six times larger than the 22 A rating, which is in the AC-4 standard, with a main circuit pole pitch of 11.4 mm.

(1) Ensuring phase-to-phase insulation

Reducing the width from 53 to 45 mm means narrowing the pole pitch of the main circuit from 13 to 11.4 mm; this makes it essential to ensure electric insulation between phases. SK18 and SK22 are not only usable for making and breaking applications of inverters and servo amplifiers but also used in familiar motor direct starting (AC-3 standard) and drive systems capable of inching operation (AC-4 standard). For that reason, in inching (repeated small movements of motors) and plucking (antiphase braking), large arc energy causes wear to the partition walls intended for ensuring insulation between phases. Excessively increasing the thickness of partition walls in order to ensure electric make/break durability decreases the space for arc extinction and reduces the breaking performance. In addition, dimensional variation in manufacturing of partition walls themselves may increase, causing dimensional defects.

In the developed products, the parts of the partition walls that are worn by arcing, which were identified by actual machine verification and simulation, have been made locally thicker (see Fig. 9). Furthermore, the groove shape for retaining arc gas has increased the arc cooling effect upon breaking, which has improved durability.

(2) Adoption of thermoplastic resin for contact supports

To provide environmentally friendly products, we have adopted a reusable thermoplastic material for

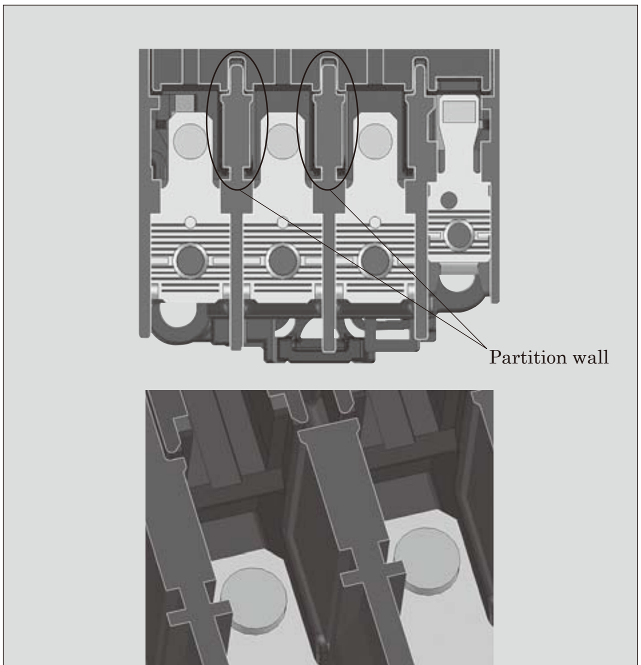


Fig. 9 Cross section of partition wall between phases

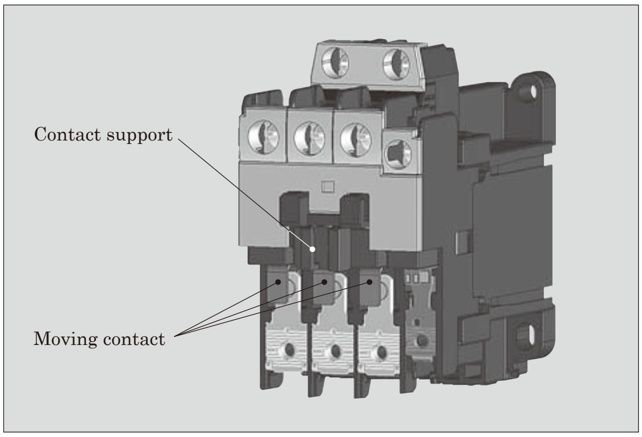


Fig. 10 Contact support structure

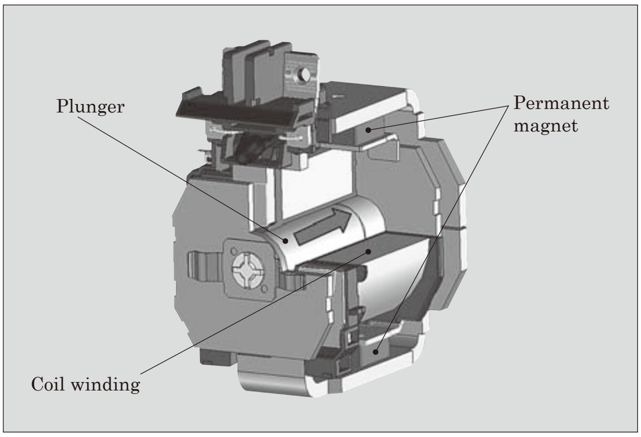


Fig. 11 DC electromagnet

contact supports. Contact supports hold moving contacts which are energized parts, and make sliding movements when switching of a magnetic contactor (see Fig. 10). Accordingly, they are required to have high heat resistance and abrasion resistance, which is why thermosetting resins including phenol resin have been used up to now. However, phenol resin has a problem in terms of its recyclability and cannot be readily molded into thin parts, which has posed obstacles to product downsizing.

The developed products have been provided with a structure having contact supports that use thermoplastic resin, which characteristically melts by heat, and high-strength polyamide resin, a type of thermoplastic resin that can undergo thin-wall molding, has been applied. By making use of the high melting point of this material that exceeds 300 °C and optimizing the cross-section area of the conductive part for improving the thermal characteristics, the temperature rise has been successfully limited to 250 °C or below.

In addition, the mechanical durability of 5 million switching actions has been ensured by optimizing the sliding portion, sliding area and clearance.

(3) DC electromagnet

To downsize products and reduce their power consumption, we have developed a new DC electromagnet. DC electromagnets are characterized by gradual increase of current in the closing operation because of the inductance of the coil winding. This has made it necessary to increase the coil AT (current × number of windings) in order to obtain the necessary attraction force. For this reason, it has been difficult to downsize the electromagnet portion and reduce its power consumption.

For the developed products, a polarized electromagnet that uses permanent magnets has been adopted (see Fig. 11). With a polarized magnet, however, the counter electromotive force that is generated when the plunger operates decreases the coil current and causes unstable operation, which posed a major challenge.

It has been found that unstable operation due to a current drop is caused by operation of the plunger that starts when the coil current rises after voltage is applied to the coil. This makes the operation force lower than the spring force of the contact pressure, which constructs the load. We have met this challenge by optimizing the amount of magnetic flux of the permanent magnets so that the plunger starts operating when the coil current has sufficiently risen in order to increase the retaining force between the permanent magnets and plunger immediately before the making operation.

3.3 Product structure enabling short delivery times

SK18 and SK22 have been designed to provide a “pile-up structure,” which allows them to be assembled by gradually building up parts starting from those in the lowest level. With the structure of the conventional products, the upper and lower level parts of the product required separate assembly, which necessitated a batch production process as shown in Fig. 12. For this reason, intermediate inventory of upper level assemblies was required, hindering the flow production.

Figure 13 shows an illustrated breakdown of the parts of the pile-up structure. The numbers show the order of assembly. It allows a chain of assembly from (a) the process of assembling the lower frame and slid-

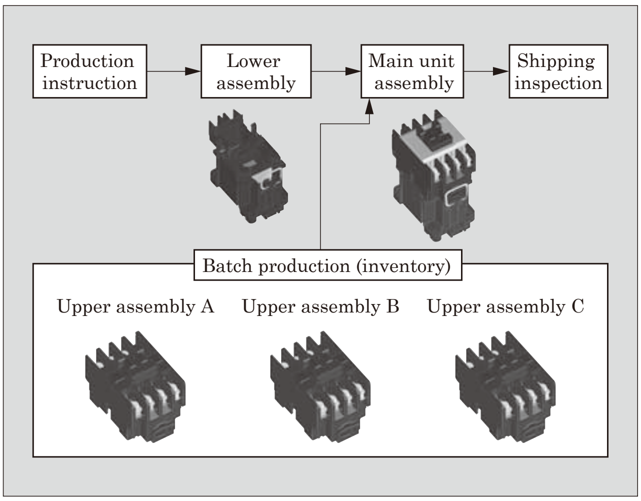


Fig. 12 Conventional order of assembly

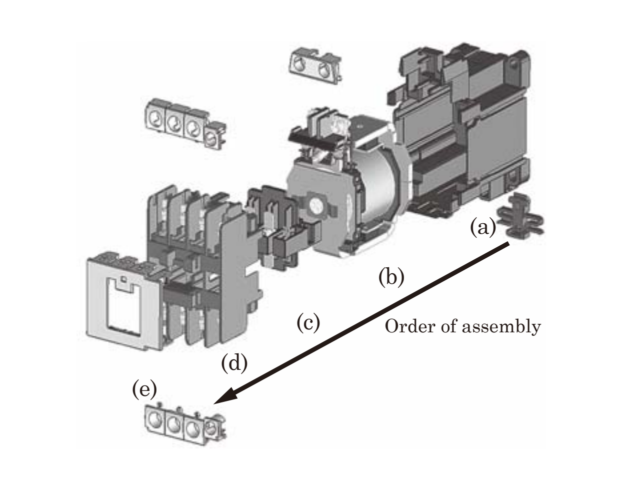


Fig.13 Illustrated breakdown of parts of pile-up structure.

er to (e) the final process of assembling the terminal cover. This has eliminated the need to have an inventory of various assemblies, which was necessary in the past, and made it possible to supply products in short delivery times.

4. Postscript

This paper has described the line expansion of the "FJ Series" and "SK Series" of magnetic contactors.

In the future, we intend to continue developing magnetic contactor technologies that match the market needs, and thereby further enhance products and contribute to increase market demand and improve customer satisfaction.

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Emergency Stop Pushbutton Switches (ϕ 22 and ϕ 30) Integrating "Synchro Safe Contact"

MACHIDA, Noriyoshi* NOMURA, Koji* SHIMOYAMA, Eijiro*

ABSTRACT

Of operation switches used for various devices and machines, emergency stop pushbutton switches are very important ones intended for preventing disasters. In order to meet various customer demands for safety, Fuji Electric has released emergency stop pushbutton switches (ϕ22 and ϕ30) integrating the "Synchro Safe Contact," which has the company's proprietary structure. A separated contact block structure has been adopted to allow safe operation of the contact mechanism when the operation and contact parts are separated. In addition, to improve mechanical endurance and contact reliability, we have realized a contact part structure with excellent environmental endurance in the panel depth dimension of 47.5 mm.

1. Introduction

The role of operation switches used for various devices and machines is to provide accurate human-machine interfaces. Emergency stop pushbutton switch (emergency stop switch), which is one of operation switches, is an important switch intended to prevent disasters by allowing a worker to bring devices or machines to an emergency stop on his/her own will when he/she finds any error in the machine or feel danger.

In order to meet various demands for safety, Fuji Electric has released a new series of emergency stop switches for ϕ22 and ϕ30, which are common mounting hole sizes of emergency stop switches. This series integrates "Synchro Safe Contact," which is the company's proprietary structure that allows the contact block mechanism to operate safely at the same time as the detachment of the operating element and contact block.

2. Overview

2.1 Aim of development

As safety philosophy has rapidly been developed in recent years, international standards relating to safety of machinery have been systematized under ISO 12100 (General principles for design - Risk assessment and risk reduction) and ISO 14121 (Principles of risk assessment), and Fuji Electric has been working on the development of emergency stop switches that conform to those standards. However, in addition to the requirements of standards, customers themselves are required to establish safety standards and conduct verification in line with the "Guidelines for Comprehensive Safety Standards of Machinery" of the Ministry of Health, Labour and Welfare, which was amended in 2007. A variety of risks are assumed by customers and the corresponding requirements for emergency stop switches are becoming diverse including improved visibility of appearance and color schemes and increased number of contacts per unit. The new series meets these diverse demands.

2.2 Safety functions provided by "Synchro Safe Contact"

Figure 1 shows the mechanism for safety functions provided by Synchro Safe Contact. The new series has a structure where the operating element, which includes an operation button and a set of a frame and nut for panel mounting, and the contact block, which has internal electric contacts, exist independently; and these two are joined together for use (see Fig. 1 (a)).

Figure 1 (b) shows the appearance of the switch with the operating element and contact block detached as the button is not pressed and status change of the normally-closed (NC) contact. Conventional emergency stop switches have a structure in which the NC contact is closed when the operating element and contact block are detached. Accordingly, with this structure, there is a risk that the device/machine may start when the operating element is detached from the contact block, regardless of the status of the button. To address this problem, we have provided the new series with a structure in which the NC contact is always open when the operating element and contact block are detached. Rotation from the spring force of the release cover of the contact block and the internal part coupled with it work together to cause the NC contact to be activated at the same time as the detachment of the contact block. This forces the NC contact to open even when the contact block comes off so the device/machine will not start.

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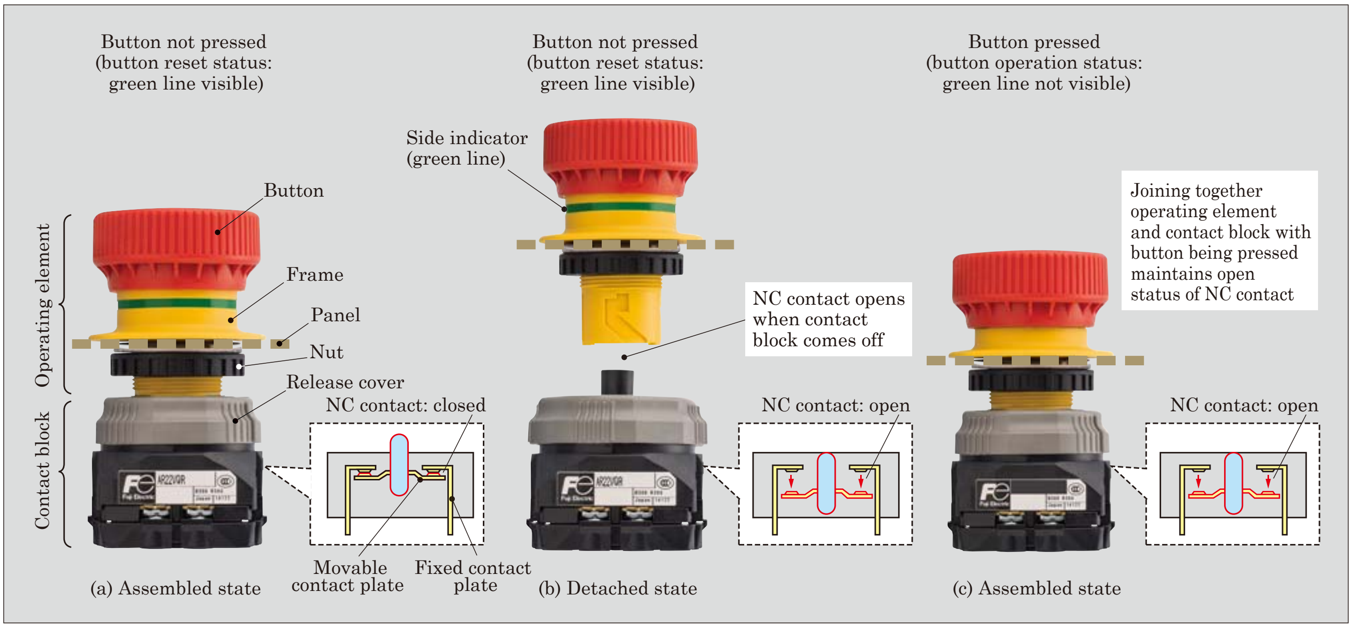

Fig.1 Safety functions offered with "Synchro Safe Contact"

Figure 1 (c) shows the appearance with the operating element and contact block joined together as the button is being pressed and the status change of the NC contact. When the operating element and contact block are detached, joining together the operating element and contact block with the button being pressed (button activated status) does not cause the button to be reset and NC contact of the contact block remains open, ensuring the safety of the worker. To restart the device/machine, it is necessary to carry out an operation to restore the state in which the button is not pressed (button reset status).

Fuji Electric has named this structure "Synchro Safe Contact" and registered it as a trademark.

2.3 Lineup of new series

(1) Types of operating element

Figure 2 shows the types of operating element. The emergency stop switch must be highly visible because it is operated in an emergency by the worker. Accordingly, as buttons for $\phi 22$ mounting holes, we have lined up non-illuminated and illuminated models for the standard $\phi 40$ size and non-illuminated models for the large $\phi 65$ size. As buttons for $\phi 30$ mounting holes, we have lined up non-illuminated and illuminated models available for the standard $\phi 40$ size.

(2) Types of contact block

Table 1 shows the types of contact block. Non-illuminated models can have up to six contacts in total: four NC contacts and two normally-open (NO) contacts. With illuminated models, the number of contacts is limited to five because one of the NO contacts is used as the terminal for the lamp but the number is much larger than the conventional type, which has the maximum of two contacts.

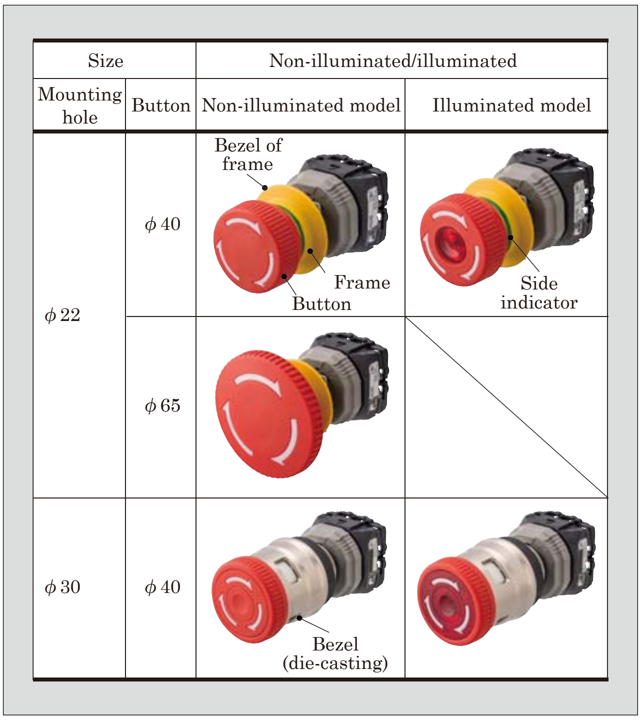

Fig.2 Types of operating element in emergency stop switch

Table 1 Types of contact block

	Operating element - non-illuminated/illuminated					
	Non-illuminated model		Illuminated model		Illuminated model (lamp circuit interlocked)	
Contact block	1NC	1NO1NC	1NC	1NO1NC	1NC	1NO1NC
	2NC	1NO2NC	2NC	1NO2NC	2NC	1NO2NC
	3NC	1NO3NC	3NC	1NO3NC	3NC	1NO3NC
	4NC	1NO4NC	4NC	1NO4NC	4NC	1NO4NC
	2NO1NC	2NO2NC	–	–	–	–
	2NO3NC	2NO4NC	–	–	–	–

2.4 Features of new series

The new series have been equipped with some functions and features to meet the diverse requirements for safety and various risks assumed by customers:

(a) Synchro safe contact: the NC contact is opened when the contact block is detached from the operating element (see Fig. 1).
(b) Side indicator: shows whether the button is in the activated or reset status as seen from the side of the button (see Fig. 1).
(c) Button size: two models, ϕ40 mm and ϕ65 mm, have been lined up for ϕ22 mounting holes (see Fig. 2).
(d) Accommodation of lockout: the operating element of models for ϕ30 mounting holes has been equipped with a die-cast bezel that allows attachment of a padlock or hasp when the button is in the activated (NC contact open) state (see Fig. 2).
(e) Attachment and detachment of the operating element and contact block: one-touch attachment is possible without rotating the contact block even if wiring connected (see Fig. 3).
(f) Terminal screw size: M3.5, which is usually used for devices in panels, has been adopted (see Fig. 3).
(g) Panel depth: 47.5mm (see Fig. 3), realizing a reduction of 16% from the conventional products.
(h) Safety trigger action: the contact is not activated until immediately before the button is locked (see Section 3.1).
(i) Contact configuration: up to 6 contacts (4NC+2NO) are available (see Table 1).

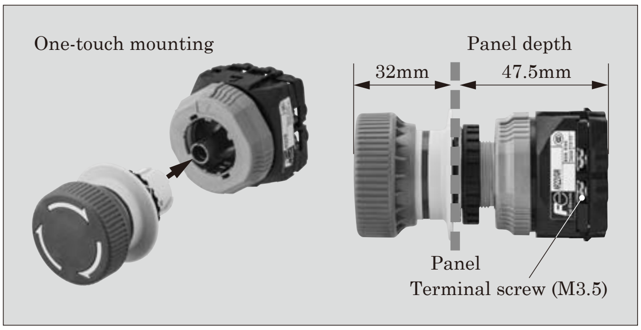

Fig.3 Mounting and dimensions of new series operating element and contact block

2.5 Major specifications of new series

Table 2 shows the major specifications of the new series. Mechanical durability, contact reliability and shock resistance have been improved from the conventional products.

