

FUJI ELECTRIC REVIEW

Power Electronics Technology



2012 VOL.58



Fuji inverters

FRENIC Series

FRENIC-Mini FRENIC-Multi FRENIC-Eco
FRENIC-MEGA FRENIC-VG



Smile to the Environment

~ Energy Saving for the environment and our children's future ~

Low voltage AC drives
for HVAC applications

FRENIC-HVAC



Low voltage AC drives for water,
wastewater & irrigation applications

FRENIC-AQUA



FUJI ELECTRIC REVIEW

Power Electronics Technology

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Cover photo:

Fuji Electric is focusing on power electronics, through which electricity can be manipulated flexibly, to contribute to the world in the field of energy. The fields of application for power electronics are diverse, and include industrial variable speed driving, industrial power supplies, solar power generation, induction heating equipment, railway electrical equipment, automotive electrical equipment, and the like. With circuit technology, control systems and power semiconductors as base technologies, power electronics technology has been independently developed in each field while incorporating market requests to contribute to the realization of a sustainable society.

The cover photo is a depiction of the application fields for power electronics and typical power electronics products.

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Power Electronics Technology: Current Status and Future Outlook

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ABSTRACT

Fuji Electric is focusing on power electronics, through which electricity can be handled flexibly, to contribute to the world in the field of energy. Power electronic devices, with circuit technique, control system, and power semiconductor as their base technologies, are expanding into various fields. For inverters, EMC analysis technology, high-speed synchronization communication technology, and water-cooling methods etc. are employed in addition to complying with functional safety standards. For UPS, nickel-metal hydride batteries are introduced and AT-NPC 3-level conversion technology is adopted. In addition, Fuji Electric is developing a wide range of power electronics technologies to enhance power electronic devices for railway vehicles and electric cars, high-efficiency power supplies for servers, and high-capacity PCS and responds to various demands such as safety, miniaturization and energy saving.

1. Introduction

Fuji Electric is focusing on power electronics, through which electricity can be manipulated flexibly, to contribute to the world in the field of energy. The fields of application for power electronics are diverse, and include industrial variable speed driving equipment, industrial power supplies, solar power generation, induction heating equipment, railway electrical equipment, automotive electrical equipment, and the like. In addition to providing power electronics equipment that supports these applications, Fuji Electric also provides the product groups of power semiconductors and electric distribution and control devices, which are critical components for power electronics equipment, to offer powerful components and powerful solutions which make use of them in the various fields (see Fig. 1).

As shown in Fig. 2, in each field, power electronics

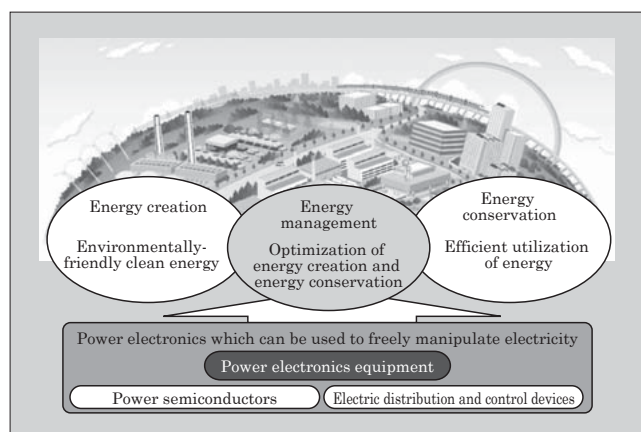


Fig.1 Positioning of power electronics equipment

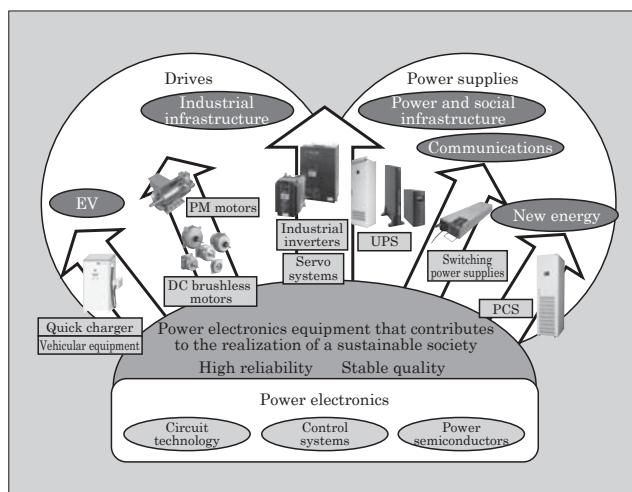


Fig.2 Business areas of power electronics equipment

equipment is contributing to the realization of a sustainable society. With circuit technology, control systems and power semiconductors as base technologies, power electronics technology has been independently developed in each field while incorporating market requests.

This paper describes the current state of the technical trends and product development of power electronics equipment from the perspective of how to meet market requests in each field.

2. Market Needs and Technical Trends

Figure 3 shows the evolution of the market needs, the product technology as well as the power semiconductors, electric distribution and control devices, basic technology and analysis technology used in products.

Fuji Electric has a history of developing the product technology necessary to meet market needs.

[†] Fuji Electric Co., Ltd.

Item	(Year)			
	2000	2005	2010	2015
Market needs	○ Safety standard (low voltage, EMC) compliant ○ Network compatible ○ Energy savings ○ Power supplies for data centers (energy-saving, space-saving) ○ Mega solar plants (overseas)		○ Functional safety standards compliant ○ High performance drive ○ Revision of energy saving law ○ Mega solar plants (domestic)	
Product technology	○ Network compatible		○ Functional safety standards compliant ○ High-speed network compatible ○ High-efficiency PM motor ○ SiC inverters ○ AT-NPC 3-level high-efficiency UPS ○ AT-NPC 3-level high-efficiency PCS	○ Safety bus technology ○ SiC UPS ○ SiC PCS
Power semiconductors		○ RB-IGBT	○ Module for AT-NPC 3-level use ○ SiC devices	
Electric distribution and control technology			○ DC distribution technology	
Basic technology, analysis technology	○ EMC analysis technology (circuit network) ○ Field bus technology ○ NPC 3-level circuit technology	○ EMC analysis technology (3D) ○ PM motor sensorless driving ○ AT-NPC 3-level circuit technology	○ Functional safety standards compliant ○ High-speed communication technology	○ Safety bus compatible

Fig.3 Trends of power electronics technology

Particularly significant achievements include the development of the power semiconductors and electric distribution and control devices required for new products. Specifically, Fuji Electric is developing a custom module that integrates a reverse-blocking insulated gate bipolar transistor (RB-IGBT) or an advanced t-type neutral-point-clamped (AT-NPC) 3-level inverter circuit containing an RB-IGBT. Additionally, Fuji is also developing DC distribution equipment for the power conditioner systems (PCS) used at mega solar plants and the like⁽¹⁾.

In this way, power electronics equipment, while responsible for driving technical innovation of power semiconductors and electric distribution and control devices, also provide powerful components that contribute to solutions in various fields through the development of elemental technologies and products.

3. Development Trends of Elemental Technologies and Current Status of Product Development

3.1 Development trends of elemental technologies in various fields

(1) Technology that supports safety standards in drive products

Various standards have been advanced for the purpose of preventing injury accidents involving machinery through performing risk assessments of mechanical systems. In particular, IEC 61800-5-2 has been enacted as a safety standard for drive products (power drive systems).

Fuji Electric is developing products that comply

Table 1 Products and corresponding safety functions

Product name	Corresponding safety function			
	STO	SS1	SLS	SBC
FRENIC-Multi	○			
FRENIC-MEGA	○			
FRENIC-VG *	○	○	○	○

STO: Safety Torque Off

SS1: Safe Stop 1

SLS: Safely Limited Speed

SBC: Safe Brake Control

*: SS1, SLS, SBC are available as an option

with this functional safety standard. Fuji Electric's inverter products listed in Table 1 support SIL2 (corresponding to ISO13849-1 category 3, performance level D).

The STO function reduces the failure rate by processing redundant stop signals with redundant circuits even inside the inverter as shown in Fig. 4, and provides a diagnostic function for detecting circuit failure.

In the future, Fuji Electric will support a safety bus and the expansion of corresponding functions.

(2) EMC^{*1} simulation technology

With globalization, EMC countermeasures for general-purpose inverters are an essential part of product development, and consideration of the type of countermeasures to implement must begin from the design stage. Noise consists of conduction noise and radiation noise, and the relationship between conduction noise and specific structures has become knowable.

*1: EMC (electromagnetic compatibility): Performance in an environment of radiation and conduction noise

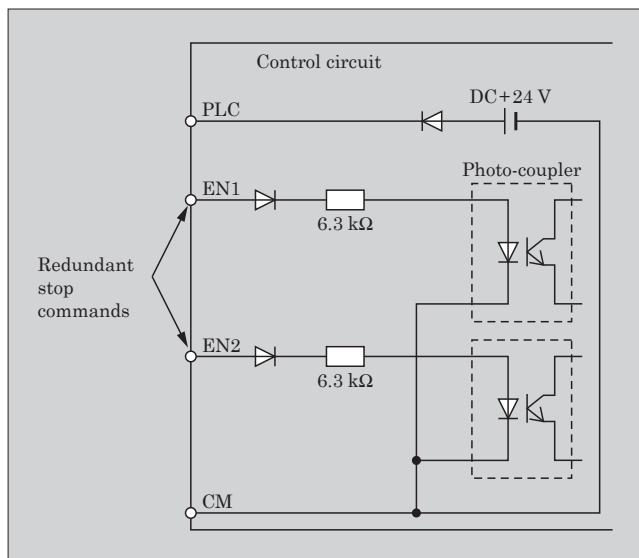


Fig.4 STO input circuit

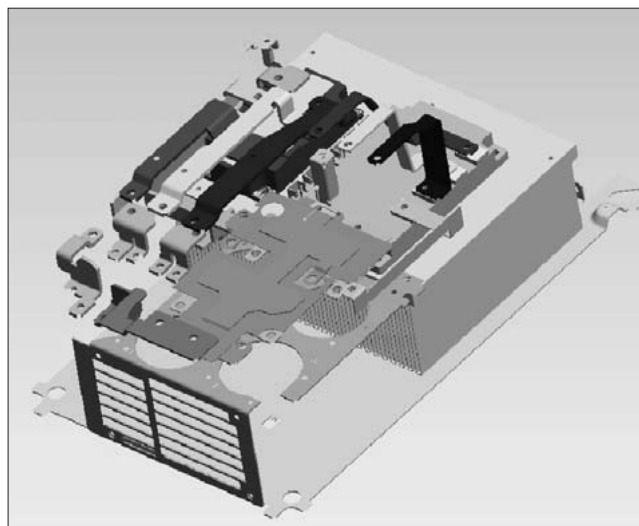


Fig.5 Three dimensional model for EMC analysis

The electrical parameters (coupling capacitance, stray capacitance, stray inductance, etc.) necessary for simulating EMC from 3D CAD data as in Fig. 5 are derived by electromagnetic field analysis, and disturbance voltages can be simulated accurately with circuit networks. Figure 6 shows that with improved simulation accuracy, the analysis results approach the measured results more closely, and this level of accuracy is sufficient for practical applications. Accordingly, EMC countermeasures can be incorporated from the early stages of structural design, leading to a shorter product development time.

In the future, front loading of the design process will continue using simulations.

(3) High-speed synchronous communication technology in high performance drive systems

In fields where high performance drives are utilized, the realization of the functions and performance of the entire system, not merely of the inverter perfor-

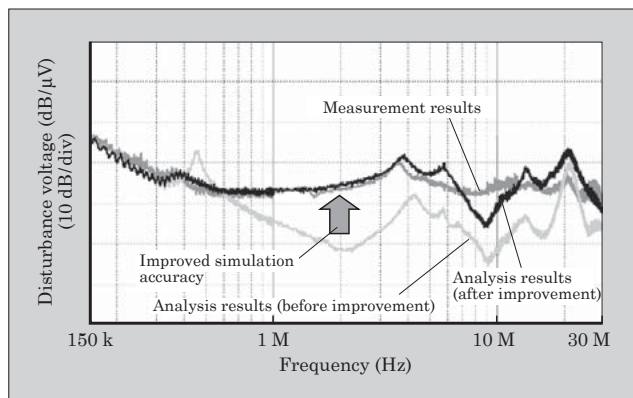


Fig.6 EMC simulation for inverters

Table 2 “E-SX bus” summary specifications

Item	Specification
Communication speed	100 Mbits/s
Synchronization accuracy between axes	$\pm 1 \mu\text{S}$ or less
Distance (distance between stations, total length)	100 m, 1 km
Minimum tact period	0.25 ms

mance, is important. In particular, system control has been implemented in systems in which the controller and bus are coupled, but even further improvements in communication speed and synchronization are needed.

The “FRENIC-VG” high performance vector inverter was designed to be compatible with the “E-SX bus” provided in the “SPH3000MM”, Fuji Electric’s new CPU module used in the “MICREX-SX Series” of integrated controllers. This bus uses Ethernet technology for high-speed communications, and can be used for multi-axis high-speed control at industrial plants, high accuracy synchronous control driving of printers, and the like. Table 2 summarizes the E-SX bus specifications, and Fig. 7 shows an application example.

In the future, Fuji Electric plans to develop high-speed synchronous communication technology for high performance drives, including motion control.

(4) Silicon carbide (SiC) device technology⁽²⁾

The development of power semiconductors is being advanced using new materials such as SiC and gallium nitride (GaN). These materials have the characteristics listed in Table 3, and the development must fully utilize these characteristics.

From these characteristics, various fields of application can be considered, for example, through miniaturizing the reactor in peripheral circuits, reducing noise, and so on.

Moreover, the inverter main circuit uses diode and transistors as shown in Fig. 8, and a hybrid module in which only the diodes have been replaced with SiC devices, and an All-SiC module in which all the diodes and transistors have been replaced with SiC devices are available (see Table 4).

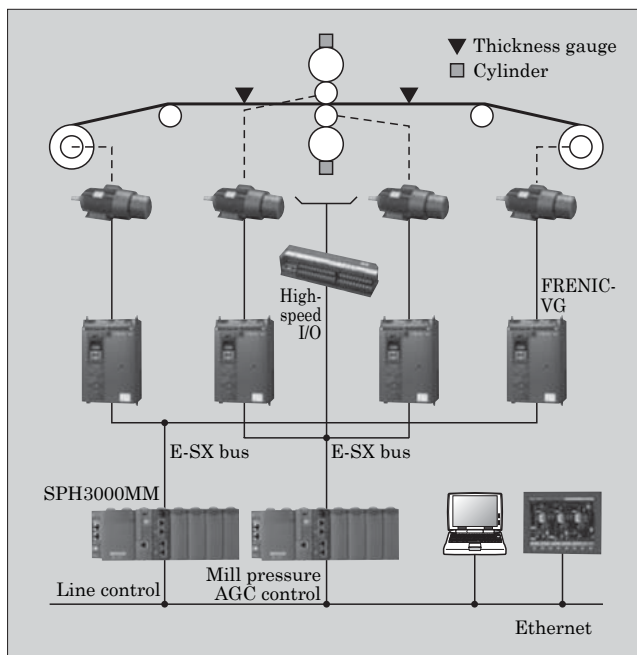


Fig.7 Example of high-speed control system using "E-SX bus"

Table 3 Characteristics of SiC and GaN devices

Characteristic	How to use
Low loss	Increase carrier frequency Reduce loss, increase efficiency
Ability to operate at high temperature	Can be used in higher temperature environment
Easy to increase withstand voltage	Miniaturize high-voltage device

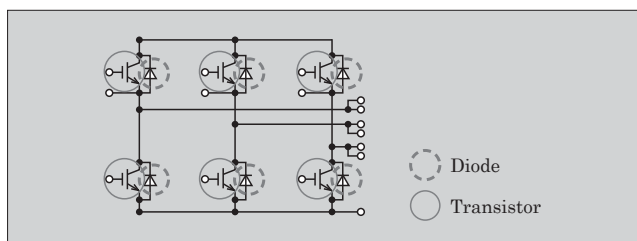


Fig.8 Internal configuration of main inverter circuit

Table 4 Types of modules that use SiC technology

Module type	Diode	Transistor
Hybrid module	SiC	Si
All-SiC module	SiC	SiC

Fuji Electric has developed the "FRENIC-MEGA GX-SiC," a high-efficiency inverter that uses this hybrid module. Compared to previous models, loss can be reduced by 25%, and in combination with a "GNS Series" or "GNP Series" high-efficiency synchronous motor, enables the realization of drive systems with even higher efficiency.

The All-SiC module enables a significant reduction in loss and has demonstrated that not only high efficiency but also small size can be achieved.

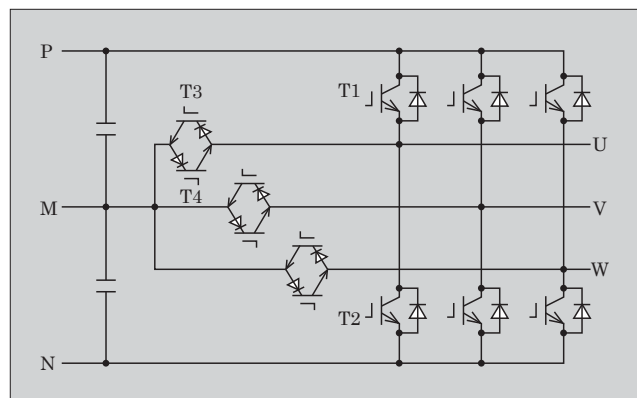


Fig.9 AT-NPC 3-level conversion circuit

(5) AT-NPC 3-level conversion technology⁽³⁾

Achieving higher efficiency in an uninterruptible power supply (UPS), a PCS or other conversion equipment is a major challenge. An AT-NPC 3-level conversion circuit as shown in Fig. 9 was developed as a means to realize such higher efficiency. With this circuit, not only is switching loss reduced by half compared to a conventional 2-level conversion circuit, but harmonic voltage is reduced and the loss in filter circuits, including reactors and capacitors, is also reduced, thereby enabling the miniaturization of equipment. The 3-level conversion circuit uses an AT-NPC 3-level IGBT module incorporating an RB-IGBT developed by Fuji Electric, and achieves a further reduction in loss.

(6) Evaluation and application technology for storage batteries

The need for electrical storage, in applications not limited to UPSs, is spreading. On the other hand, lithium ion batteries are being put to practical use in EVs and HEVs as new storage devices that replace the conventional lead-acid batteries. In addition to evaluating the characteristics and service life of various lithium ion batteries, Fuji Electric has also established proprietary technology for evaluating safety and reliability from the perspective of the end user. As a result, the development period and evaluation period for products that use lithium ion batteries can be shortened.

3.2 Current status of product development

(1) Inverters for specific applications

In recent years, low-voltage inverters, known as general-purpose inverters, have tended to become specialized as dedicated inverters for specific applications, i.e., inverters for elevators, inverters for air conditioning, inverters for industrial use, and the like.

The "FRENIC-HVAC/AQUA" inverters for use in air conditioning and water treatment systems target the large markets for heating ventilation and air conditioning (HVAC) and for water treatment.

Additionally, because these inverters support IP55*2, they do not have to be stored inside a panel, thus reducing costs. Also, because they are used in air

conditioning applications in buildings and factories, the inverters have a built-in DC reactor (DCR) for improving the power supply power factor and a built-in EMC filter. Moreover, dedicated functions for fan and pump control have been strengthened so that pressure and temperature can be controlled with the inverter only.

A summary of the specifications are listed in Table 5.

(2) Permanent magnet synchronous motor (PM motor)

A permanent magnet (PM) motor that uses a permanent magnet has the characteristics of higher efficiency, smaller size and lighter weight than an induction motor. To fully leverage these characteristics, the PM motor models shown in Table 6 have been developed.

The “GNS Series” and “GNP Series” of ultra high-efficiency motors are energy-saving motors that are installation-compatible with induction motors, and in terms of efficiency, are 3 to 8.5 percentage points more efficient than induction motors in general. The high-efficiency “GNB” of energy-savings motors is compact and lightweight. The sensor-equipped “GNF” is 1 to 2 frame sizes*3 smaller than an induction motor, and can be used in general industrial machine control applications such as printing equipment to leverage its small size and light weight.

Table 5 “FRENIC-HVAC/AQUA” product specifications

Item	Specifications
Voltage	400 V
Capacity range	0.75 to 710 kW
Protective structure	IP21/55 (90 kW or less) IP00 (110 kW or less)
Built-in DCR	(90 kW or less)
EMC filter	Internal
Functions	Estimated terminal pressure control, pump control, temperature control, FireMode, etc.

Table 6 List of PM motor series

Product type	Rotation sensor	Efficiency	Use
GNS	Sensorless	IE4 or higher	Energy savings, replacement of existing induction motor
GNP		IE4 equivalent	
GNB		IE3 equivalent	Energy savings, small size, light weight
GNF	With sensor	IE3 equivalent	General industrial machine control

*2: IP55: Code indicating the dustproof and waterproof performance stipulated in IEC 60529 and JIS C0920, and corresponding to dustproof and water jet proof models

*3: Frame size: A series of motors often has a common frame size for 2 or 3 different capacities

(3) Power electronics equipment for rail vehicles

For the propulsion systems of Shinkansen trains, Fuji Electric supplies main transformers, main converters, and main motors. The main converters have been improved with each successive generation, and have been made compact, lightweight, blowerless, and so on. Additionally, for auxiliary power supply units, distinctive products that realize high performance and high reliability are being delivered.

For the door system, linear motor and flat cup permanent magnet motor (FCPM) methods exist, and have been used both in Japan and overseas.

(4) Power electronics equipment for electric vehicles

As ground-based quick charger, 44 kW, 39 kW and 25 kW models that support the CHAdeMO*4 specification have been developed and have been introduced to the market.

In particular, a 25 kW model was developed based on server power supply technology for information devices, for which Fuji Electric has a proven track record, allowing for miniaturization and scalability.

