Power Electronics Contributing to Energy Saving, Compactness, and Increased Productivity

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1. Introduction

As the working-age population in Japan declines due to the decreasing birthrate and aging population, there is a growing need for production reforms to improve productivity. It is against this backdrop that automation is being promoted in various fields, including industrial plants and infrastructure, using artificial intelligence (AI), the Internet of Things (IoT), and high-speed communication technologies. At the same time, the power consumption of production systems is rapidly increasing. Power electronics technology and applicable products are indispensable for achieving both automation to improve productivity and energy saving to make more effective use of power.

Fuji Electric has been thoroughly pursuing synergies between its core power semiconductor and power electronics technologies, and is contributing to productivity improvement and energy saving in industrial plants and infrastructure by combining its cultivated expertise in highly reliable power electronics products, as key devices, with engineering services, advanced control technologies, and IoT. Figure 1 shows Fuji Electric's power electronics devices and applicable fields. In this special issue, we will describe Fuji Electric's power electronics devices as products that reduce environmental burdens by achieving energy saving and compactness in industrial plants and infrastructure in order to help realize a sustainable society. Furthermore, we will discuss technologies and applied products that contribute to the improvement of equipment reliability and maintainability using predictive diagnostics, in addition to the enhancement of the performance of power electronics equipment in order to improve productivity.

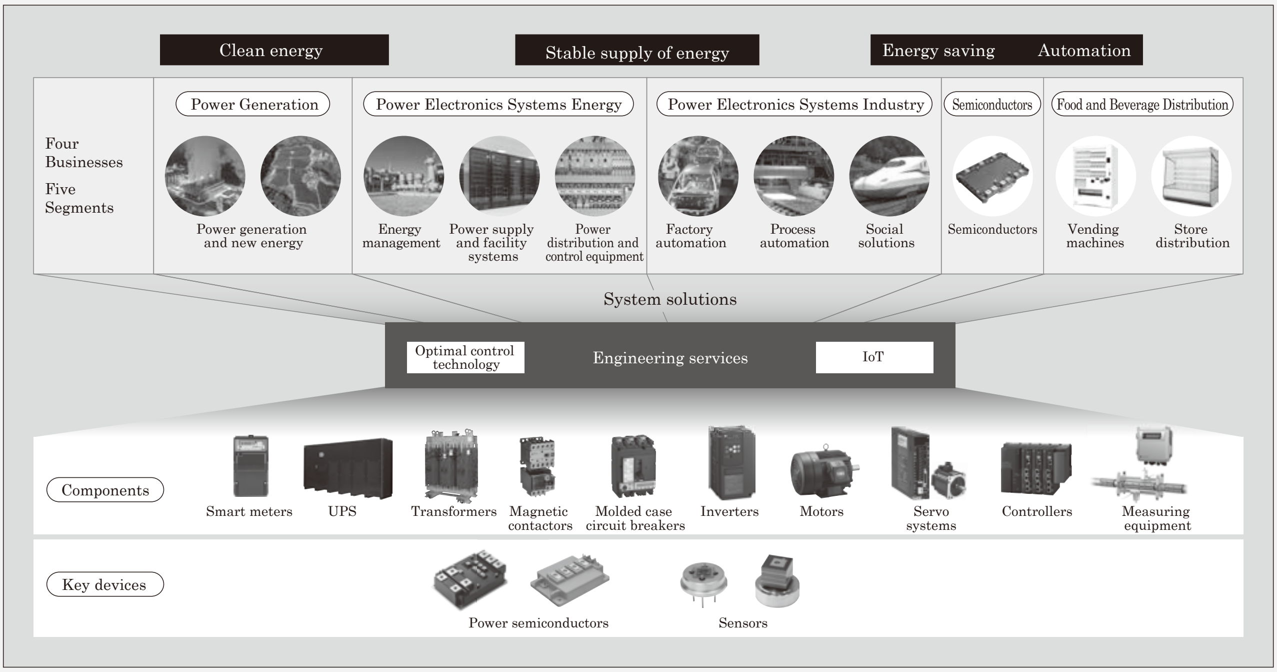

Fig.1 Fuji Electric's power electronics equipment and its application fields

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2. Technology and Product Development to Support Energy Saving and Compactness