3. Structure and Features of Operating Element and Contact Block

3.1 Operating element in ϕ22 switch

The role of the operating element is to transmit operating force while ensuring the visibility required for an emergency stop switch and functionally satisfying the direct contact opening operation and latching required by international standard IEC 60947-5-5 (Electrical emergency stop device with mechanical latching function), etc. Figure 4 shows a schematic diagram of the ϕ22 pushbutton switch, which has the following features:

(1) The button is colored in vivid red. The same red color as that used for traffic signals is used to im-

Table 2 Major specifications of new series

Item			Performance	
			New series	Conventional product
Rated insulation voltage			250 V AC/DC	
Rated thermal current			5 A	
Durability	Mechanical		Min. of 250,000 switching actions	Min. of 100,000 switching actions
	Electrical	15, 240 V AC, 1.5 A	Min. of 100,000 switching actions	
		13, 24 V DC, 1.0 A		
Contact reliability (minimum applicable load)			5 V DC, 1 mA	5 V DC, 2 mA
Vibration resistance		Variable vibration	Frequency 10 to 55 Hz, double amplitude 1 mm	
		Fixed vibration	Frequency 16.7 Hz, double amplitude 3 mm	
Shock resistance		Malfunction	150 m/s^2	
		Impact durability	1,000 m/s^2	500 m/s^2
Operational ambient temperature	Non-illuminated model		−20 to +60 °C	
	Illuminated model		−20 to +50 °C	
Operating part degree of protection			IP65	
Live part degree of protection			IP2X	
Maximum number of contacts	Non-illuminated model		4NC+2NO	2NC or 1NC+1NO
	Illuminated model		4NC+1NO	2NC or 1NC+1NO
Light source of full voltage illuminated models			LED	
Voltage of full voltage illuminated models			24 V AC/DC	
Panel depth			47.5 mm	57.0 mm

prove visibility.

(2) The frame is colored in yellow. A frame structure is provided in which the bezel with the diameter larger than the ϕ40 red button is integrated, which forms part of the background color (see Fig. 2).

(3) A gentle slope is provided on the opposite side of the button's operation surface to prevent any object from being caught between the button and the panel (see part *a in Fig. 4).

Pressing the button causes the rigid part to project from the frame bottom. This rigid part moves the contact stroke of the contact block combined with the operating element to switch the NC contact status "from closed to open."

When the NC contact state is switched "from closed to open" by button operation, this state must be retained by using the latching mechanism of the operating element. Accordingly, we have provided a safety trigger action mechanism inside the operating element. The operating element has been provided with a trigger spring, which is equivalent to a "trigger," to prevent the button from resetting immediately after the NC contact is opened. When the trigger spring is activated, the energy of the spring ensures the button to be latched.

Figure 5 shows the relationship between the stroke and load during button operation. The load increases at the time of latching, which makes the worker aware of the emergency stop operation.

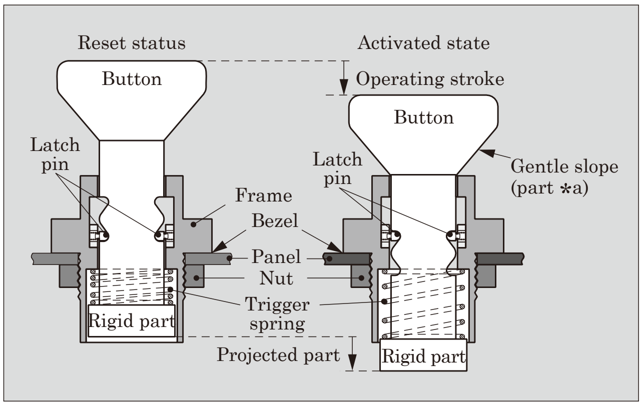

Fig.4 Schematic diagram of ϕ22 operating element

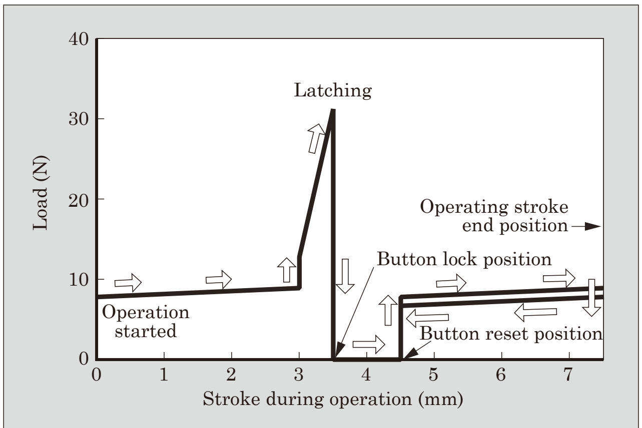

Fig.5 Stroke and load during button operation

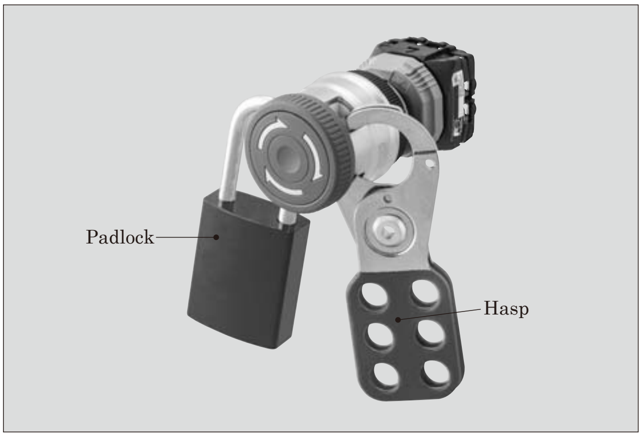

Fig.6 Padlock and hasp on ϕ30 operating element

3.2 Operating element in ϕ30 switch

In addition to the functions of the operating element in ϕ22 switch, the ϕ30 switch is provided with a structure that allows a padlock or hasp to be attached to the die-casting bezel.

Figure 6 shows how a padlock and hasp can be attached. Button operation rotates the cylinder of the part located inside the bezel to expose the keyhole, which was blocked before the button's operation, allowing a padlock/hasp to be attached. By giving a padlock to individual workers who may enter the work area and making it a rule for them to padlock the button when they enter the work area, the emergency stop switch cannot be reset (the NC contact remains in the open state) while any worker is in the work area. This prevents any accident from being caused by unexpected starting of the device.

Unlike the ϕ22 switch, the structure of the ϕ30 switch causes the internal cylinder to rotate during button resetting operation. This minimizes the play in the direction of the rotation of the button so that the workers do not feel awkward when operating the switch.

3.3 Contact block

The contact block is common to ϕ22 and ϕ30 switches. The contact block's mechanical durability and resistance to a corrosive environment have been ensured with six pairs of M3.5 terminal screws (total 12) provided.

With the new series, the mechanical durability has been improved to 250,000 switching action as compared with 100,000 of the conventional products. To achieve this, we have improved the durability against repetitive operation for all components. For example, the moving contact plate, which is the thinnest part, has a structure where the protrusion that retains the contact spring is pressed out to the central part to form the seat (see Fig. 7). In processing the material, we

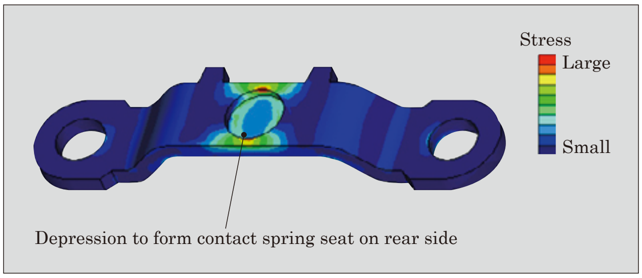

Fig.7 Example of stress analysis of moving contact plate

have prevented the central part, which comes under the highest stress, from becoming thin and suffering from cracks due to repetitive operation. To do this, we have established processing conditions for the protrusion and taken them into account when conducting stress analysis to optimize the shapes and methods of processing for the protrusion and cross section, and the shape of the contact spring seat.

Meanwhile, products have come to be used in poor environments in recent years. As the contact block of the new series has a structure with six contacts located in a narrow space, we have adopted brass, which is easy to process to complicated shapes, for the fixed contact plates. Brass is a material with sensitivity to stress corrosion cracking*1. Accordingly, we have conducted stress analysis on all fixed contact plates for optimization in order to minimize residual stress due to bending, which tends to lead to cracking. This has enabled us to give the fixed contact plates an environmental resistance equivalent to or higher than that of existing emergency stop switches. Figure 8 shows an example of stress analysis.

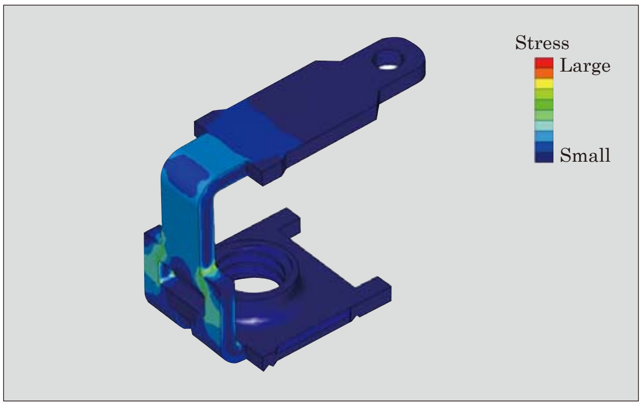

Fig.8 Example of stress analysis of fixed contact plate

*1: Stress corrosion cracking: a phenomenon that occurs when a metal component is placed in a corrosive atmosphere as it is subjected to a tensile stress lower than the mechanical strength. As a result, a crack is generated in the component due to a synergistic effect of the corrosive atmosphere and tensile stress that leads to a fracture. With copper alloys, it tends to occur in an ammonia gas atmosphere.

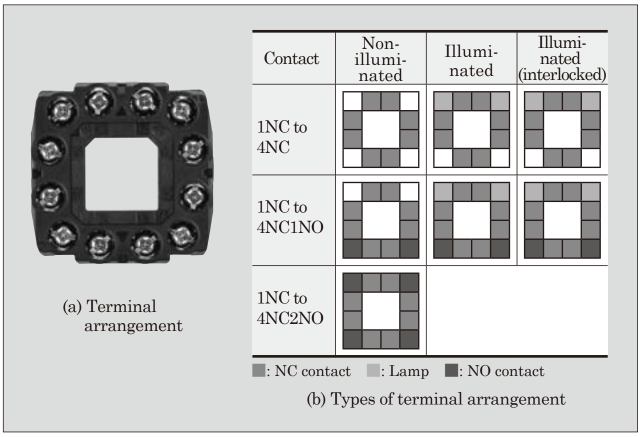

Fig.9 Terminal arrangement of new series

4. Product Safety

In addition to the safety offered by Syncrho Safe Contact as described in Section 3.1, we have achieved safety in the ways described below.

4.1 Certification of overseas safety standards

The new series has acquired the certification of international safety standard IEC 60947-5-5 specific to emergency stop switches and certification as pushbutton switches.

As emergency stop switches, the series has acquired IEC international certification for IEC 60947-5-5 as with the conventional products. In addition, it has acquired NISD category certification subject to UL examination based on IEC 60947-5-5.

As pushbutton switches, the series has acquired certification of the IEC standards, C-UL standards of the US and Canada and the GB standards of China.

4.2 Terminal arrangement

The locations of the terminal screws of the NC contacts and the terminal screws of the NO contacts or lamp have been clearly demarcated and standardized among all models (see Fig. 9). Even if a worker replaces the product with one having a different number of contacts, since the location of the terminal screws of the NC contacts is not changed, it reduces the risk of accidents caused by wrong wiring.

5. Postscript

We have developed emergency stop pushbutton switches (ϕ22 and ϕ30) equipped with "Synchro Safe Contact" and they meet customers' recent requirements for safety and provide improved user-friendliness. In the future, we will continue to value human sensitivity in terms of the operability and visibility of human-machine interface devices and develop devices that pursue safety further.

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

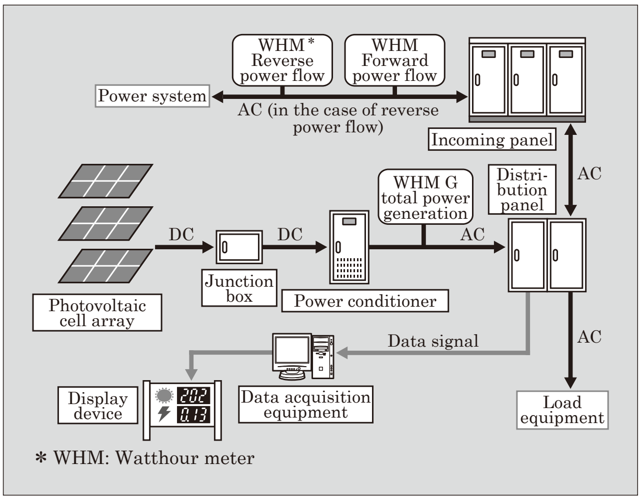

Fig.1 Overview of photovoltaic power generation facilities

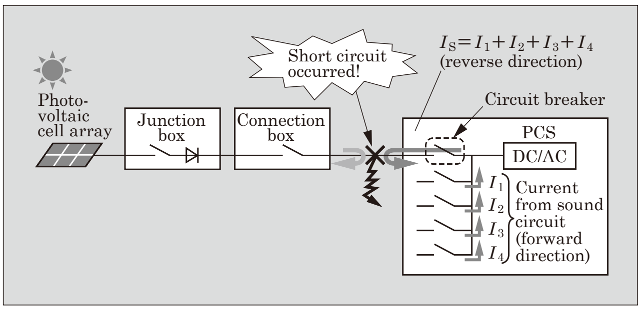

Fig.2 Flow of current in short circuit accident

* 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

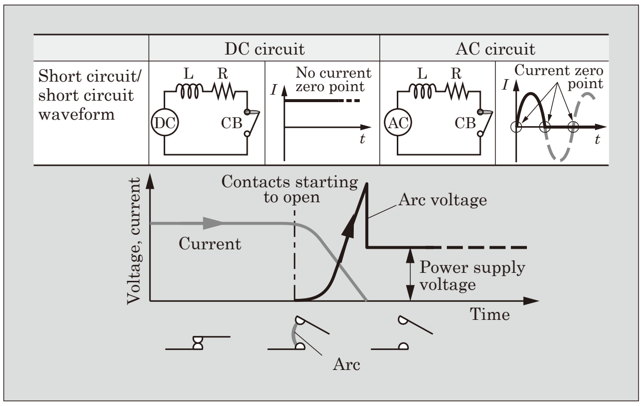

Fig.3 Current interruption and arc voltage

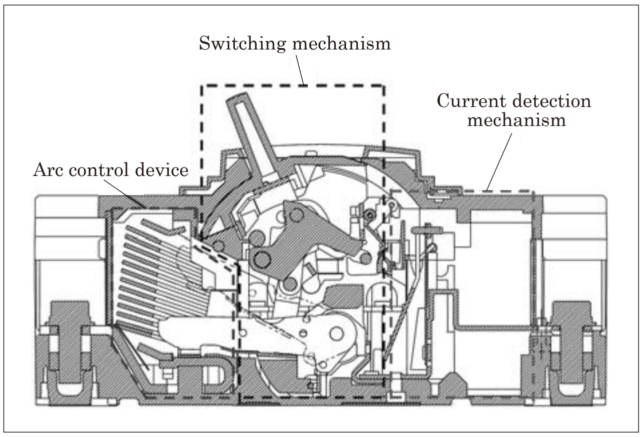

Fig.4 Overall structure of circuit breaker

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.

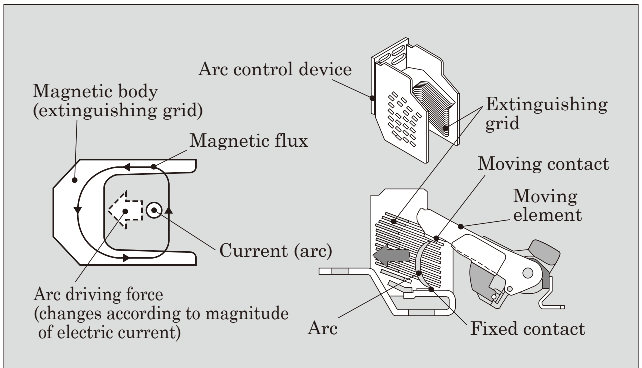

Fig.5 Basic principle of arc driving

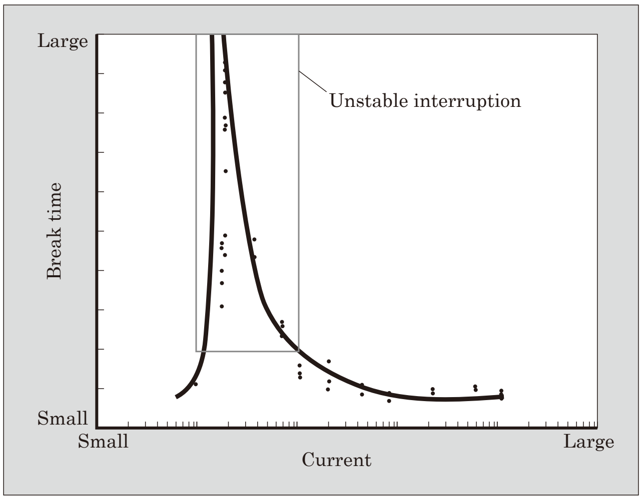

Fig.6 Relationship between current value and break time of DC circuit breaker

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

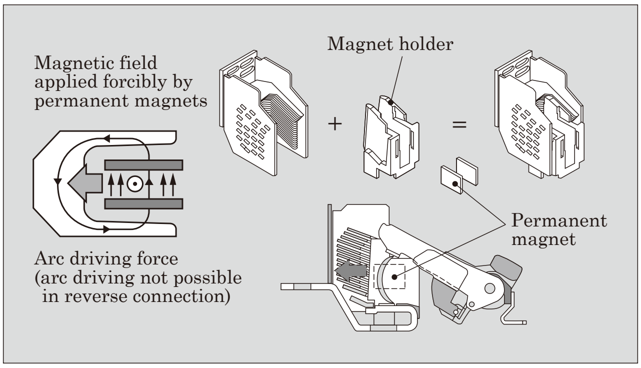

Fig.7 Structure of conventional arc control device

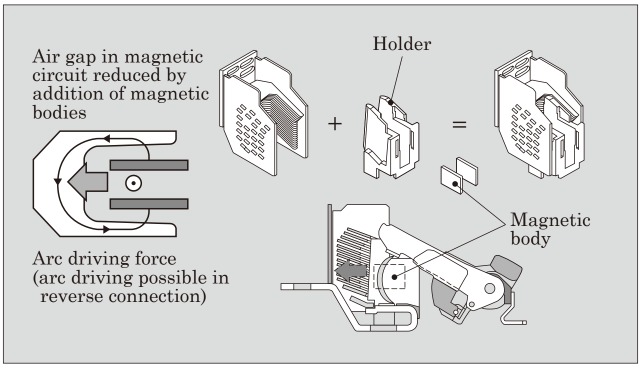

Fig.8 Proposed structure 1

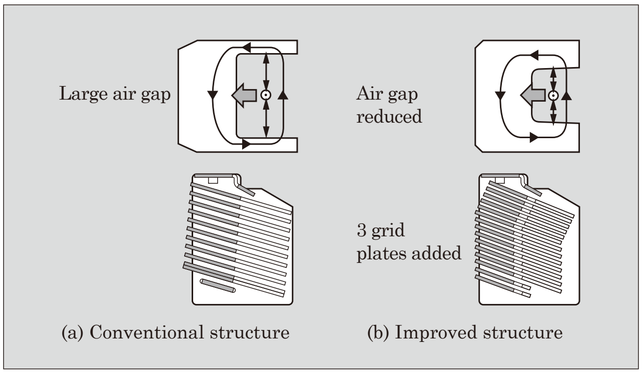

Fig.9 Proposed structure 2

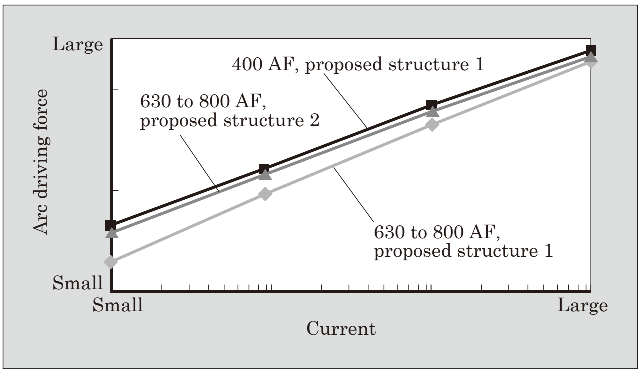

Fig.11 Analysis result of arc driving force

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.