(5) High-efficiency power supplies for servers

DC stabilized power supplies for computers and servers are required to be highly efficient and to have a high power density. Comprehensive high-efficiency guidelines are provided that, rather than merely assess the maximum efficiency, also prescribe efficiency in the low load region.

Fuji Electric has applied device application technology, circuit technology and digital control technology to obtain 80 PLUS*5 Platinum certification for its 2.1 kW and 2.5 kW power supplies.

(6) Mini UPS

The market for data centers that provide Web services and the like has been expanding recently, and for the purpose of reducing equipment installation cost and shortening construction and delivery times at these data centers, server rack-mounted products have been increasingly selected instead of electrical equipment with a separate UPS. Moreover, in order to reduce running costs, air conditioning power is being decreased and server room temperature settings are being raised. Meanwhile, in the pursuit of added-value, high density arrangements of servers on racks are increasingly demanded. Longer service life and smaller size are strongly required of UPS installed in such server rooms under high temperature conditions.

Focusing on nickel-metal hydride batteries that can be used even in high ambient temperatures, Fuji Electric has developed the “LX Series” of mini UPS equipped with nickel-metal hydride batteries and housed in a server rack. In particular, this series of mini UPS is suitable for use in container data centers under severe temperature conditions.

*4: CHAdeMO: Trademark or registered trademark of the CHAdeMO Association

*5: 80 PLUS: See “Explanation 1” on page 217

(7) Large capacity UPS

At large-scale data centers that handle public systems and corporate infrastructure systems, because higher reliability and long-term stability are sought, UPSs are positioned as critical devices for electrical equipment. Systems are typically configured with redundancy using multiple 500 kVA class large-capacity UPSs. For these types of UPS for data centers, efficiency and small size are considered to be extremely important and particularly, as in the case of the aforementioned power supplies for servers, efficiency in the low load region attracting attention.

The “HX Series” that uses AT-NPC 3-level conversion technology not only realizes high efficiency and smaller size, but by reducing the no-load loss, which is a characteristic of 3-level conversion, greatly improving efficiency at low loads.

(8) Large capacity PCS

PCS for mega solar plants are required to have high efficiency and low installation costs.

In a PCS inverter unit, AT-NPC 3-level conversion technology is used to realize higher efficiency. Also, an outdoors-type package product that integrates a PCS, transformer and switches has been developed. As a result, the installation cost can be reduced and the construction period can be shortened, enabling a reduction in the total construction cost of a mega solar system.

4. Postscript

This paper has discussed the technical trends and current status of product development for power electronics equipment.

In response to market demands, power electronics equipment have driven innovation in the basic technologies of circuit technology, control systems and power semiconductors. This innovation corresponds to RB-IGBTs and AT-NPC 3-level circuit technology as well as to dedicated modules, DC distribution devices and the like, and SiC devices are expected to continue to be used in the future. Additionally, in the application fields of power electronics equipment, various peripheral technologies have been actively incorporated to meet market demands in each field.

In the future, Fuji Electric intends to contribute to society by further increasing the technical level and expanding the application areas of power electronics equipment.

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Latest Technology for General-Purpose Inverters and Servo Systems

SAKAI Toshiaki † IMOTO Hiroyuki †

ABSTRACT

General-purpose inverters are used in a wide range of industrial fields, including transportation machinery, air conditioners, and machine tools. Fuji Electric offers a lineup of new products that meet various needs. We have realized easy system construction with auto tuning and vector control for synchronous drive system, and enforced energy savings and reduced electric power for air conditioning dedicated inverters using temperature difference constant control and estimated end pressure control functions, and lined up a new product expanding the range of applications to high-speed and multi-axial control for high-performance vector control inverters. For servo systems, we have developed new products that realize optimal adjustment through application-specific auto tuning and enrich replacement methods from older models, as well as packaged products designed for ease of use.

1. Introduction

The market for general-purpose inverters and servo systems appeared to have recovered from the recent economic downturn precipitated by the collapse of the Lehman Brothers, but due to the Great East Japan Earthquake occurring in 2011 as well as the effects of monetary tightening in China, is still in the bottom of the trough. Market requests for not only improved performance, but also for improved ease of use of these drive equipment are increasing. This paper introduces the latest technologies of general-purpose inverters, based on technical trends, to meet such market demands, and also describes several application examples.

2. Production Lineup

2.1 General-purpose inverters

Figure 1 shows Fuji Electric’s product lineup of general-purpose inverters.

Fuji Electric provides five series of general-purpose inverters: the “FRENIC-Mini,” “FRENIC-Multi,” “FRENIC-Eco,” “FRENIC-MEGA” and the vector control type “FRENIC-VG.” The main features and uses of these products are shown in Table 1.

2.2 Servo systems

Figure 2 shows Fuji Electric’s product lineup of servo systems.

The “ALPHA5 Smart Series” has been developed as a functionally limited version of the “ALPHA5 Series.” With capacities ranging from 0.05 to 3 kW and a frequency response of 1,500 Hz, the ALPHA5 Smart Series provides the same performance as the ALPHA5

Series, but by limiting its functions, such as by removing a USB terminal, realizes an advantage in terms of price. This product is intended primarily for deployment overseas.

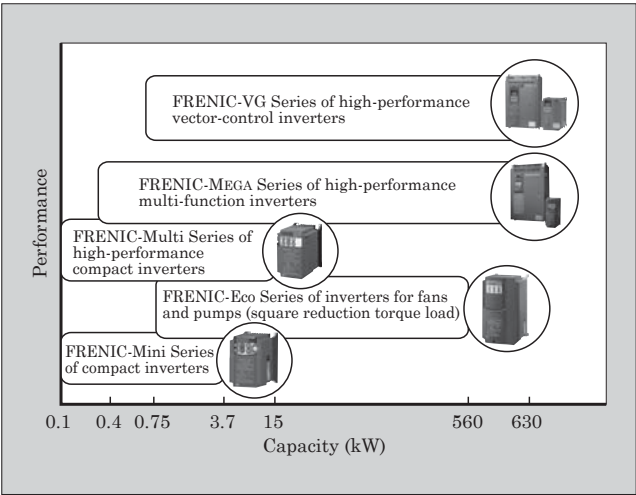


Fig.1 Fuji Electric’s product lineup of general-purpose inverters

Table 1 Features and uses of general-purpose inverters

Inverter series name	Main features and uses
FRENIC-Mini	Compact size for variable speed control of 3.7 kW or less
FRENIC-Multi	Compact size for variable speed control of 15 kW or less, for constant torque load
FRENIC-Eco, FRENIC-Eco Plus	Standard size for variable speed control of 560 kW or less, for square reduction load
FRENIC-MEGA	Standard size for variable speed control of 630 kW or less, for constant torque load
FRENIC-VG	High-performance vector-control inverter of 630 kW or less

† Fuji Electric Co., Ltd.

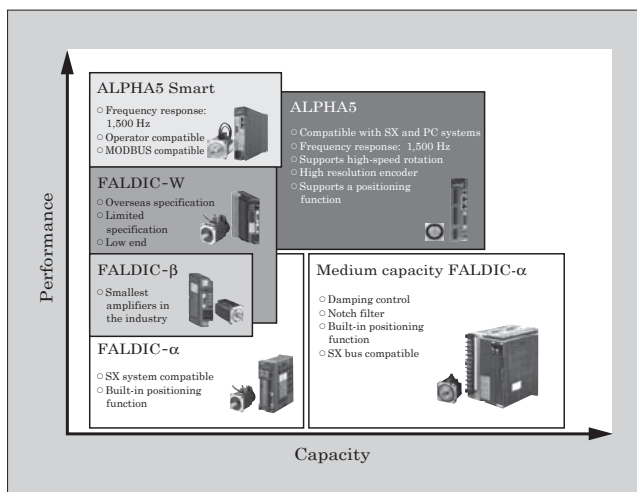


Fig.2 Fuji Electric's product lineup of servo systems

3. Latest Technology for General-Purpose Inverters and Examples of Their Application⁽¹⁾

General-purpose inverters are used for the variable speed control of three-phase induction motors. In recent years, with application to synchronous motors and support of application-specific control functions, there has been an increased variety of models.

3.1 “FRENIC-MEGA Series” of synchronous drive systems

An IPM motor containing an internal permanent magnet in the rotor of a motor has low loss and enables smaller size and higher efficiency. An overview of Fuji Electric's synchronous motors is shown in Table 2.

The synchronous motors of each series are driven by a single inverter with sensorless vector control or with sensor vector control. In typical inverters for induction motors and inverters for synchronous motors, the following points differ significantly depending on the presence of a motor magnet.

(1) Auto tuning of synchronous motors

In the vector control of synchronous motors, information of the electrical parameters of a motor (armature resistance, inductance and back electromotive force) is necessary. When driving a synchronous motor with an inverter, the type and capacity of the motor can be specified, and all the other electric parameters will be set automatically.

Additionally, by performing auto tuning for the motors, electrical parameters can be read from the inverter. This allows a synchronous system of maximum efficiency to be constructed easily.

(2) Vector control of synchronous motors

Even if the electrical parameters of a synchronous motor have been set, the actual rotation angle of the motor (magnetic pole location) must be known. With sensorless vector control, a sensor is not used and therefore the magnetic pole location is detected at motor startup. According to the magnetic pole location, alternating magnetic flux is generated with high-frequency waves oriented in a fixed direction so that the shaft does not rotate inside the motor, and estimation calculations are performed based on the value of current flowing in the windings. In the case of sensor vector control, once the magnetic pole location is detected, the motor will be able to output maximum torque from its stopped state to the rated rotational speed. For this reason, synchronous motors can be used in the fields where conventional DC motors have been applied, such as extruders.

Table 2 Overview of Fuji Electric's synchronous motors

Series	Capacity range	Shape	Efficiency level	Control method
GNS type	5.5 to 200 kW	Induction motor compatible	IE4	Sensorless vector control
GNP type	5.5 to 90 kW	Induction motor compatible	IE4	
GNB type	5.5 to 540 kW	Compact	IE3	
GNF type	5.5 to 425 kW	Compact	IE3	Sensor vector control

quency waves oriented in a fixed direction so that the shaft does not rotate inside the motor, and estimation calculations are performed based on the value of current flowing in the windings. In the case of sensor vector control, once the magnetic pole location is detected, the motor will be able to output maximum torque from its stopped state to the rated rotational speed. For this reason, synchronous motors can be used in the fields where conventional DC motors have been applied, such as extruders.

3.2 “FRENIC-Eco Plus” dedicated inverter for air conditioning

The method of using an inverter with an induction motor driven by a commercial power supply and reducing the rotational speed to save energy is well known. Additional energy savings and a further reduction in power usage can be achieved with an autonomous control-type “FRENIC-Eco Plus” inverter. This inverter has functions for temperature difference constant control and estimated end pressure control, and realizes the optimal control for fans and pumps. Display settings can be specified in units of flow rate and pressure.

(1) Temperature difference constant control

In air-conditioning equipment such as refrigerating machines, the temperature difference between the inlet and outlet may be controlled to be constant. If the temperature difference becomes constant, rather than circulating cooling water unnecessarily, the rotational speed of the motor can be reduced to save energy. As shown in the application example of Fig. 3, the FRENIC-Eco Plus has two temperature sensor inputs, and this temperature difference can be held constant.

Figure 4 shows measured values of power consumption as a result of constant temperature difference control. In particular, the significant reduction in power consumption during the winter is the result of a lower cooling water temperature due to the outside temperature, and because the cooling water is not circulated unnecessarily.

(2) Estimated end pressure control

In the case where water is delivered by a pump, a method exists for maintaining constant pressure (water pressure) at the end terminal of the path. The water

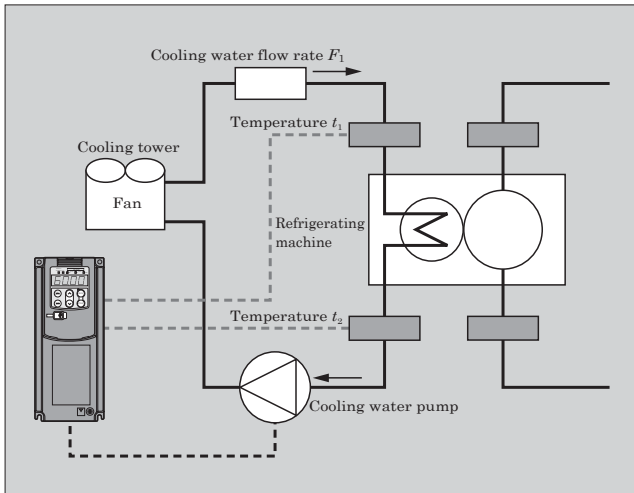


Fig.3 "FRENIC-Eco Plus" application example

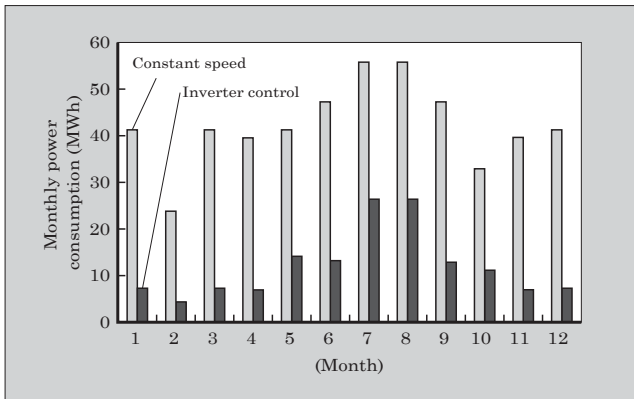


Fig.4 Measured power consumption as a result of temperature difference constant control

ter pressure decreases due to pipe resistance along the path to the end terminal. Because the pipe resistance for water is closely correlated with the flow rate, the flow rate and pressure characteristics are recorded in the inverter and are used in controlling the rotational speed of the pump. Consequently, operation that is significantly more energy-efficient than constant discharge pressure (constant pressure at the pump outlet) control can be realized. Estimated end pressure control, which does not require a pressure sensor at the end terminal, enables simplification of the installation work and can be used to configure a maintenance-free system.

With the FRENIC-Eco Plus, proportional control and constant temperature and pressure control can additionally be selected, and a system configuration other than the conventional simple PID control is possible. This is the only example in Japan of a commercialized autonomous control-type inverter that does not require an additional regulator.

3.3 "FRENIC-VG" high-performance vector-control inverter

The FRENIC-VG Series has 600 Hz frequency re-

sponse, and supports not only a 1,024 pulse encoder that is compatible with conventional models, but also a 17-bit serial encoder (131,072 pulse resolution) that is used with servo systems. Various systems can be configured with the following control methods.

(1) Precise synchronous control

In the case where a single machine is driven by multiple motors, the amount of rotation of each motor must be in agreement at all times, including when decelerating or accelerating. With the FRENIC-VG Series, precise synchronous control can be configured easily with a "MICREX-SX" programmable controller and an "E-SX bus." The "SPH3000MM" CPU module of the MICREX-SX has a minimum tact time of 0.25 ms, and tact fluctuation of less than 1 μ s. For this reason, synchronicity is fully ensured on the position control side, and the machine-side moment of inertia, the position adjustment system and the speed adjustment system affect the synchronous precision.

The E-SX bus is a system that features a 100M bits/s communication rate, maximum separation between stations of 100 m, and a total length of up to 1 km. Even in a large capacity precise synchronous control system, an inverter and a motor can be arranged freely with few restrictions relating to the layout on the control board. Figure 5 shows a system configuration of the E-SX bus.

(2) Multi-axis control

Semiconductor manufacturing equipment and metal processing equipment require many types of motion control, including spindle control, traverse control, dancer control, PTP positioning control, winding control, and the like. Motor control comprises the categories of positioning control, speed control and torque control, but there are also many devices in which these are mixed. With the MICREX-SX system, programs can be incorporated that mix these types of control, and there are few restrictions on the number of control spindles. Because both vector inverters and servo inverters can be connected directly to the SX bus system, mixed systems ranging from the 0.05 kW minimum capacity of a servo system to the 630 kW maximum



Fig.5 System configuration of E-SX bus

capacity of a vector inverter can be constructed easily.

The SX bus is a system that features a 25 Mbits/s communication rate, maximum separation between stations of 25 m, and a tact time of 1 ms. A high-speed communication interface (SX bus interface) is available for general-purpose inverters and other devices.

4. Latest Technology of the “ALPHA5 Smart Series” of Servo Systems and Application Examples

The latest technology used in the “ALPHA5 Smart Series” and an application example of a packaging machine that uses a programmable operation display (POD) and a MICREX-SX controller are described below.

(1) Individual tuning modes selectable for each application

In a servo system, internal gain must be adjusted in order to drive the associated mechanical system optimally. Previously, adjustment was typically performed by auto tuning. In the case of belt driving with a long travel distance, however, resonance or vibration may occur midway during the travel, requiring an engineer to adjust the parameters one-by-one. The adjustment of equipment of overseas customers required a significant amount of time just to reach the overseas site, and a quick response was not possible in some cases.

With the ALPHA5 Smart Series, in order to solve these problems, rules for optimal adjustment with individual tuning modes selectable for each application have been established. Figure 6 shows a block diagram of the individual tuning modes that are selectable for each application. The ALPHA5 Smart Series automatically changes its internal gain adjustment depending on the machinery configuration, and in addition to auto tuning, is provided with three other modes: interpolation operation, short cycle time operation and trace operation. The tuning setting method changes according to the type of mechanical system (ball screw, belt, and the like), and can be selected by the customer

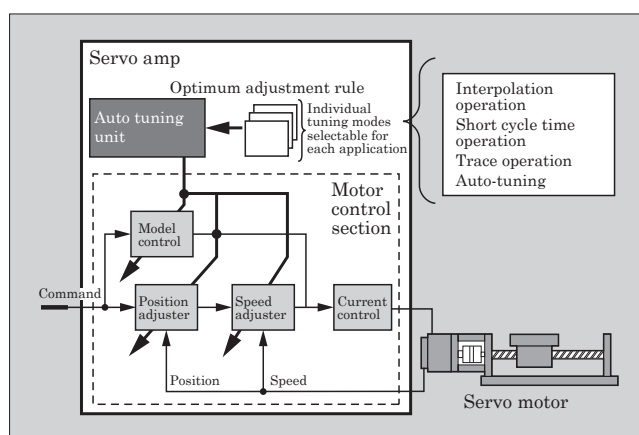


Fig.6 Modes selectable for each application

according to the application or the type of mechanical system. Because many electrical engineers are usually in charge of making the adjustments, this series has adopted a method for selecting the tuning mode according to the application.

(2) Parameter conversion technology using a PC loader

The previous method for replacing an older machine with a new machine had been to read out the parameter data, and then transfer that data to the new machine. This method required an operator to check the parameter values one-by-one, convert the values to the corresponding parameter values of the new machine and set the parameters accordingly, but there was a risk of notational errors or of conversion mistakes. As long as a single machine was targeted for replacement, the parameters could be checked and the replacement completed. When tens of spindles are to be replaced with a single system, however, the parameter conversion work becomes very time-consuming, and the likelihood of a mistake increases. Accordingly, it was necessary to proceed with caution, and a tremendous amount of time was required.

Consequently, Fuji Electric created a new parameter conversion tool. Figure 7 shows the PC loader screen of the parameter conversion tool. Using this tool, the parameters readout from an older machine can be converted directly to the parameters for a new machine, thus allowing the parameter conversion task to be completed simply by transferring the parameters after conversion to the new machine.

Because humans are not involved in the conversion process, the possibility of mistakes occurring is nearly zero, and even in cases of a large number of spindles, parameter replacement can be accomplished reliably within a short amount of time. This function is intended to provide compatibility with older machine models.