Energy saving and compactness are required not only for power electronics equipment but for all products. In particular, since industrial plants and infrastructure consume large amounts of electricity, high efficiency and energy saving have become increasingly important. As for transportation vehicles, such as railcars and electric vehicles, only a limited installation space is available for equipment, and downsizing and weight reduction are also attracting attention. This chapter describes examples of Fuji Electric's initiatives to improve the efficiency, energy saving, size, and weight of its power devices, power electronics equipment, and systems.

2.1 High efficiency and energy saving

(1) Power devices

Fuji Electric has been commercializing IGBTs*1 as typical power device elements and has realized a number of technological innovations, including improvements in device structure and process technology, enabling it to create more efficient and smaller devices that have less than half the initial loss(1). However, silicon (Si) semiconductors, which have been the mainstream for over 50 years, are approaching their theoretical performance limits. Therefore, we are developing and commercializing power devices that use silicon carbide (SiC) as wide bandgap semiconductors with dramatically improved performance.

We have developed a high-speed hybrid module that combines a low-loss SiC Schottky barrier diode (SiC-SBD) with a Si-based IGBT with high-speed switching characteristics, instead of the conventionally used Si-based free wheeling diodes (FWDs)(2). Moreover, we have developed SiC trench-gate metal-oxide-semiconductor field-effect transistor (MOSFET) chips and are planning to develop a series of All-SiC modules with a breakdown voltage of 1,200 to 3,300 V(2).

Furthermore, we have optimized the drive technology and peripheral circuits of these power devices to significantly reduce the loss generated by the main circuits of power electronics equipment, resulting in higher efficiency and energy saving

(2) Power electronics equipment

As the capacity of large-capacity power electronics equipment used in industrial plants and infrastructure increases, the current of internal main circuits and feeding current from power electronics equipment to devices to be controlled are also increasing. This has, in turn, created greater power transmission loss in power cables. In order to increase power while suppressing power loss, power electronics equipment have been upgraded to handle higher voltages.

For example, in medium-frequency induction furnaces that use electromagnetic induction to heat and melt metals, the voltage applied to the induction coil is being increased to 6 kV, twice the conventional voltage. To achieve this, the insulation structure and materials have been revised to suppress occurrences of partial discharge even in high temperature, high humidity, and high dust environments.

In power conditioning systems (PCS) that convert DC power generated by solar panels into AC for interconnection with power transmission systems, the input voltage from the solar panels is being increased from the conventional voltage of 1,000 V DC to 1,500 V DC, thereby reducing the current in the DC cable to suppress transmission loss.

Since power electronics equipment capacity is limited by the current of individual power devices, we have increased the capacity by using a parallel connection of power devices, power units, and power electronics equipment. However, it is not always the case that equipment is operating at 100% load all the time. We have developed a quantity control technology to reduce no-load loss by reducing the number of power units used in parallel when the load is low, and have applied it to our products to achieve high efficiency and energy saving at low loads.

Moreover, in addition to improving the efficiency of power electronics equipment, we are also improving the efficiency of the rotating machines used as power sources in industrial plants and infrastructure. We have also developed a high-efficiency permanent magnet synchronous motor (PM motor)*2 for fluid apparatuses by taking advantage of the excellent features of PM motors, such as their small size and high efficiency, further reducing the iron loss of the rotating machines by using a high-grade, thin electrical steel sheet for the iron core, and optimizing the shape of the parts to minimize loss

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***1 IGBT:**
This stands for insulated gate bipolar transistor. This is a voltage control device that has a gate insulated with an oxide insulated film, having the same structure as MOSFET. It makes use of the strong points of MOSFET and bipolar transistors. Its bipolar operation means that it can make use of conductivity modulation, and as a result, it is able to achieve a high blocking voltage, low on-resistance and switching speed sufficient for use with inverters.