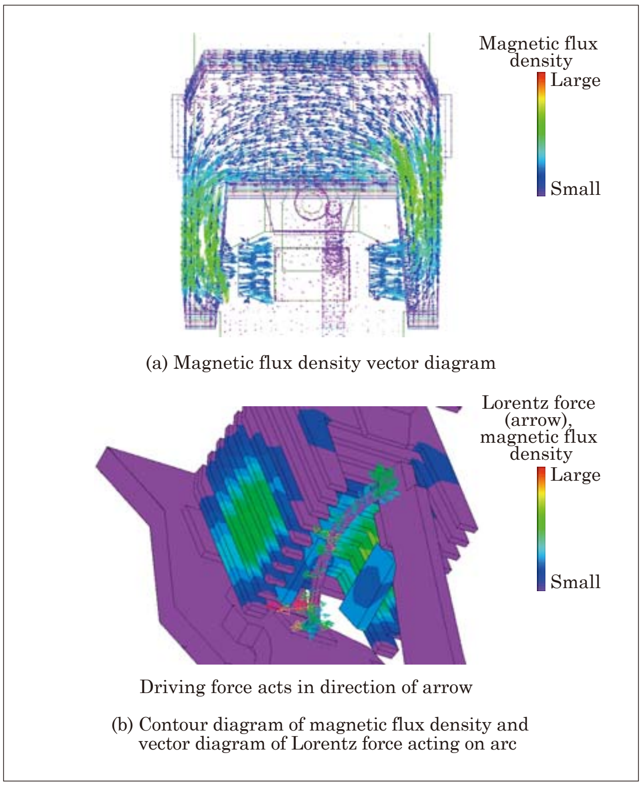

Fig.10 Analysis result of magnetic flux density and Lorentz force

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

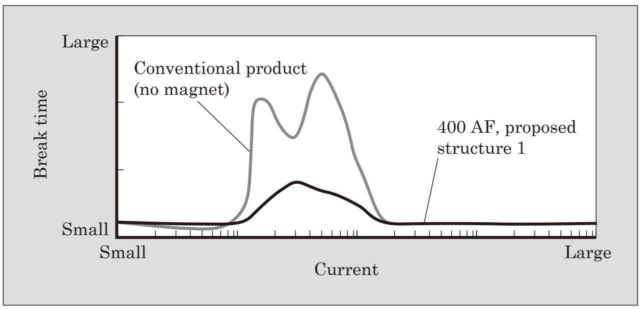

Fig.12 Result of interruption over entire region (400 AF)

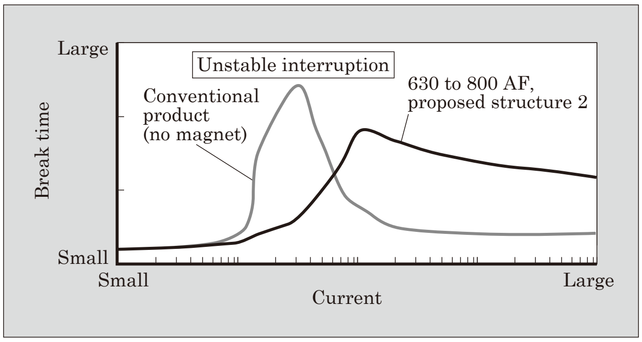

Fig.13 Result of interruption over entire region (630 to 800 AF)

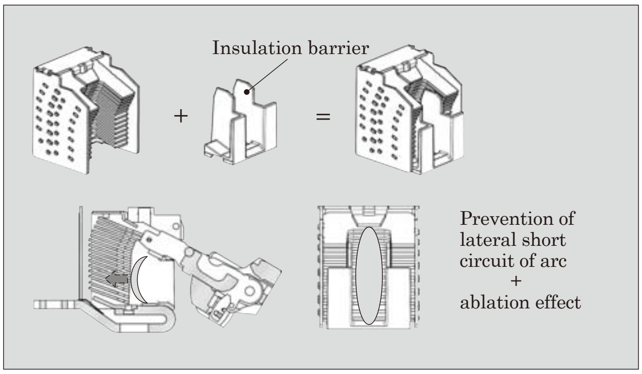

Fig.14 Improved structure

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

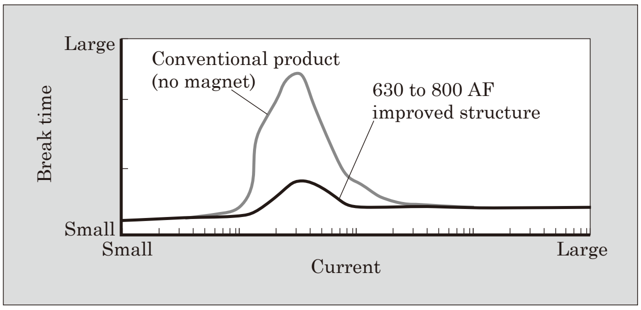

Fig.15 Result of test on improved structure (630 to 800 AF)

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.

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Technology of Estimating Short Circuit Current and Ground Fault for Direct Current Distribution Systems

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ABSTRACT

Applications of Direct Current power distribution systems are expanding along with the expansion of renewable energy use, and this has created an urgent need to establish protection technology for their safe operation. Fuji Electric has verified and established short circuit and ground fault estimation technology as protection technology for direct current power distribution systems. We have built an equivalent circuit based on the impedance characteristics of a storage battery to estimate a short circuit fault in the vicinity of a storage battery. We have analyzed the ground fault current waveforms of grounded and ungrounded systems to estimate the ground fault. Moreover, based on the estimation technology, we have built our product line to make it easier for users to select the appropriate protection devices.

1. Introduction

Greater use of renewable energy sources and the dissemination of smart grids and electric vehicles have been promoted for the purpose of solving the problems of fossil fuel depletion and global warming. Under these circumstances, power distribution systems using direct current are expanding to use energy efficiently and this has created an urgent need to establish protection technology to ensure their safe operation. To satisfy such a need, Fuji Electric has been working on the development of protection technology and protective devices for direct current distribution systems.

Protection technology for direct current distribution systems is broadly divided into overvoltage protection, overcurrent protection and electric shock protection. The overcurrent protection and electric shock protection have such problems as follows. The peak value and rate-of-rise when a short-circuit fault occurs vary depending on the dispersed power supply to be connected, and the current flowing path and peak value when a ground fault occurs differ depending on whether the converter is an insulated type or non-insulated type.

This paper describes the short-circuit fault and ground fault estimation technologies on which Fuji Electric has been working to solve these problems. It also explains how to select protective devices based on the estimation result.

2. Issues in Typical Direct Current Distribution Systems

(1) Wind power generation system

Since wind conditions change depending on the season or weather, the output of a wind power generation system greatly fluctuates in the course of a year or a day. Consequently, if a large amount of output is connected directly to a commercial system, the frequency or power flow of the commercial system may be affected by the output fluctuation.

To solve this problem and achieve a stable system connection, there is a method called the DC link system that first converts the output from the generator into a direct current with an AC/DC converter and then converts it into an alternating current with a DC/AC converter (see Fig. 1). This method prevents any fluctuations from influencing the system by charging or discharging the storage battery connected to the direct current section, and thus keeping the output voltage constant.

A lead-acid battery or lithium-ion battery is used as the storage battery. Since their energy density is higher than capacitors or other electricity storage devices, an excessive current may flow continuously when a short-circuit fault occurs. Moreover, in the case of lithium-ion batteries, the internal temperature may rise abruptly due to the short-circuit current, resulting

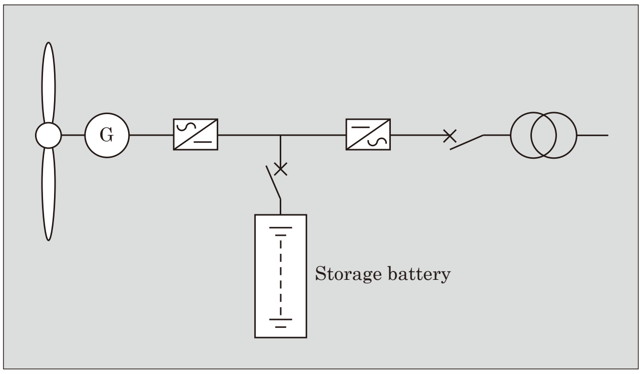

Fig.1 Wind power generation system using DC link system

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in an explosion or fire in the worst case. Consequently, when a short-circuit fault occurs, it is necessary to break the current immediately.

(2) Photovoltaic power generation system

Photovoltaic power generation systems became more popular after the introduction of the "Feed-in Tariff Scheme (FIT)" that encourages the use of renewable energy. As shown in Fig. 2, a photovoltaic power generation system consists of parallel connections of multiple groups (strings) of photovoltaic cell panels connected in series. In order to improve the power generation efficiency, each string is designed to generate power higher than 500 V. Outside Japan, an increasing number of systems are designed to generate around 1,000 V. When a short-circuit fault occurs in a photovoltaic cell panel, a typical increase of the current is about 10 to 20% of the rated current. As a result, a protective device is required to provide a breaking performance and insulation ability to deal with 120% of the rated current of such high voltage systems.

(3) Direct current supply system

In data centers, direct current supply has been proposed instead of conventional alternating current supply in order to reduce power loss in the entire system and ensure energy saving[1]. As shown in Fig. 3, the system supplies power by using an AC/DC converter to convert AC power into a direct current and then using a DC/DC converter to convert it into DC voltage in accordance with the device connected to the DC bus. Since a storage battery for backup can be connected directly, the loss caused by voltage conversion can be reduced compared with conventional AC power supply. Since DC voltage of 300 to 400 V is supplied, this system is characterized by having the DC bus grounded at the center tapped grounding on high impedance in order to lessen the influence on the human body in the event of electric shock accidents.

When a storage battery is connected, immediate breaking is required because an excessive short-circuit current may flow due to a short-circuit fault as is the case with the wind power generation system described above.

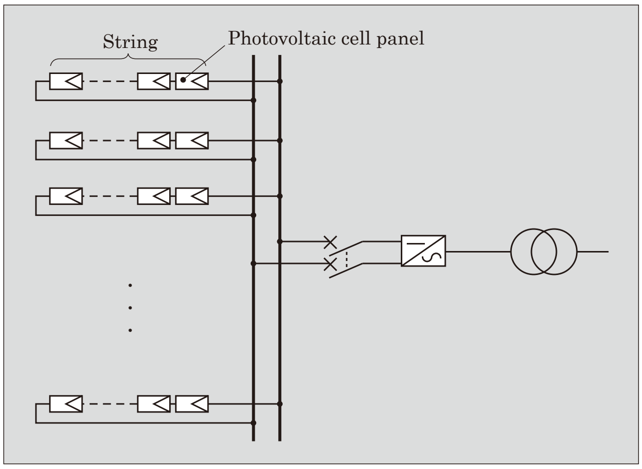

Fig.2 Configuration of photovoltaic power generation system

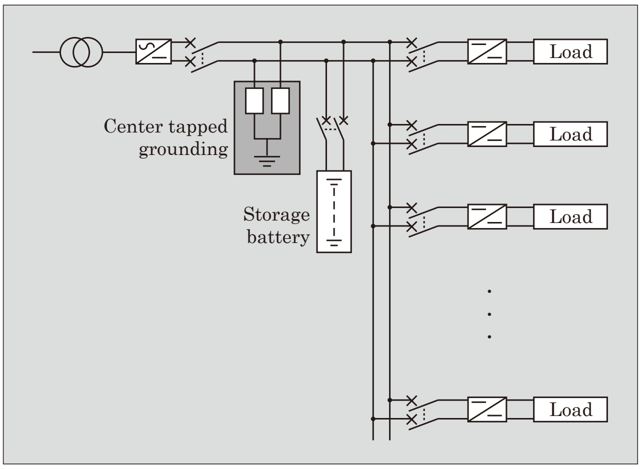

Fig.3 Direct current supply system in data center

3. Short-Circuit Fault Estimation Technology

A short-circuit current flowing in a photovoltaic power panel is about 110 to 120% of the rating. Since storage batteries used in direct current supply systems or wind power generation systems have high energy density, a short-circuit current flows continuously in the event of a short-circuit fault. In addition, when a short-circuit fault occurs between the DC/DC converter and storage battery, a short-circuit current from the storage battery and a current from the capacitor in the AC/DC converter flow into the short-circuit point. In order to isolate the short-circuit fault point to prevent such accidents, it is necessary to know the amount of the short-circuit current flowing from the storage battery and AC/DC converter at the system design stage and select an appropriate protective device.

3.1 Short-circuit fault in the vicinity of storage battery

The current discharged from storage battery due to short-circuiting is determined by the electromotive force of the storage battery, the internal impedance of the storage battery and the line impedance to the short-circuit point. Figure 4 shows an equivalent circuit of a storage battery. This equivalent circuit consists of resistors (R1 to R3) and capacitors (C1 and C2). The parallel circuits of the resistors and capacitors represent the positive or negative poles of the storage battery and the resistor connected in series represents

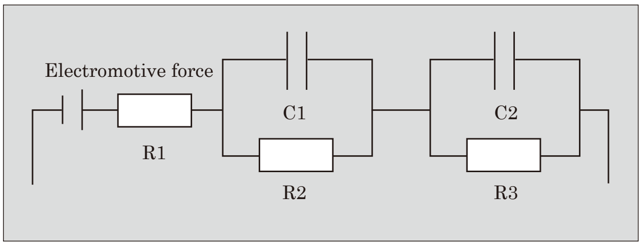

Fig.4 Equivalent circuit of storage battery

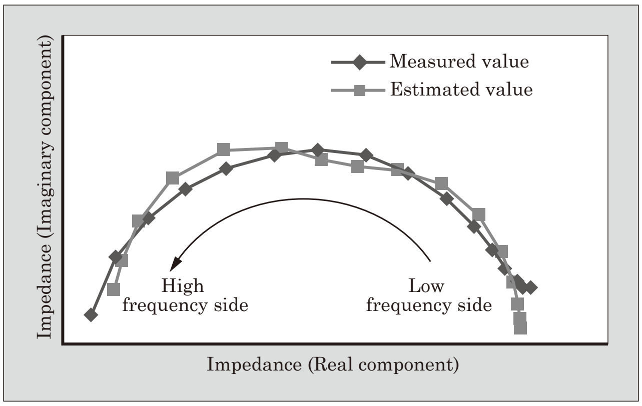

Fig.5 Impedance characteristics of storage battery

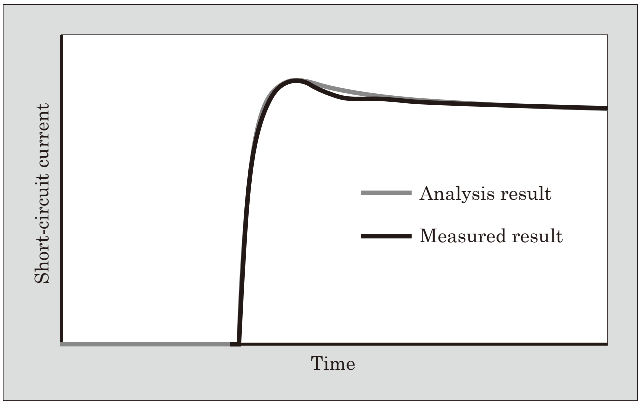

Fig.6 Short-circuit current waveform at short-circuit fault in the vicinity of storage battery

ion conductance. By applying an impedance up to the short-circuit fault point on the equivalent circuit and creating a shorted circuit line, it becomes possible to estimate the value of the short-circuit current.

Figure 5 shows a comparison of the impedance characteristics between the equivalent circuit of a storage battery cell and actual measurement. The impedance characteristics of the equivalent circuit are in good agreement with the measurement across the ranges from low to high frequencies. Consequently, we confirmed that an equivalent circuit consisting of resistors and capacitors can be used to simulate a storage battery. As shown in Fig. 6, the estimated value of the short-circuit current in the equivalent circuit is in good agreement with the measurement, indicating that it is possible to estimate a short-circuit current. In this way, we can easily estimate the value of a short-circuit current by establishing an equivalent circuit based on the impedance characteristics of a storage battery.

3.2 Short-circuit fault in the vicinity of converter

A converter has a capacitor connected to its output terminal to suppress the voltage fluctuation in the DC bus. When a short-circuit fault occurs in the system, an electric charge flows from this capacitor to the fault point. Figure 7 shows the short-circuit current waveform when a short-circuit fault occurs in the vicinity of a DC/DC converter in the DC bus of a direct current supply system.

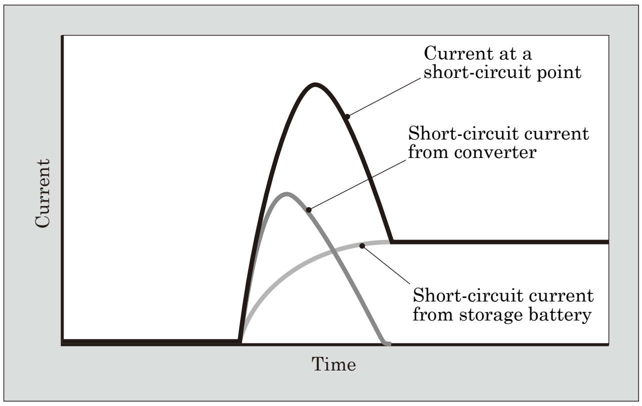

Fig.7 Short-circuit current waveform at short-circuit fault in the vicinity of converter

4. Ground Fault Estimation Technology

In some direct current supply systems used for data centers, etc., center tapped grounding is applied to the DC bus. The phenomenon of a ground fault depends on whether the system is grounded or not.

4.1 Ground fault in grounded system

This section describes the ground-fault current when center tapped grounding is provided in a direct current supply system for data centers, etc. As shown in Fig. 3, center tapped grounding is established by connecting kΩ-level resistors to the positive and negative poles as ground-fault resistance. Figure 8 shows the ground-fault current waveform in the DC bus with center tapped grounding. The ground fault condition assumes contact with a human body and the kΩ-level resistor is used to simulate a ground fault. As the figure shows, the measured value of the ground-fault current (solid line) is good agreement with the calculated value. This indicates that the ground-fault current in a grounded system can be obtained from the voltage and ground-fault resistance of the DC bus.

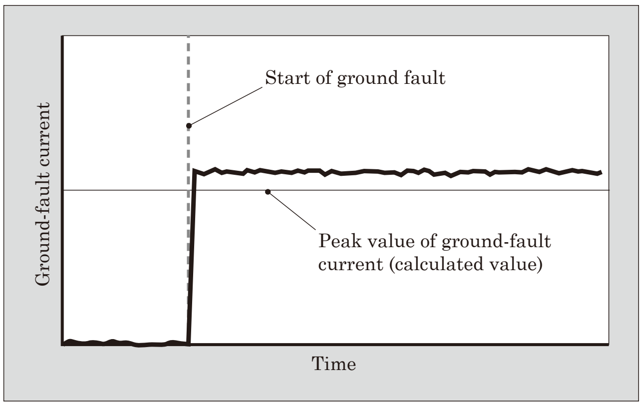

Fig.8 Ground-fault current waveform at ground fault in grounded system

4.2 Ground fault in ungrounded system

In an ungrounded system, when a ground fault occurs in the system, a ground-fault current does not flow as long as there is only one ground fault point, because a path for current flow is not formed. As shown in Fig. 9, we simulated the case of a ground fault and confirmed that the ground-fault current flowing to the ground fault point does not change before and after the ground fault event.