(3) Example application to packaging machine

Packaging machinery can be broadly classified into the three categories of vertical intermittent motion, vertical continuous motion and horizontal continuous motion. Each type can be used to package surface

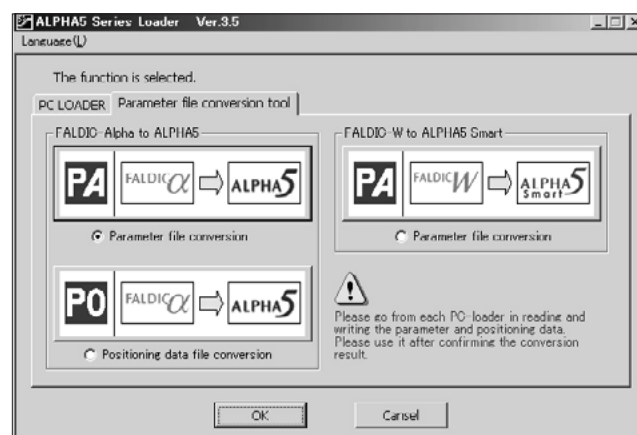


Fig.7 PC loader screen for parameter conversion tool

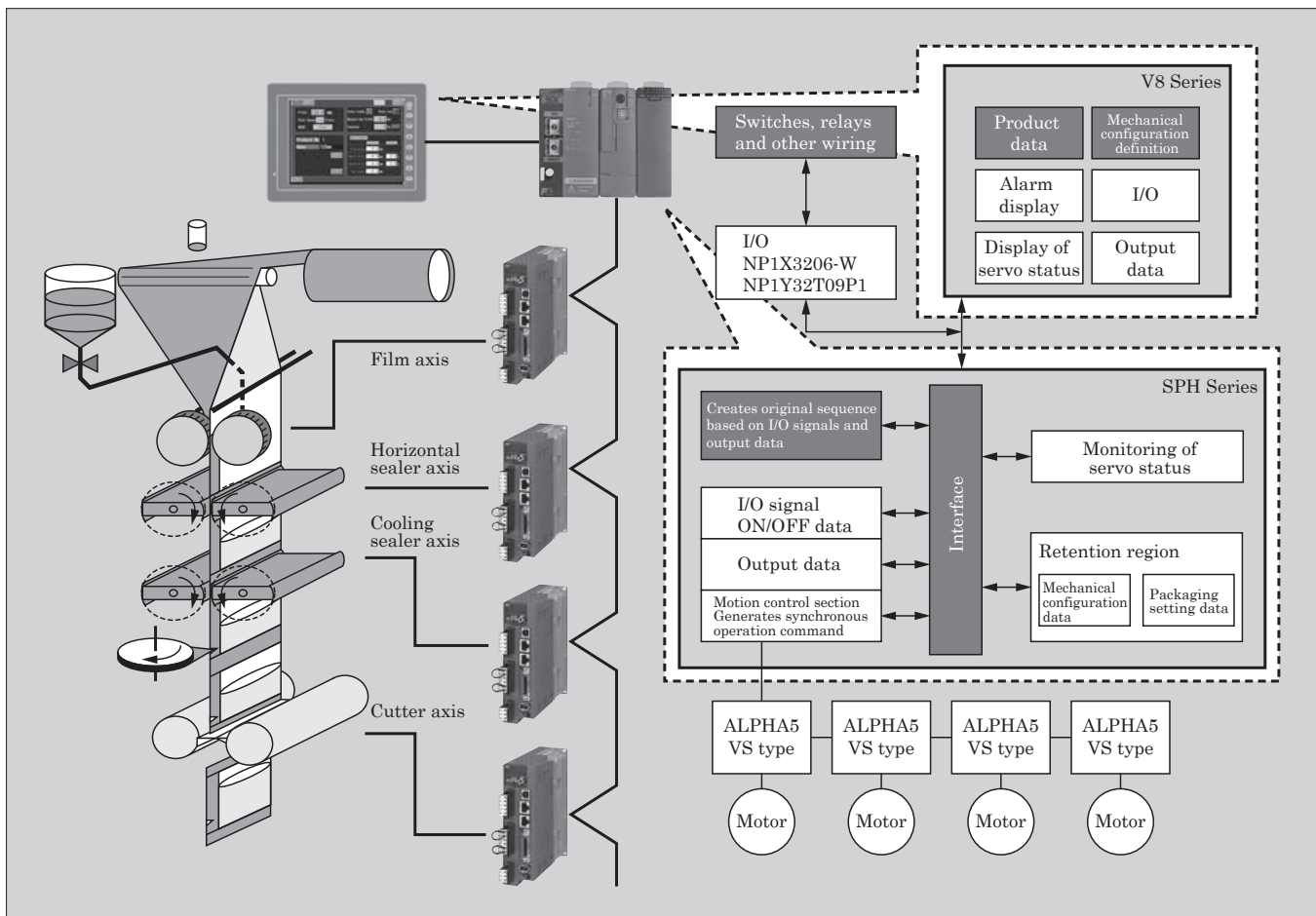


Fig.8 Example application to vertical packaging machine using a software package

sheets for plastic bottles, powder for medicine and bread, and the like.

Fuji Electric has extensive experience and expertise in control technology in Japan. In addition to providing close technical support to its customers, so that overseas customers can easily construct a system themselves, Fuji Electric has incorporated its control system expertise into a software package so as to be able to provide systems that do not require constant monitoring.

Figure 8 shows an example application to a vertical packaging machine. This system is configured from a POD, a MICREX-SX controller and a 4 axis servo system, and is used for packaging powders such as medicines, and liquids such as food flavorings.

Previously, in order to control this vertical packaging machine, it had been necessary to create a POD screen and a MICREX-SX program. With the POD, screens for product data settings, mechanical configuration definitions (required for each servo system axis), I/O settings, and the like had to be created. Additionally, with the MICREX-SX, programs for I/O data, motion control unit, mechanical configuration setting data, and the like had to be created, and the development thereof required a tremendous amount of time.

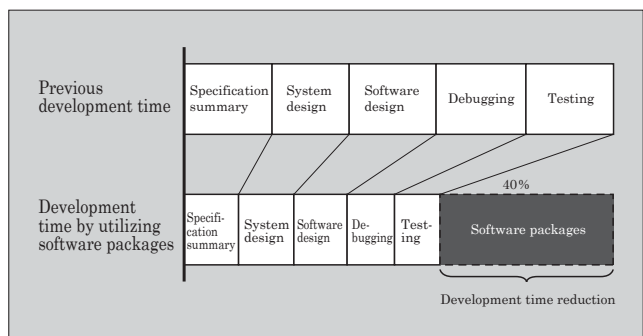


Fig.9 Comparison of development times when creating programs

The newly created software package incorporates a motion control unit for controlling the servo system and can be applied directly. Customers only have to create the remaining specific programs for their packaging machines. By providing a specific software package for packaging machines, the time required for development has been reduced by approximately 40% compared to that of conventional development (see Fig. 9).

Furthermore, for machinery manufacturers attempting to enter overseas markets for electronically-controlled packaging machines, system construction

had presented a barrier to entry in the past, but this method has brought the benefit of enabling easy construction, even if developing such a system for the first time. A software package tailored to a certain industry such as this is a breakthrough accomplishment of Fuji Electric.

5. Postscript

This paper has introduced the latest technology of general-purpose inverters and servo systems, and has described examples of their applications.

General-purpose inverters are expected to become further tailored to individual applications through

combination with highly efficient synchronous motors and the provision of energy-saving and power reducing functions. For servo systems, rather than simply improving motor control performance, the provision of a system capable of realizing a function for suppressing machine vibration and of shortening the startup time of the machinery itself is needed. Fuji Electric intends to continue to develop products that fully meet these needs.

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“FRENIC-VG,” a High-Performance Vector-Control Inverter

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ABSTRACT

Inverters for variable speed control of AC machines used in general industry applications mainly use either V/f constant control or vector control. Fuji Electric has developed the “FRENIC-VG”, a new high-performance vector control model, which realizes high precision and high functionality while complying with functional safety standards. It has various outstanding features, including optimized detection circuits, improved speed control precision, speed sensorless vector control, use of multiplex systems, and connection to “E-SX bus.” Application examples include optimal tension control and miniaturization of winder control circuits in wire drawing machines, and high-capacity support, high starting torque, and load adaptive control for cranes.

1. Introduction

Inverters used for the variable-speed control of AC machines in general industrial applications primarily use either V/f constant control or vector control. In applications for which simple variable-speed control and vector accuracy at low speeds are not critical, V/f constant control has evolved as the mainstream control method. On the other hand, vector-control inverters have continued to evolve in response to the desire to control torque as easily in an AC motor as in a DC motor.

Fuji Electric provides a product line of vector-control inverters, and Fuji’s newest series of high-performance vector-control inverters, the “FRENIC-VG,” was launched in 2011.

This paper describes the new technology and functions incorporated into the FRENIC-VG, and introduces application examples.

2. Concept and Features

2.1 Concept

Fuji Electric has been providing general-purpose vector-control inverters as products for use primarily by machinery manufacturers and in small and medium-sized plants. In recent years, there has been increasing demand for the higher functionality and precision of machinery and equipment, and for higher plant productivity and the like, and there is a growing need for vector-control inverters capable of performing high-precision detailed control.

Under these circumstances, the trend toward larger capacity drive systems for such machinery and equipment as servo press machines and injection mold-

ing machines has advanced, and the support of such machinery and equipment with present-day servo systems would be difficult. On the other hand, in order to prevent personal injury and accidents involving machinery, the concept of risk assessment in functional safety standards is attracting attention, and functional safety standards for inverters have also been increasingly demanded.

To meet these market needs, the FRENIC-VG provides high accuracy, high functionality and capacities of up to 630 kW, and also complies with functional safety standards. Figure 1 shows the appearance of the FRENIC-VG.

2.2 Features

- (1) Improved high-speed response



Fig.1 “FRENIC-VG”

[†] Fuji Electric Co., Ltd.

The FRENIC-VG speeds up the vector control computation period by adopting a hardware system construction that uses an optimized detecting circuit and high-speed high-resolution analog-to-digital conversion technology for detecting the motor current and voltage, and is also equipped with a microprocessor able to perform high-speed computations.

A speed response of 600 Hz was realized with speed sensor-equipped vector control, enabling application to the aforementioned servo systems, in addition to wire drawing machines, winding machines, printing presses and other applications that require responsiveness, thereby expanding the field of application further (see Table 1).

(2) Improved accuracy of speed control (reduction of rotational fluctuation)

In vector control with speed sensor, pulse signals are received from a speed sensor (PG: pulse generator) attached to the motor, and the actual motor speed is computed from changes in this pulse. However, because the frequency of this pulse decreases as the speed decreases and because the change in pulse rate is small within the control period, the speed could not be computed accurately. As a result, the accuracy of the speed control deteriorated and rotational fluctuation occurred.

With the FRENIC-VG, a new pulse change detection function is provided in a custom LSI and the speed computation algorithm has been improved to enhance the accuracy of speed computation at low speeds.

At low speeds, where changes in the pulse rate are smaller within the control period, the speed is computed according to the time required from one pulse change point until the next change point and from measured values. At very low speeds with a non-varying pulse rate during the control period, the speed is estimated from the previously computed value of the

speed. With this method, even without using a high-resolution PG, the speed control performance at low speed is improved and rotational fluctuation is reduced to approximately 1/3rd that of previous models (see Fig. 2).

(3) Vector control without speed sensor

Vector control with a speed sensor provides excellent performance, including high responsiveness and high accuracy, but requires the installation of a PG on the motor, as well as wiring and the like.

Vector control without speed sensor is a control method in which the motor speed is computed from the motor terminal voltage and current and from electrical constants of the motor.

With the FRENIC-VG, in addition to a faster computation period, the motor voltage detecting circuit has been improved so as to enable 3-phase detection, the detection resolution has been improved, the speed control range has been expanded and low speed torque characteristics have been improved (see Fig. 3).

(4) Multiplexed system

Previously, to increase capacity, either a multi-winding motor with split windings was driven using multiple inverters, or a method of coupling the inverter output with reactor was used. With the FRENIC-VG, a direct parallel connection method for directly connecting the inverter outputs in parallel with the motor terminals is realized, thereby eliminating the need for the use of a reactor or a motor with special windings. In this method, the problem of cross current flow between inverters due to an imbalance in output voltage caused by fluctuation of the switching timing of an Insulated Gate Bipolar Transistor (IGBT) was solved using high-speed cross current suppression control.

Table 1 Comparison of speed response

Product name	Speed response
FRENIC-VG	600 Hz
FRENIC5000-VG7 (prior model)	105 Hz
FRENIC5000-VG5 (model of 2 generations ago)	54 Hz

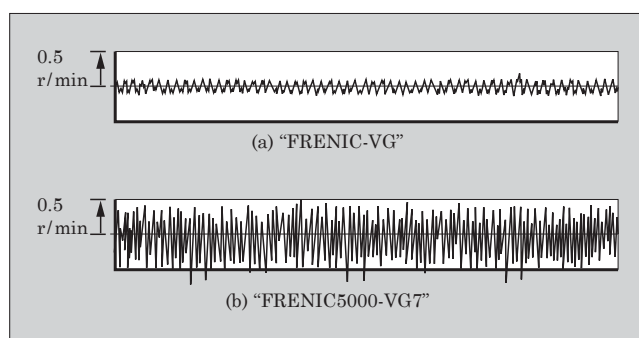


Fig.2 Suppression of rotational fluctuation

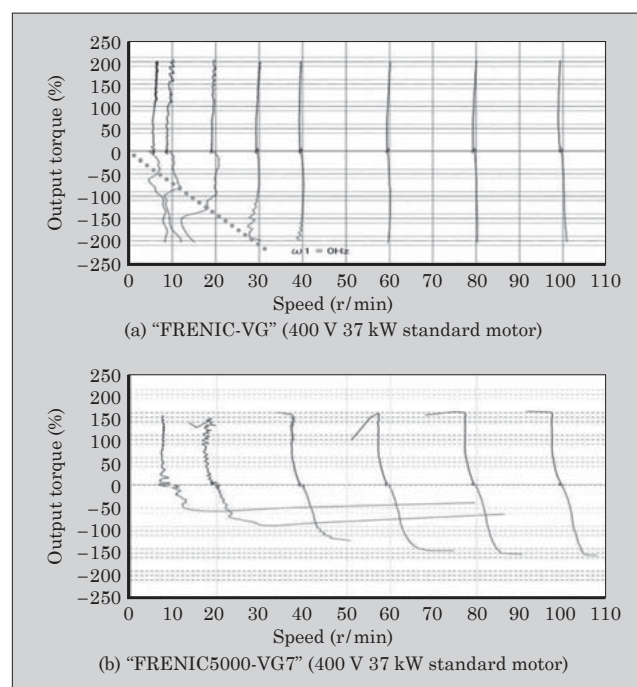


Fig.3 Torque characteristics at low speed

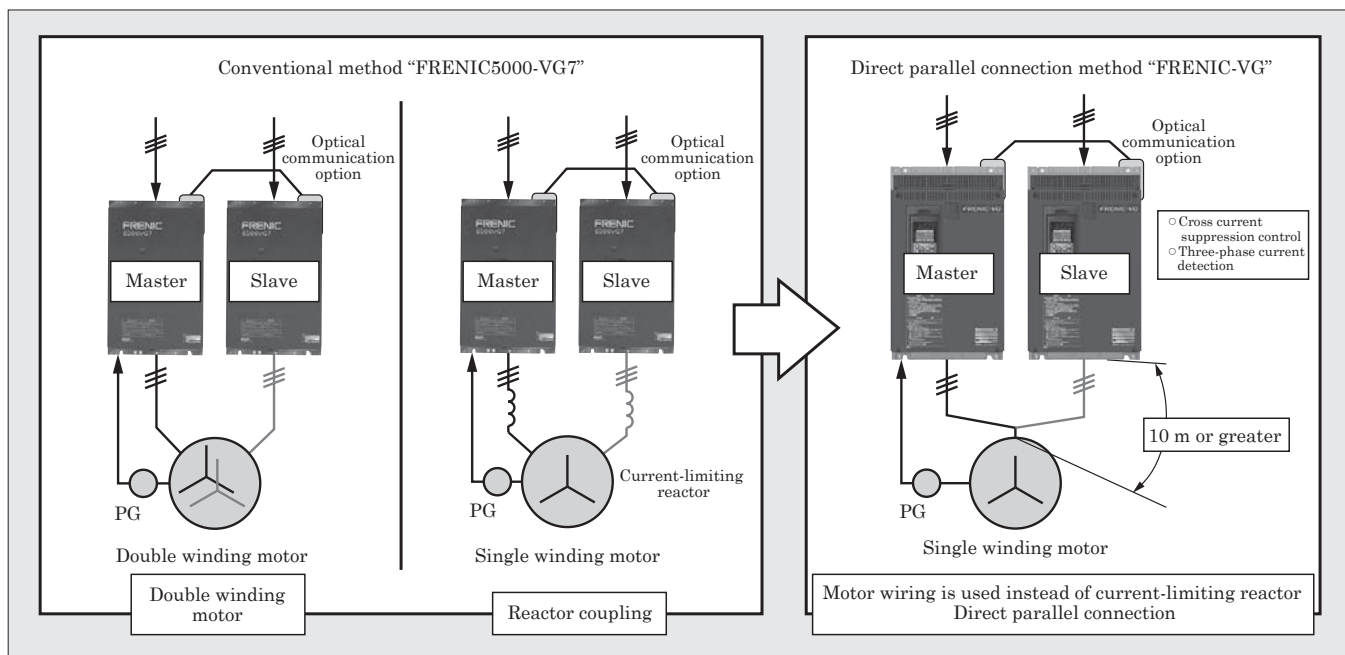


Fig.4 Direct parallel connection of inverters

Additionally, in the case where even one of the inverters fails, remaining inverters can operate, and applications to plant equipment and other critical facilities that require redundancy is anticipated (see Fig. 4).

(5) “E-SX bus”

The FRENIC-VG is equipped with a communication option that enables connection to the “E-SX bus” used with Fuji Electric’s “MICREX-SX SPH3000MM” integrated controller.

The E-SX bus realizes faster bus communication (I/O refresh at up to 250 μ s) and a new control method that synchronizes the task cycles of devices connected to the bus to improve the overall control performance of the MICREX-SX SPH3000MM. This new bus communication specification synchronizes the data I/O timing with accuracy of ± 1 μ s.

With the FRENIC-VG, in order to support the E-SX bus, the computational speed of the communication software was increased and the communication LSI was improved. A portion of the feedback control, such as torque and speed control of the motor, can be implemented with the MICREX-SX SPH3000MM, thereby expanding the versatility of the control. Additionally, the MICREX-SXSPH3000MM is capable of synchronously controlling multiple motors through multiple FRENIC-VG inverters, and in the case of a printing press or the like for which multi-axis control is implemented, multiple mechanical mechanisms that had been required in the past can also be simplified.

(6) Support of functional safety

The FRENIC-VG is standardly equipped with an STO function (EN terminal) that complies with the IEC 61800-5-2 standard for functional safety, and the safety functions shown in Table 2 can be added by installing an optional safety function card.

Table 2 Safety function
(Functional safety standard: IEC61800-5-2)

Level	Function
STO: Safe Torque Off	Shuts down the output, sets motor to free-run state
SS1: Safe Stop 1	Decelerates motor and shuts down output at specified condition
SLS: Safely Limited Speed	Prevents motor from rotating faster than specified speed
SBC: Safe Brake Control	Outputs signals for controlling the motor brake

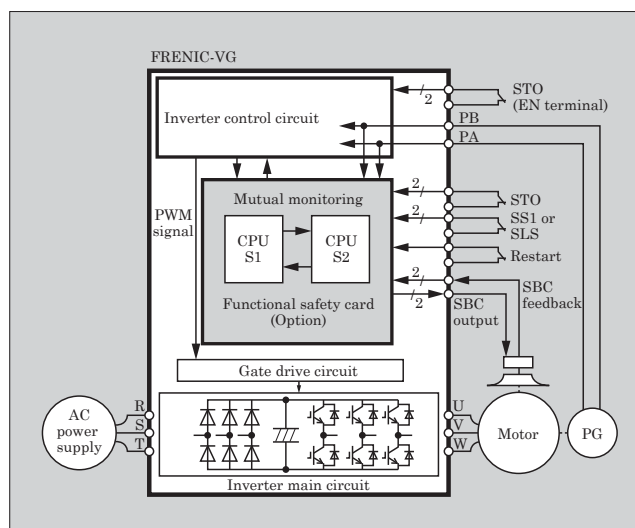


Fig.5 Configuration of functional safety system

Figure 5 shows the configuration of the functional safety system. A commonality of the functional safety system is that there are two systems for each terminal so that reliable operation can continue even if one

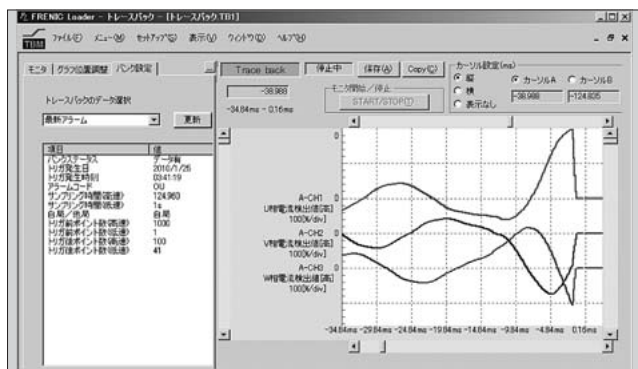


Fig.6 Trace back

of the systems fails. Additionally, the safety function card incorporates redundancy and is equipped with two CPUs, each of which monitors the normal operation of the other CPU. In the case where an error is detected, the output to the motor is shut off.

(7) PC loader, trace back

The FRENIC-VG is equipped with a PC loader and a clock function, and a PC connected through the USB connector on the front of the FRENIC-VG is able to set and reference function codes, and to monitor and trace various types of data during operation.

With the trace back function, the time and date of occurrence of an event, and various operational data immediately before and after the occurrence of an alarm are stored in internal memory. This data can be displayed as a waveform with the PC loader and facilitates cause analysis in the case of an alarm (see Fig. 6).

3. Application Examples

Examples of the application of the FRENIC-VG to a wire drawing machine and a crane are described below.

3.1 Application to wire drawing machines

A wire drawing machine is a type of metalworking machinery that processes thin wire diameters by pulling an iron wire or other wire material with a wind-up pot and passing it through a die. After processing is complete, the wire can be wound with a winding machine. Speed control as well as tension control of a winding machine is important for a wire drawing machine.

(1) Overview of wire drawing machines

In the case where the wire diameter will be subjected to a large amount of processing, because the wire would break if processed in all at once, the processing is carried out with multiple wire drawing machines to narrow the diameter gradually. In some cases, the wire is processed continuously using about ten wire drawing machines. Additionally, a dancer roll is provided between each wire drawing machine so that wire tension is not a cause of interference. Dancer rolls are able to move vertically (or horizontally accord-

ing to the configuration of the machine), and provide slack with the appropriate tension between each wire drawing machine. However, because thick wires and the like cannot easily be placed into a wire drawing machine, straight wire drawing machines that do not use dancer rolls between the wire drawing machines are also needed.

(2) System configuration

Figure 7 shows an example system configuration of straight wire drawing machines. The main components of a wire drawing machine are the die for processing the wire, and the wind-up pot for pulling the wire. Depending on the amount of processing to be carried out on the wire, multiple wire drawing machines may be used with the wire being wound onto a winding machine in the final stage. In the case where a traverse winding device^{*1} is attached to the winding machine, disturbances due to operation of the traverse winding device can cause tension fluctuations to occur in the winding machine. Providing a dancer roll between the master wire drawing machine and winding machines prevents interference between the master wire drawing machine and the winding machine.

(a) Control of a wire drawing machine

The master wire drawing machine implements speed control with line speed commands output from a soft start/stop circuit based on speed commands from a line speed setting device. The soft start/stop circuit adds a time gradient to the acceleration and deceleration.