***2 PM motor:**
This stands for permanent magnet synchronous motor. This is a synchronous motor that uses a permanent magnet for the rotor, and is characterized by its high efficiency and small size and weight compared to induction motors.

Fig.2 “FRENIC-RHC Series”

in consideration of the ratio of copper loss to iron loss (Refer to “PM Motors for Fluid Apparatus with Small Size, High Speed, and High Efficiency” on page 26).

(3) Power electronics equipment systems

In industrial plants and infrastructure, a large number of power electronics equipment are operated under cooperative control. In order to quickly decelerate or stop a high-speed mechanical system, it is necessary to quickly consume the kinetic energy of the machine. A typical general-purpose inverter uses diode rectification to generate DC intermediate voltage from AC power. Therefore, even when the kinetic energy of the mechanical system was converted into electrical energy, it was not be possible to perform regeneration from the DC intermediate circuit of the inverter for the power system. As a result, the energy could only be consumed using a regenerative resistor. In response to this, Fuji Electric has released the “RHC-C Series” of PWM converters with power regeneration functions to facilitate system-wide energy saving in industrial plants and infrastructure. In addition, we have newly developed the “FRENIC-RHC Series” as a line-up of products with improved functions and operability (see Fig. 2). These products regenerates the braking energy back to the power supply, while at the same time shaping the current waveform on the power supply into a sine wave, enabling them to comply with guidelines of harmonic suppression measures.

2.2 Compactness and light weight

(1) Power devices

As mentioned above, Fuji Electric has developed and commercialized a high-speed hybrid module that combines a SiC-SBD and IGBT capable of high-speed switching, as well as SiC trench-gate MOSFET chips. This new power device has low loss, and it not only greatly reduces the loss generated by the main circuit and improves efficiency, but also makes it possible to significantly reduce the size of the cooling unit needed to cool the power device, resulting in smaller and lighter equipment overall. In addition, these power devices are capable of high-speed switching and can operate at high frequencies, and the filters and reactors in the peripheral circuits can be downsized, leading to smaller equipment. For example, main power converter of the N700S Series Shinkansen train uses SiC power semiconductor modules to reduce the size and weight of the cooling system. We optimized the structure and conductor configuration in the power unit and all of which resulted in a 9% smaller and 14% lighter main power converter.

(2) Power electronics equipment

In order to reduce the size and loss, it is important to focus on the structural design and thermal cooling design technology of power electronics equipment when using new power devices.

When large-capacity power electronics equipment is installed outdoors, it is necessary to ensure the protection class of the inverter unit and control equipment since they are precision devices, while also cooling the heat generated by the large-capacity main circuit.

In the 2.5-MW-class PCS for solar power generation installed outdoors is divided into two internal areas: an airtight area and an open-air area. Precision devices are installed in the airtight area and heat sinks for IGBTs and other high heat-generating components are installed in the open-air area and cooled using outside air (see Fig. 3). These innovations have reduced the size of equipment and achieve the industry’s smallest installation footprint (Refer to “‘PVI1500CJ-3/2500’ 1,500-V DC PCS for Mega Solar Systems” on page 16).

In the N700S Series Shinkansen train, we designed the main transformer with lower copper loss, used aluminum wires for the windings, and adopted a unit-type cooling system, all of which resulted in a 12% smaller and 10% lighter main transformer. (Refer to “Power Electronics Equipment for Railcars