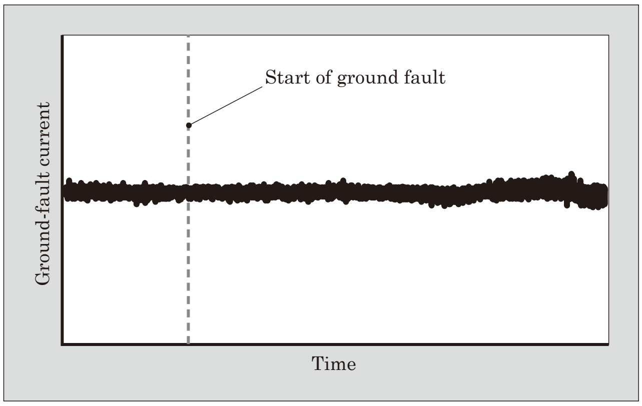

Fig.9 Ground-fault current at ground fault in ungrounded system

5. Selection of an Appropriate Protective Device for the Fault Mode

The characteristics of the fault current in a short-circuit fault depend on the configuration of the dispersed power source. For a storage battery, in particular, immediate breaking is required because a short-circuit current flows continuously. It is therefore effective to obtain the value of a short-circuit current beforehand by using the short-circuit fault estimation technology for storage batteries described in Chapter 3. Table 1 lists the lineup of DC circuit breakers offered by Fuji Electric. You can select a suitable DC circuit breaker by knowing the voltage of the system, the current flowing in steady state and the current value of a short-circuit fault described above at the system design

Table 1 Lineup of DC circuit breakers (400 to 1,000 V DC)

<table>
<tr><th rowspan="2">Rated voltage DC (V)</th><th rowspan="2">Model</th><th rowspan="2">Series name</th><th rowspan="2">Connection</th><th colspan="25">Rated current (A)</th><th rowspan="2">Breaking capacity I_{cu} (kA)</th></tr>
<tr><th>0.1</th><th>1</th><th>5</th><th>10</th><th>15/16</th><th>30/32</th><th>40</th><th>50</th><th>63</th><th>80</th><th>100</th><th>125</th><th>160</th><th>200</th><th>250</th><th>300</th><th>350</th><th>400</th><th>500</th><th>630</th><th>700</th><th>800</th><th>1,000</th><th>2,000</th><th>4,000</th></tr>
<tr><td>400</td><td>MCCB</td><td>G-TWIN</td><td>3-pole (Series connection)</td><td colspan="2"></td><td colspan="9">EW32□G-3P C4 to BW100□G-3P C4</td><td colspan="14"></td><td>2.5 to 5</td></tr>
<tr><td rowspan="8">500</td><td rowspan="3">MCB</td><td rowspan="3">Acti9</td><td>2 poles</td><td colspan="9">C60H-DC</td><td colspan="16"></td><td>6</td></tr>
<tr><td rowspan="2">4-pole (Series connection)</td><td colspan="7"></td><td colspan="5">C120N</td><td colspan="13"></td><td>10</td></tr>
<tr><td colspan="3"></td><td colspan="9">C120H</td><td colspan="13"></td><td>15</td></tr>
<tr><td rowspan="3">MCCB</td><td rowspan="3">G-TWIN</td><td rowspan="4">3-pole (Series connection)</td><td colspan="2"></td><td colspan="9">BW50□G-3P LV=500 V-02015 to BW100□G-3P LV=500 V-02015</td><td colspan="14"></td><td>2.5</td></tr>
<tr><td colspan="4"></td><td colspan="11">BW125□G-3P C5-BW250□G-3P C5</td><td colspan="10"></td><td>10 to 40</td></tr>
<tr><td colspan="14"></td><td colspan="8">BW400□G-3P to BW800□G-3P</td><td colspan="3"></td><td>20 to 40</td></tr>
<tr><td>MCCB</td><td>DC only</td><td colspan="22"></td><td colspan="3">SD1003B to SD4003B</td><td>40</td></tr>
<tr><td>ACB</td><td>Master pact</td><td>2-pole (Series connection)</td><td colspan="22"></td><td colspan="3">NW10DC to NW40DC</td><td>25 to 100</td></tr>
<tr><td rowspan="5">600</td><td rowspan="4">MCCB</td><td rowspan="4">G-TWIN</td><td rowspan="2">3-pole (Series connection)</td><td colspan="3"></td><td colspan="6">BW50SBG-3P C6, BW63SBG-3P C6</td><td colspan="16"></td><td>10</td></tr>
<tr><td colspan="4"></td><td colspan="11">BW125JAG-3P CP, BW250JAG-3P CP</td><td colspan="10"></td><td>3</td></tr>
<tr><td rowspan="2">4-pole (Series connection)</td><td colspan="4"></td><td colspan="11">BW125□G-4P C6 to BW2580□G-4P C6</td><td colspan="10"></td><td>25 to 40</td></tr>
<tr><td colspan="14"></td><td colspan="8">BW400□G-4P to BW800□G-4P</td><td colspan="3"></td><td>40</td></tr>
<tr><td>MCCB</td><td>DC only</td><td>3-pole (Series connection)</td><td colspan="22"></td><td colspan="3">SD1003B to SD4003B</td><td>20</td></tr>
<tr><td>650</td><td>MCB</td><td>Acti9</td><td>2-pole (Series connection)</td><td></td><td colspan="4">C60PV-DC</td><td colspan="6">Up to 25 A rating</td><td colspan="14"></td><td>1.5</td></tr>
<tr><td rowspan="2">750</td><td>MCCB</td><td>Compact</td><td>3-pole or 4-pole</td><td colspan="4"></td><td colspan="15">NS100DC to 630DC</td><td colspan="6">Up to 550 A rating</td><td>100</td></tr>
<tr><td>MCCB</td><td>G-TWIN</td><td>3-pole (Series connection)</td><td colspan="14"></td><td colspan="8">BW400RAG to BW800RAG</td><td colspan="3"></td><td>10</td></tr>
<tr><td>900</td><td>ACB</td><td>Master pact</td><td>3-pole or 4-pole (Series connection)</td><td colspan="22"></td><td colspan="3">NW10DC to NW40DC</td><td>25 to 85</td></tr>
<tr><td>1,000</td><td>MCCB</td><td>G-TWIN</td><td>4-pole (Series connection)</td><td colspan="14"></td><td colspan="8">BW400RAG to BW800RAG</td><td colspan="3"></td><td>5</td></tr>
</table>

stage and checking the values against the lineup table.

The characteristics of a ground-fault current depend on the grounding type in the system. The value of the ground-fault current in the system with center tapped grounding can be estimated from the voltage, grounding resistance and ground fault resistance of the DC wiring for which a ground fault is assumed. The sensitive current setting for the earth leakage circuit breaker must be determined based on both of the possible current flowing range when a ground fault occurs and the protection target. For example, it is several hundreds of mA to mainly protect equipment and around 30 mA to protect a human body.

A ground-fault current is not generated in an ungrounded system. If, however, a first ground fault is overlooked and then a second ground fault occurs, a current close to a short-circuit level may flow. One method to detect a ground fault in an ungrounded system is to monitor the insulation resistance in the system and detect a drop in the insulation resistance caused by a ground fault. This makes it possible to detect a ground fault even when a ground-fault current is not generated.

Table 2 Ground fault protection method corresponding to each grounding system

Grounding type	Ground fault detection method
Ungrounded system	○ Detection with an insulation monitoring device (Fuji Electric's "Vigilohm")
High resistance grounding (Center tapped grounding)	○ Detection with an earth leakage circuit breaker (High sensitivity model: The sensitive current should be set according to the protection target.) ○ Detection based on the fluctuation in the middle electric potential
Low resistance grounding (Negative grounding)	○ Detection with an earth leakage circuit breaker

Table 2 shows ground fault protection methods according to the grounding type of system. As the table indicates, the method of detecting a ground fault depends on the grounding type of the system. It is necessary to select a device suitable for the detection method. Moreover, when an earth leakage circuit breaker is used, it can be selected based on the sensitive current judged from the estimated ground-fault current value and protection target.

6. Postscript

This paper describes the short-circuit fault and ground fault estimation technologies on which Fuji Electric has been working. These technologies relate to direct current distribution systems that are expected to continue expanding in the future. We also explained the way to protect against these faults. Fuji Electric offers various protective device products designed for a short-circuit fault and a ground fault. We will continue with technological development for more user-friendly products.

References

(1) Nozaki, Y. Development of Higher-voltage Direct Current Power Feeding System for ICT Equipment. NTT Technology Review. 2009, vol.7, no.10.

Product Evaluation of Power Distribution, Switching and Control Equipment Components

MIYAZAWA, Hidekazu* HATA, Junichiro* NUMAGAMI, Takeshi*

ABSTRACT

In the development process for distribution, switching and control equipment components, product evaluations encompassing many items are required to satisfy product specifications and meet market demands. Fuji Electric builds product quality by implementing four kinds of evaluation: a screening evaluation on factors determining product performance, a reliability evaluation in view of a product use environment, an interface evaluation that considers handleability, and a characteristic evaluation based on product standards. With these evaluations, Fuji Electric makes our products meet their specifications to increase customer satisfaction while improving the efficiency of our overall development.

1. Introduction

Fuji Electric's major products for power distribution, switching and control equipment components include magnetic starters, low-voltage circuit breakers, operation indicators (command switches), middle-voltage circuit breakers and power monitoring equipment.

The development of these products requires technologies for breaking low-to-middle voltage currents by opening and closing the circuit in the air or in a vacuum, for operating them manually or remotely with an electromagnet or with an opening and closing mechanism, and for detecting or measuring electric currents. We prepare concept designs based on these technologies and establish the basic structure that satisfies the development-required specifications by using partial prototypes of opening and closing mechanisms, contact blocks or other parts which are the elemental technologies for the products. We then use type test prototypes to evaluate the performance required for the products and elaborate their quality. With mass-production prototypes in the final stage, we establish the quality that ensures stable manufacturing.

This paper explains the product evaluation process that verifies a product's performance while considering quality elaboration and various product usages in the market.

2. Product Evaluation

As globalization progresses, Fuji Electric's power distribution, switching and control equipment components are required to conform to or comply with not only Japanese JIS but also overseas standards such as IEC and UL as shown in Table 1. They need to satisfy multiple standards and obtain standard certifications.

In the development process, product evaluation encompassing the many items shown in Table 2 is required to satisfy product specifications and meet market demands. Fuji Electric elaborates product quality by implementing four kinds of evaluation: a screening evaluation on factors determining product performance, a reliability evaluation in view of a product's use environment, an interface evaluation that considers handleability, and a characteristic evaluation based on product standards.

(1) Screening evaluation on factors determining product performance

In the early stage of development, design factors are screened through simulation or other methods. Selecting optimum materials is especially of great importance. In the prototyping stage, design parameters such as the shape, dimensions and adopted material of the components are evaluated experimentally to determine optimum values that satisfy the target perfor-

Table 1 Japanese and overseas standards for each product

Model	Japan	Overseas	
Magnetic starters	JIS C 8201-4-1	IEC 60947-4-1	UL60947-4-1
Low-voltage circuit breakers	JIS C 8201-2	IEC 60947-2	UL489
Operation indicators (command switches)	JIS C 8201-5-1	IEC 60947-5-1	UL508
	JIS C 8201-5-5	IEC 60947-5-5	
Middle-voltage circuit breakers	JEC-2300	IEC 62271-100	–
Power monitoring equipment	JIS C 1102-□	IEC 61000-□	–
	JIC C 1216	(IEC 255-3)	

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Table 2 Product evaluation

Item	Evaluation verification technology	Product evaluation standpoint
Operation evaluation	High-speed/high-accuracy measurement technology Visualization technology Automatic measurement technology Mechanism analysis technology Optimization technology (application of quality engineering)	(a) Screening evaluation on factors determining product performance Design control factor parameters that cannot be determined only through design consideration are identified experimentally to determine design values. (b) Reliability evaluation in view of a product's use environment Evaluation is implemented in accordance with the load to be used. Stability is evaluated in the envisaged use environment. (c) Interface evaluation that considers handleability Handleability is tuned based on the understanding of the limits. (d) Characteristic evaluation based on product standards A test method conforming to the standard is used to efficiently confirm that the characteristic values satisfy the acceptable product standard. Product knowledge 
Breaking evaluation	Large current evaluation technology Transient phenomenon analysis technology Arc observation technology DC evaluation technology Magnetic field analysis technology	
Life span evaluation	Prediction technology Actual load simulation circuit technology Accelerated evaluation technology	
Environmental resistance evaluation	Statistics technique application technology Material technology Failure analysis technology	
Current carrying performance evaluation	Thermal analysis technology	
Insulation evaluation	Middle-voltage measurement technology	
Vibration/shock evaluation	Combined evaluation technology	
EMC evaluation	EMC&EMS measurement technology High accuracy measurement technology	
Handleability evaluation	Quantification technology Visualization technology	

mance.

(2) Reliability evaluation in view of a product's use environment

Due to efforts in recent years for renewable energy, efficiency improvement and energy saving, our products have been used in various ways and the adoption of high-energy efficiency equipment and DC equipment is increasing. In order to deal with such diversification, we ensure our products are reliable by understanding their adaptation to customers' equipment or their use environment such as their mounting location and conducting accelerated evaluation considering their age-related degradation.

(3) Interface evaluation that considers handleability

The portions directly operated by worker must be easiest to operate. They also require a fail-safe design providing the strength and safety to withstand every operation imaginable during an emergency. We therefore refer to data on previous usage, evaluate operations with strong force exceeding the recommended value or using tools, and grasp the strength limit values or breakdown process to verify it is fail-safe.

(4) Characteristic evaluation based on product standards

To evaluate mass-production prototypes, we conduct tests to check their characteristics within the range between the minimum and maximum values while taking the drawing tolerance of the design values into account, and confirm that the characteristic values are within the reference values for acceptable products. Since products such as power monitoring equipment must be usable in a wide variety of conditions of customers, we implement tests efficiently to obtain electric energy measurement data in every envisaged combination of those conditions. Moreover, in order to obtain standard certifications, we establish trusting relationships not only with Japanese certification authorities but also with overseas authorities such as the UL and CCC and carry out the evaluation tests faithfully based on those standards.

3. Case Examples of Product Evaluation Tests

3.1 Screening evaluation test on factors determining product performance

(1) Operational and life span evaluation of magnetic contactors

A magnetic contactor roughly consists of a contact opening/closing part and an electromagnet part. The major components that make up the contact opening/closing part are moving contact, fixed contact, contact spring and contact support. The electromagnet part

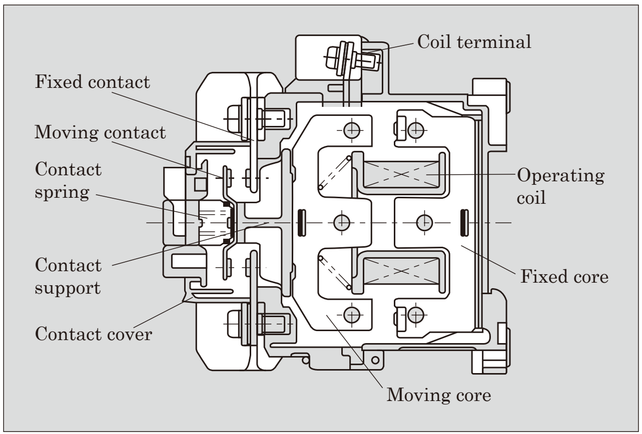


Fig.1 Magnetic contactor components

consists of a moving core, a fixed core and an operating coil, and it is covered with a resin-molded frame part (see Fig. 1).

In a magnetic contactor, when voltage is applied to the operating coil, electric current flows and generates magnetic flux inside the core, and the moving core is attracted to the fixed core. In conjunction with this action, the contact support connected to the moving core moves accordingly, causing contact between the fixed contacts on the frame and the moving contacts, resulting in flow of electric current.

This switching action is conducted at high speed of about 10 to 20 ms. We therefore utilize an optical displacement meter and a high-speed camera that can visualize movement to evaluate the operation accurately and check for problems with the optimization of the spring load to allow stable contact making and with the connection shape of the contact support and moving core. As for the AC power supply, we implement efficient evaluation by changing the phase of the voltage applied to the coil within the range of 0° to 180° to enable automatic measurement of the operation.

In the life span evaluation, we conduct an accelerated test by simulating starting/stopping of the motor. Figure 2 shows an example of the measurement of contact dissipation amount caused by contact-making operations and the generated arc energy. We reduced the arc energy by using contact material/shape (A) to optimize the operation. Furthermore, we determined an optimum contact shape and used contact material/shape (B) to satisfy the target wear limit and achieved the target life span.

Through such optimization and limit design, the “FJ Series” has been downsized by about 28% to 38% in volume, while satisfying the price level applicable to overseas markets (refer to “Magnetic Contactor ‘FJ Series’ and ‘SK Series’ Line Expansion” on page 163).

(2) Middle-voltage DC MCCB breaking evaluation test

Low-voltage distribution equipment, such as molded-case circuit-breakers (MCCBs) and earth-leakage circuit-breakers (ELCBs) are designed to detect over-

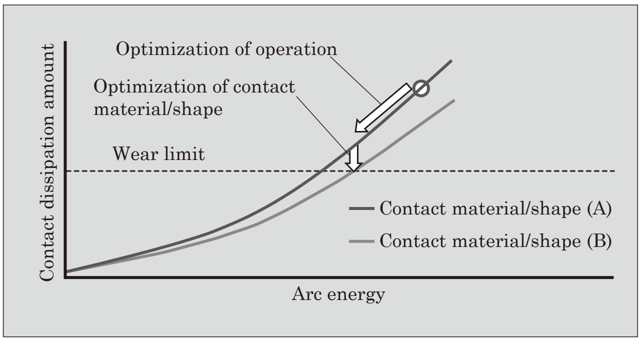


Fig.2 Relationship between arc energy and contact wear

current or ground fault and break the circuit for alternate currents up to 600 V.

In order to confirm that MCCBs or ELCBs can safely break the current specified in their required specifications, we take advantage of a short-circuit generator facility to create an actual accident current (150 kA max.) that could possibly occur in the market, and evaluate the transient breaking phenomenon in 10 ms or less, to determine the dimensions and material of the portions around the contact.

In recent years, DC power feeding (300 to 400 V) has been increasing with the proliferation of renewable energies such as photovoltaic power generation and data centers, and the request for circuit breakers supporting middle voltage DC (1,000 V) is increasing to reduce transmission loss. Normally with an AC circuit, we controlled the arcs generated between contacts before reaching zero points of the current that occur periodically, and ensured insulation to break the current. Since no zero point exists in a DC circuit, we need to extend the arc in a limited space and increase the voltage, which occurs between the contacts, to be higher than or equal to the power supply voltage (see Fig. 3).

As for circuit breaking, JIS C 8201-2 specifies that you only need to check the rated current (800 A) and rated breaking capacity (5 kA). We, however, conduct verification in all regions up to the rated breaking capacity in order to ensure reliable breaking in DC circuits with actual load.

Breaking a direct current requires commutating an arc into an arc-extinguishing grid instantaneously and extending it to increase the voltage between con-

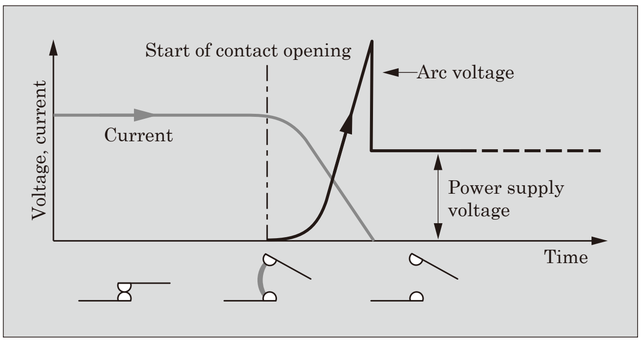


Fig.3 Waveform at the breaking of DC circuit

tacts. We used simulation to efficiently refine the design parameters including the inner wall shape of an arc control device and the grid shape and its quantity. We also used a high-speed camera to visualize the phenomenon in 10 ms to determine the structure that enables arc commutation most easily for current breaking at 1,000 V DC (see Fig. 4).

The direct current breaking performance is proportional to the number of contacts (poles). To use four poles to handle 1,000 V DC, a breaking performance of 250 V DC per pole is sufficient. Consequently, we used a single-phase 250 V DC test circuit for the evaluation.

By using the developed arc control device and the testing condition of single-phase 250 V DC, we evaluated the length of the arcing time and arc energy to judge whether the breaking was successful or not in the entire current range guaranteed for the normal/reverse connection. We confirmed that the product could unfailingly break a direct current when 1,000 V DC was applied. As for the life span, we conducted a switching durability test 1,000 times with a rated current based on the JIS C 8201-2 standard. In photovoltaic power generation, it is expected that the current will sometimes become extremely small depending on the amount of sunlight. With direct current, the arcing time is generally long in the range of small currents of about 10-odd A as shown in Fig. 5. We conducted evaluation on the assumption that switching would be also frequently performed in this region, and confirmed that our products have sufficient durability even when

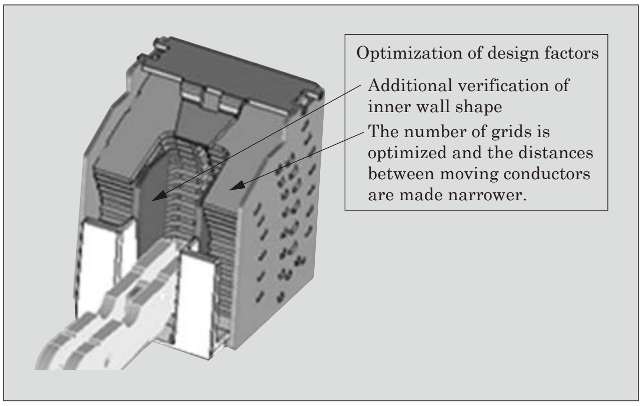


Fig.4 Shapes of arc control device and inner walls

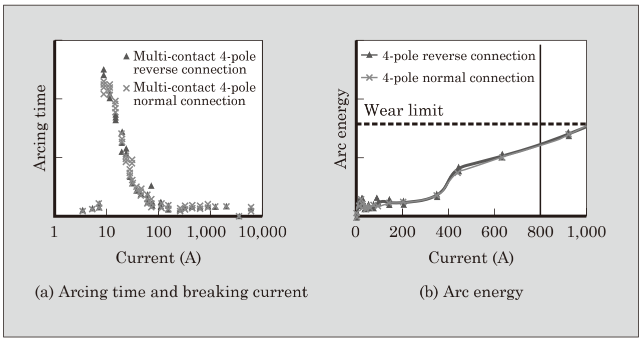


Fig.5 Arcing time and arc energy in the entire range

the current drops to lower than the rated current. As described here, we enhance the quality of non-polar DC breakers so that they can be used safely in all DC field including solar power generation facilities (refer to "No-Polarity Interruption Technology of Circuit Breakers for High-Voltage Direct Current" on page 174).