A tension calculation circuit detects the tension with torque signals from each inverter, and implements control so that the tension balance between wire drawing machines is stable, and applies the appropriate tension to the wire. The speed correct-

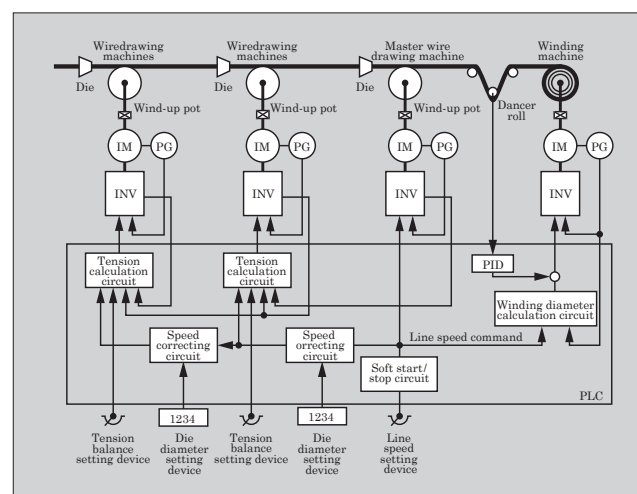


Fig.7 Example system configuration of straight wire drawing machines

^{*1}: A traverse winding device is a cross-winding device for distributing wire so that it does not clump in one place on a winding machine and become unwindable.

ing circuit corrects for fluctuation in the speed of wires that have passed through the dies and have been made narrower. For the other wire drawing machines, tension is controlled with this tension controlling circuit and speed correcting circuit.

(b) Control of the winding machine

Tension between the winding machine and the master wire drawing machine is controlled with a dancer roll. Changes in speed due to fluctuations in the winding diameter are corrected by a winding diameter calculation circuit. Also, the winding diameter is computed for the current winding diameter according to line speed commands and the actual speed of the winding machine motor (detected with a PG).

(3) Benefits of using the FRENIC-VG

Benefits of the FRENIC-VG are described for the case when used in conjunction with a straight wire drawing machine.

(a) Realization of optimal tension

The torque accuracy and torque ripple required for tension control have been improved compared to the previous model, and the use of an E-SX bus enables faster communication of the control signals from a PLC. As a result, tension can be controlled appropriately for the wire material, wire breakage and slack and the like is reduced, and stable operation is possible even at faster line speeds. Additionally, because rotational fluctuation at low speeds can be mitigated, cases in which the wire is narrow but the winding diameter ratio (minimum winding diameter: maximum winding diameter) is large can also be supported.

(b) Miniaturization of the braking circuit for winding machines

When a traverse-equipped winding device is attached to a winding machine, disturbances occur, and the operation periodically changes to a braking mode in which regenerative energy is produced. The FRENIC-VG is standardly equipped with a DC common bus terminal to which DC circuits for the inverters for winding machines and wire drawing machines are connected, enabling regenerative energy of the winding machine to be processed with the wire drawing machine. As a result, the winding machines can be miniaturized without a braking circuit. Additionally, a braking circuit (a driving circuit for the braking resistor) for emergency stopping such as in the case of wire breakage is also equipped as a standard feature (200 V and 55 kW or less, or 400 V and 160 kW or less).

3.2 Application to cranes

As the size of cranes used at manufacturing plants, harbor ports and the like increases, the capacity of the installed drive systems is also increasing. Also, in the event that an inverter fails, early recovery is required.

(1) Overview of cranes

Cranes are configured from a main hoisting mechanism for raising and lowering a suspended load, a hoist traverse mechanism for moving the hoisting mechanism horizontally, a travel mechanism for moving the crane itself forward and backward, and a derricking mechanism for raising and lowering the boom.

(2) Crane system configuration

The mechanical configuration of a quayside crane used for loading and unloading containers to and from a container ship at a harbor port is described below. Approximately one-half of the operating patterns for the main hoisting mechanism are the braking mode. Also, a pulse width modulation (PWM) converter is provided in the power supply to handle harmonic current.

(a) Inverter for main hoisting mechanism

With the main hoisting mechanism that raises and lowers a container or other load, because main hoisting and travel operations are not performed simultaneously, the main hoist motor and the travel motor are switched to implement control. When driving the main hoisting motor, because holding torque and starting torque are required in order to raise and lower a container, operation is carried out by vector control with speed sensor. The main hoisting mechanism rarely operates at rated capacity, and often operates with a load that is lighter than the rated load. Thus, load adaptive control is used in a speed range corresponding to the load, and the operational efficiency is improved.

(b) Inverter for hoist traverse mechanism

The traverse mechanism that moves horizontally in the lateral direction may operate simultaneously with the main hoisting mechanism, and is therefore operated by vector control with speed sensor since traverse speed responsiveness is also required.

(c) Inverter for derricking mechanism

The derricking mechanism that raises and lowers the boom around a cantilever or other attachment does not operate simultaneously with the travel mechanism, and is therefore controlled with the same motor switching control as the main hoisting mechanism. Also, because the derricking speed is slow, vector control without speed sensor is used in some cases.

(d) Inverter for travel mechanism

In order to drive multiple small-capacity motors simultaneously, the travel mechanism is operated with V/f control.

(3) Benefits of using the FRENIC-VG

(a) The normal driving inverter and the backup inverter have been combined to achieve lower cost of the electrical equipment

The main hoisting mechanism achieves lower cost of the electrical equipment by employing the direct parallel connection of the FRENIC-VG so that a single-winding motor can be used. Moreover, driv-

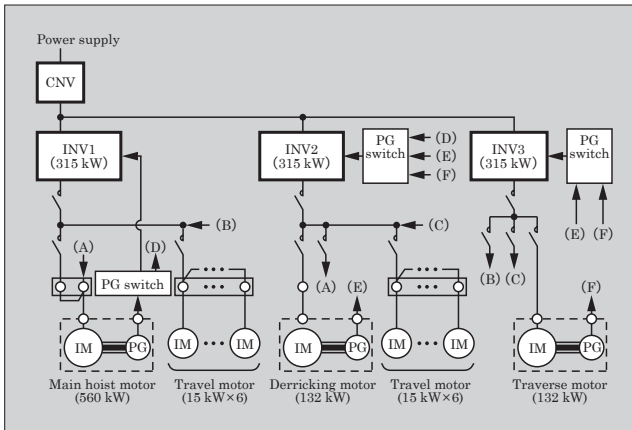


Fig.8 Example application to quayside crane

ing the motor with two inverters has the advantage of enabling reduced device operation, whereby if one inverter fails, the other remaining inverter can be used easily as a backup.

Figure 8 shows an application example using FRENIC-VG inverters. In this example, INV2 is available to backup the main hoisting, derricking, traveling and traversing operations, and INV3 is available to backup the traversing, main hoisting, traveling and derricking operations; and even if an inverter fails, depending on the location of the failure, the crane will be able to carry out its normal operation without impediment, and without a recovery and replacement operation.

(b) Support for large capacity motors

Large capacity motors can be driven by connecting multiple inverters via the direct parallel connection.

(c) High starting torque

The FRENIC-VG inverters have an overload capability of 200% -3 s and can handle the high torque often required when cranes are started.

(d) Load adaptive control

In the case of a load that is lighter than the rated load, load adaptive control is performed for the main hoisting mechanism to increase automatically the allowable elevating speed limit value beyond its value for rated loads. The load is detected with a load estimating calculation based on the torque current at startup. With the improved torque ripple and responsiveness of the FRENIC-VG compared to prior models, more accurate load estimating calculations, higher allowable elevating speed limit values, and improved operating efficiency can be achieved.

(e) Functional improvement of brake release and applying sequence calculation

A function has been added to permit individual adjustment of the releasing and applying sides during the processing sequence at the time of a brake release/engagement sequence. As a result, the brake adjustment time can be shortened and load swaying can be reduced further.

4. Postscript

The main features and application examples of the newly commercialized “FRENIC-VG” of high-performance vector-control inverters have been introduced.

A lineup of DC power distribution stacking inverters, which are necessary primarily in large-scale plants, is planned to expand the application fields of the FRENIC-VG further. Technical issues such as high-capacity motor driving and redundancy at large-scale plants are solved with the direction parallel connection method.

Fuji Electric will continue to expand the functionality of the FRENIC-VG of inverters and will work to expand their fields of applications to servo systems, large-scale plants and the like.

“GNS Series” & “GNP Series” of High-Efficiency IPM Motors

HIROSE Hideo[†] NAKAZONO Hitoshi[†]

ABSTRACT

Attempting to reduce energy use, as well as rapid resource demands rise, has been a problem worldwide in recent years. To solve this problem, Fuji Electric developed the “GNS Series” and “GNP Series” of high-efficiency interior permanent magnet (IPM) motors, which quest the ultimate reduction of generated loss.

In addition to increased efficiency of electric motors, these motors can greatly reduce power consumption in fan and pump applications through implementing revolution speed control by combining with power electronic devices such as inverters. In addition, their design considers ease of replacement from electric motors already in use and ease of exchanging bearings, arousing demands for energy reduction.

1. Introduction

The electric motor is a key component indispensable for life in society and industrial activity. Electric motors are used in a variety of devices and systems including infrastructure equipment such as air-conditioning fans and compressors, blower fans, water pumps and elevators, and as a motive power supply for various industrial machines such as machining tools, printing machines and cranes. Environmental protection measures for increasing energy savings, curbing CO₂ emissions and the like are being carried out worldwide, and increasing the efficiency of electric motors has become an important matter.

The interior permanent magnet (IPM) motor, a type of permanent magnet motor, has outstanding motor efficiency characteristics. Unlike a typical electric motor, however, the IPM motor cannot be simply connected to a commercial power supply and driven, and instead can only be driven in conjunction with the power electronics equipment known as an inverter. As will be described later, if a high efficiency IPM motor is used in a suitable application, a further energy-savings effect can be obtained as a result of a reduction in energy consumption of the electric motor by itself and by the variable speed control enabled by the inverter. The accurate identification of applications that will exhibit large energy-saving effects as a result of the introduction of a high-efficiency IPM motor and power electronics equipment is extremely important.

This paper introduces representative technologies for increasing the efficiency of electric motors, and describes features of the “GNS Series” and “GNP Series” of high efficiency IPM motors.

2. Electric Motors and Amount of Power Consumption

In 1997, the “Kyoto Protocol” for preventing global warming was adopted, and the curbing of greenhouse gas emissions became a global commitment. Thereafter, efforts to reduce power consumption in the industrial equipment field began in earnest. In particular, in Japan, the “Act on the Rational Use of Energy” (Energy Conservation Law) was amended in 2010, the “standards of judgment for factories etc. on rational use of energy” was announced, and businesses have been mandated to work toward the rationalization of energy usage.

Twenty trillion kWh of power is consumed worldwide, approximately 40% of which is consumed by electric motors⁽¹⁾ (see Fig. 1). A 1% improvement in electric motor efficiency would reduce the worldwide power consumption by 80 billion kWh, and curb CO₂ emissions by 32 million tons. At factories, the power consumption by electric motors used to drive fans and pumps, and to move equipment and the like accounts for a significant proportion of the total power consump-

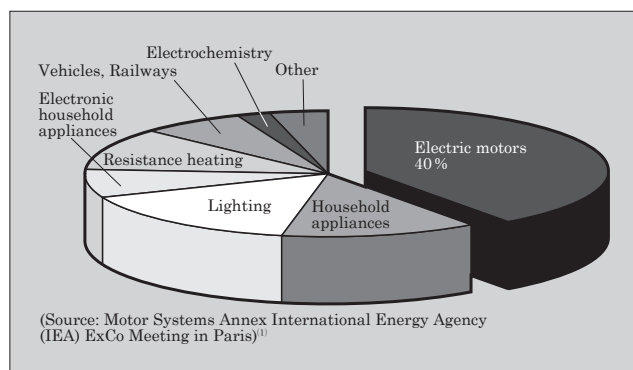


Fig.1 Breakdown of worldwide power consumption

[†] Fuji Electric Co., Ltd.

tion.

To reduce the consumption of power by electric motors, the usage of IE3 premium efficiency motors was made mandatory in the USA as of December 19, 2010, while in Europe, mandatory usage has been set for 2015. Various countries, including Japan, are considering or are planning mandating such usage, and efforts to regulate the efficiency of electric motors themselves are being advanced.

3. Techniques for Increasing the Efficiency of Electric Motors

Figure 2 shows a structural cross-section of an IPM motor. Loss occurs in each part of the electric motor, and techniques for reducing these losses are introduced below.

3.1 General techniques

(1) Reduction of copper loss

Copper loss is Joule loss caused by electrical resistance and current in the motor windings, and is proportional to the resistance value. By optimizing the shape of the stator slots, improving the filling rate and enlarging the cross-sectional area of the conductor, the electrical resistance is decreased and copper loss is reduced.

(2) Reduction of iron loss

Iron loss is the sum of eddy current losses caused by changes in the magnetic flux in the core and hysteresis loss. To reduce the change in magnetic flux in the core, the magnetic flux density is designed to be low, and to reduce iron loss in the material itself, high-grade electromagnetic thin steel sheets that exhibit low iron loss are used.

Additionally, because loss increases if stress is applied to parts of the iron core, it is also important to relieve the stress. For example, when punching an electromagnetic steel sheet in a press mold, loss in the material increases due to the punching strain, but strain-relieving annealing can be performed to prevent an increase in loss and to restore the original magnetic properties.

Iron loss accounts for approximately 40% of the

loss in an electric motor, and it is important that the power loss be computed accurately at the time of design. Iron loss had conventionally been calculated numerically based on the assumption of an alternating magnetic field. Inside an actual electric motor, however, a rotating magnetic field is generated in addition to an alternating magnetic field, and the conventional method did not account for the effect of the rotating magnetic field. Therefore, in order to improve the calculation accuracy, highly accurate computations are presently being implemented using the finite element method or the like to account for the loss due to the rotating magnetic field. In consideration of the balance with copper loss, the number of poles, winding method, number of slots and core shape are optimized to realize higher efficiency.

(3) Use of permanent magnet

An induction motor generates magnetic flux on the rotor side by flowing an induction current in a secondary conductor of aluminum, copper or the like, but a permanent magnet type electric motor uses a permanent magnet as the rotor to create magnetic flux and therefore does not require current flow and has extremely low loss on the rotor side. Accordingly, a permanent magnet motor can achieve higher efficiency than an induction motor.

Moreover, because a permanent magnet motor generates little heat, the area for heat dissipation can be made smaller, allowing permanent magnet motors to be made smaller and lighter in weight.

(4) Reduction of eddy current loss generated in various parts

When driven by a pulse width modulation (PWM) inverter, the carrier frequency component of the current in an electric motor contains harmonic current, and as a result, unnecessary eddy currents generated inside the electric motor may result in loss.

In a permanent magnet motor, neodymium magnets capable of generating a strong magnetic field are often used. Neodymium magnets have the characteristic of high conductivity, and eddy currents flowing inside the magnet result in loss. One countermeasure is to reduce the interlinking harmonic flux in the permanent magnet. Also, the magnetic flux generated in the coil leaks to the frame shield and other members of the electric motor, causing eddy currents to be generated that result in loss. As a countermeasure, the parts that configure the electric motor must maintain a proper distance from the stator coil.

(5) Reduction of loss with an electric motor cooling fan

An electric motor is equipped with a cooling fan, and the mechanical loss caused by the rotation of the cooling fan is included in the loss of the motor. Accordingly, to make fan-based cooling a minimum requirement, the motor temperature must be computed with high accuracy at the design state.

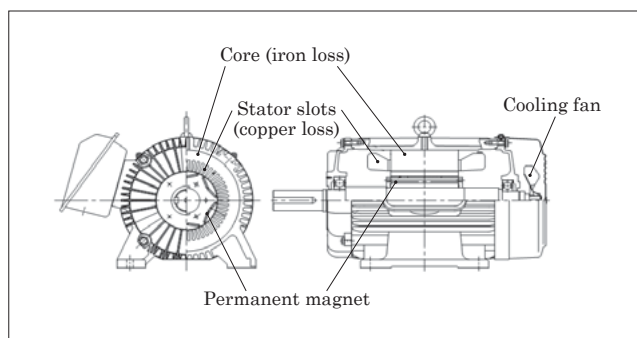


Fig.2 Structural cross-section of IPM motor

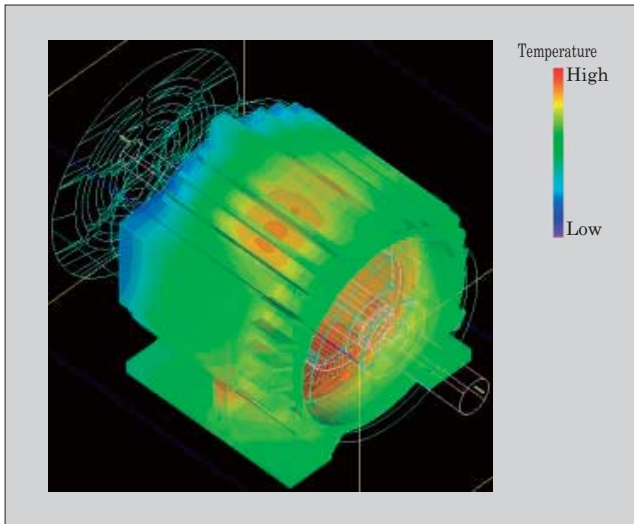


Fig.3 Example of thermo-fluid analysis of electric motor

3.2 Fuji Electric's efforts

At Fuji Electric, highly accurate thermal design for typical electric motors such as a totally enclosed fan-ventilated motors is carried out using a fluid circuit network calculation to compute the wind speed and then using a thermo-fluid circuit network method to compute the temperature of each part of the motor.

Additionally, thermo-fluid analysis may also be used when consideration of natural convection and the like is necessary (see Fig. 3). For both the thermo-fluid circuit network method and thermo-fluid analysis, the way in which elements that cannot be analyzed simply, such as the contact resistance of different components, are defined as thermal resistances is important and it is extremely important that basic data be accumulated through experimentation and the like.

4. Characteristics of High Efficiency IPM Motors

In addition to applying the various techniques for increasing efficiency described in Chapter 3, high-efficiency IPM motors have also been specially developed for higher efficiency, and realize extremely high efficiency. Fuji Electric provides a lineup of its "GNS Series" of IPM motors featuring higher efficiency than the IE4 level and standard output power in the range of 11 to 160 kW, and a lineup of its "GNP Series" of IPM motors featuring an IE4 level of efficiency and standard output power in the range of 5.5 to 90 kW.

In particular, the GNP Series has a multi-rated specification for voltage, and have been designed so that a single motor is compatible with a domestic 200 V power supply or a 400 V power supply. Standard stocking of all models in the 5.5 to 90 kW output range enables instant delivery.

Additionally, IPM motors are smaller than induction motors and naturally had different mounting dimensions than induction motors in the past. The GNS Series and the GNP Series both have the same mount-

ing dimensions, however, facilitating the replacement of induction motors already in use.

4.1 Realization of effect of higher efficiency

Electric motor efficiency is prescribed by IEC 60034-30 (see Fig. 4). The IE1 standard value is at the level of a general-purpose induction motor, and the IE2 standard value is at the level of a high-efficiency induction motor and is the same as the EPAct level.

Furthermore, IE3 and IE4 standard values that are higher than those of the prior EPAct have been enacted. The GNS Series has the highest level of efficiency standards, surpassing the IE4 standard values, and is 8.5 to 3 points above the level of commonly used induction motors (IE1 level) and 2 to 1 points above the IE3 level.

As for the measured results of efficiency of the GNS Series motor of 75 kW rated output and the induction motor, the reduction effect at the rated load is shown in Table 1(a) and the reduction effect at a 50% load factor, which is close to actual usage, is shown in Table 1(b). The efficiency is improved 4.1 percentage points at the rated load and is improved 5 percentage points at the 50% load factor.

The reduction effect in terms of power consumption, electricity price and CO₂ emissions is as shown in Table 1.

4.2 Maintainability

In electric motors, the bearings are consumable parts and will need to be replaced. In the case of an induction motor, on-site replacement is possible since the bearings can be replaced by removing brackets on the directly coupled side and on the non-directly coupled side and pulling out the rotor.

On the other hand, because a magnetic force exists in the case of a permanent magnet motor, pulling out the rotor would be substantially difficult to accomplish on-site, and typically the motor is returned to the man-

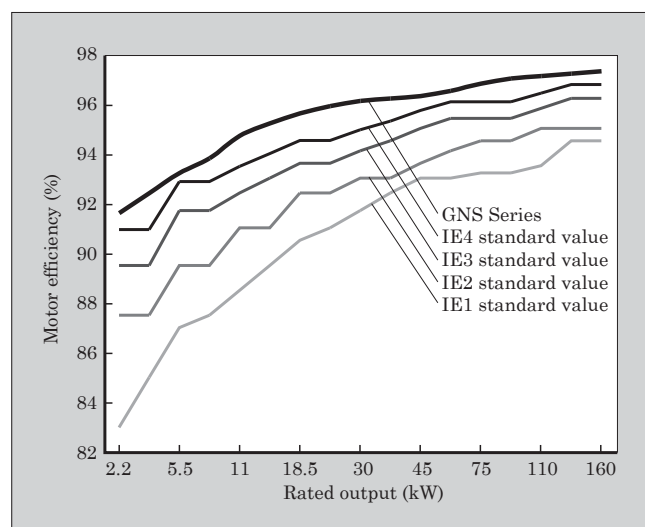


Fig.4 Values of efficiency standards for electric motors

Table 1 Reduction effect due to “GNS”

(a) Rated load, 1,465 min⁻¹

	Induction motor	High-efficiency IPM motor	Reduction effect
Output (kW)	75	75	
Motor efficiency (%)	93.2	97.3	4.1 percentage point improvement
Power consumption (kWh)	704,900	675,200	29,700
Electricity price (1,000s of yen)	8,459	8,103	356
CO ₂ emissions (t)	282.0	270.1	11.9

(b) Load factor 50%, 1,480 min⁻¹

	Induction motor	High-efficiency IPM motor	Reduction effect
Output (kW)	37.5	37.5	
Motor efficiency (%)	91.9	96.9	5 percentage point improvement
Power consumption (kWh)	357,400	339,000	18,400
Electricity price (1,000s of yen)	4,289	4,068	221
CO ₂ emissions (t)	143.0	135.6	7.4
Computation conditions			
Operating time	8,760 hours (continuous for 1 year)		
Unit price of electricity	12 yen/kWh		
Equivalent CO ₂ emissions	0.4 kg/kWh		

manufacturer for replacement of the bearings. However, because the GNS Series and the GNP Series have been constructed so as to allow the bearings to be replaced simply by removing the brackets on either side, on-site bearing replacement is possible and maintainability is enhanced.