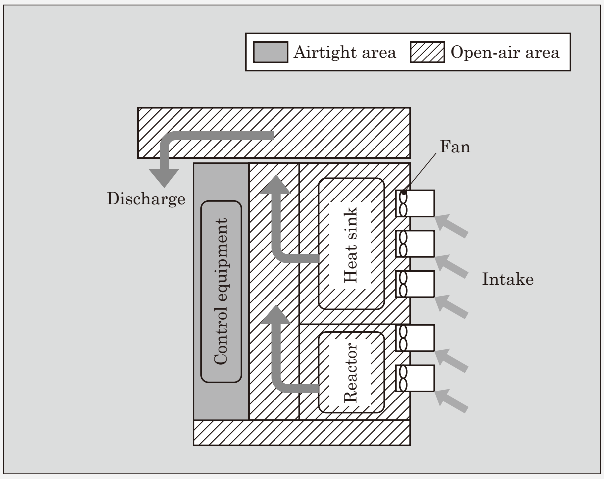

Fig.3 Cooling structure of PCS for mega solar

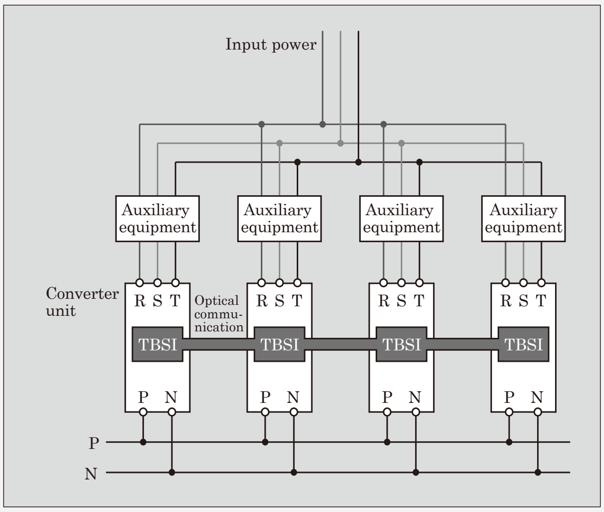

Fig.4 Configuration of the “FRENIC-RHC Series” transformerless parallel system

Contributing to Safe, Secure, and Comfortable Public Transportation in the World” on page 21).

(3) Power electronics equipment systems

To respond to the need for even larger capacity, we arrange multiple pieces of power electronics equipment in parallel. In order to mitigate cross currents and current imbalances that occur between parallel equipment, it is common to install them in parallel via output transformers or reactors. However, output transformers and reactors are large and heavy objects. In medium-frequency induction furnaces, Fuji Electric has suppressed the current imbalance caused by the parallel connection of multiple main circuit stacks to a sufficiently small level by connecting them at the shortest distance. This eliminates the need for current-balancing reactors. As a result, we reduced the width dimensions of the panel by approximately 25% compared to a conventional panel with the same power supply capacity (Refer to “‘F-MELT100G Series’ High-Efficiency, Medium-Frequency Induction Furnace” on page 11).

In the FRENIC-RHC Series of PWM converters, by connecting each multiplexed unit with an optical fiber for high-speed serial communications (see Fig. 4), the phase of the current on the input side of each converter is controlled in an identical phase, enabling up to four units to be installed in parallel without a transformer (Refer to “‘FRENIC-RHC Series’ High Power Factor PWM Converters with Power Regeneration Function” on page 40).

3. Technology and Product Development to Support Productivity Improvement

Improving productivity means making the most effective use of an organization’s management resources to produce maximum results with minimum investment. In this chapter, we describe our efforts to improve productivity in production facilities, industrial plants, and infrastructure through the use of power electronics and control technologies.

3.1 Improving production efficiency through higher performance

In order to improve the production efficiency of production facilities and industrial plants, it is important not only to operate the equipment at high speed, but also to have the equipment be responsive to operations. Fuji Electric has further developed its control technology for general-purpose inverters and servo systems used in production facilities and industrial plants, while greatly improving their responsiveness.