3.2 Reliability evaluation test in view of a product use environment

As inverters and servo amplifiers have become prevalent and popular in recent years, magnetic contactors have come to be used not only in the conventional application of direct motor start but also as a primary side switch for a drive control device. This section describes the evaluation test to ensure switching performance in the latter application.

When a magnetic contactor is used as primary side switch for an inverter or a servo amplifier, the performance of closing the capacitor charging current generated at power-on is important. While the inrush current during direct start becomes 6 times the rated current, the inrush current during capacitor charging is 8 to 15 times greater than the rating (see Fig. 6). We evaluated the welding resistant characteristics of the contact against this inrush current and the durability (life span) of the contact under repeated switching.

For utilization category AC-3 simulating the current at the startup of a motor (closing the current that is 6 times the rated current in half wave of 10 ms and opening the rated current), the current flowing when the contact is closed in the capacitor circuit forms a steep half wave of around 3 ms, and the contact loss will be approximately 10 times of that of AC-3. Figure 7 shows photographs of the contacts after the switching test. They indicate that the contact wear after switching 1 million times in the AC-3 test is equivalent to 100 thousands times in the capacitor switching.

It is normally possible to evaluate the life span of the contact by using the drive control device used in the market. In this case, however, you cannot increase the switching frequency because the capacitor charging/discharging time in an actual circuit is not uniform. Hence we used a typical drive unit to execute

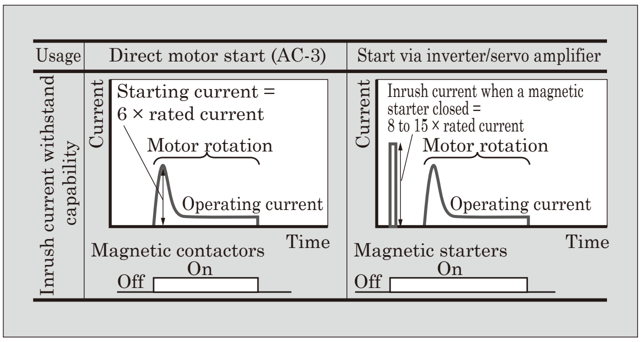


Fig. 6 Comparison of direct motor start and servo amplifier driving

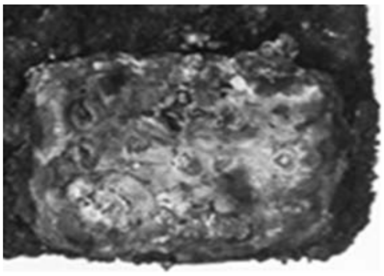
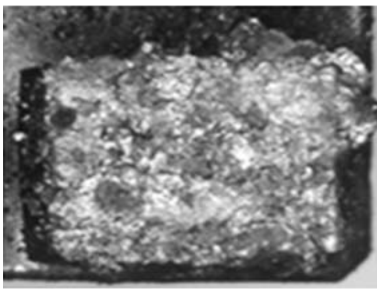
Testing conditions	Contact state after switching test
AC-3 (1 million times switching)	
Capacitor switching (100 thousands times)	

Fig.7 Photographs of contacts after switching test

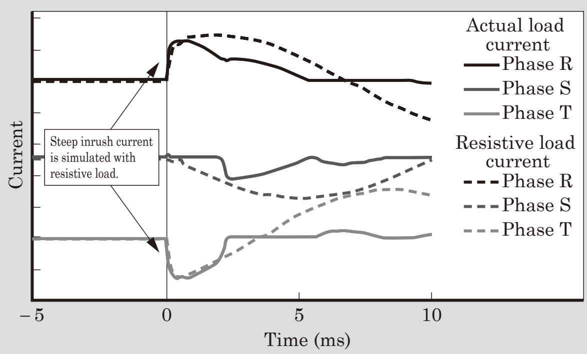


Fig.8 Waveform comparison between servo actual load and resistor simulated load test

actual opening/closing so as to obtain the voltage and current waveform. By simulating this actual waveform with a resistive load circuit of the contact closed, we enabled evaluation in a simulation circuit that generates an equivalent waveform of a rising current affecting the contact wear (see Fig. 8).

For the "SK Series," we used such actual load data to evaluate the life span of contacts and welding resistant limit, and expanded the models that satisfy the required switching life by considering the primary side switching of inverters/servo amplifiers.

3.3 Interface evaluation test that considers handleability

Command switches are used as operating switches or pilot lights of control panels or other equipment and machinery (operating panels) and have an important role to play as a quick and accurate human-machine interface.

Since an emergency stop pushbutton switch is operated by many different persons, it must provide an operating feeling to indicate that it operated just as the operating person expected and be activated by an appropriate operating force. In addition, since it is operated during an emergency, we should expect it to be handled harshly such as being hit by a tool. We basically tune the operating force in terms of ergonomics by assuming the force that can be exerted by a person. We, however, confirm and evaluate the actual force by operating it harshly by referring to previous data. Although it is out of specification and seldom occurs, we assume cases where the switch is hit with a plastic hammer or a padlock and its housing is cracked or damaged, and confirm the fail-safe design that does not impair its functionality. We synchronize the switch with electrical contact signals, use a high-speed camera to visualize the behavior of the mechanism in high-speed shots and confirm that there is no problem with its "cutoff" capability.

In order to quantify the operating force which varies depending on the way of hitting, the above evaluation has also adopted a method to replace the plastic hammer with a cylindrical rigid body weighing 1 pound (0.453 kg) and dropping it from the height at which the shock load used as judgment criterion is generated. The emergency stop pushbutton switch featuring the "Synchro Safe Contact," which is Fuji Electric's original structure, has been designed with consideration given to every safety factor. It is a product that undergoes substantial user interface evaluations including the handling described above and also provides fail-safe functionality and robustness (refer to "Emergency Stop Pushbutton Switches (ϕ22 and ϕ30) Integrating 'Synchro Safe Contact'" on page 169).

3.4 Characteristic confirmation test based on product standards

This section describes the evaluation for elaborating quality in the mass-production prototyping process based on the internal product standards for power monitoring equipment.

As a way of further streamlining energy usage, we commercialized the power monitoring unit "F-MPC04 Series" offering various model lineups satisfying the power monitoring needs of customers. To evaluate this product, we need to accurately assess the main functionality of the watt-hour meter function, combine all variable conditions of the factors required in the product standard (see Table 3) and complete 288 evaluations in a short period.

The F-MPC04 Series uses a voltage transformer (VT) and a current transformer (CT) to measure voltage and current as well as the phase difference of the voltage and current to obtain active power, reactive power and power factor.

The watt-hour meter of the F-MPC04 Series corre-

Table 3 Evaluation combination required for the product standard

Factor	Variable condition	
Applicable CT rating	5 A, 50 A, 100 A, 200 A, 400 A, 800 A	6 ratings
Voltage	110 V, 220 V, 440 V	3 conditions
Current	5% and 100% of CT rating	2 conditions
Frequency	50 Hz, 60 Hz	2 conditions
Power factor	1.0, 0.5	2 conditions
Electric energy direction	Normal, reverse power flow	2 conditions
Evaluation combination		288 combinations

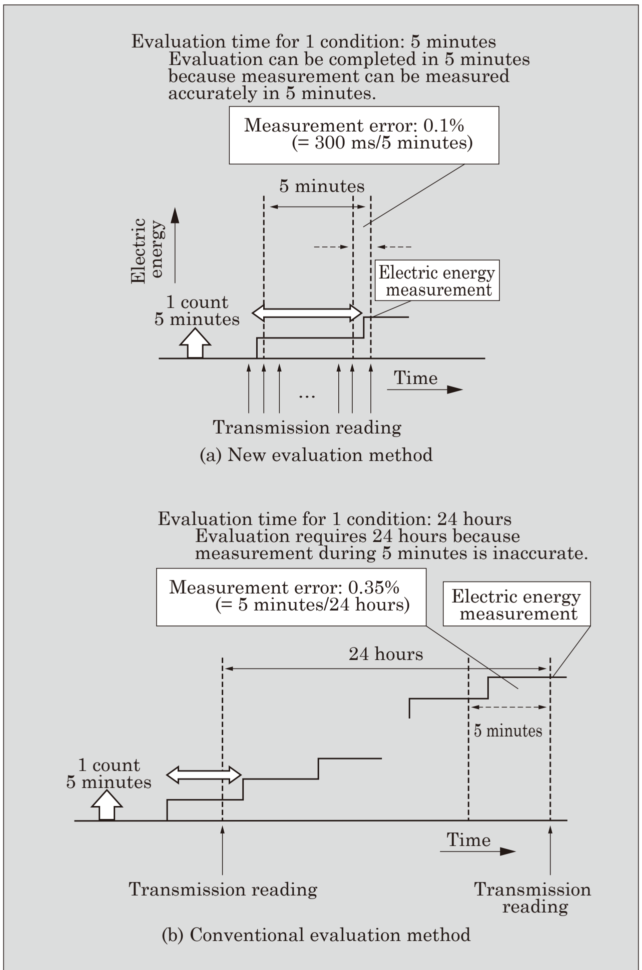


Fig.9 Comparison of electric energy measurement methods

sponds to JIS C 1216 ordinary watt-hour meters category. Consequently, we need to ensure a measurement accuracy of 2.0% even for a low current that is about 5% of the rated current of the CT. In order to decrease the measurement error in such a low current, we enabled transmission of the electric energy (watt-hour) at 300 ms intervals in 5 minutes per count, instead of the previous method of reading data only at the starting and ending times of a 24-hour period through transmission, so that the change in the electric energy could be measured accurately. Improving the measurement resolution has reduced the measurement error in the evaluation to less than 0.1% (300 ms/5 minutes) (see Fig. 9).

This improves evaluation accuracy as well as saves evaluation time. We then introduced automatic measurement technology to allow all combinations of evaluation conditions in a short period, instead of the previous evaluation of limited points.

Such evaluation has made it possible to add the multi-circuit type power monitoring unit F-MPC04P to the lineup. This is a model with improved quality as a watt-hour meter providing high measurement accuracy even under actual load.

4. Postscript

Construction of a new development building is underway at the Fukiage Factory, scheduled to be completed in December 2014. This building will be a global mother base for creating new products and new technologies for the renewable energy field and Asia and Chinese markets.

Since this new development building is next to the building in which the development design, production engineering and quality assurance departments are located collectively, Fuji Electric will further enhance the team power, increase customer satisfaction by achieving shorter development period and improved product quality, and improve the efficiency of overall development. Furthermore, we will augment a new breaking test facility supporting middle voltage DC products including solar power generation to enhance the product evaluation technology.

We at Fuji Electric continue to actively promote the development of products that anticipate the needs for power distribution, switching and control equipment components and provide product evaluation technologies to support our solutions including stable energy supply, energy saving, safety/security and the environmental conservation.

Environmentally Friendly Material Technology for Power Distribution, Switching and Control Equipment Components

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ABSTRACT

With distribution, switching and control equipment components, requirements for employed materials are becoming stricter year by year due to the tightening of environmental regulations such as the RoHS Directive and to address environmental issues including global warming.

Concerning metal materials, Fuji Electric has worked on eliminating Cd from contacts and realized it by achieving the wear resistance and temperature rise targets. For polymeric materials, we have successfully replaced thermosetting resin in insulating parts with thermoplastic resin and reduced waste in thermosetting resin.

1. Introduction

For power distribution, switching and control equipment components, it has become essential to develop products satisfying global requirements. Beginning with the RoHS Directive*1 which came into effect in 2003, regulations restricting hazardous substances are spreading in terms of environmental protection and healthcare.

This paper describes the trend in environmental efforts and the environmentally friendly material technologies for metal and polymeric materials currently developed by Fuji Electric.

2. Trend of Environmental Efforts

2.1 Major EU environmental regulations

From July 2006, the RoHS Directive has made it obligatory to keep the content percentage of six restricted substances of lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium (Cr^{6+}), polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE) to specified extremely low levels or less in the products in Categories 1 to 7 and 10 (such as household appliances and toys) ahead of other categories. Power distribution, switching and control equipment components are classified as monitoring and control instruments and became subject to the directive officially

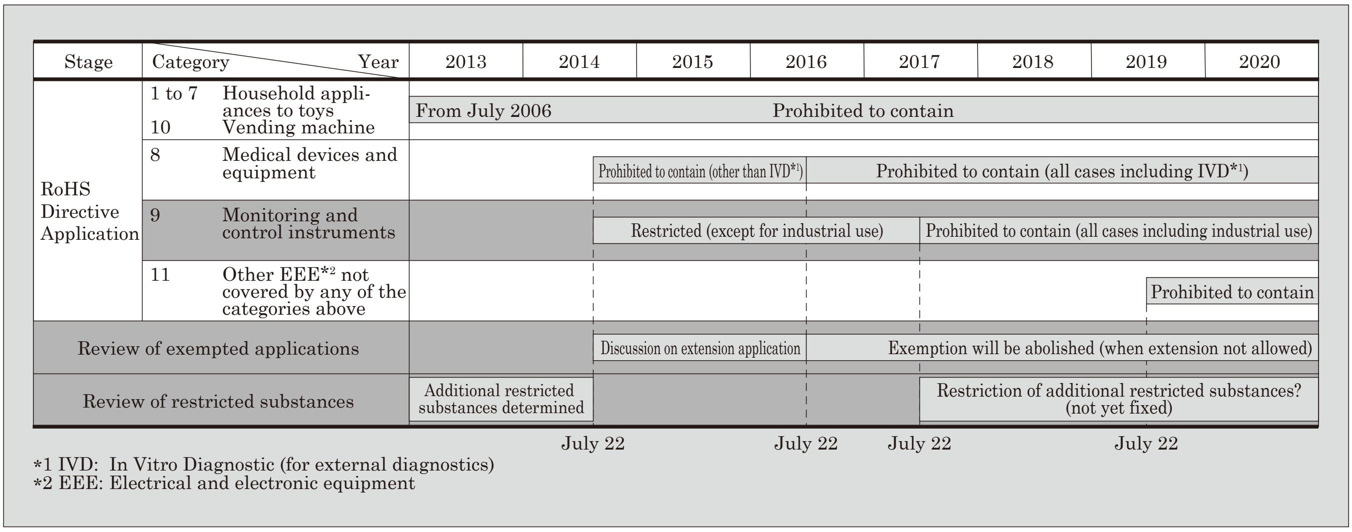


Fig.1 Time schedule for revising RoHS Directive

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

*1: RoHS Directive: European Union (EU) Directive regarding restrictions of the use of certain hazardous substances contained in electrical and electronic equipment from July 2014 (see Fig. 1).

2.2 Trend of environmental efforts in Japan

In Japan, companies are required to reduce power consumption and CO_2 emissions through their products, aiming to construct an environmentally friendly economic society to solve global warming and other environmental problems. Moreover, the "Basic Act on Establishing a Sound Material-Cycle Society" stipulates that companies should promote 3R (Reducing waste generation, Reusing products and parts and Recycling wastes as raw material) in order to construct a sound material-cycle society while encouraging the recycling of non-ferrous metal resources and developing alternative materials in order to secure a stable supply of mineral resources.

This trend of promoting 3R is sharply accelerating also for polymeric materials. As for thermosetting resin parts which were discarded as industrial wastes, efforts have been made including reducing wastes amount, changing over to thermoplastic resin, recycling in production sites and reusing or recycling recovered parts.

3. Environmental Efforts for Metal Materials

3.1 Fuji Electric's previous efforts

As for the substances restricted by the RoHS Directive, such as chromate containing Cr^{6+} and Pb containing solder, Fuji Electric and its affiliated manufacturers developed alternative technologies and switched to using them in 2005 through 2006[(1)]. However, we continued using Cd contained components in some products of power distribution, switching and control equipment components that required high electric performance and long operating life. This was because Cd was exempted from the restriction by the RoHS Directive [Annex III-8(b)], and that AgCdO contacts had an excellent balance of the characteristics required of electrical contacts such as wear resistance and welding resistance.

The use of AgCdO contacts, however, is anticipated to be prohibited after the RoHS Directive exemption provisions are reviewed. Consequently, we are moving forward with changing all contacts in power distribution, switching and control equipment components to Cd-free materials ahead of the regulation.

3.2 Changeover to Cd-free contacts in low-voltage circuit breakers

Contacts are the heart of power distribution, switching and control equipment components and they are required to have a "stable open/release mechanism" and "stable low contact resistance" as shown in Fig. 2. In order to provide these characteristics, we need to optimize the product structure, its electrical and mechanical characteristics and mass productivity (ease of assembly, cost). For contacts, however, one characteristic is often improved at the sacrifice of the others. It is important to attain a proper balance of characteristics.

Some of the Cd-free contacts applicable to low-voltage circuit breakers are silver tin oxide ($AgSnO_2$) contacts and silver tungsten carbide/silver tungsten carbide carbon (AgWC/AgWCC) contacts (see Table 1).

We conducted a product evaluation for these two types of Cd-free contacts. As a result, we confirmed that $AgSnO_2$ contacts showed no problem in wear resistance and welding resistance and that they were applicable to products with a low-to-middle breaking

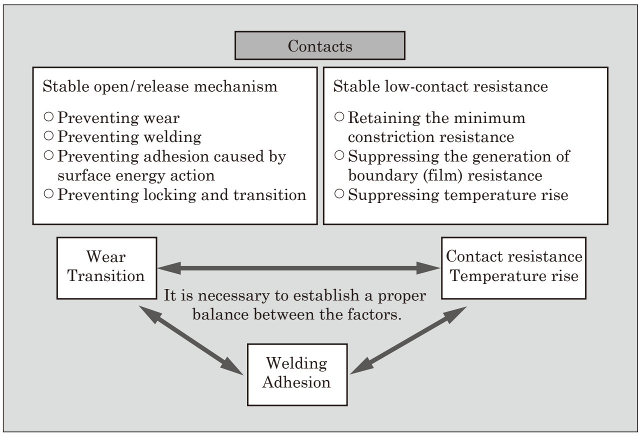


Fig.2 Basic characteristics of contacts

Table 1 Cd contact and Cd-free contact for low-voltage circuit breakers

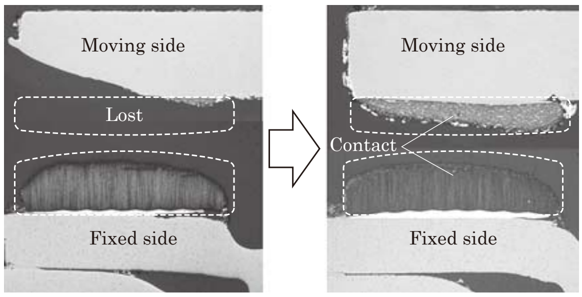
Contact material	Characteristic	Performance*			Applicable current range
		Wear resistance	Welding resistance	Contact resistance	
AgCdO	Cd contacts have been used for over 40 years. Their performance has been greatly improved by internal oxidation and other methods. The sublimation of CdO provides advantageous temperature characteristics.	○	○	○	Small to medium current
$AgSnO_2$ +α	This is the prime candidate for replacing Cd contacts. Their performance has been greatly improved with In and other additives.	◎	○	△	
AgWC/ AgWCC	A large amount of W, which has a high melting point, has been added to improve the arc resistance. Moreover, the transformation into WC suppresses the oxidation of W. The combination with Ag-WC-C used for a fixed contact improves contact resistance. The problem is that Ag-WC-C contacts wear quickly.	△	◎	○	Medium to large current

*Performance ◎: excellent, ○: favorable, △: somewhat inferior capacity. As for AgWC contacts, those having the same composition as the contacts already used in the products with a large current rating could not satisfy the wear resistance and other specifications.

Hence we tried to improve the wear resistance and temperature characteristic by making the constituent particles finer and ensuring a more uniform distribution at a higher density while reducing the thermal load placed on the contact by redesigning the open/release mechanism, for both moving and fixed contacts.

Figure 3 shows photographs of the cross-section surfaces of the contacts before and after the composition improvement taken after a interruption test finished. Before the improvement, the fixed contact was lost, whereas after the improvement, the contact remained. Moreover, we parameterized the thicknesses of the moving and fixed contacts respectively and investigated their relationship with the wear after an interruption test to optimize their volume.

Figure 4 shows the resultant relationship between the arc energy at breaking and the volume wear ratio of the moving contact for samples of AgCdO and AgWC/AgWCC contacts.



(a) Before improvement (b) After improvement

Fig.3 Photographs of the cross-sectional surfaces of contacts after an interruption test

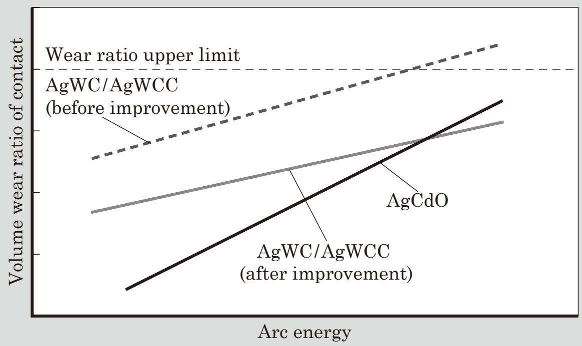


Fig.4 Arc energy vs. volume wear ratio of moving contacts at breaking

The AgCdO contact showed the least wear and the AgWC/AgWCC contact before improvement was very much inferior to AgCdO contact. The improved AgWC/AgWCC contact, however, showed no difference from the AgCdO contact in the region of high arc energy, proving that there is no problem with its wear resistance.