4.3 Ease of installation

A permanent magnet motor is typically smaller and lighter in weight than an induction motor. However, the GNS Series and the GNP Series are not downsized, but instead maintain compatibility with the mounting dimensions of induction motors. This facilitates the task of motor replacement in existing equipment and stimulates demand for energy conservation.

5. Energy saving Effect of Inverter Driving

Permanent magnet motors do not have a starting winding and must operate in conjunction with an inverter. Therefore, by utilizing the capability of an inverter to freely change the rotational speed of a motor, using the motor in a fan pump of the type that employs the centrifugal force of the rotating blades, and adjusting the flow rate according to the change in rotational speed, further energy savings can be attained.

5.1 Application to fluidic devices that utilize the centrifugal force of the blades

The motive power (W) of the fluid system can be expressed as follows.

Motive power (W) =

$$\text{Pressure (N/m}^2\text{)} \times \text{Flow rate (m}^3\text{/s)} \dots\dots\dots (1)$$

In the case of a fluidic device that uses the centrifugal force of the blades to deliver water, air or other flow, the pressure is proportional to the centrifugal force of the blades.

Generally, in the case of a fluidic device that uses the centrifugal force of the blades, the centrifugal force can be expressed as $m r \omega^2$ where m is the mass, r is the radius and ω is the angular velocity, and the pressure is proportional to the square of the rotational speed.

$$\text{Pressure} \propto \text{Rotational speed}^2 \dots\dots\dots (2)$$

Also, since the blades rotate to push out fluid, the flow rate is proportional to the rotational speed

$$\text{Flow rate} \propto \text{Rotational speed} \dots\dots\dots (3)$$

As shown in equation (1), motive power is the product of pressure and the flow rate, and in the case of a fluidic device that uses the centrifugal force of the blades, the motive power of the fluidic device, i.e., the power consumption, is proportional to the cube of the rotational speed of the motor.

$$\text{Power consumption} \propto \text{Rotational speed}^3 \dots\dots\dots (4)$$

If the rotational speed is halved, the flow rate is halved, the pressure becomes $(1/2)^2 = 1/4$ and the power consumption becomes $(1/2)^3 = 1/8$. However, because the pressure is proportional to the square of the rotational speed, in applications that require pressure such as in pumping water and water jet machines, the rotational speed cannot be reduced by much, and a power-saving effect may not be obtainable. Table 2 and Fig. 5 show these relationships and their effects (theoretical values).

Also, the rotational speed, flow rate, pressure and power are expressed as 100% in the case when the induction motor is driven by a commercial power supply,

Table 2 Energy saving effect with fluidic device utilizing centrifugal force of blades

Rotational speed (%)	Flow rate (%)	Pressure (%)	Power during control of inverter speed *1 (%)	Power change *2 (Point)
100	100	100	105	5
90	90	81	77	-18
80	80	64	54	-36
70	70	49	36	-49
60	60	36	23	-57

*1: Assuming an inverter efficiency of 95%, and assuming a 5% increase in power with the addition of the inverter.

*2: Indicates the power change in response to a flow rate adjustment with a damper opening of 50 to 100%.

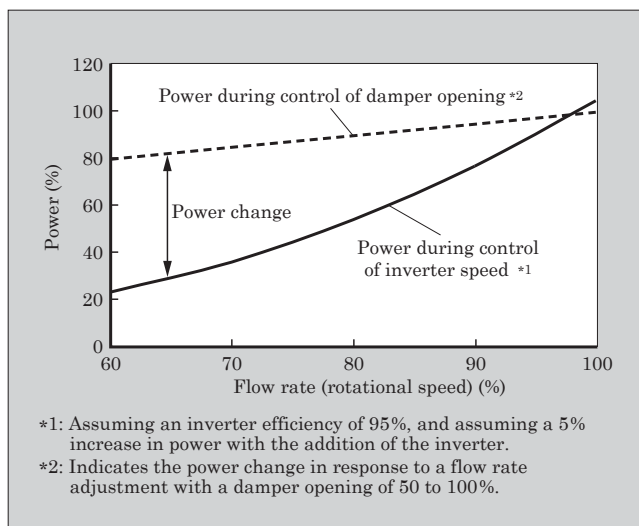


Fig.5 Energy saving effect with fluidic device utilizing centrifugal force of blades

without using an inverter.

5.2 Measurement example and effect

A 75 kW induction motor and a 75 kW “GNS” high-efficiency IPM motor were operated side-by-side at the same time at Fuji Electric’s Suzuka Factory which has test equipment capable of measuring the input power of the inverter.

Table 3 shows the results of the in-house experiment using that test equipment and assuming an 80% flow rate.

A comparison of the power consumption of the “GNS” high-efficiency IPM motor at a rotational speed of 1,422 min⁻¹ (1,778 min⁻¹ × 0.8) with the power consumption of an induction motor driven by a commercial power supply, revealed that the power consumption was reduced by 31.9 kW.

Table 3 In-house experimental results assuming an 80% flow rate

	Induction motor *1	High-efficiency IPM motor *2	Reduction effect
Flow rate (%)	80	80	—
Rotational speed (min ⁻¹)	1,778	1,422	—
Input power (kW)	73.1	41.2	31.9

*1: Assuming that the induction motor runs on a commercial power supply, and that flow rate is adjusted by the degree of valve opening.

*2: In a high-efficiency IPM motor, the flow rate is adjusted by inverter speed control, and the input power indicates the inverter input power.

6. Postscript

This paper has described representative technologies for increasing the efficiency of electric motors, and features of the “GNS Series” and “GNP Series” of high-efficiency IPM motors. In particular, Japan has a history of innovation in permanent magnet technology, and this field is also very advanced throughout the world. Moreover, inverter drive technology is also advanced in this field. Japan is a leader in the technical field of permanent magnet motor systems that combine permanent magnet technology with inverter drive technology, and within this context, Fuji Electric offers solutions with a high level of technical expertise.

In response to the global challenges of increasing energy savings, curbing CO₂ emissions, and protecting the environment, expectations for the higher efficiency of electric motors have increased further, and both as a supplier and as a partner who increases the value of our customers’ products, Fuji Electric intends to promote the advancement of technology in order to meet those expectations.

Reference

- (1) Rolamd Brüniger. Motor Systems Annex. IEA ExCoMeeting in Paris 14/15 April 2008.

“FRENIC4800VM5,” a Water-Cooled High Capacity, High Voltage Inverter

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ABSTRACT

High-voltage inverters used to drive main rolling mills for steel and non-ferrous metal materials, large blowers and compressors are seeing increased demands for higher capacities and reduced size of board dimensions as facilities increase in scale. Fuji Electric is conducting researches in the water cooling and miniaturization technologies needed to meet these requests. Through repeated analysis and testing, we aimed to improve cooling performance and reliability through water cooling technology and as a result released the “FRENIC4800VM5,” a water-cooled, high-capacity, and high-voltage inverter, which has 2.4 times more output capacity and 1/3 smaller panel dimension compared to our previous models.

1. Introduction

High-voltage inverters used to drive main rolling mills for steel and non-ferrous metal materials, large blowers and compressors are showing increased demands for higher capacities and reduced size of panel dimensions as facilities increase in scale and installation area becomes narrowed down.

In this paper, we will present the “FRENIC4800 VM5,” a water-cooled, high-capacity, and high-voltage inverter as a product that is able to meet these increasing demands. In addition, we will also provide an application example of the FRENIC4800 VM5.

2. Water-cooled, High-capacity, and High-Voltage Inverter

The development of high-voltage inverters that have both higher capacity and reduced panel dimension requires to suppress temperature increases due to converter heat loss that occurs at the time of controlling large electric currents by using heat dissipation,

In recent years, insulated gate bipolar transistor (IGBT) modules have advanced toward higher-voltage and higher capacity, and inverters in a high-voltage range, which conventionally used flat components, can be configured with modules that have low power loss.

The panel of the FRENIC4800VM5 is shown in Fig. 1 and its electrical specifications are indicated in Table 1.

In producing the FRENIC4800VM5 for commercial use, Fuji Electric decided to adopt water cooled method for the high-voltage IGBT module so that it could suppress temperature rise caused by heat loss generated from conversion circuits. The adoption of the water

cooled method has the effect of greatly increasing cooling efficiency compared to previous air cooled method. The FRENIC4800VM5, in addition to the high capacity and reduced panel dimension, is equipped with the high degree of functionality needed for main rolling mills for steel and non-ferrous metal materials.



Fig.1 Control panel comprising “FRENIC4800 VM5”

Table 1 Electrical specifications of the “FRENIC4800VM5”

Item	Specification			
Configuration (Multiplexing)	Single unit	Double-multiplex	Triple-multiplex	Quadruple-multiplex
Converter capacity (MW)	5.2	10.4	15.6	20.8
Inverter capacity (MVA)	6.2	12.4	18.6	24.8
Voltage	Input 3 kV 3φ 50/60 Hz, Output 3.1 kV			
Overload capability	150% for 1 minute			
Driving motor	Induction machine, synchronous machine			

† Fuji Electric Co., Ltd.

The features of the inverter are as follows:

- (1) Large capacity output 2.4 times larger than that of our previous products⁽¹⁾
Capable to configure a single unit capacity of 6.2 MVA and a maximum capacity of 24.8 MVA utilizing quadruple multiplexing (Overload capability: 150% for 1 minute)
- (2) Compact panel dimensions 3 times smaller than that of our previous models⁽¹⁾
 - (a) Single unit 6.2MVA
 - (b) W 2,800×D 1,650×H 2,400 (mm) (Excluding water cooling equipment)
- (3) Employing 3-level PWM control both in the converter and inverter
 - Capable of full regeneration 4 quadrant operation
 - Power supply power factor ≈ 1
- (4) Supporting various transmission methods PROFIBUS-DP, SX Bus, T-link, etc.
- (5) Equipped with high-speed pulse tracing function
 - Acquires and saves gate output command signals of the inverter as well as on-off state signals of the IGBT with time resolution of μs orders
 - Capable of quickly performing cause analysis at the time of faults

3. Water Cooled Technology

High-capacity power electronics equipment including high-voltage inverter requires strong demand for small, light-weight, and low-cost. In order to meet this demand, we have constructed a high-performance and highly reliable water cooled technology and have been progressing in the development of our product design.

Through repeated analyses and experiments, we have strived to improve cooling performance and reliability. The main points of our water cooled technology are as follows:

- (a) Highly-efficient heat sink
- (b) Piping for cooling with a good split flow balance
- (c) Simple cooling structure in panel inside
- (d) Water cooled heat sink that is very durable and corrosion resistant

3.1 Heat sink design

At rated output, water-cooled high capacity, high-voltage inverters suffer about a 100 kW loss, and as a result, heat generation occurs. From the power devices in a power unit, heat is generated at a level of 100 W in semi-conductor chips of approximately 1 cm square size. Highly-efficient water cooled heat sink that can cool the high-density generated heat, regardless the small difference in temperature between the power devices and the cooling water, is required. As a result, we have carried out the following design:

- (a) In order to expand the liquid contact area, an internal fin structure that arranged narrow ducts in parallel has been adopted.

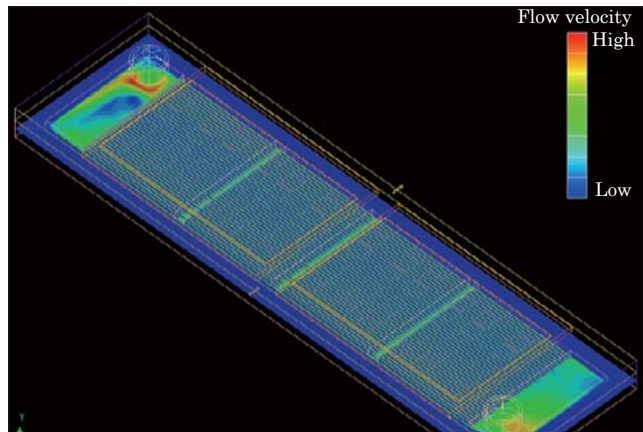


Fig.2 Internal flow velocity distribution in water cooling heat sink

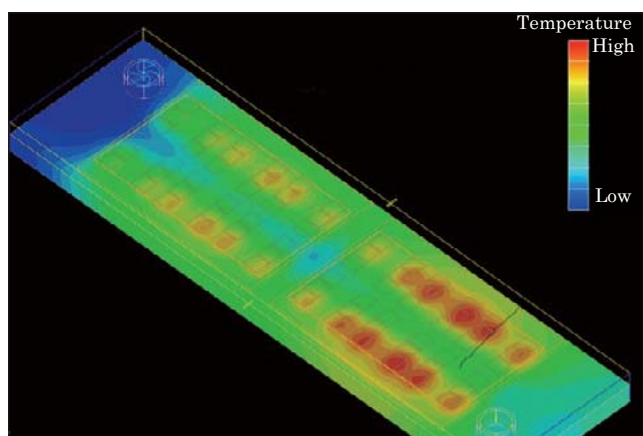


Fig.3 Surface temperature distribution of water cooling heat sink

- (b) In order to accelerate the heat transfer due to turbulent flow, an internal fin structure that divided to the flow direction has been adopted.
- (c) In order to equalize the flow balance between the parallel ducts, a vertical inflow header structure has been adopted.

Figure 2 shows the internal flow velocity distribution of the water cooled heat sink, and Fig. 3 shows the surface temperature distribution. From these figures, it is apparent that a good cooling capability has been obtained.

3.2 Cooling pipe design

Figure 4 shows a typical structure of the cooling pipes for water-cooled high capacity, high-voltage inverters. Configuration is made by combining two components; one is a heat exchanging water cooling devices composed of pumps, tanks, flow adjustment valves, ionic exchange devices and outside water cooling equipment, and the other is a parallel piping system that connects numerous water cooled heat sinks installed in numerous quantity to the multiple power stacks configuring the inverter and converter panels.

Even if a total of 30 water cooled heat sinks are

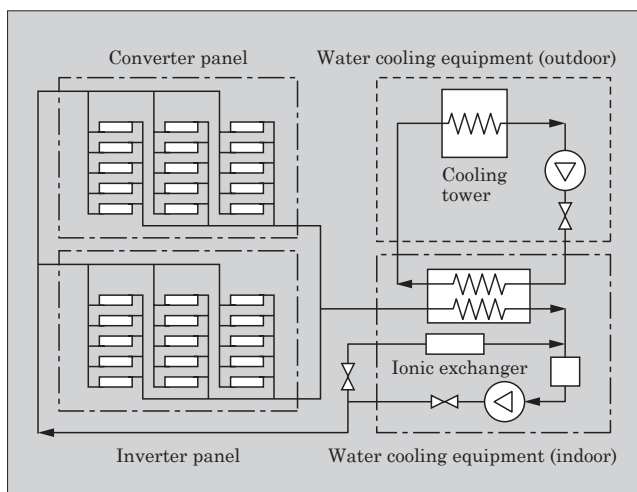


Fig.4 Configuration of cooling pipe system

connected in parallel to water-cooled high capacity, high-voltage inverters, great skill is needed to make appropriate combination of the piping configuration, which includes the main pipe, diverging pipes and branch pipes, so as to obtain flow balance of the cooling water.

Therefore, in order to accurately design the flow and pressure loss of each cooling pipe, which is a combination of numerous components and various pipes, we performed a highly precise design utilizing a pipeline resistance network method.

Figure 5 shows an analysis model example of the pipeline resistance network when the water cooling heat sinks are configured in 6 parallel pipelines. By properly matching the internal diameters of the main pipes and diverging pipes, it is possible to suppress flow unbalance within approximately 5%, and as a result, valve adjustment for each heat sink duct becomes not required. In addition, since calculation results can be obtained in several seconds even when actual system pipes amount to hundreds of nodes, comparative

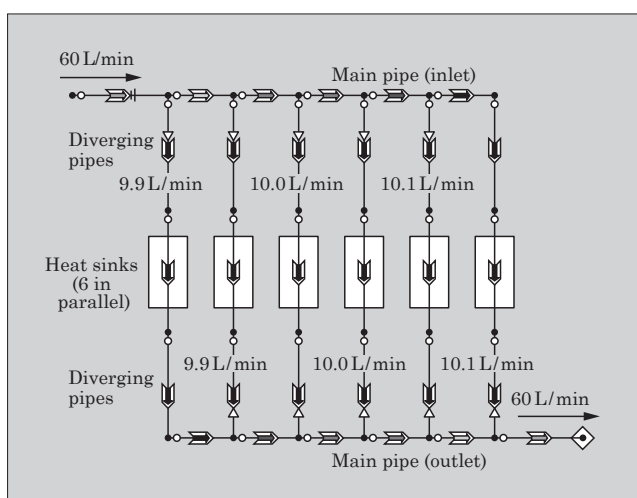


Fig.5 Analysis model example of the pipeline resistance network

calculations can be made very quickly for diameter and length of pipes, and shape of heat sinks and joints to be used in the system, and theoretical studies regarding how to minimize pressure loss, etc. can be carried out with very accurate precision.

3.3 Cooling structure design in panel inside

Since the heating components such as reactors, capacitors, contactors, and control devices, etc. are incorporated with high density in high-capacity power electronics equipment besides the power devices, efficient cooling within the panel is required. Although there are differences depending on part shape and heat density, cooling is carried out through water cooling or air-cooling.

Figure 6 shows the cooling situation of the capacitors, reactor and control devices in a power stack. An air-cooling system is adopted a method that carries out cooling of panel inside by circulating cooled air which is cooled by water cooled heat exchanger. Air flow in the panel inside can be carried out with good balance by adopting a simple structured fan ventilation path that optimizes parts arrangement, partition plate installation, etc.

3.4 Corrosion-resistance evaluation and durable design

A corrosion-resistance evaluation was implemented for copper, aluminum, and two types of water, and examination was carried on a life durable design.

In the corrosion-resistance evaluation, a running water circulation test was implemented for 5,000 hours that combined copper with deionized water, aluminum with deionized water, and aluminum with an antifreeze solution. The following results were obtained through observation of the surface (see Fig. 7) and cross-sections of the sample and by measuring the amount of thinning.

- A passive film formed on the wetted surface.
- The early stages of the test resulted in some mass reductions (corrosive progression), but al-

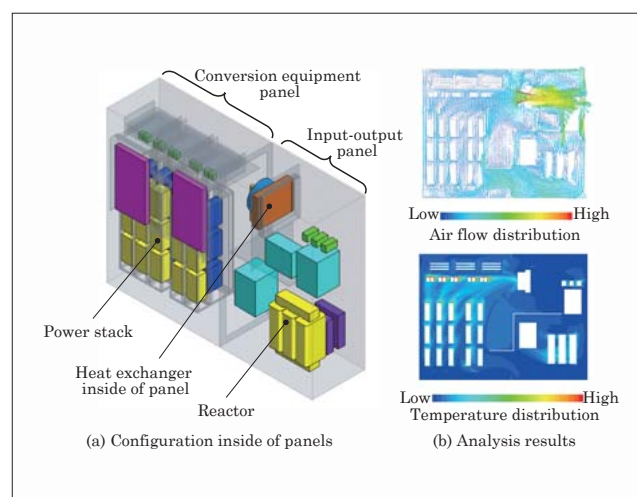


Fig.6 Cooling structure design in panel inside

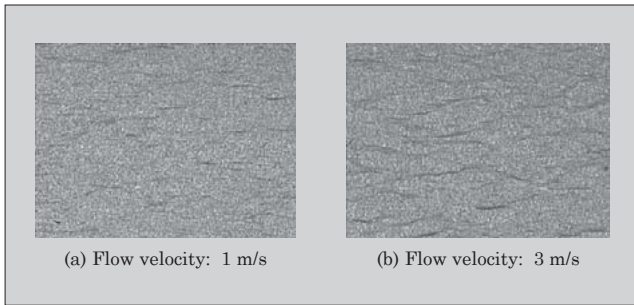


Fig.7 Surface condition after the corrosion-resistance evaluation for aluminum with deionized water

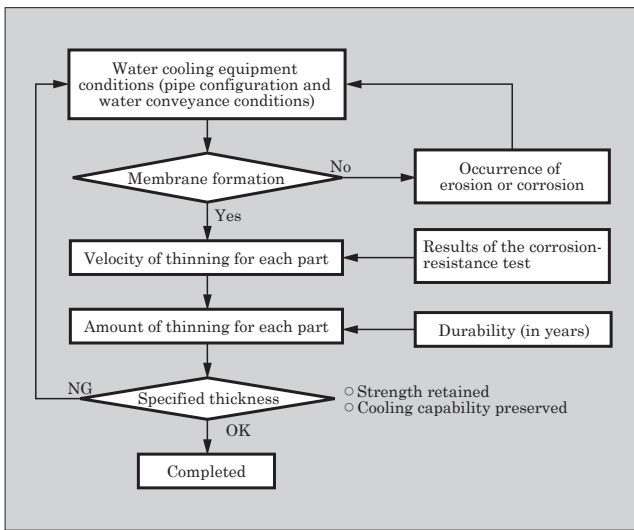


Fig.8 Outline of corrosion-resistance evaluation and life durable design method

most no further corrosion occurred after about 500 hours elapsed.