The “FRENIC-MEGA (G2) Series” uses a faster micro controller unit (MCU) to further enhance the original motor control technology that we have cultivated to date, and has achieved a current response of 100 Hz or higher and a speed response of 200 Hz or higher, which is twice as fast as previous models. Its high responsiveness reduces the effects of disturbances on machines and ensures stable, high-speed operation. “ALPHA7 Series” servo systems have improved their frequency response from 1,500 Hz to 3,200 Hz and achieved a positioning control setting time of less than 1 ms by further enhancing the control algorithm developed for conventional servo systems. They can improve the mechanical performance of equipment that require short takt time and high precision.

At the same time, the motor shaft output is connected to the mechanical system. For example, in a springy structure such as a robot arm, vibration may be generated at the tip of the workpiece during rapid acceleration and deceleration of the motor. Simply achieving high speed and high responsiveness does not improve production efficiency if there is a long waiting time before the vibration at the tip of the workpiece is attenuated. Therefore, the ALPHA7 Series has revised the vibration suppression control system for suppressing vibration at the

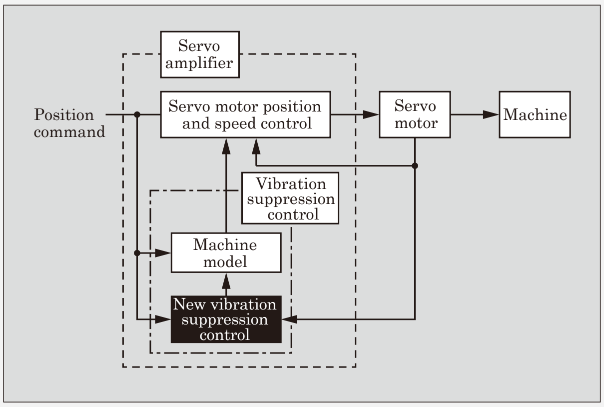

Fig.5 Block diagram of new “ALPHA7 Series” vibration suppression control system

tip of the workpiece (see Fig. 5) to reduce vibration by approximately 50% compared to conventional vibration suppression control systems. This has contributed to improved equipment production efficiency.

In this way, by developing power electronics equipment with advanced functions and performance, we are contributing to the improvement of production efficiency and productivity of production facilities and industrial plants.

3.2 Improved reliability through diagnostic technology and redundancy

In order to improve the reliability of production facilities and industrial plants, Fuji Electric has been providing power electronics equipment with excellent environmental resistance and compliance with functional safety standards to enable customers to build highly reliable systems. The FRENIC-MEGA (G2) Series applies a full coating to the printed circuit board to provide it with an environmental resistance rating of Class 3C2*[3] as defined by JIS 60721-3-3 / IEC 60721-3-3. Moreover, the ALPHA7 Series comes standard with the safe torque off (STO)*[4] functionality specified in the functional safety standards IEC 61800-5-2 / IEC 61508 (SIL3) and ISO 13849-1 (PL-e). By combining the ALPHA7 Series motor with the safety option (WSU-ST1), it supports safety functions such as Safe Stop 1 (SS1)*[5].

It is important not only to install power electronics equipment that makes use of these measures, but also to quickly detect signs of abnormality and problems in the entire facility to ensure systematic preventive maintenance.

The FRENIC-MEGA (G2) Series estimates the life of IGBT modules as key devices of inverters based on the inverter's operating conditions (accumulated load, temperature, etc.) and notifies operators that maintenance is required before the module reaches the end of its life. In addition, it can estimate the deterioration of the cooling performance of the inverter caused by clogged cooling fins based on the temperature inside the inverter measured by the temperature sensor, and notifies operators that cleaning or inspection is necessary. By notifying the upper-level control system of such signs of abnormality in the power electronics equipment using communications functions compatible with various communications protocols, and by encouraging operators to take measures such as maintenance, it facilitates the building of highly reliable systems that incorporate functions to prevent sudden system shutdowns.