As for the problems of welding and temperature rise, we could satisfy the product specifications by optimizing the WC and C concentration.

4. Environment Effort for Polymeric Materials

4.1 Changeover to thermoplastic resin for the parts of the "SK Series"

The changes in the plastic materials used for small magnetic contactors are shown in Fig. 5. For the "S Series" released in 1965, thermosetting resin (phenol

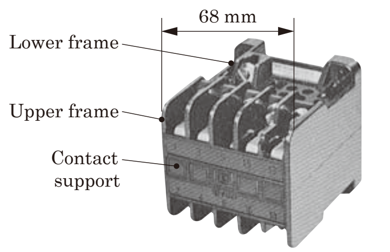
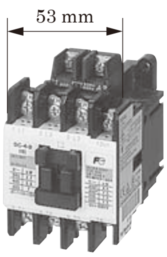
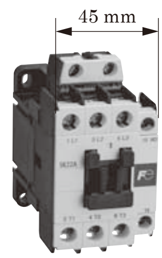
Series	S Series	SC Series	SK Series
Appearance	 68 mm; Lower frame; Upper frame; Contact support	 53 mm	 45 mm
Volume	338 cm^3	343 cm^3	292 cm^3
Lower frame	Thermosetting resin	Thermoplastic resin	Thermoplastic resin (Engineering plastic)
Upper frame	Thermosetting resin	Thermosetting resin	Thermoplastic resin (Engineering plastic)
Contact support	Thermosetting resin	Thermosetting resin	Thermoplastic resin (Super-engineering plastic)
Sales period	1965 to 1988	1988 to present	2011 to present

Fig.5 Changes in the plastic materials used for small magnetic contactors

Table 2 Characteristic comparison among plastic materials

Plastic material	Strength	Thermal resistance (melting point)	Recycling
Thermosetting resin	Medium	No effect	Not possible
Thermoplastic resin (Engineering plastic)	High	200°C to 270°C	Possible
Thermoplastic resin (Super-engineering plastic)	High	290°C to 350°C	Possible

resin) was used for the lower frame, upper frame and contact support parts. For the "SC Series" released in 1988, we promoted the use of thermoplastic resin, which allowed thin-wall molding, for the lower frame, in order to achieve the productivity improvement (recycling) and downsizing of the parts.

For the "SK Series," it was essential to use thermoplastic resin also for the upper frame having current-holding function and the contact support in order to meet the market demand of further downsizing. To use thermoplastic resin for the parts, we needed to improve its heat-resistant characteristics (ability to retain shape, wear resistance) against the heat and arc generated when an overload current flows.

We reduced the heat generated by a current flow in the "SK Series" by increasing the conductivity and cross-sectional area of the contact base that is a current-carrying part. Furthermore, we satisfied the heat-resistant characteristic of the contact support, which is a current-holding part, by applying thermoplastic resin with a high melting point that does not cause melting or deformation but provides good wear resistance. We also achieved downsizing, 15% reduction in volume compared to the "SC Series." The thermoplastic resins we used are engineering plastics and super-engineering plastics (aromatic nylon, cross-linked nylon). Their characteristics are shown in Table 2.

4.2 Suppressing the waste of insulation shaft "MULTI. VCB"

The "MULTI.VCB" is a middle-voltage circuit breaker designed to improve stability and reliability in a power supply. Its parts are required to have stable strength and voltage resistant capability.

The insulation shaft of the MULTI.VCB (see Fig. 6), in particular, is required to function as mechanical parts that open/close the contact inside a three-phase vacuum valve and ensure insulation among the phases. To satisfy these requirements, the parts are manufactured in a production process where a metal shaft is inserted into thermosetting resin BMC (bulk molding compound material using polyester premix) before compression molding. Although BMC is a material with excellent electrical characteristics, heat resistance, dimensional stability and mechanical characteristics, this material is difficult to recycle, so defective parts are discarded as industrial waste. To solve the problem, we studied a way to reduce the number of defective parts and thus suppress wastes generation.

In the stage of prototyping the insulation shaft in the development of the MULTI.VCB, defects (voids, cracks) were found inside the molded parts, resulting in a pressure resistance failure rate of 40%. We conducted factor analysis on the parts shape, mold structure and molding conditions and implemented improvements shown in Table 3.

As for the fluidity of the material, we optimized the parts shape in ways such as changing the thickness and corner roundness to prevent the formation of a weld line (a line which is formed when resin flows meet) that often causes internal defects in the section where withstand voltage is required.

The insulation shaft mold has three separate phases of insulating parts as shown in Fig. 6. Consequently, appropriate amount of BMC is measured for each phase, placed in the respective mold and molded with compressed pressure and heat. The pres-

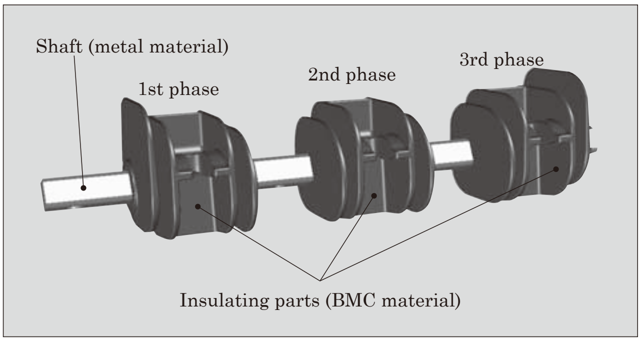


Fig.6 Molded parts on the insulation shaft of "MULTI.VCB"

Table 3 Cause of pressure-resistance failure (internal defects) and countermeasure

Cause	Countermeasure (improving factor)
Fluidity of the material	Shape optimization in the fluidity study (components shape)
Change in the internal pressure due to separate structure	Change of the mold pressurizing method (mold structure)
	Monitoring the mold internal pressure (molding condition)

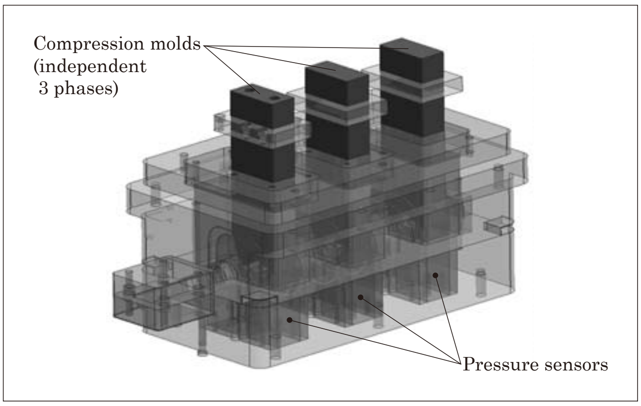


Fig.7 Insulation shaft mold structure

issue: Electric Distribution, Switching and Control Devices

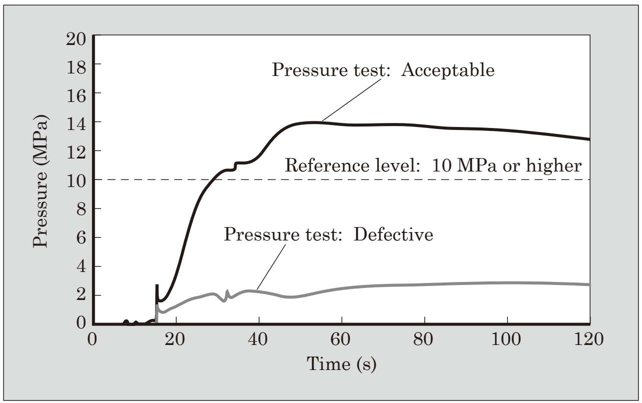


Fig.8 Mold internal pressure

sure applied to each phase varies greatly due to the difference in the amount of material, resulting in defects. Therefore, we adopted a mold structure that enabled independent pressurization of the three phases (see Fig. 7) to stabilize the pressure.

In addition, we embedded pressure sensors in the mold to visualize the internal pressure as shown in Fig. 8 to optimize the molding conditions and set production control values at the production site. In this way, we could reduce the number of defects inside the molded parts.

With these measures, we could completely eliminate the pressure resistance failure rate, which had been 40% in the prototyping stage, by the time of mass production and release and thus have reduced waste and environmental impact.

5. Postscript

The polymeric materials and metal materials used for power distribution, switching and control equipment components are constantly required to provide both environmental resistance and functionality. Consequently, the requirements for material development are anticipated to become more difficult and strict. Fuji Electric will continuously contribute to the realization of a society in which people can live without worry by actively promoting the development of environment-friendly materials and applying them to our products ahead of global laws and regulations.

References

(1) Shiozaki, K. Environmentally Responsive Technology for New Global MCCB and ELCB. FUJI ELECTRIC REVIEW. 2006, vol.52, no.4, p.124-129.

Arc Simulation Technology

SAKATA, Masayoshi* ENAMI, Yoshiaki ‡

ABSTRACT

With distribution, switching and control equipment components, finding a way to predict and control the behavior of the arc generated by contact switching is an important technological challenge. Fuji Electric has developed arc simulation technology that couples thermal fluid analysis with electromagnetic field analysis for further miniaturization of components, improvement of performance and accommodation of direct current devices. The arc simulation technology makes it possible to use structure of an actual device to visualize its behavior or arc for quantitative evaluation of gas flow and electromagnetic force.

1. Introduction

For power distribution, switching and control equipment components, predicting and controlling arc behavior generated by switching contacts is an important technological concern. Fuji Electric has been committed to the improvement of interruption characteristics by making effective use of numerical analysis technologies, such as current limiting interruption simulation technology combining electromagnetic field analysis and circuit analysis, gas flow analysis technology for molded-case circuit-breakers based on thermo-fluid analysis, and prediction of arc behavior by electromagnetic field analysis[1].

Interruption by an electric distribution device is a phenomenon that continues for only several milliseconds, and the current and the voltage waveforms are the only information obtained through measurement. Although pressure and temperature can be observed by making a special test sample and even arc behavior can be measured through a high-speed camera by setting a window in the interruption section, it is difficult to measure them with the product in its original shape. Arc behavior depends on the pressure or gas flow at the time of arc generation or on the Lorentz force produced in the arc. These factors are governed by the structure or material of the case, the material or switching speed of the contact, or the grid structure. To conduct a more in-depth study at the stage of development, Fuji Electric endeavored to develop simulation technology capable of quantitatively evaluating all of these factors and visually reproducing arc behavior.

This paper outlines the effort in the arc simulation technology combining thermo-fluid analysis and electromagnetic field analysis and its application to products.

2. Arc Simulation Method

2.1 Calculation method

An arc is the phenomenon in which a gas as hot as several thousand to several tens of thousands of degrees is ionized and becomes conductive; the temperature rises as a result of self-heating induced by the current, and a charged state is consequently maintained.

To accurately reproduce this phenomenon, arcs must be handled at the level of electrically charged particles, such as electrons and ions. In the simulation presented herein, the arc phenomenon is calculated using the physical properties of a plasma-state gas and a general-purpose thermo-fluid analysis program (STAR-CCM+*1). However, the force working on the plasma-state gas consists of electromagnetic force induced by flowing current in addition to the pressure and heat generation that can be calculated by thermo-fluid analysis.

Thus, Fuji Electric created a program designed to calculate the magnetic field from the current density based on the Biot-Savart law, and reproduced arc behavior by applying Lorentz force induced by the interaction between the current and the magnetic field etc. to the fluid element (see Fig. 1).

The equation for calculating the magnetic field based on the Biot-Savart law is shown below.

* Technology & Manufacturing Group, Fuji Electric FA Components & Systems Co., Ltd.
‡ Corporate R&D Headquarters, Fuji Electric Co., Ltd.

*1: STAR-CCM+: Trademark or registered trademark of CD-adapco.

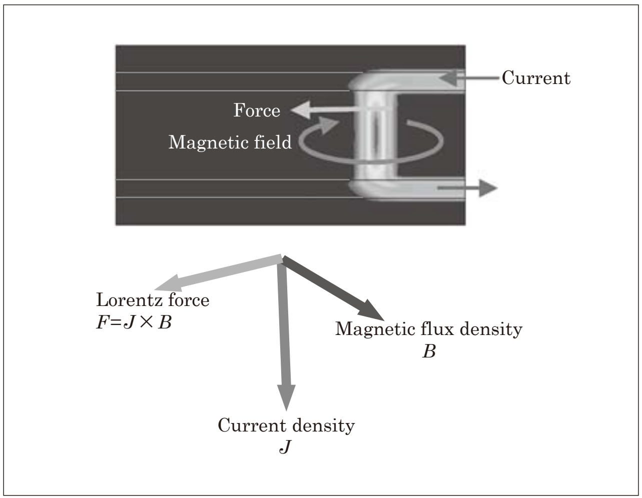


Fig.1 Calculation of Lorentz force

$$B(r)=\frac{\mu_0}{4\pi}\int_{r'\neq r}\frac{J(r')(r-r')}{|r-r'|^3}dV' \quad\text{......} (1)$$

B : Magnetic flux density vector
J : Current density vector
r : Position vector
V : Cell volume
μ_0 : Magnetic permeability of vacuum

If Equation (1) is applied as it is, calculation time will increase in proportion to the square of the number of cells. For this reason, the calculation is sped up by excluding minute current cells from the integration range.

When handling the arc behavior of electric distribution devices, metallic vapor produced by contacts or grids, ablation gas generated by resin, and the effects of external magnetic fields induced by grids and magnets, must be taken into account in addition to the voltage drop characteristic in the sheath region close to the electrode.

2.2 Arc root model

In the portion where the arc comes into contact with the electrode (arc root), temperature and electric potential significantly vary, and complicated phenomena, such as electron discharge and absorption, occur. This portion is consequently brought into the non-equilibrium state (see Fig. 2), in which the local thermal equilibrium (LTE) assumption of the electrons and plasma temperatures being equal is not satisfied.

There is a method of describing the arc root as a non-equilibrium model taking into account the temperature of electrons, but we adopted a model designed to reduce the calculation workload(2). With the voltage drop of the arc root defined as a function of the current density J, the electric conductivity of the arc root of thickness δ is derived, as shown in Equation (2).

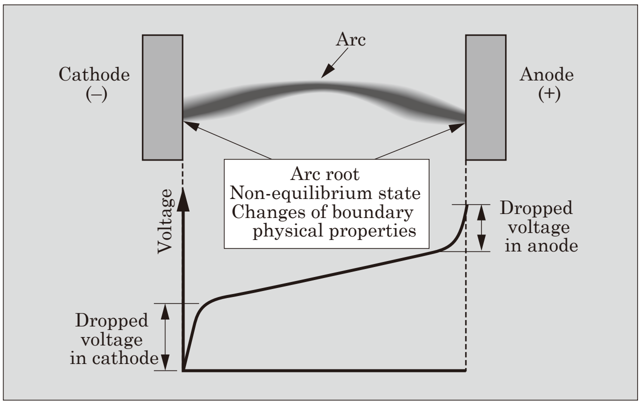


Fig.2 Voltage drop of arc root

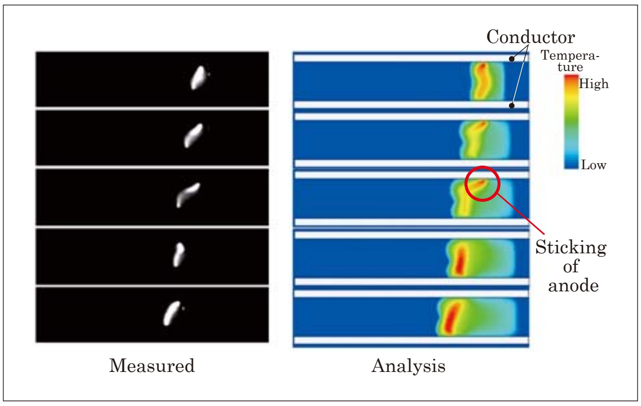


Fig.3 Inchworm movement of arc on parallel conductors

$$\sigma=\frac{\delta J}{E} \quad\text{......} (2)$$

σ : Conductivity of arc root (S/m)
δ : Thickness of arc root (m)
J : Current density vector (A/m^2)
E : Dropped voltage (V)

A layer of mesh of thickness δ was placed on the surfaces of the electrodes and the grid. We caused a voltage drop of the electrodes and sticking of the anode by changing the characteristics of the cathode and anode sides of this arc model and successfully reproduced a phenomenon called inchworm moving (see Fig. 3).

2.3 External magnetic field (permanent magnet and magnetic body) model

Magnetic bodies such as permanent magnets and, grids generate external magnetic fields, and it is necessary to analyze these effects.

The magnetic field produced by the permanent magnet is calculated as an initial condition using the magnetic field calculation function of STAR-CCM+ in advance, and the external magnetic field is calculated by superimposing the magnetic field induced by the free current, which is obtained using Equation (1) over this magnetic field. Figure 4 shows the traveling state of the arc when permanent magnets are placed at a middle point on parallel conductors. It was verified

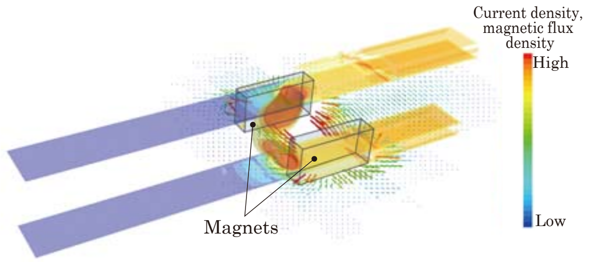


Fig.4 State of arc traveling when permanent magnets are placed

that the arc traveled at a speed equivalent to the measured actual speed by the effect of the magnetic field generated by the magnets.

In the case of grids and other magnetic bodies, magnetic field distribution, including magnetic bodies, must be calculated because they affect the magnetic field distribution and determine the driving force of the arc itself. As this calculation method, a method combining magnetic field analysis using the finite element method and the magnetic moment method are available, but we selected the surface current method[5] for its short calculation time (see Fig. 5).

The surface current method reproduces changes of the magnetic flux density due to a magnetic body by applying a virtual current (magnetizing current) to the surface of the magnetic body. A kind of boundary element method, this surface current method is linear analysis and cannot deal with the non-linear B-H characteristic or magnetic saturation but takes less time to calculate because it can reuse an LU-decomposed coefficient matrix. Thus, with this method, the magnetic flux density can be calculated using Equation (1), which is not generally available for magnetic bodies.

Figure 6 shows a comparison of magnetic field distribution induced by the current flowing near a grid between the finite element method and the surface current method. We obtained results from the surface current method that were equivalent to those produced by the finite element method with the aid of an elaborated element breakdown method and calculation algorithm.

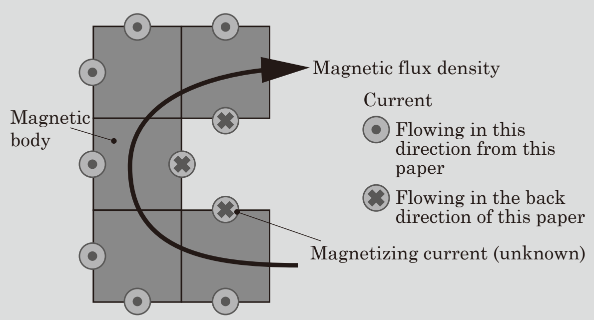


Fig.5 Surface current method model

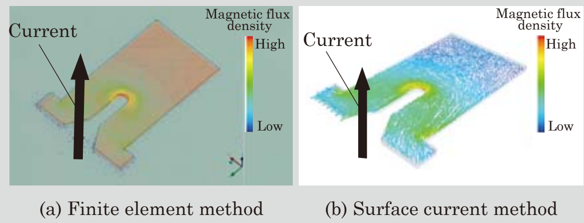


Fig.6 Magnetic field analysis results of grid

2.4 Evaporative gas (ablation gas) generation model

One of the factors that greatly affect arc behavior is evaporative gas generated from contacts or the inside of the case.

As evaporative gas generation models, we simulated evaporation proportional to arc power and arc current and evaporation based on the panel heat transfer coefficient h_{arc}[3] of the arc, and verified that the evaporation model based on h_{arc} ensured relatively high calculation accuracy[4].

The evaporation model based on harc is set to generate evaporative gas (or pyrolysis gas in the case of resin) when the panel temperature T exceeds boiling point Tkof the adjacent solid substance in the fluid cell of the first layer of the wall surface. The evaporation rate m_k can be obtained from Equation (3).

$$m_k = \frac{h_{arc}(T - T_k)}{Q_k L} \quad \cdots\cdots (3)$$

m_k : Evaporation rate (kg/m^{3}s)
h_{arc} : Wall surface heat transfer coefficient of arc (W/m^{2}K)
Q_k : Sum of melting heat and evaporation heat (J/kg)
T : Wall surface temperature (K)
T_k : Boiling point of solid matter (K)
k : Type of solid substance
L : Thickness of wall surface layer (m)

The optimum value of harc was calculated based on various basic experiments, such as electrodes butting (see Fig. 7).