- (c) No local corrosion occurred at a flow velocity of 1 to 3 m/s.

Based on these results, a life durable design method was put together. The outline of the method is shown in Fig. 8. In addition, material and water quality control standards have been separately provided.

4. Voltage & Capacity Enhancement, and Miniaturization Technology

4.1 Voltage & capacity enhancement technology

Water-cooled, high-capacity, and high-voltage inverters make use of the circuit configuration of neutral point clamped (NPC) 3-level conversion circuits shown in Fig. 9, aiming to increase output voltage and suppress harmonics. Power unit components adopt high-voltage module type IGBT components that facilitate high-voltage and large currents, aiming to streamline the structure and simplify the assembly. Furthermore, we have achieved a higher voltage and larger capacity of 6.2 MVA (3.1 kV) for single unit, which is 2.4 times greater than our previous products. These gains have been realized through connecting IGBT modules in

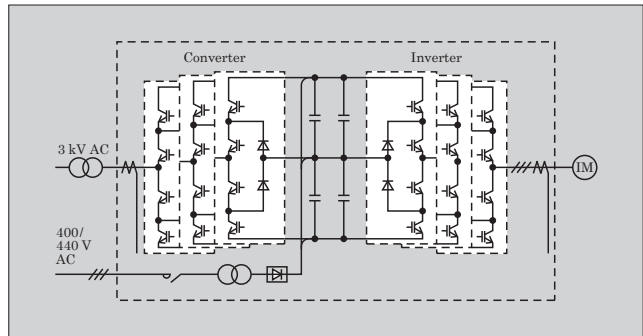


Fig.9 Configuration of NPC 3-level conversion circuit

parallel as well as by adopting the water cooling technology introduced in Chapter 3.

4.2 Miniaturization technology

Snubber circuit that controls the transient high-voltage generated at the time of current cutoff tends to increase the equipment size. If inductance can be reduced, IGBT voltage jumps can be controlled at the time of current cutoff without the need of using snubber circuit. In order to reduce inductance, we have carried out the following improvements:

- (a) Laminated bus bars were adopted which enable low inductance for the power circuit conductor and insulated boards of the internal parts of the IGBT stack.
- (b) By stacking up the conductors of different current flow directions, inductance can be reduced through negating magnetic fluxes.
- (c) High-voltage film capacitors that have a small internal inductance were adopted for direct-current intermediate circuits.
- (d) A simulation tool was used to compute the inductance in the laminated bus bar design, and an optimal conductor structure was designed to conduce both of reduced inductance and appropriate current sharing between IGBT modules (see Fig. 10).

In order to decrease the panel size of the power unit, the width of the IGBT stack needs to be reduced. Therefore, we have implemented the following improvements:

- (a) Low-profile high-voltage film capacitors were

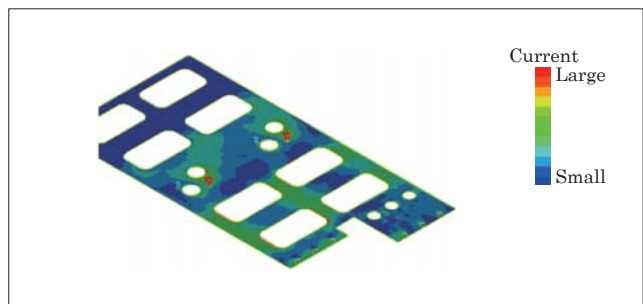


Fig.10 Current distribution simulation results of the laminated bus bars

used in direct-current intermediate circuits.

- (b) The configuration of laminated bus bars, IGBT modules, water cooled heat sinks, and water cooling pipes were optimized (currently patent applied for).
- (c) Through using the water cooling technology introduced in Chapter 3, good flow rates can be allocated without using adjustment valves in each water cooled heat sink duct.

As the result of these improvements, we attained to store 3 power unit IGBT stacks in panel widths of 1,000 mm.

5. Application Example of Water-cooled, High-capacity, and High-voltage Inverter

We present an application example for a twin-drive

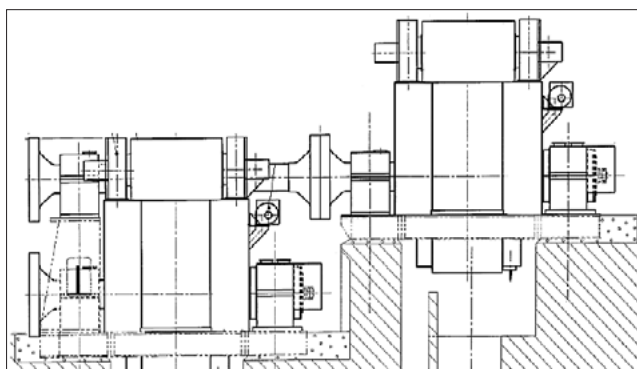


Fig.11 Example of twin-drive electric motor layout



Fig.12 Example of synchronous electric motors for main rolling mill

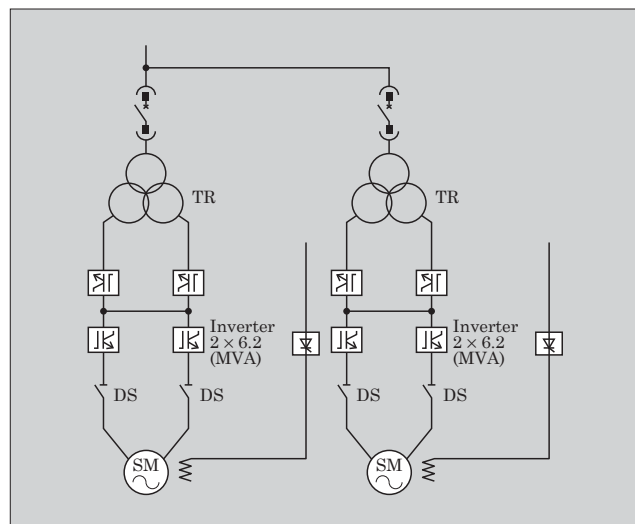


Fig.13 Example of single system diagram for twin-drive reverse rolling mill

reverse rolling mill. In this rolling mill, top and bottom rolls are individually driven using two electric motors as shown in Fig. 11. Synchronous motors (see Fig. 12) are used for the electric motors, and each electric motor is driven by a 6.2 MVA FRENIC4800VM5 double-multiplex configuration (see Fig. 13).

By utilizing the FRENIC4800VM5, inverter panels were able to be installed in the existing electric room as a result of greatly decreasing the panel dimensions.

6. Postscript

The “FRENIC4800MV5” water-cooled, high-capacity, and high-voltage inverter enables full regeneration of systems. In addition to rolling mill systems, we are anticipating that it will play an active role in various fields such as wind tunnel test facilities and large-sized conveyors. We look forward to expanding the application of the FRENIC4800MV5 to these fields as well as further developing the water cooling, capacity enlargement, and miniaturization technologies introduced in this paper to other power electronics equipment.

Reference

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“FRCM Series” of EV Quick Chargers

KAWAURA Masato † HATAKENAKA Shinji † MORIYAMA Toru †

ABSTRACT

Electric vehicles are being released one after another, and the quick-speed charging spots construction is accelerating in Japan to deal with global warming. Fuji Electric developed quick-speed charging units that use general-purpose inverters and released them on the market. This time, we developed the “FRCM Series”, a quick charger for electric vehicles based on front-end power supplies. The power unit, insulated from high-frequency waves, and has solved the problem caused by harmonics. The charger cabinet is lightweight at 210 kg and its depth is 480 mm, similarly thin as a general vending machine. The panel has a universal design seeking ease of use, and employs safety design using a hardware sequence that blocks both input and output to reliably cut the current in emergencies as well.

1. Introduction

Automobile emission regulations have been increasing in severity year after year as a means of dealing with global warming. For example, the “ZEV mandate” in California, the United States stipulates that 10% of all cars sold must be pollution-free or eco-friendly. In order to deal with this situation, each automobile manufacturer has been stepping up its development and market introduction of eco-friendly cars.

In the year 2010, car manufacturers were making announcements one after another of market launches or planned market launches of electric vehicles (EV), thereby making it quite apparent that there has been an increasing trend toward the development of eco-friendly electric vehicles. Japan has seen an increase in the building of quick charging spots, and efforts are being made to build an infrastructure environment that allows electric vehicles to be used without anxiety.

Fuji Electric has developed quick chargers that use general-purpose inverters, and successfully introduced the products to the market. Recently, we have launched a series of electric vehicle quick chargers called the “FRCM Series.” FRCM Series quick chargers are based on a new concept that incorporates a high-frequency isolated power supply unit, a panel with a thin-plate structure, etc.

2. Product Characteristics

(1) High frequency isolated power supply unit

Previous models have used a general purpose inverter for a power supply unit, and have suffered from problems such as issues involving power supply harmonics and their inability to extend output power.

Therefore, we developed a power supply of 12.5 kW per unit based on front-end power supplies. By connecting the two power supply units in parallel, this charger enables the rated output of 25 kW. This charger is available to connect low-voltage switchgear, and it is free from the power supply harmonics problem.

(2) Thin structure enabling installation space-saving

As shown in Fig. 1, the FRCM Series makes use of the thin panel structure technology of vending machines. The charger cabinet is lightweight of 210 kg and its depth is 480 mm, the same thinness as a general vending machine. Our previous “FRCH Series” models had a weight of 700 kg and a depth of 700 mm. Most of quick chargers are placed in the corner of parking place since their thin structure enables effective use of space. Fuji Electric's vending machines



Fig.1 “FRCM Series”

† Fuji Electric Co., Ltd.

have an outstanding track record with over 5 million units shipped in total. Therefore, our company has the know-how of products used by the general public people, including technologies that ensure durability and anti-crime performance. The FRCM Series quick chargers are designed using this know-how.

(3) Universal and safety design features

The exterior side of charger door employs the same general universal design^{*1} of vending machines. In addition, Fuji Electric's safety design policy was adopted, making the quick chargers safe and easy to use.

3. Power Supply Unit

3.1 Outline functionality and characteristics

(1) External appearance and functions

Figure 2 shows the external appearance of the power supply unit. The output power of a single power supply unit is 12.5 kW. Since it is possible to connect and operate several power supply units in parallel, the output of the charger cabinet can be increased to 25 kW, 37.5 kW, or 50 kW etc.

A cooling fan is prepared at the top of the charger and constructed so as to evacuate cooling air from bottom to top. When connecting the power supply units in parallel, all terminal blocks and connectors are placed at the front of the charger so that they can be arranged and installed side by side.

If an uncontrollable abnormality or malfunction occurs inside the power supply unit, it can be disconnected safely from the power supply line of the charger cabinet using the circuit protector located at the top of the AC input terminal.

Furthermore, the configuration switches located at the bottom make fall back operation possible when using multiple units in parallel or if a failure occurs.

(2) Outline of operation

This power supply unit uses a constant current

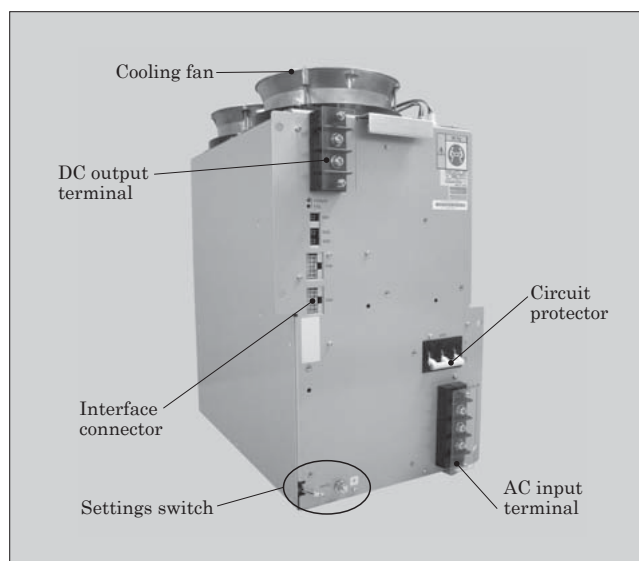


Fig.2 Power supply unit

control system so as to be used for battery charging. It measures a variety of different information such as internal voltage, current, and temperature. If a malfunction occurred, the error log function of the unit records this information into its internal memory. The various kinds of information can be accessed by connecting the unit to a PC, and thereafter, be easily used in factor analysis to discover fault causes at the time of malfunction.

(3) Electrical specifications and characteristics

Table 1 shows the major specifications of the power supply unit. In stand alone power supply units, an efficiency of 92% is guaranteed. This level of efficiency falls sufficiently above the CHAdeMO^{*2} specification of 90% for charger cabinet as a whole. Since the AC-

Table 1 Major specifications of power supply unit

Item		Specification
Input characteristics	Input voltage	3-phase 170 to 264 V AC
	Frequency	50/60 Hz
	Inrush current	50 A or less
	Efficiency	92% or more
	Power factor Harmonic current regulation	95% or more IEC, EN61000-3-2 (Compliant)
Output characteristics	Output voltage	50 to 500 V DC
	Output current	0 to 31.25 A
	Ripple spike	Within ± 10 V
	Output ripple current	1.25 A p-p or less
	Overvoltage protection level	520 to 540 V
	Overcurrent protection level	102 to 130%
Environmental conditions	Operation temperature/humidity	-20 to 50°C/5 to 95%RH
	Storage temperature/humidity	-40 to 70°C/5 to 95%RH
	Vibration resistance	0.5 G, 3 to 60 Hz, 1 cycle/2 minutes $\times 5$
	Overheat protection	Yes
Regulation	Conformable standard	CHAdeMO Ver 0.9 compliant
	Overseas safety standard	UL2202
Others	Dimensions	W230 $\times$ D465 $\times$ H380 (mm) (Not including projecting parts)
	Weight	26 kg or less
	Cooling conditions	Forced air-cooling (bottom air intake, upper exhaust)

*1: Universal design: This refers to a design that optimizes its ability to be used by numerous different kinds of people regardless of age, disability, etc.

*2: CHAdeMO: Trademarks and/or registered trademarks of the CHAdeMO Association

DC converter in the input block of the power supply unit has a power-factor correction circuit in it, an input current wave takes a form similar to a sine wave, and thus, there is no need to install a capacitor for power-factor correction on the outside of the charger. In addition, this product conforms to the “Guideline of Harmonics Reduction for Consumers who have High-Voltage or Ultra-High-Voltage switchgear.”

The output part of the DC/DC converter aims to reduce output ripple current and downsize the isolation transformer by using a high frequency switching of 80 kHz.

Since a long-service life fan is used for the purpose of cooling, the unit is designed so as not to need parts replacement during the 8-year lifetime of the charger under ambient temperature conditions of 40 °C. Furthermore, since a variable speed fan is used, acoustic noise can be reduced by controlling the fan rotation to appropriate speed by measuring temperature in the power supply unit. This power supply unit can also be used in the United States as it conforms to UL2202, the safety standard for chargers.

3.2 Circuit configuration and power supply technology

Figure 3 shows a circuit block diagram of the power supply unit.

(1) Input part

The AC-DC converter of the input part makes use of 3-level power-factor correction circuits (patented). By treating 3-phase AC input correctively and carrying out control so that input current takes the form of sine wave, a stable direct intermediate current is obtained. Through digital control with a digital signal processor (DSP), control circuit realizes waveform shaping of input current as well as the stabilization of output voltage. Compared with conventional analog control systems, the number of control circuit parts has been reduced by 80%, thus cutting down the size of the board area significantly.

(2) DC intermediate part

Two electrolyte capacitors are connected in series in the DC intermediate part. The voltages at the top

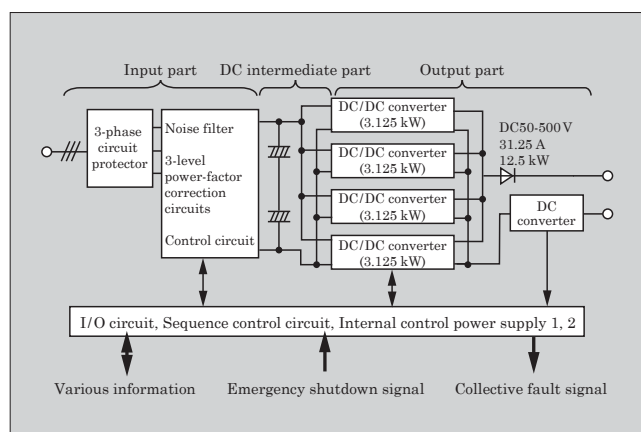


Fig.3 Circuit block diagram of power supply unit

and bottom of the electrolyte capacitors are controlled to be the output voltage. Since the voltages at the top and bottom of the electrolyte capacitors are controlled, the circuit system becomes compatible with an AC input voltage of 400 V by changing only the voltage settings that output to DC intermediate voltage. There is no need to change circuit configuration or parts.

(3) Output part

A phase shift converter system is used in the DC/DC converter of the output part. By employing zero volt switching (ZVS), switching loss of the metal-oxide-semiconductor field-effect transistor (MOSFET), which is used as a switching element, is reduced and efficiency is improved. This DC/DC converter provides output of 3.125 kW per one circuit. By connecting four circuits in parallel, an output power of 12.5 kW is obtained as one power supply unit.

The power supply unit is also equipped with a current balance circuit so that even when several units are connected together, each unit can produce an identical output current divided equally. Reliability is increased by equalizing the load of each power supply unit. Since diodes are also installed for the prevention of backflow in the output, even in the rare case that the power supply unit is damaged, it is possible to prevent current backflow from the battery.

4. Cabinet

4.1 Outline of charger

(1) Thermal design

When the efficiency of a charger with an output of 25 kW is 90%, 2.5 kW of heat must be discharged during times of maximum output. Therefore, the biggest issue is the emission of heat. Since it is the greatest priority of the power supply unit, which is the hottest part, construction has been made so that unit's case is located as close as possible to the top. This design allows for generated heat to be immediately discharged to the outside of the cabinet from the top plate.

Figure 4 shows the arrangement of parts inside the cabinet. Two power supply units are connected

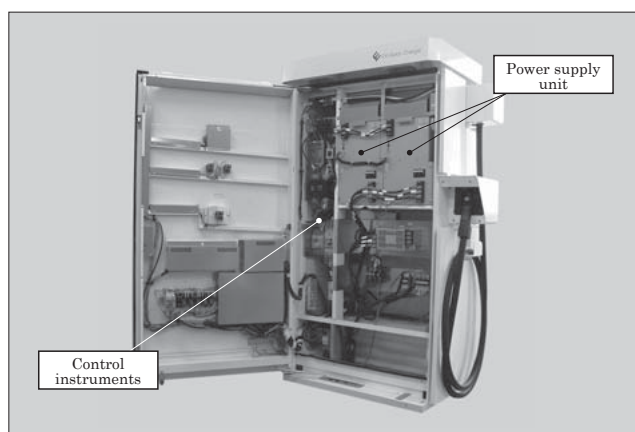


Fig.4 Arrangement of parts inside the cabinet

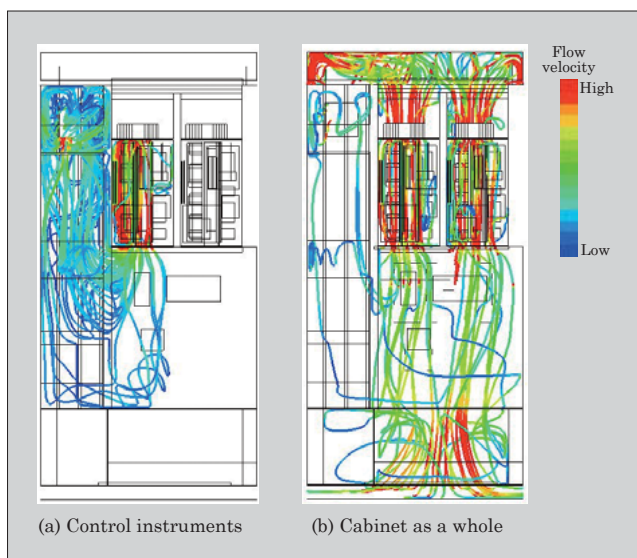


Fig.5 Air-flow simulation analysis inside of the cabinet

in parallel to the top part of the cabinet, and the least number of parts possible are arranged at the bottom of the power supply units considering air-flow. All of the main circuit-related parts such as earth leakage breaker, magnetic contactor and fuses are arranged on the left side. By separating them from the power supply units, air-flow is secured and heat issues are solved.

Figure 5 shows the results of the air-flow simulation inside of the cabinet. The air-flow and temperature distribution inside of the cabinet can be seen easily, and this makes it possible to carry out theoretical studies regarding parts arrangement. Validity was evaluated before a trial manufacture of the product, and we were able to confirm that everything conformed very well.

(2) Universal design and safety features

The exterior side of the door employs a universal design to perform layout of an LC display, manual operation buttons and the like.

For the main circuit interruption, a breaker with earth leakage breaking function and a magnetic contactor for interrupting main circuit are allocated in input part, and super rapid fuses and a DC contactor for interrupting DC output are allocated in output part. Emergency cutoff, which is carried out using the emergency stop switch, door switch etc., has been configured by a hardwired sequence using a safety relay. Dual cutoff of both the input and output circuit allow to ensure cutoff, which is designed with safety in mind. Furthermore, a protective function is also incorporated into the charger to halt the output of the power supply unit in the case of detecting an abnormality in the output, etc. of the control part.

The power supply unit is made of two units connected in parallel, which operate cooperatively during normal operation. If one unit were defected, the other unit can carry out operation in fall back.

4.2 Employing design know-how of vending machines

The thickness of a sheet steel of a switchgear cabinet, etc. is typically 2.3 mm. However, vending machines make use of a cabinet technology that combines reinforcement parts and materials on a thin board, thereby providing sufficient cabinet rigidity. We have incorporated this same design technology into the production of this charger, which possess sufficient cabinet rigidity with a board thickness of 0.7 mm in both the main body and door. As a result, we have enabled to reduce the weight of the charger to 210 kg from the conventional unit weight of 700 kg, thus achieving a considerable weight savings.