In addition to diagnosing the signs in power electronics equipment, the ALPHA7 Series includes a load torque monitoring function to extract the load torque, which does not include acceleration and deceleration torque or friction and gravity torque, from the command torque. This function can be used to detect abnormalities such as collisions with machinery and equipment and mitigate the impact of collisions with machinery to prevent serious damage (see Fig. 6). Furthermore, this function can help determine machining defects due to abnormal torque, preventing the outflow of defective products and contributing to quality improvement (Refer to "'ALPHA7 Series' Servo System: New Functions and Application Examples" on page 54).

Moreover, in industrial plants and infrastructures, DC power needs to be supplied to systems consisting of various types of information equipment, in addition to drive equipment. To ensure stable operation of these systems, Fuji Electric has developed a power supply for control panels that comes with built-in redundancy functions and facilitates connection to equipment using connectors. If necessary, it can provide highly reliable DC power using the power supply's built-in redundancy function or a redundant unit installed externally to the product (Refer to "AC-DC Power Supplies for Control Panels" on page 30).

Systems that make use of products that support these types of predictive diagnostics and redundancy functions are highly reliable and increase

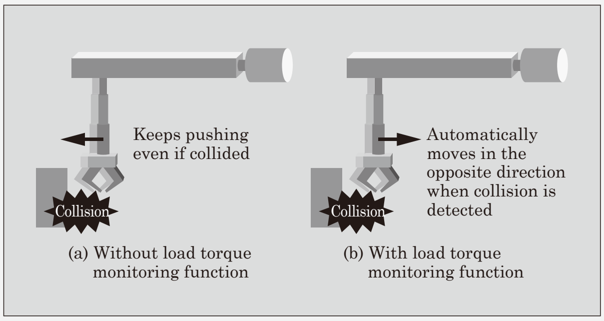

Fig.6 Interference detection using the load torque monitoring function of the "ALPHA7 Series"

***3 Class 3C2:**
These are the environmental conditions specified in JIS C60721-3-3 (IEC 60721-3-3). This refers to locations with normal levels of pollution that occur in urban areas where industrial activities are dispersed throughout the region or where there is heavy traffic.

***4 STO:**
This refers to a safety function defined by the IEC that immediately stops the motor.

***5 SS1:**
This refers to a safety function defined by the IEC that allows the motor to decelerate to a stop and then operate in STO mode.

equipment availability and productivity.

3.3 Easier maintenance through improved maintainability

Although the implementation of preventive maintenance through the aforementioned diagnostic functions and redundancy can greatly improve the reliability of the overall system, it is difficult to completely prevent accidental failures caused by operating conditions and the operating environment. Fuji Electric is working to reduce equipment downtime caused by accidental failures and faults caused by the operating environment.

(1) Traceback function

In the event that a power electronics device should fail, we provide tools to quickly identify the location and cause of the failure. For example, many types of power electronics equipment, such as those in the "FRENIC-MEGA (G2) Series" and "FRENIC-RHC Series," come with traceback functions. The traceback function acquires and records time series data of internal and external conditions immediately before and after an alarm occurs in the power electronics equipment. The recorded time series data can be read out using the "FRENIC-Loader 4" PC support tool to check the waveforms immediately before and after alarms (see Fig. 7). This makes it easier to identify the location of failures and reduces the time required for maintenance and equipment downtime. Moreover, since this makes it easier to identify the cause of failures, it can be effectively used as a measure to prevent recurrence (Refer to "'FRENIC-MEGA (G2) Series' High-Performance, Multifunctional Inverters" on page 34).