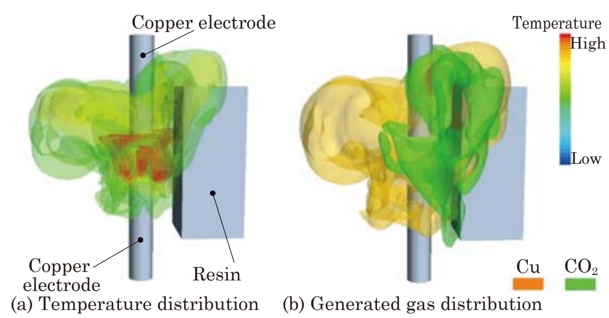


Fig.7 Example of arc simulation by electrodes butting

Evaporative gas will condense and returns to the liquid or solid state again if its temperature drops below the boiling point. When T was lower than the boiling point T_k of each material, the condensation rate was calculated using Equation (4) and set as the source term of the fluid cell.

$$n_k = Y_k R_c (T - T_k) \cdots\cdots (4)$$

n_k: Condensation rate (kg/m^{3}s)
Y_k: Mass fraction
R_c: Condensation rate coefficient (kg/m^{3}sK)
T: Wall surface temperature (K)
T_k: Boiling point of solid matter (K)
k: Type of solid substance

In addition, the solid substance will absorb energy from the surroundings when it evaporates and reaches the temperature of the fluid cell, and will discharge the energy to the surroundings when it condenses. This relation was calculated using Equation (5) and set to the fluid cell.

$$S = -\sum_k (m_k + n_k) Q_k \cdots\cdots (5)$$

S: Energy source term (W/m^3)
m_k: Evaporation rate (kg/m^{3}s)
n_k: Condensation rate (kg/m^{3}s)
Q_k: Sum of evaporation heat and melting heat (J/kg)
k: Type of solid substance

Simulations of arc behavior entail technical issues in addition to the above-mentioned concerns, such as physical property values and radiation models in the plasma (hot) state, the displacement of the mesh when moving the electrodes, and mesh subdivision. Arc simulations can be achieved by resolving these issues.

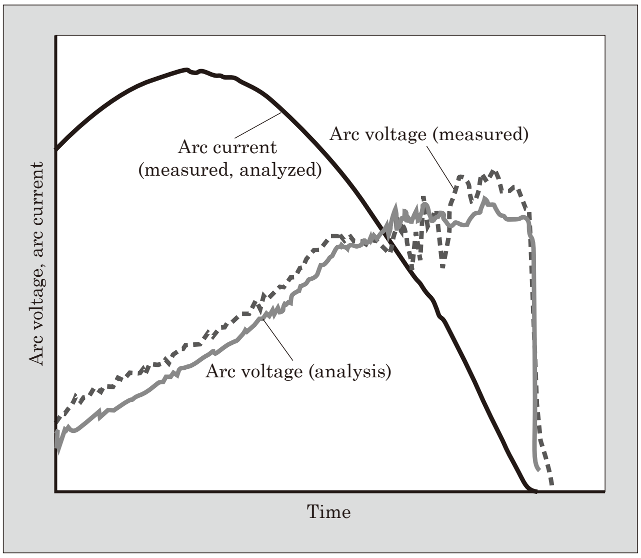


Fig.9 Arc current and arc voltage at the time of interruption

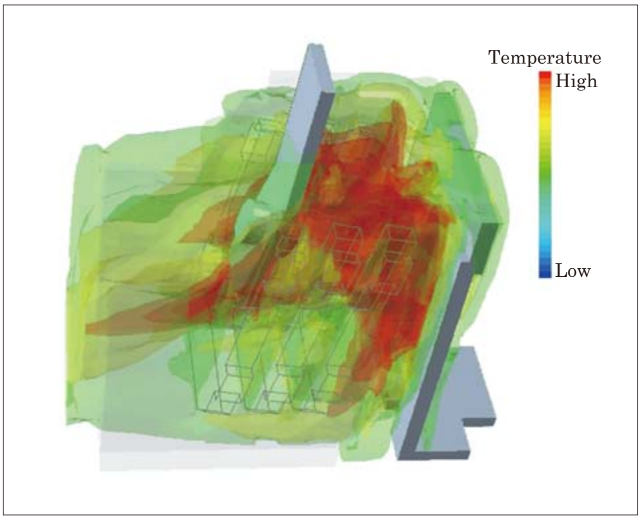


Fig.10 Arc simulation results of circuit protector

3. Application Examples of Arc Simulations

3.1 Arc simulation of circuit protector

A circuit protector is a circuit breaker combining an overcurrent protection function for protecting the circuits within equipment and a switch function for the equipment. It is compact in size but has a large breaking capacity of 2.5 kA (240 V AC). We performed an arc simulation to study whether a large-capacity interruption, including a grid, could be reproduced.

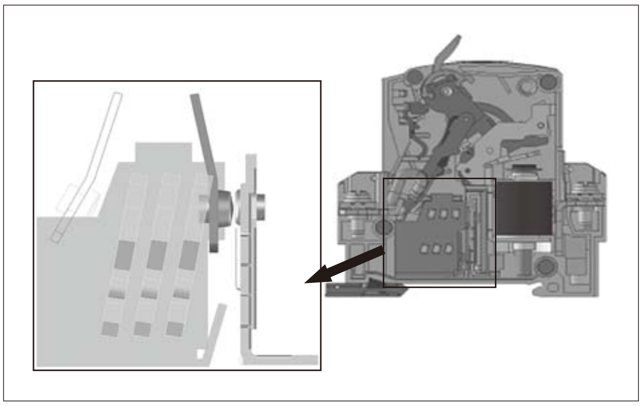


Fig.8 Structure of circuit protector

Figure 8 shows the structure of the circuit protector we adopted. We modeled the portion of the arc control device shown in the frame, and performed an arc simulation with an actually measured AC current as input. Figure 9 shows the arc current and the arc voltage in an interruption at 2.5 kA. The figure demonstrates good agreement between the calculated result of the arc voltage and the measured value. The state of the arc at the time of the interruption is shown in Fig. 10.

Arc simulations enable us to calculate temperature distribution, current density, gas flow rate, pressure, gas components, etc. in time sequence. Exhaust area, grid shape, arrangement, case rigidity, and other factors for the design of the arc control device can be studied based on the calculation results.

3.2 Arc simulation in DC interruption by molded-case circuit-breaker

A molded-case circuit-breaker protects a device connected to a distribution system from overcurrent. Recently, higher levels of DC current interruption have been required as DC transmission/distribution for photovoltaic power generation and data centers are diversifying and they work on higher voltages. This section describes an example of DC current interruption we studied.

Figure 11 shows an arc simulation model for molded-case circuit-breakers. In this simulation, the calculation was performed by inputting a definite DC voltage based on the test circuit.

Figure 12 shows a comparison between the measured and analyzed values of arc current and arc voltage when a DC current of 820 A was interrupted. Although the timing of arc commutation is slightly earlier, the analyzed values of both the current and the voltage are in good agreement with the measured values. The arc commutates from the moving contact to the arc runner and then moves to the grid. In response to it, the phenomenon of a temporary rise and subsequent drop of the arc voltage is observed with both the measured value and the simulation.

The simulation results of the arc current density and the generated gas components at the time of the arc voltage drop are shown in Fig. 13. The arc current density indicates that the arc voltage decreased as a consequence of restriking the arc on the contact side after it reached the grid. Another finding is that the metallic vapor of copper with high conductivity commutated from the generated gas components to the contacts and the potential between the contacts consequently decreased, resulting in restriking of the arc.

As stated above, performing a simulation enables us to visually and quantitatively identify what phenomenon is manifested inside equipment. Simulations are effective in planning measures.

The arc produces high driving force at a large current because of the gas flow or Lorentz force but is low in driving force and may fail to move to the grid at a small current. As a solution to this problem, a magnetic body or permanent magnet is placed to promptly drive the arc. To verify the effect of a permanent magnet, we compared the results of arc simulations with and without a permanent magnet.

Figure 14 shows simulation results when 100 A was interrupted. It was verified that the driving of the arc stopped before the grid when permanent magnet

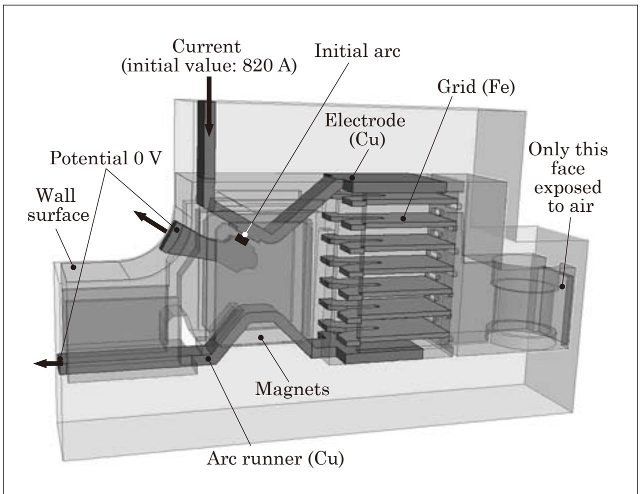


Fig.11 Arc analysis model for molded-case circuit-breakers

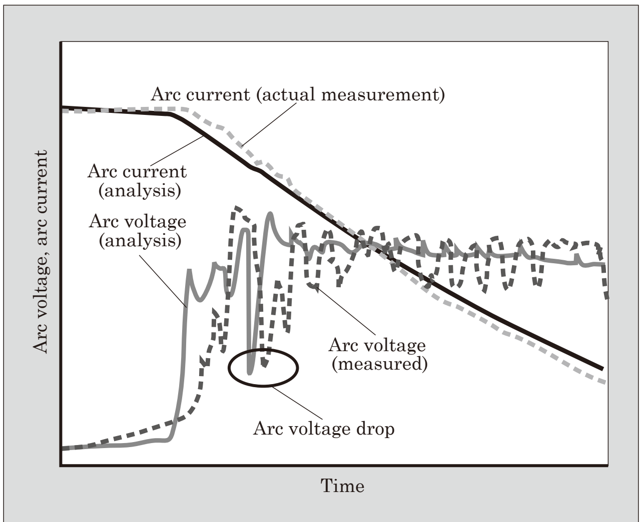


Fig.12 Arc current and arc voltage at the time of interruption of 820 A

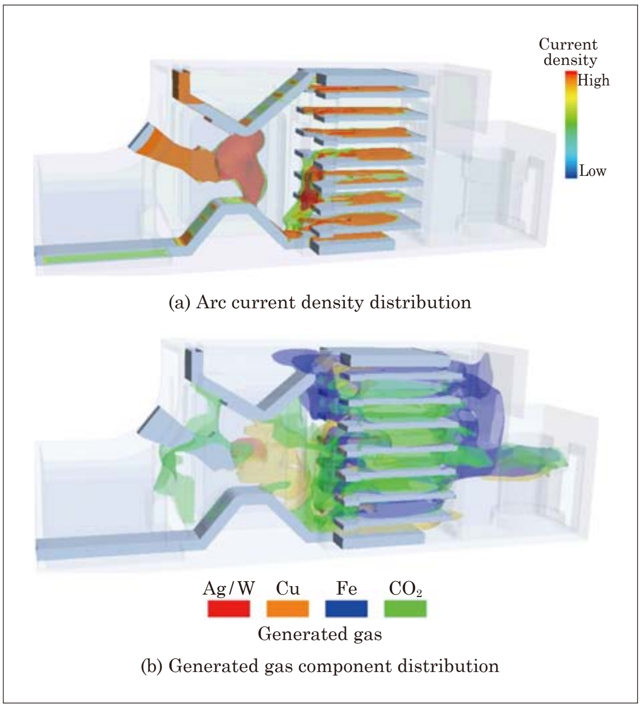


Fig.13 Simulation results of arc current density and generated gas components

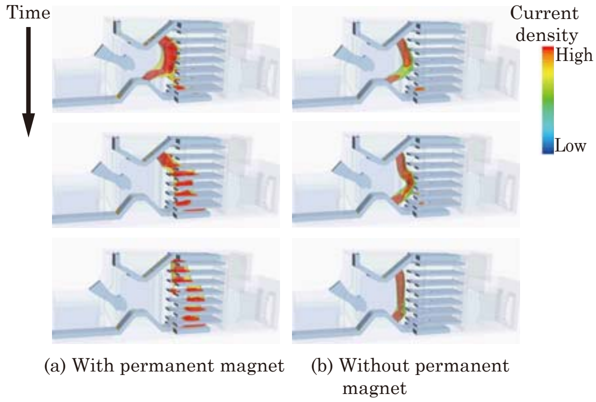


Fig.14 Simulation results at the time of interruption of 100 A

was not used, and a similar result was also obtained in an actual test.

4. Postscript

In this paper, we described simulation technology combining thermo-fluid analysis and electromagnetic field analysis for predicting and evaluating arc behavior. This technology made it possible to visualize arc behavior, which had not been visible, and quantitatively identify whether the behavior is induced by electromagnetic force or by a gas flow. In addition, with this technology we can arbitrarily set parameters to study, thus verify structures of unprecedented concepts without making prototypes. We are determined to further improve analysis accuracy and develop products of high performance and high quality through the application of this technology.

We would like to express our heartfelt thanks to Professor Yasunori Tanaka at Kanazawa University for the provision of various physical properties and advice to our analyses.

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Manufacturing to Meet Diversifying Needs

OGAWA, Taku*

ABSTRACT

The market environment of distribution, switching and control equipment components is rapidly changing due to globalization and widespread direct current power supply systems, and the market's needs are becoming increasingly diversified. In order to supply products with a guaranteed quality and delivery time that are better than before, it is necessary to construct a global supply chain system and develop new production technologies in manufacturing. As part of the construction of a global supply chain system, Fuji Electric is working to have local production for local consumption, establish an integrated system and adapt production lines to handle high-mix low-volume production. We are also developing new production technologies including parts supply technology, joining technology and robot utilization technology.

1. Introduction

Fuji Electric has provided markets in the world with receiving and distribution, switching and control equipment components over the last 70 years. In 2014, cumulative production of magnetic starters that are our flagship products has reached 300 million units. One mission in the field of manufacturing is to stably deliver products to customers at the required quality and delivery times, and our success in establishing trusting relationships with customers while fulfilling this mission is what has enabled us to continue manufacturing up to this day.

Meanwhile, the market environment surrounding Fuji Electric's products is undergoing rapid changes due to globalization and widespread of DC power supply, which has caused a diversification of needs. It is necessary to supply products with better quality and shorter delivery time than ever while meeting these needs.

This paper describes a production system that realizes high-mix, low-volume production and new production technologies for supplying diversifying products at shorter delivery times.

2. Characteristics of Manufacturing of Receiving and Distribution, Switching and Control Equipment Components

Fuji Electric's wide variety of receiving and distribution, switching and control equipment components including magnetic starters, low-voltage circuit breakers, middle-voltage distribution and pushbuttons (see Fig. 1) have the following characteristics from the perspective of manufacturing.

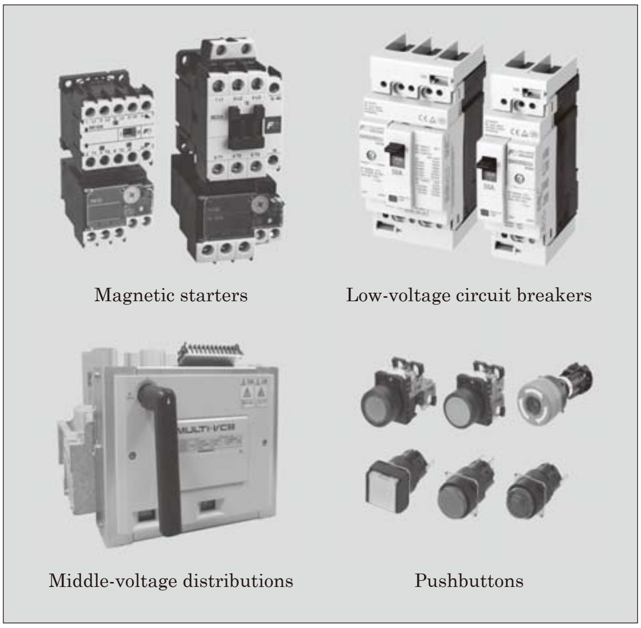

Fig.1 Typical receiving and distribution, switching and control equipment components

(1) Parts count and production volume

Parts count and production volume per lot vary greatly depending on the product. Parts counts vary widely from around 10 to tens of thousands. While some products have an annual production volume of only a few units, others are produced in a few million units a year.

(2) Types

Products may require a large number of types depending on the application. For example, there are needs to supply magnetic starters with various specifications suited for different applications including for rated current, overcurrent protection, operating volt-

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age, installation method and additional functions. In some products, 1 production line is used for manufacturing more than 10,000 types.

In order to meet diverse needs of customers, we have built production lines optimized for efficiently manufacturing a variety of products while ensuring stable quality and delivery times. We made efforts in these lines to pursue efficiency in mass production while not affecting the efficiency of small-lot production, so that they can accommodate high-volume as well as small-lot production.

3. Changes and Challenges of Environment Surrounding Manufacturing

Fuji Electric is proactively rolling out products to new markets with the focus on the following points.

(a) Global market centered around Asia
(b) Renewable energy market

We have long worked on overseas business expansion based on products intended for the Japanese market. In order to roll out business more deeply rooted in the respective regions, it is necessary to precisely meet different standards as well as functional and quality requirements in different regions, and launch specialized products intended for the individual markets. To that end, we launched products specialized for the Chinese market in 2010 and intend to roll them out in the same way in the Southeast Asian and other markets in the future.

For the renewable energy market, which has been significantly growing in recent years, we are working on rolling out new products using novel technologies including DC current interruption.

The number of product types is increasing along with this market expansion. In order to ensure stable supply in this environment, manufacturing is faced with the need for innovation that is not simply an extension of the conventional way of doing things.

4. Construction of Global Supply Chain System

The ideal way to promptly supply products to a market is to implement an integrated system including procurement of parts, product assembly and shipment in a factory closest to the market. We are taking various approaches to achieve this ideal goal.

4.1 Local production for local consumption

In order to supply products to a market faster and more flexibly, we have made it a principle to manufacture at a production site close to the market. For the thermal relay “TK13 Series” and “TK26 Series” released in FY2012, we built lines in both the Fukiage Factory in Japan and Fuji Electric (Changshu) in China in time with the release and successfully reduced the lead time in overseas markets from about 1 month to 1 week. While the percentage of export articles of the conventional products was 60%, the “TK13 Series” and “TK26 Series” have achieved a low percentage of 36% (see Fig. 2).

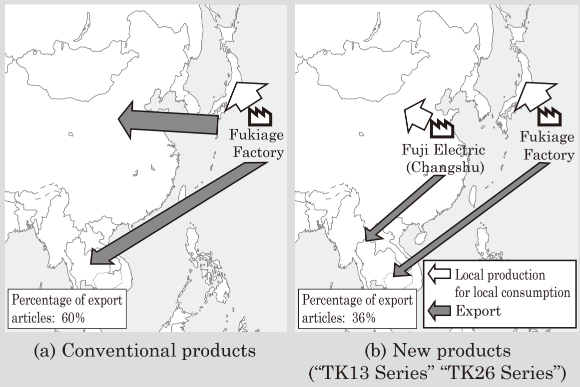

Fig.2 Local production for local consumption in thermal relays

4.2 Establishing an integrated system

Our production sites for receiving and distribution, switching and control equipment components include 3 domestic and 2 overseas sites: the Otawara Factory, Fukiage Factory and Chichibu Fuji in Japan and Fuji Electric (Changshu) and Fuji Electric Dalian in China. We have recently been taking various measures for building an integrated system to cover parts processing, assembly and shipment in each factory. In the Otawara Factory, the respective tasks for low-voltage receiving and distribution equipment, which were distributed across the factory, were consolidated into the new building in FY2013 (see Fig. 3). By directly connecting the warehouse and assembly line to link the inventory information to the production plan, we realized a pull production system to achieve a significant reduction in the lead time. In the Fukiage Factory, we consolidated the middle-voltage receiving and distribution equipment line, which was distributed across the factory, to build an integrated production line in FY2013. At Chichibu Fuji, we plan to consolidate in FY2014 the production lines distributed among 3 facto-

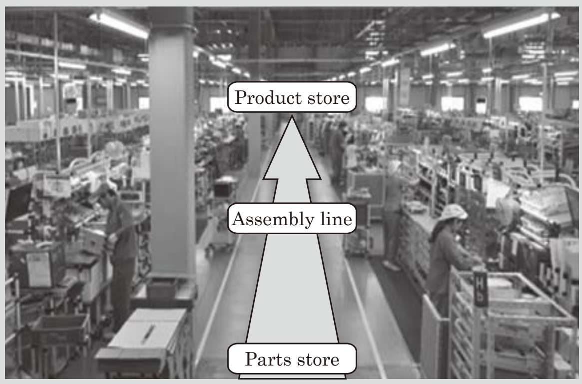

Fig.3 New production line in Otawara Factory

Fig.4 Low-voltage receiving and distribution equipment production line in Otawara Factory

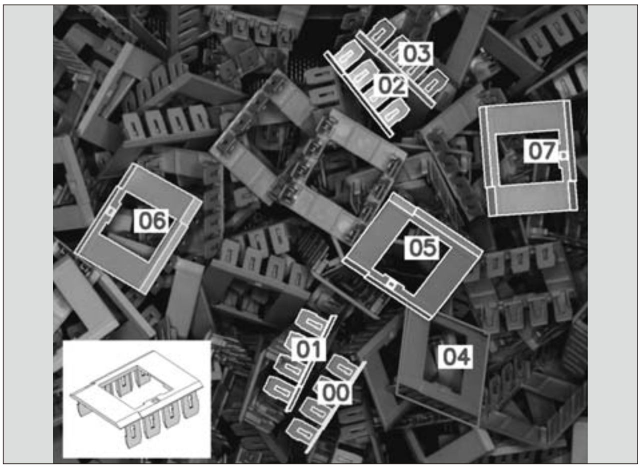

Fig.5 Recognition of parts location and orientation using image processing

ries into 2 factories for magnetic contactors and control equipment to cover parts processing, product assembly and shipment in the same factory.