Figure 6 shows the structure of door part and Fig. 7 shows an example of a stress analysis. Since the door exhibits cantilever motion with the opening and closing of the door, strength is a particular issue. In addition, another issue is the support structure of the main body since the power supply unit is approximately 60 kg. Therefore, structural stress analysis was carried out using 3D CAD for the reinforcement parts and support structure, and numerous tests were implemented before carrying out the trial production. As a result, we were able to prepare an optimized design that ensures a sufficient strength for the product. None of the parts use commercially sold steel materials, but use parts of optimal shapes and sizes obtained by bending and curving thin plates of sheet metal used for vending machines. Reinforcement parts in the door are also structured so as to serve as gutters when water drips down from various devices attached to the door such as the display device and switches.

In addition, other functional parts such as a door lock mechanism, hinge mechanism and door stopper were prepared so as to be compatible, to the extent possible, with parts used in vending machines in order to achieve enhancements in reliability.

With the exception of the main circuit, the wiring work avoided the screw wiring that uses terminal block, and adopted a wire harness that uses connec-

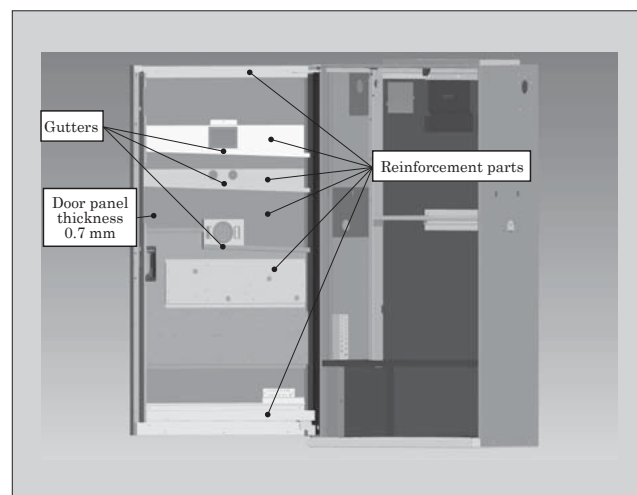


Fig.6 Structure of door panel

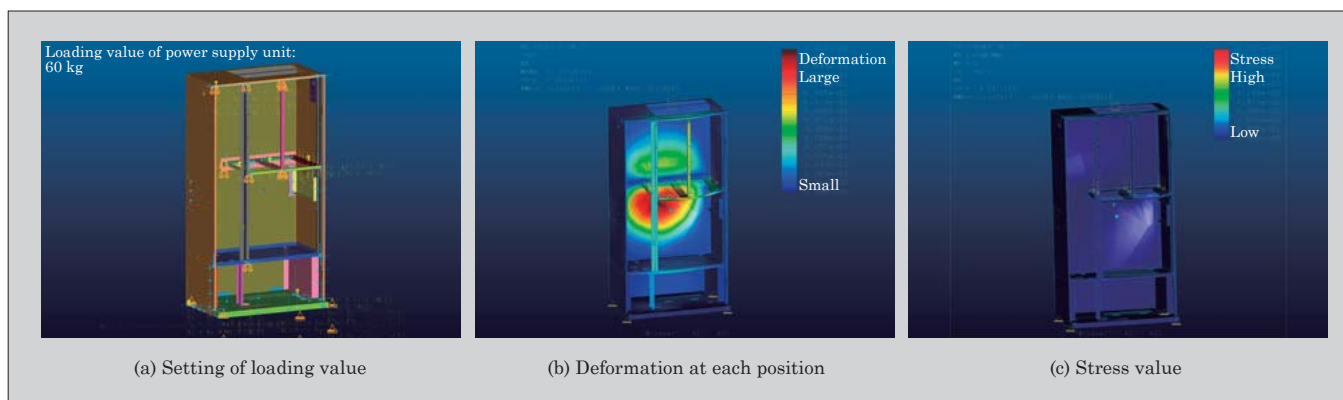


Fig.7 Example of stress analysis

tors, which is the same configuration used in vending machines. As a result, the wiring work by only using connectors was accomplished. Furthermore, by fixing the wiring with angle clamps, reliability as well as assembly easiness was realized.

In addition, each of the electric parts was integrated as a unit type so as to create a design that could contribute to the assembly line whereby electric parts and wiring are connected beforehand to attached metal fittings.

5. Postscript

In this paper, we have introduced “FRCM Series” of quick chargers for electric vehicles. The market for electric vehicles and quick chargers is expected to expand from now on as the market takes on a new form and creates new types of demand. In the midst of this

changing market, many companies are trying out various possibilities in order to discover and meet customers' needs.

Fuji Electric will dedicate itself to the development of electric vehicles community using its power supply technology. Our power supply units will be globally certified with UL and CE markings as well as compatible to overseas voltage specifications (480 V AC). In addition, our charger units will be able to meet the various needs of customers, being fully equipped with applications compatible with billing networks, coin-operated fee collection equipment, etc.

As we work to develop products that meet the new market opportunities brought about by electric vehicles, we look forward to continuing to make contributions toward the construction of a low carbon society through our power electronics technology.

Power Electronic Devices for Railway Vehicles

UMEZAWA Kotaro [†]

ABSTRACT

As effects on the global environment are becoming a problem, the world is focusing on railway vehicles for their better energy efficiency so they can be a means of transport that is environmentally friendly, high capacity, fast, safe, and economical. Fuji Electric has anticipated market needs related to energy efficiency and the environment and used the latest power electronics technology to provide environmentally-friendly electric equipment with increased consideration for the user comfort for railway vehicles such as vehicle propulsion (driving) system for Shinkansen etc., auxiliary power supply and door system in the Japanese and world markets. In addition, we are proactively expanding into markets around the world such as North America and Asia, as well as working to support international standards and localized production.

1. Introduction

As the effects to the global environment are becoming a problem due to the emissions of greenhouse gases such as CO₂, the world is focusing on railway vehicles since they exhibit high energy efficiency while providing a means of transport that is environmentally friendly, high capacity, fast, safe and economical.

In light of this situation, the demand for railway vehicles has been showing steady growth in Japan. Overseas markets such as China, Taiwan, South Korea and Southeast Asian countries have been constructing new lines as well as electrifying existing lines in order to strengthen transportation volume. Furthermore, the demand for railway vehicles in these countries has been increasing significantly, being bolstered by the economic growth that they have experienced in recent years. Likewise, the U.S. is facing the need to upgrade old and dilapidated railway vehicles, and demand there has also been expanding.

Fuji Electric has been helping to meet this growing need by providing its state-of-the-art power electronics equipment for railway vehicles as an eco-friendly means of transportation in order to contribute to the protection of the global environment by energy savings and conservation.

In this paper, current status of Fuji's power electronics equipment for railway vehicles and future trends will be presented.

2. Current Demand for Electronic Equipment for Railway Vehicles and Fuji Electric's Response

Items in demand among power electronics equipment for railway vehicles include technologies that fa-

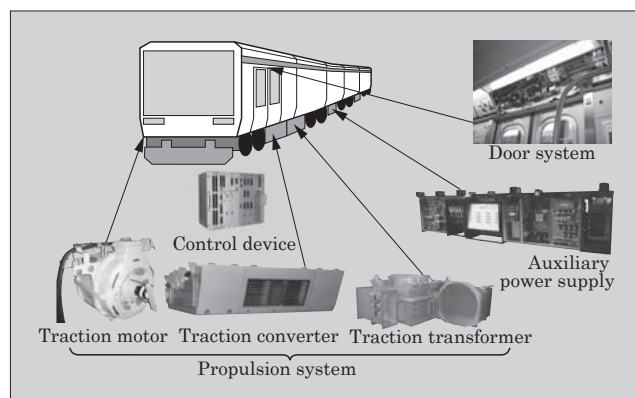


Fig.1 Electronic equipment for railway vehicles

cilitate energy-savings and harmonization with the environment as well as provide the needed levels of safety and reliability demanded from public transportation systems. In addition to these demands, the market is requiring a diversity of enhancements in economic efficiency, speed, size and weight savings, maintainability, and ride quality and comfort.

Fuji Electric has been dedicated to the development of next-generation technologies such as a vehicle propulsion (driving) system for the Shinkansen etc., auxiliary power supply and door system (see Fig. 1). In particular, our door system has been highly evaluated both in the Japanese and overseas markets as a highly safe product with a highly reliable performance record that conforms to international standards.

3. Propulsion System for the Shinkansen

The Shinkansen has attracted world-wide attention as a symbol of Japan's advanced railway technology. Shinkansen railcars have continuously incorporated the state-of-the-art technology of the times. Fuji

[†] Fuji Electric Co., Ltd.



Fig.2 Series N700 Shinkansen (Photo courtesy of JR Central)

Electric has delivered its propulsion system (including traction motors, traction converters, and traction transformers) for successive generations of Shinkansen trains from the first-generation series 0 Shinkansen train through the latest series N700 Shinkansen train. In this paper, we will present an outline of the traction converter of the series N700 (see Fig. 2) operated by the Central Japan Railway Company (JR Central) as a representative example.

3.1 Traction converter of series N700 Shinkansen railcars

(1) Configuration

The traction converter shown in Fig. 3 is configured from a 3-level pulse width modulation (PWM) converter and a variable voltage variable frequency (VVVF) control system inverter, where a single 3-level VVVF inverter collectively drives 4 traction motors connected in parallel. In order to increase efficiency and reduce weight, a low-loss snubber-less system has been employed, where insulated gate bipolar transistor (IGBT) modules (3,300 V, 1,200 A) that have a high blocking voltage, high capacity, and low loss are used. Two types of cooling systems are employed in the traction converter. The two types of systems include: (a) TCI3 model traction converter that employs a combination of ebullient cooling using a coolant, and forced cooling with a blower; (b) TCI100 model traction converter that uses a simple aluminum radiating fin, and a natu-

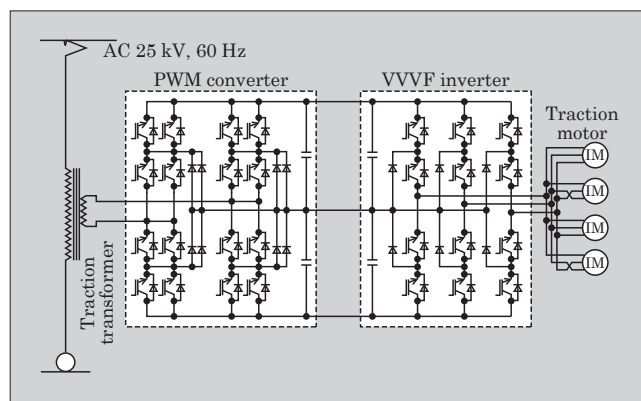


Fig.3 Configuration of series N700 traction converter

ral ventilation method of self-cooling without using coolant or blower.

(2) Reduced size and weight

The TCI3 model traction converter has achieved a reduced size by omitting a snubber circuit, optimizing its structure, etc. Compared to the series 700 TCI-2 model, the TCI-3 model aims to improve output by approximately 10% and realized to reduce volume by about 3% and unit mass by about 15%.

In addition, the blower-less TCI100 model traction converter has achieved a reduced weight of 12% compared to the TCI3 model.

We are also scheduled to provide traction converters in the series N700A, which is to make its debut in 2012.

3.2 Control of the traction converter for series N700 Shinkansen railcars

(1) Non-contact control equipment

The controller has a multi-processor configuration composed of 64-bit CPUs. The controller performs diverse control computations at high speed and with high accuracy, and for the purpose of advanced train control, also transfers operating commands and transmits operating status monitoring data. By utilizing the latest microelectronics, data transmission technology and the like, multi-functionality and high reliability have been achieved aiming at reducing part count and achieving.

(2) Converter and inverter control

Depending on the operating condition, a 3-level converter may cause a voltage imbalance at the positive and negative sides of the filter capacitor with respect to the DC neutral point, and there is a risk that an excessive voltage may be applied to certain components. While focusing on the behavior of the potential voltage of the neutral point during periods in which power device switching is idle in a traction converter, Fuji Electric developed neutral point potential control that does not depend on the polarity of power or current, and has applied this control to practical applications.

(3) Motor control

In the control of a railway vehicles propulsion system, the motoring^{*1} and braking torque of traction motor must be controlled responsively and accurately. In the industrial sector, vector control is typically employed as a means to realize this type of control, but the vector control of a single inverter connected to a parallel configuration of 4 motors, as in the case of Shinkansen trains, is difficult to implement in principle. However, by using the phase angle of primary flux, which is considered to be a common state variable

^{*1}: Motoring: With regards to railways, this term refers to speed increases by transmitting the dynamic force to the wheels from a motor or engine of an electric train car or locomotive engine.

unrelated to the number of motors connected in parallel, as a basis for the vector control, Fuji Electric has used vector control in practical applications and has achieved good results.

4. Auxiliary Power supply

The auxiliary power supply supplies stable power to the air-conditioning and lighting equipment necessary for maintaining comfortable conditions inside a railcar. It is an essential device for modern railway vehicles; it functions to supply control power for devices such as the traction converter and power supply for various IT devices such as the train control unit and display indicators inside a railcar.

Configuration of auxiliary power supplies varies greatly depending on the various types of power supply installed for the railway vehicle.

4.1 Auxiliary power supply for DC electric railcars

Figure 4 shows an example of the configuration of the power circuit of the auxiliary power supply for DC electric railcars

The feeding voltage for a DC feeding system is 1,500 V DC, 750 V DC or 600 V DC. In accordance with the output capacity and specifications required of the feeding voltage and equipment, an optimal voltage and current are selected for a semi-conductor insulated gate bipolar transistor (IGBT) configuring the circuitry or applying to the power circuit.

Usually, IGBTs having a withstand voltage capability that corresponds to the feeding voltage is used to configure a 2-level inverter, thereby streamlining the circuit, reducing the part count, and increasing the reliability.

4.2 Auxiliary power supply for AC electric railcars

The loads connected to the auxiliary power of AC electric railcars are indicator lamps, interior lighting, control power and the like, and are comparatively small in capacity. However, since these loads are critically important, a high level of reliability is required of the auxiliary power supply.

Figure 5 shows an example of a configuration of the power circuit of the auxiliary power supply for AC

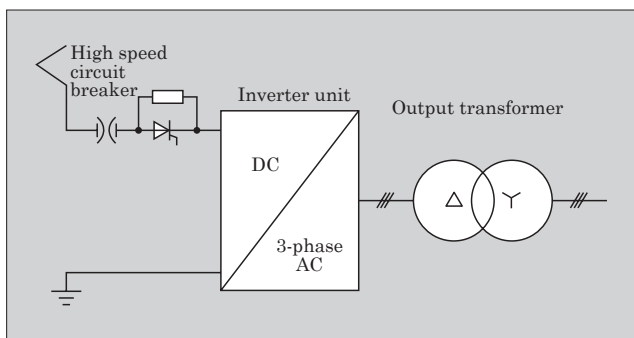


Fig.4 Example of the configuration of the power circuit of the auxiliary power supply for DC electric railcars

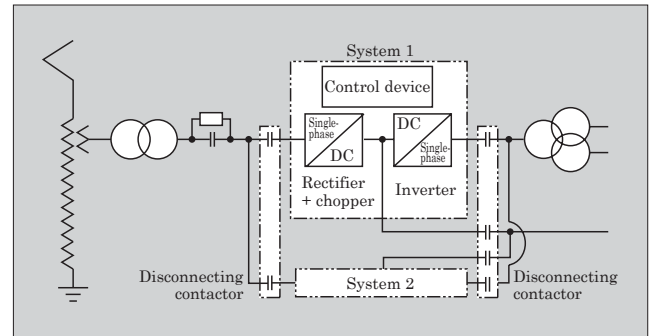


Fig.5 Example of power circuit configuration in auxiliary power supply for AC electric railcars

electric railcars. This is a case where the single-phase AC power of the tertiary winding of the traction transformer is rectified using a diode rectifier and an IGBT chopper, and then is supplied as DC power to a DC load. As for an AC load, that DC power is converted by an IGBT inverter unit and an output transformer into single-phase AC power and then supplied to the AC load.

4.3 Electric power supply for diesel-powered railcars

Diesel-powered railcars are unable to receive power externally, and therefore the installed diesel engine drives a generator to produce electric power. Fuji Electric has a history of manufacturing and supplying numerous electric power supplies for diesel-powered railcars to train companies, mostly including Japan Railway companies.

Figure 6 shows an example of configuration of the power circuit of the electric power supply for diesel-powered railcars. The rotational speed of the diesel engine for driving the main shaft, which is the power source of the power supply, will vary depending on the operating conditions. Constant-frequency AC power is supplied directly to a load such as the air-conditioning system by obtaining from a 3-phase AC power generator which is made run at a constant speed. The power control unit controls the excitation of the generator so that the generator output voltage is maintained at a constant level, and AC to DC conversion is performed to supply DC power to the controller, etc.

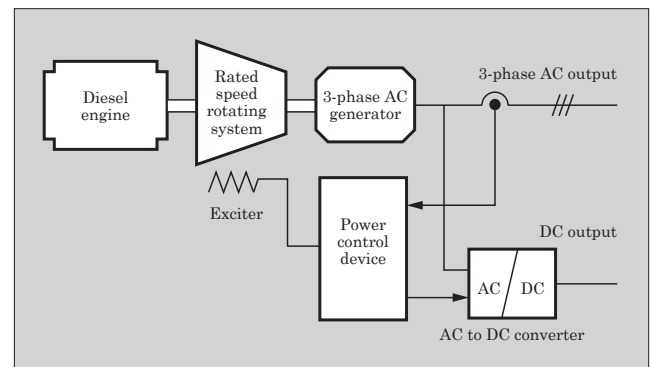


Fig.6 Example of power circuit configuration in electric power supply for diesel-powered railcars

4.4 Features of Fuji Electric's auxiliary power supply

(1) High performance control

The auxiliary power supply is required to provide a stable electric power supply with little waveform distortion or voltage fluctuation even in the case of sudden changes in the feeding voltage, the load current when a compressor or the like is turned-on or shut-off, or an unbalanced 3-phase load such as a single-phase load operation. Responding to this requirement, Fuji Electric uses individual 3-phase waveform control, as shown in the control block diagram of Fig. 7, in the output voltage control. Individual 3-phase root mean square (RMS) value control is implemented, based on detected values of the 3-phase output voltages, so that the RMS voltage value of each phase becomes constant. Furthermore, by combining with individual 3-phase instantaneous control, transient fluctuations in the output voltage due to load changes and so on can be suppressed. As a result, even in the case of sudden changes in the feeding voltage or load, stable voltage control performance is realized with a high-accuracy sinusoidal voltage having an output voltage deviation of $\pm 1\%$ or less and waveform distortion of approximately 1%.

(2) Higher reliability

Generally, a long rake of railway vehicles is equipped with 2 to 3 auxiliary power supply units, while a short rake is often only provided with a single unit. Consequently, failure of the auxiliary power supply directly leads to a deterioration in service, and may

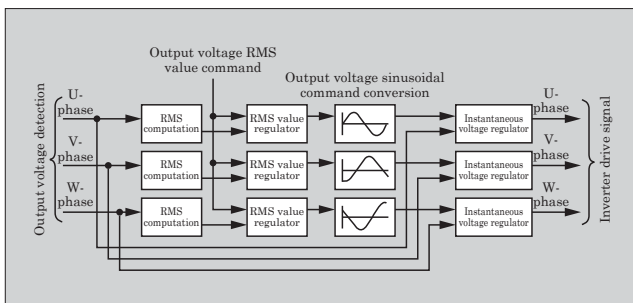


Fig.7 Control block diagram of high performance auxiliary power supply

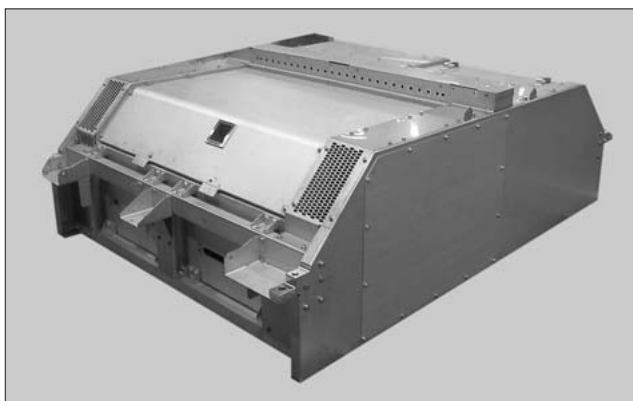


Fig.8 Roof-mount type auxiliary power supply

even result in a suspension of the railway vehicle operation. Fuji Electric has commercialized an auxiliary power supply equipped with dual-redundant inverters and controllers, and the unit itself has a standby redundancy system configuration for improved redundancy. When a failure occurs, the failed unit and standby unit are switched over so that operation will continue. During the system design phase, parts to be redundant are selected based upon computed values of the failure rate and upon historical data to create the most appropriate system as railway vehicle-use electric products for which small size and light weight are strongly requested. This method is being used as the auxiliary power supply for AC electric railcars in Japan.

(3) Enhanced functionality

IT is being incorporated into equipment for railway vehicles to achieve advanced railway vehicle operation and to improve the ease of maintenance. IT equipment with a data transmission function has become indispensable. The auxiliary power supply usually employs a data transmission system with an RS-485 for the physical layer and a transmission procedure based on polling/selecting. To advance further the functionality of a data transmission system for railway vehicles, Fuji Electric was early to commercialize a transmission system for railway vehicles based on the highly-versatile MODBUS on TCP/IP protocol, and has shipped auxiliary power supplies for railway vehicles overseas. Figure 8 shows the appearance of the roof-mount model of an auxiliary power supply unit.