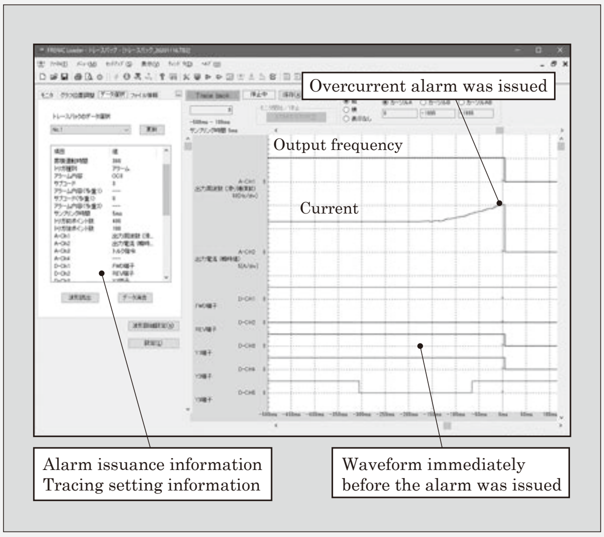

Fig.7 Traceback function of the "FRENIC-MEGA (G2)"

(2) Unitization of the main circuit of high-capacity power electronics equipment

In high-capacity power electronics equipment, the main circuit part, which is an important limited-life component, is unitized so that they can be easily replaced. If the circuit is diagnosed as needing replacement by the aforementioned lifespan diagnosis function, or if it fails due to accidental factors, it can be replaced as a unit. This enables quick recovery for user facilities. In addition, casters are placed at the bottom of heavy units to make them easy to pull out and replace.

(3) Retrofit*6

In industrial plants and infrastructure, the replacement of equipment that uses power electronics products housed in a large panel can require long-term shutdowns of customer facilities if the replacement work starts from the foundation work. Moreover, depending on the installation location, it may not be possible to carry in the panel due to the narrow entrance way for materials. To solve this problem, Fuji Electric developed retrofit products (see Fig. 8) that do not require replacing the entire panel, but only the inverter cells, control stack, and some electrical components that have limited life cycles. These products can shorten the time required to replace equipment (Refer to "Retrofit Components for 'FRENIC4600FM4 Series' Medium-Voltage Inverters" on page 45).

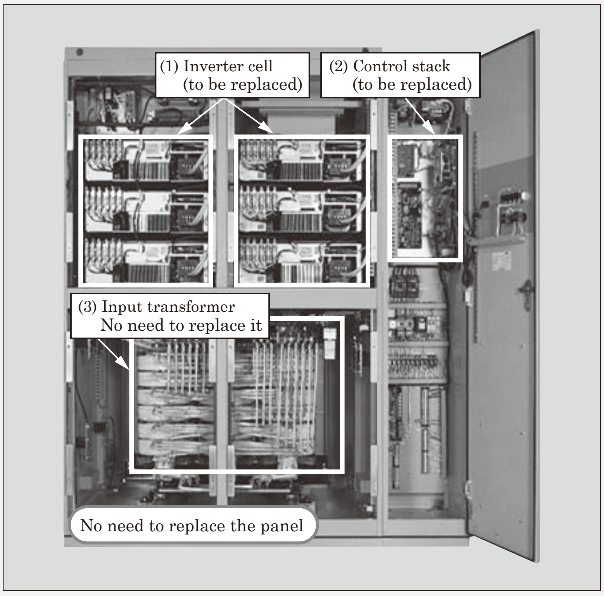

Fig.8 Image of medium-voltage inverter retrofit

***6 Retrofit:**
This term originated in the United States in the 1960s and has been used to refer to the modification of general-purpose machine tools to convert them into NC machines. Recently, the term has been used in a broader sense to describe the process of matching new and old products to improve functionality, or the refurbishing or modification of an old model product to make it a new model.

By making it easy to identify the location and cause of failures in power electronics equipment, and by facilitating the replacement of main circuit parts that are prone to failure, we are able to improve the productivity of industrial plants and infrastructure through the reduction of customer equipment downtime caused by accidental failures.

4. Postscript

In this paper, we gave an overview of Fuji Electric's efforts in power electronics that contribute to energy saving, compactness, and increased productivity.

Fuji Electric will continue to develop highly efficient and compact power electronics equipment. We are also determined to contribute to the realization of a sustainable society by promoting energy saving and increased productivity in the fields of industrial plants and infrastructure through the use of predictive diagnosis technology, IoT, and AI.

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