Along with these approaches, we are working on in-house production to realize parts processing on the same site as the assembly line in order to minimize the time lost in supplying parts due to transportation between sites. At Fuji Electric (Changshu) and Fuji Electric Dalian, the 2 overseas sites, we are striving to localize parts, which were supplied by factories in Japan, and build a system capable of self-contained production.

4.3 Adapting production lines to handle high-mix, low-volume production

The magnetic starter assembly line and plating factory in the Fukiage Factory are fully automatic production lines capable of high-mix, low-volume production. A system has been built to cover the entire scope from receipt of orders through production to shipment, and mixed production of various product types is carried out. Products are shipped within 24 hours of receiving orders regardless of the type. The production line for low-voltage receiving and distribution equipment at the Otawara Factory (see Fig. 4) is a developed form of the line in the Fukiage Factory and is used for more complex high-mix, low-volume automatic production.

5. Development of New Production Technologies

In order to readily meet customer needs, it is necessary to construct an efficient high-mix, low-volume production line capable of flexibly accommodating quantitative variations and instantly switching between different types.

5.1 Parts supply technology

A production line capable of switching between different types per unit without affecting the productivity needs to be able to feed in parts per unit. Conventionally, feeding in parts by pallets or by dedicated equipment for aligning parts (parts feeders) was common. Since each set of equipment corresponds to 1 product type, a type changeover required the line to be stopped for a certain period to change the setup. To address this issue, we have developed a technology that uses 2D or 3D image processing to recognize each part and allow a type changeover without a tooling change (see Fig. 5). This technology makes it possible to feed multiple types of parts using 1 device simply by changing the recognition conditions.

5.2 Joining technology

Receiving and distribution, switching and control equipment components use combinations of various types of conductive materials for welding current paths and separate conductive parts are often joined together in the assembly process. Spot welding, a major method of joining, requires a change of electrodes for welding according to the material and shape to deal with different product types. To improve this situation, we are working on the application of laser welding, which does not require electrodes and is capable of non-contact joining (see Fig. 6). Conventionally, this welding method was only applied to joining iron parts, which are relatively easy to join. We have recently established a joining technology that can handle various special materials including copper alloys, and expanded the scope of its application to magnetic starters and circuit breakers. This has allowed high-mix, low-volume production in parts processing lines.

5.3 Robot utilization technology

Fuji Electric has long been using robots for automatic production. Robots are very effective for repetitive tasks composed of predefined operations but have drawbacks such as requiring a large amount of time and dedicated engineers for transport and adjustment and lacking flexibility. For that reason, they are generally fixed to 1 process of 1 production line. We have

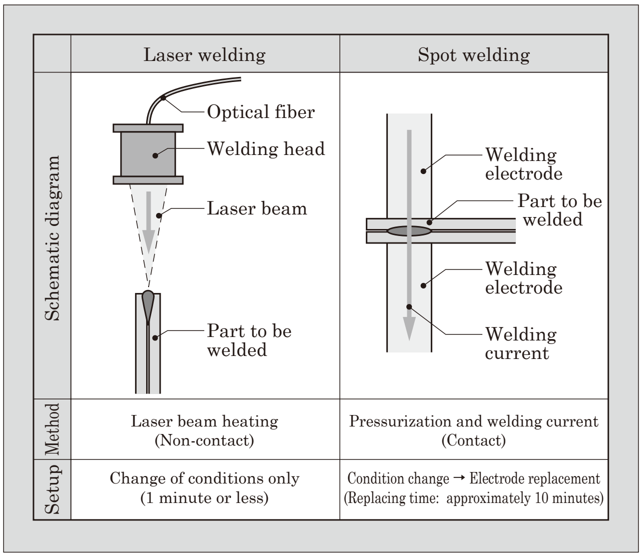

Fig.6 Reduction of setup time by laser welding

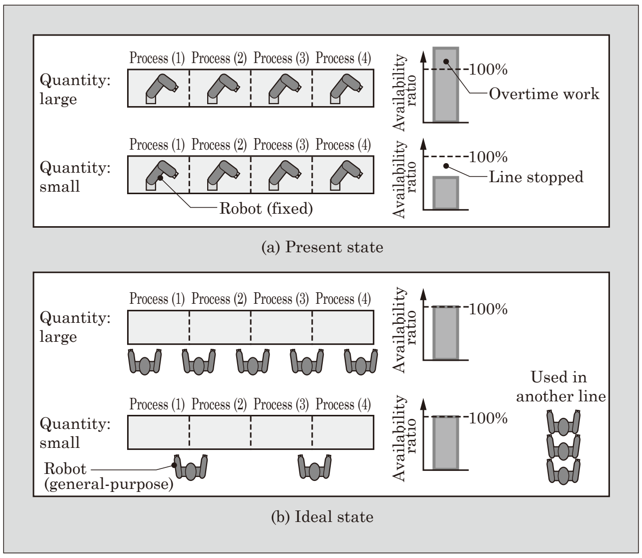

Fig.7 Robot utilization technology in production line for "SK Series"

developed a robot utilization technology that makes it possible to flexibly change tasks within a line or between lines, and applied it to part of the production line for the magnetic starter "SK Series" released in 2014 (see Fig. 7).

5.4 Product design suited for high-mix, low-volume production

To improve the flexibility of production lines, the concept of product design needs to be changed as well as manufacturing technologies.

For thermal relays released in FY2012, we have made significant revisions to the product structure and simplified various adjustment tasks, which were time consuming, to make the production line simpler. This has allowed us to revise the conventional batch production, which is production in groups of a certain number of units, and improve flexibility by realizing 1-piece-at-a-time production.

6. Postscript

This paper describes a production system for realizing high-mix, low-volume production and new production technologies as part of manufacturing that meets diversifying needs.

For the purpose of flexibly meeting the demands of the rapidly changing market while taking advantage of the manufacturing know-how we have developed over our long history, we intend to continue developing technologies and constantly evolving the production lines to work on even more sophisticated manufacturing.

Large-Capacity UPS “7000HX-T4”

TAMAI, Yasuhiro*　IWAMARU, Yosuke*　TAKEUCHI, Masao*

As IT is increasingly developing, the environmental performance and economic efficiency of buildings including data centers have been gaining importance recently in the Asian market. For that reason, there is increasing demand for high efficiency, high reliability and space saving in power supply facilities that are used in buildings. In order to meet these demands, we have developed the large-capacity UPS “7000HX-T4” (400 V system, 500 kVA) with specifications intended for overseas markets (see Fig. 1).

1. Features

(1) High efficiency

The maximum equipment efficiency has been improved by 2 points from the conventional model to achieve the world’s highest class of efficiency at 96.5%. Improving the equipment efficiency not only enables reduction in the amount of power consumed by operating an uninterruptible power supply (UPS) but also reduces the amount of power consumed by air conditioners that are used to cool the UPS along with the decrease in its heat generation.

In addition, duplication and redundancy is provided at data centers for improving the reliability of UPS and the load factor during normal operation is low at 20% to 50%. As described in Section 3, the 7000HX-T4 has successfully improved the equipment efficiency by about 4 points from the conventional model even with a low load factor.

Fig.1 “7000HX-T4” (400 V system, 500 kVA)

* Power Electronics Business Group, Fuji Electric Co., Ltd.

(2) High reliability

Data centers are required to ensure that UPS supply power 24/7 even during maintenance operations or in the unlikely event of a failure. To achieve this functionality, configurations such as parallel redundancy and stand-by redundancy systems have been made available with the 7000HX-T4.

(3) Space saving

Compared with the conventional model, both the installation footprint and mass have been decreased by approximately 30% to realize downsizing and weight reduction. At a data center, saving the space taken up by a UPS leads to an increase in the available space for installing servers and other equipment.

(4) Specifications for overseas markets

The 7000HX-T4 is a product intended for overseas markets mainly in Asia. Its features are as described below.

(a) The main circuit connection is a 3-phase, 4-wire system, which is the most common system outside Japan.

(b) In view of use in countries and regions where the AC input is unstable, unlike Japan, measures have been taken concerning power failure judgment and recovery. A decrease in the input voltage of 35% or more from the rating is judged as a power failure and it switches to storage battery operation, where the storage battery is used to supply power to the load. The system is designed to continue normal operations when the rate of decrease is less than 35%. Before recovering from a power failure, it is essential to make sure that the AC input is stable. For that purpose, we have specified a voltage range of ±15% of the rating for the AC input. A voltage within this range is judged as normal and the system is restored regular operation.

2. Specifications

Figure 2 shows an outline drawing of the 7000HX-T4 (400 V system, 500 kVA) and Table 1 lists the specifications. A 3-level power conversion circuit[*1] of the advanced T-type neutral-point-clamped (AT-NPC) system has been adopted to reduce the converter loss and downsize the filter circuit, thereby realizing compact and highly efficient equipment.

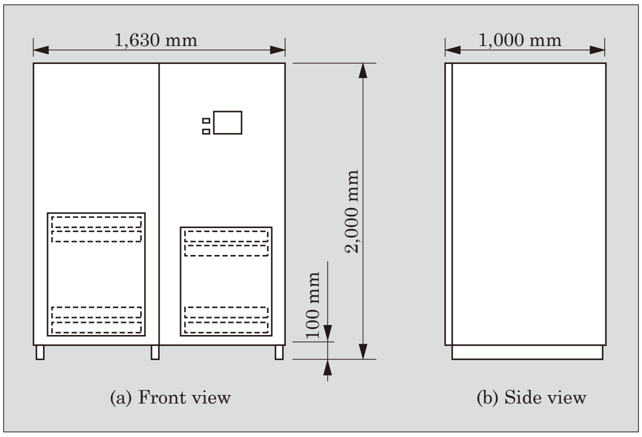

Fig.2 Outline drawing of “7000HX-T4” (400 V system, 500 kVA)

Table 1 Specifications of “7000HX-T4” (400 V system, 500 kVA)

Item		Specifications
UPS system		Normal inverter feeding
Rated output power		500 kVA/450 kW
Dimensions		W1,630×D1,000×H2,000 (mm)
Weight		2,100 kg
Maximum equipment efficiency		96.5%
Switch-over time at power failure		Uninterrupted
AC input	No. of phases	3-phase 4-wire
	Voltage	380/400/415 V ±15%
	Frequency	50/60 Hz ±5%
	Power factor	0.98 or more
	Current harmonic distortion factor	5% or less
By-pass input	No. of phases	3-phase 4-wire
	Voltage	380/400/415 V ±15%
DC input	Nominal voltage	480 to 528 V Equivalent to 240 to 264 cells of lead storage battery
AC output	No. of phases	3-phase 4-wire
	Voltage	380/400/415 V
	Frequency	50/60 Hz
	Load power factor	0.7 (delay) to 1.0
	Voltage tolerance (at stabilized state)	Within ± 1%
	Transient voltage variation	Within ± 3% (load: 0% to 100%)
	Stabilizing time	50 ms or less
	Voltage waveform distortion	2% or less (linear load) 5% or less (rectifier load)
	Frequency precision	0.01% or lower (with internal oscillation)
	Range of external synchronization	Within ± 5%
	Overload capability	125%: 10 minutes 150%: 1 minute

In addition, the system redundancy of the 7000HX-T4 allows parallel operation of up to 8 units.

3. Circuit Configuration and Operation

(1) Main circuit configuration and overview of operation

Figure 3 shows a block diagram of the main circuit. For the main circuit, a double-conversion system composed of a rectifier to convert AC to DC and an inverter to convert DC to AC is adopted. The DC part has a chopper connected in order to control the charge and discharge of the storage battery. The chopper, which converts the DC voltage value, allows a storage battery to be connected that may have widely varying specifications with different voltages from that of the DC part.

During normal operation, in which the AC input is within the normal range, the AC input power is processed in the rectifier and inverter to obtain stable power with a constant voltage and frequency, and the AC power is supplied to the load and the storage battery is charged through the chopper. When a power failure occurs in the AC input, the power in the storage battery is converted through the chopper and inverter into AC output and is supplied to the load. In this process, the chopper maintains a constant output voltage to the DC part even if the output voltage of the storage battery is decreased by discharging, and this allows for a stable power supply.

During parallel operation, the inverter functions to equalize the output currents of both paralleled UPSs. When one UPS is stopped and detached for mainte-

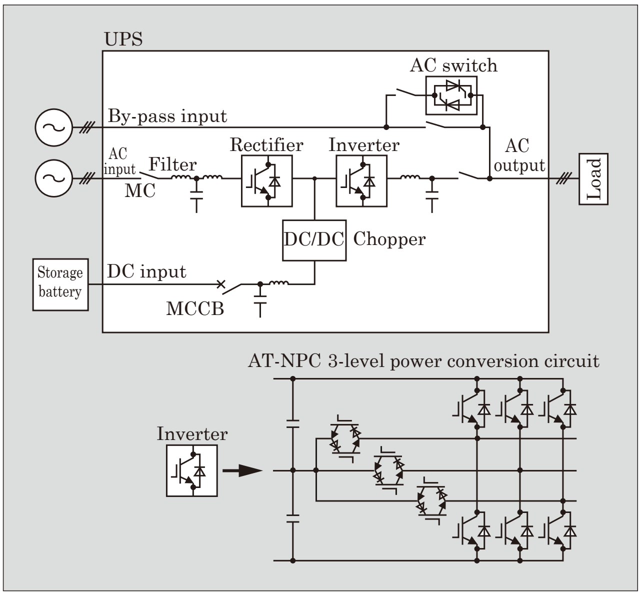

Fig.3 Block diagram of the main circuit.

*1: 3-level power conversion circuit: a new multi-level conversion circuit that has significantly reduced power loss of power conversion equipment such as power supplies and inverters. Refer to Fuji Electric REVIEW 2013, vol.59, no.4, p.255 for details.

nance or other purposes, or when a UPS in a stopped state is started for parallel connection with another UPS in operation, gradually changing the share of current makes it possible to reduce transient variation in the output voltage caused by a change in the number of units, which allows for the stable supply of power.

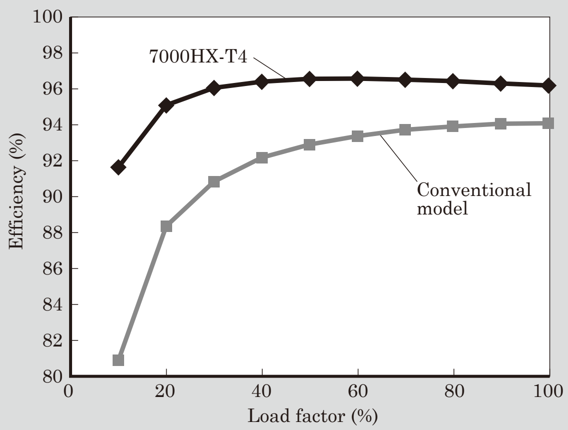

Fig.4 Equipment efficiency characteristics

(2) Efficiency and loss

Figure 4 shows the equipment efficiency characteristics of the 7000HX-T4 during normal operation. The efficiency is 95.0% or higher with a load factor of between 20% and 100%, which indicates that high energy-saving performance is realized over a wide range of load factors. With the 7000HX-T4, the equipment efficiency has been improved by about 4 points from the conventional model even in low load factor. The major factor that helps to realize this high efficiency is the use of a 3-level power conversion circuit in the AT-NPC system. This system has not only reduced the switching loss but also achieved lower conductive loss than other 3-level power conversion circuit systems and realized the world's highest level of efficiency.

Launch time

February 2014

Product Inquiries

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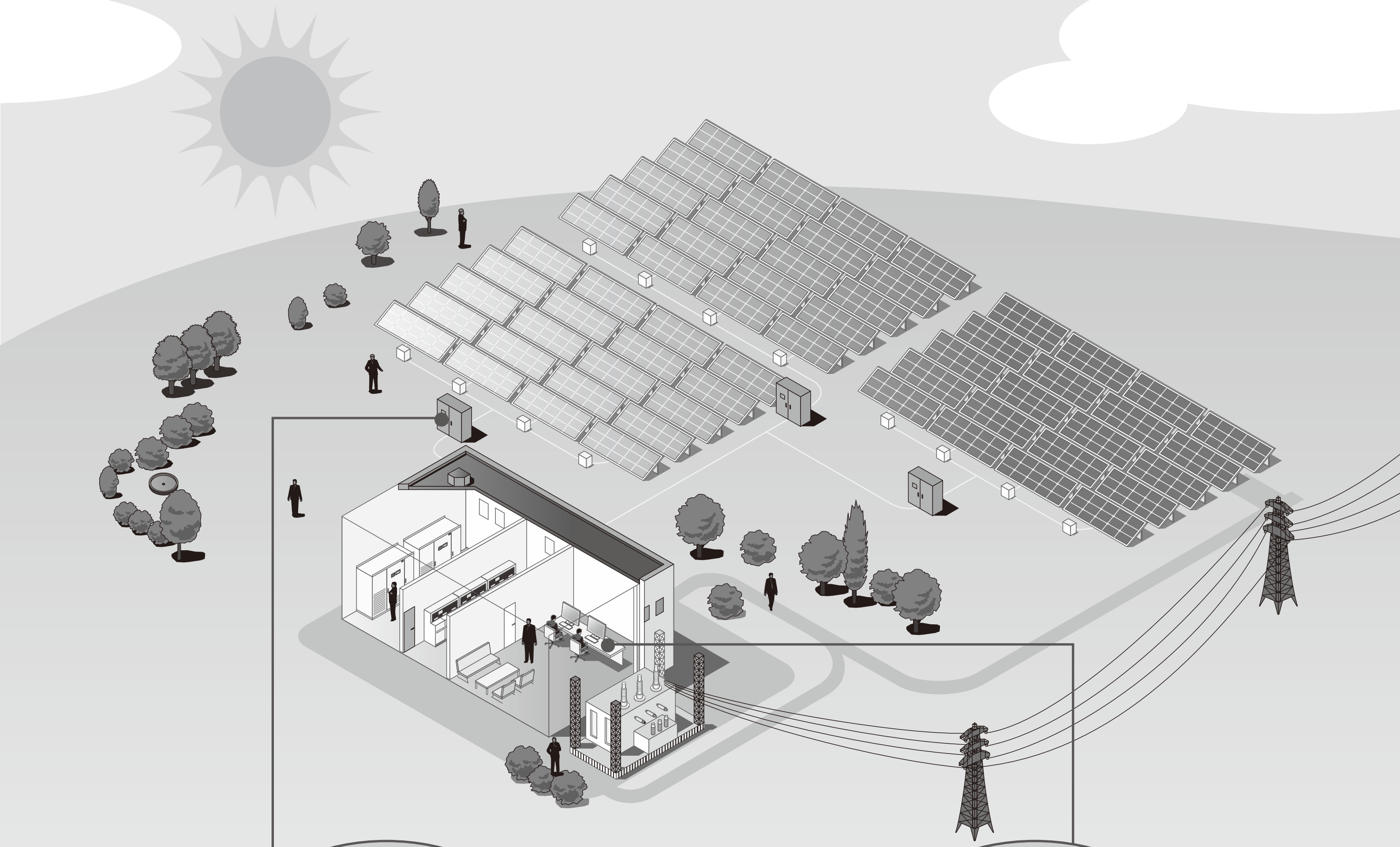

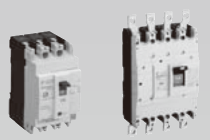

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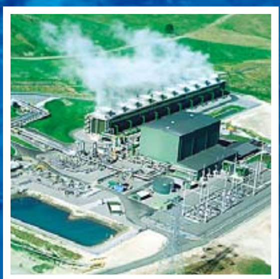

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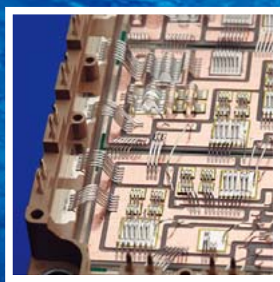

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