We will study our auxiliary power supply to include a revised structure and new circuitry since we often receive requests from overseas to reduce the size and weight of the auxiliary power supply.

5. Door System

Among the types of equipment used in railway vehicles, a door system is the most familiar to passengers. Many systems are installed in a railway vehicle, each of them operating independently. Therefore, train doors have particularly strong requirements for safety, reliability, high functionality and low maintenance. Electric door systems have been long in use overseas. On the other hand, air-operated door systems have often been used in Japan. However, in recent years, the popularity of electric door systems have been quickly increasing as a result of reduced maintenance owing to self-diagnostic functions as well as improved safety through the use of high-speed control response systems in situations where a passenger or a passenger's luggage gets caught in a door.

5.1 Linear motor door system

Fuji Electric has commercialized and delivered door systems that use linear motors that simplify the door driving mechanism through utilization of the mo-

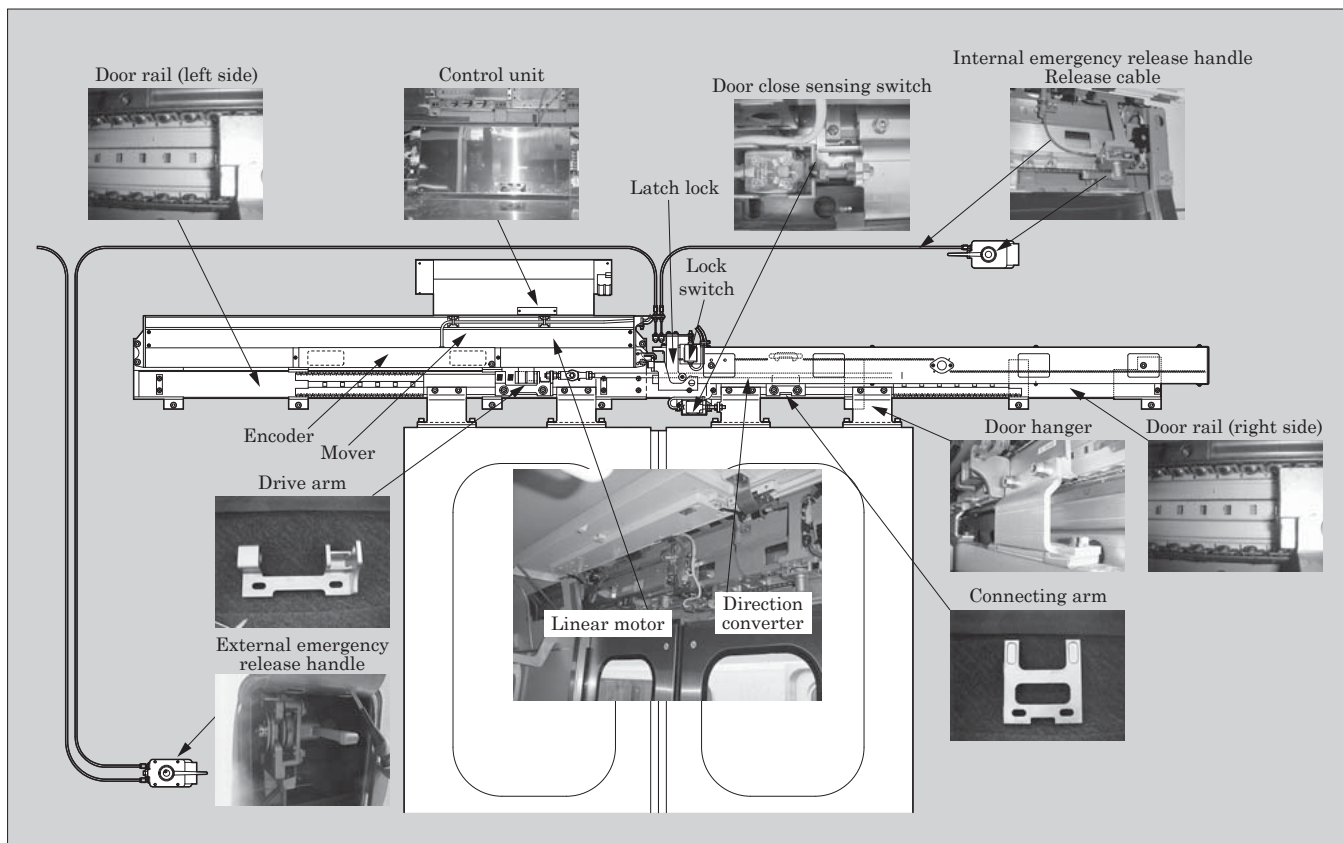


Fig.9 Configuration of door system

tion of motor itself.

In biparting type side doors, two motors drive the right and left doors respectively, pulling them apart from each other. In another type of system, both doors are driven by a single motor, using a mechanism to connect and interlock the doors. Decision regarding which system to employ depends on the needs (redundancy, economic efficiency, etc.) of each railroad company. Fuji Electric is producing door systems so as to meet each and every customer's need.

(1) One motor per one door opening type

This implementation is used in JR East's series E231, E233 and E531, and Seibu Railway's series 30000, and a total of more than 17,000 of these doors were being used in commercial operations at the end of 2011.

Figure 9 shows the configuration of a door system. One door leaf of a biparting type door is driven directly by the mover of a linear motor via a universal joint that isolates the motor from mechanical shocks from the door, and the other door leaf is driven in the opposite direction by a mover via a rack-and-pinion mechanism (mechanical direction converter). When a door is about to open, an unlocking operation is performed using a self-unlocking mechanism of which drive force is supplied by the linear motor.

The series E231 and subsequent models of railway vehicles of the Tokaido Line use a standby redundancy system that features dual-redundant signal I/O inter-



Fig.10 New York City Transit (NYCT) R160 train car

face circuits, control circuits and VVVF inverters so that even if a failure were to occur, operation is able to continue without any decrease in functionality.

Also, we have delivered our door systems overseas for use in Taipei on the Xinyi and Songshan Lines. We are currently waiting for the operation of the doors system to begin.

(2) Two motors per one door opening type

This implementation is used in the R160 subway cars operated by the New York City Transit (NYCT) Authority. By the end of 2011, more than 5,000 of these doors were in operation (see Fig. 10).

To ensure stable operation despite voltage fluctuations in the 37.5 V DC power supply, the supplied

power is boosted to a constant voltage and stabilized by a chopper circuit, and then input to inverters. In addition, an unlocking mechanism that uses a solenoid is applied to support customer specifications based on a safety concept that emphasizes functional independence. This door system greatly increases reliability over other door systems that have been previously used by NYCT, and has been well-received by the customer.

5.2 FCPM type door system

This is a system that drives side doors, by rotating (via a rotary motor) the pinions of a rack and pinion mechanism, which were applied in one motor per one door opening type of linear motor. In order to provide storage in the narrow space inside the head jamb, the motor has made use of a flattened flat cup permanent magnet motor (FCPM). This system realizes a weight that is lighter than linear motor type systems, while having the ability to change the movement of the side doors in the same manner as a linear motor. We are starting to make deliveries of the FCPM system as it is beginning to be employed in several railway vehicle projects both in Japan and overseas.

5.3 Features of electrical driven door and Fuji Electric's door system

(1) Advantages of electrical driven door

In comparison with air-operated systems, electrical driven door systems do not need pneumatic piping, and as such, they suffer aging effect scarcely and there is no need for on-site adjustment as pneumatic piping. These features reduce both the initial cost and maintenance cost associated with railway vehicle systems. In addition, our door system employs data transmission technology and controller functions that flexibly respond to changes in opening-and-closing operations, and achieves streamlining of pre-operation checks, increased intelligence, and a complete self-diagnostic function for individual door unit.

(2) Power transmission mechanism

In conventional electrical door systems, ball screw type system had been widely employed. The ball screw type is a system in which a nut moves when a screw is turned by a driver. It is a mechanism for opening and closing doors that are connected to parts that touch nuts via rotating the shaft that cut the screw thread by a rotary motor. This system requires many parts, since a mechanism is needed for converting the motor's rotational movements to linear door motion. This method has problems of requiring frequent lubrication in the sliding part and a decreased sensibility of door obstructions as described later.

Fuji Electric is employing both FCPM system and linear motor system to directly drive door system by using the motor's direction of motion directly. This has streamlined the door driving mechanism and improved the sensibility to obstruction. Figure 11 shows a com-

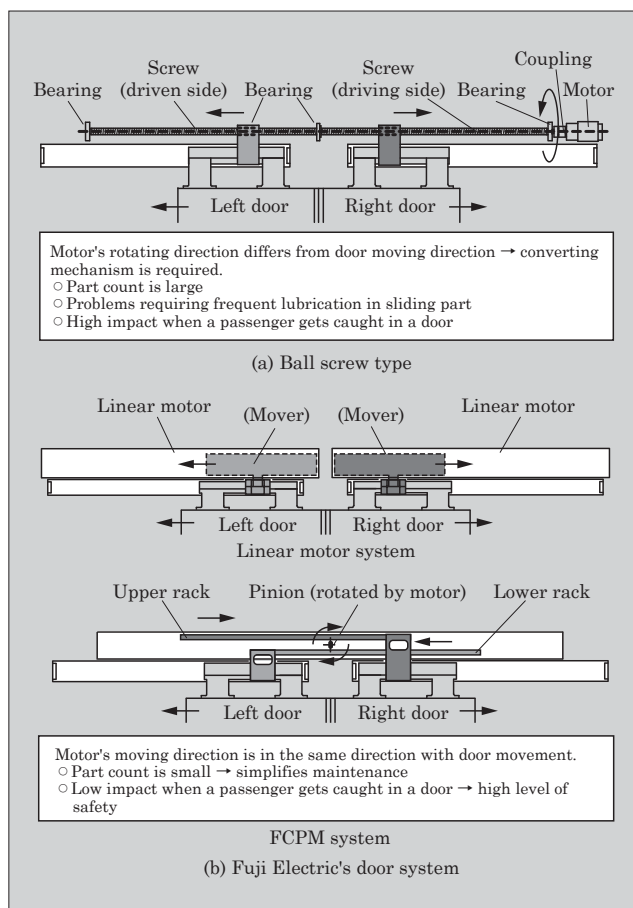


Fig.11 Comparison of door driving systems

parison of door driving systems.

(3) Locking/unlocking mechanism

In order to assure the door closed position and secure the safety, a locking mechanism with a lock pin is used. An unlocking mechanism is also provided for releasing the locked state when the door is about to open.

(4) Safety function

In recent years, accidents in which a passenger gets caught in a closing door have occurred frequently, and door safety has become an important issue. Fuji Electric's linear door employs highly sensitive door obstruction sensing based on the door speed and other control information. Additionally, after sensing a door obstruction, the safety operation is achieved with detailed control action based on various different requirements of railway companies.

6. Overseas Development

The demand for railway vehicles has been expanding in overseas markets, mostly owing to new rail line construction in Asia and renovation of existing lines in North America. To meet this demand, Fuji Electric has been actively advancing in its development overseas.

In order to do this, it is necessary to comply with overseas regulations and meet requests for local pro-

duction.

6.1 Implementation of SIL, SSIL

In Asian markets, SIL certification is required sometimes as a measure of safety according to IEC 61508 regulations stipulating functional safety. Electrical products destined for the Singapore subway system were required to implement SIL (SSIL) for software, and we acquired SSIL certification through gradual evaluation at each development stage.

Furthermore, we have been actively working to obtain this SIL certification since the door system itself also requires compliance to SIL in the Asian countries that we are currently advancing into.

6.2 Implementation of CMM, CMMI in North America

Doors for the NYCT-R160 require implementation of CMM^{*2}, and we have acquired certification based on a public assessment (assessed by a certified assessor) for CMM.

In addition, since we are currently involved in new auxiliary power supply and door projects to be carried out in North America, we have been actively pursuing CMMI^{*3} certification, which expands on CMM. Many projects in North America require implementation of CMMI, and as such, acquiring certification will be a big key to obtaining future orders.

*2: Capability Maturity Model (CMM): A model for appraising the software development maturity of an organization. CMM was developed by the Software Engineering Institute (SEI) at Carnegie Mellon University on the request of the U.S. Department of Defense.

*3: Capability Maturity Model Integration (CMMI): Guideline for integrating the capability evaluation model to help improve processes for organizations that perform system developments.

6.3 Response to request for local production

We have been finding it increasingly necessary to set up local production facilities in the overseas markets where we do business so that we can reduce costs associated with transportation, expenses required in mitigating foreign exchange risk as well as meet the demands of our overseas partner countries. In the U.S., it is required by law (as set forth by the “Buy American Act”) that at least 60% of the cost spent on production content and components be of the U.S. origin. In order to continue receiving North American projects in the future, we have been making efforts to comply with this law by setting up cooperative work projects and alliances with our affiliated American factories and parts makers.

7. Postscript

In this paper, we presented information on our power electronics equipment that are currently being used in railway vehicles and introduced some future trends. We are utilizing our state-of-the-art power electronics technology as a base for our developments in the railway vehicle industry in order to provide products that have reduced size and weight, high performance, high functionality, low maintenance, and a high level of comfort. In addition, we are committed to develop products that help conserve the global environment, as we believe that this will become a critical issue. We have been actively promoting our research and development anticipating the market needs of energy conservation and eco-friendly products, and we will strive continually to provide products that contribute to reducing the environmental burden of society as a whole.



High-Efficiency Front End Power Supplies Certified as 80 PLUS

KARUBE Kunihiko † TAWADA Nobuyuki † NAKAHARA Tomoki †

ABSTRACT

Switching power supplies that convert from AC to DC are installed in many electronic devices, and their market is expanding as these devices are becoming more advanced. Fuji Electric has developed and released switching power sources including front-end power supplies for information communication applications, an area that demands compactness, high efficiency, and high quality. We are focused on increasing power supply efficiency as promoted by the 80 PLUS program. We have released five models certified as Gold level, and one model certified as Platinum level. By using the latest semiconductor elements, we are continuing to improve power supply efficiency and increase high power density, and working toward compliance with the newly established Titanium level.

1. Introduction

Switching power supplies that convert from AC to DC are installed in many electronic devices. It is estimated that the world market scale in 2012 is 1.7 trillion yen, and the market is expanding as these electronic devices are becoming more advanced. Fuji Electric has been working on development of power supplies corresponding to changes in various customer needs in information communication field and industrial field for 35 years.⁽¹⁾

2. Front-End Power Supply

Front end power supply is a switching power supply that converts commercial 100 V or 200 V AC input in servers and storage devices to DC, such as 54, 48 or 12 V DC by rectifying and smoothing. For example, in November 2011, it became a popular topic of conversation that the domestic super computer achieved a speed of 10 quadrillion per second in November, 2011. The front-end power supply that is used for this computer system was developed and commercialized by Fuji Electric. Figure 1 shows the external appearance. This power supply converts 200 V AC to 48 V DC and output power is 3,000 W. The development of this power supply had a high degree of difficulty because compactness, high efficiency and high quality were required.

Fuji Electric is concentrating on development and commercialization of switching power supplies including these information communication related front-end power supplies, and is focusing on improving power supply efficiency as promoted by the 80 PLUS program.

This paper describes the high efficient front-end



Fig.1 Front-end power supply of 3,000 W output

power supplies that are certified as this “80 PLUS*1.”

3. Front-End Power Supply Certified as 80 PLUS “Platinum”

There is a need for improvement of efficiency in switching power supplies typically used for servers and hard disk devices. As one index, there is a guideline of industry group, called 80 PLUS. In this guideline, the following two categories are included. One is single output (there is a case for two outputs) and the power supply that enables parallel redundancy operation. The other is multi output (two outputs or more) and

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*1: 80 PLUS: See “Explanation 1” on page 217

Table 1 80 PLUS efficiency guidelines

80 PLUS rank	Load factor *			
	10%	20%	50%	100%
80 PLUS Titanium	90%	94%	96%	91%
80 PLUS Platinum	—	90%	94%	91%
80 PLUS Gold	—	88%	92%	88%
80 PLUS Silver	—	85%	89%	85%
80 PLUS Bronze	—	81%	85%	81%
80 PLUS Standard	Not applicable			

* : For input power voltage 230 V AC

the power supply with no provisions regarding parallel redundancy operation. The demand for efficiency is higher in the former type and is categorized into 6 ranks (see Table 1)⁽²⁾.

Five models of Fuji Electric power supplies are certified and registered as “Gold” rank, and one model is certified and registered as “Platinum” rank which are shown in Table 1 (as of April 2012). Of the models that are registered as 80 PLUS, 131 models are Gold rank and 88 models are Platinum rank. There are 43 companies with which products are certified in guideline of 230 V AC, including information device manufacturers and electric power supply manufacturers (as of April 2012).

Requirements for front-end power supplies are compactness, high efficiency, parallel redundant function and communication function with external devices. As for external dimensions, 3,000 W power supply presented in Chapter 2 conforms to the standard called, server system infrastructure (SSI). However, as with recent trend of downsizing in customers devices, three to four units of power supply can be basically stored in the rack with dimensions of 1U (44.5 mm) height and 19 inches width.

Although the difference in efficiency between Gold and Platinum is 2%, considering the fact that several thousand units of power supply are used in the large-scale systems such as a data center, this difference is large. For example, if power consumption is 10 MW, the difference in loss of electric power is 2%, which is 200 kW. Furthermore, reduction in cooling device equivalent to 200 kW is also possible, achieving further energy conservation effect.

4. AC-DC Front-End Power Supply “FH02500UAD” of 2,500 W Output

Figure 2 shows external appearance and Table 2 shows main specification of the power supply. The characteristics of the front-end power supply “FH02500UAD” is introduction of digital control using

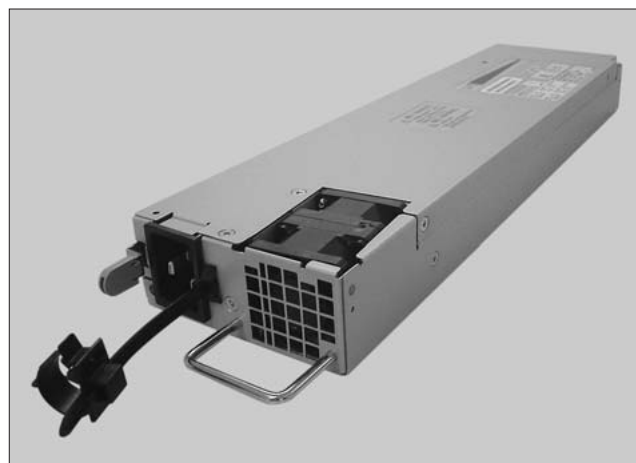


Fig.2 AC-DC front-end power supply “FH02500UAD” of 2,500 W output

Table 2 Main specification of “FH02500UAD”

Item		Specification	
Input characteristic	Input voltage	100/200 V AC	
	Frequency	50/60 Hz	
	Inrush current	20 A or below	
	Efficiency	94% or higher (certified as 80 PLUS Platinum)	
	Power factor Harmonic current regulation	98% (load factor 50 to 100%) JEIDA EN61000-3-2 (compliant)	
Output characteristic		ch. 1	ch. 2
	Output voltage	+54 V	+12 VSB
	Rated current	46 A*1	4 A
	Minimum current	0.4 A	0 A
	Ripple noise	480 mVp-p	120 mVp-p
	Total fluctuation	±5%	±5%
	Overvoltage protection	51 to 55 V	—
	Overcurrent protection	110 to 150%	100 to 150%
Environmental condition	Operational temperature/humidity	0 to +50 °C*2/20 to 95%RH	
	Storage temperature/humidity	−40 to +70 °C/20 to 95%RH	
	Vibration resistance	0.5 G, 3 to 60 Hz, 1cycle/2 minutes×5	
	Heating protection	Yes	
Standard	Safety standard	UL/CSA/TÜV/CCC	
	Noise standard	CISPR/FCC Class A (compliant)	
Others	Dimensions	W102×D355×H41 (mm) (protruded section is not included)	
	Mass	2.5 kg or less	
	Output per unit volume	1.68 W/cc	
	Cooling condition	Forced air cooling	

*1 : 23 A when inputting 100 V system

*2 : With output derating at 35 to 50 °C

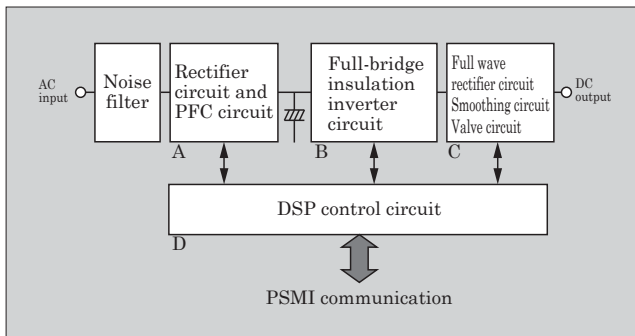


Fig.3 Block diagram of "FH02500UAD"

digital signal processor (DSP) instead of using analog IC for control circuit. Figure 3 shows block diagram of this power supply.

Digital control is introduced for controlling the power factor correction (PFC) circuit, full-bridge insulation inverter circuit and full-wave rectifier circuit.

4.1 Advantage of digital control

There are the following advantages from performing digital control

- (1) It became easy to switch control method corresponding to the load factor, which was difficult with analog control, and efficiency at light-load was improved. Improvement was 2 points or more at load factor 20% compared to the previous control.
- (2) Influence of switching noise can be eliminated by information processing inside the power supply, without setting up a large filter circuit, improving the output accuracy when communicating with outside. Monitor accuracy was improved by 5 points.
- (3) The number of control circuit parts was reduced by 30% compared to before, and downsizing was achieved.
- (4) For reduction of lead time and modification, it became possible to set or change constant value without changing hardware circuit via communication function with personal computer, and 20% reduction of shipping inspection time was achieved compared to before.
- (5) Simulation accuracy is high due to software control, and it became easier to perform desk study for operation of switching power supply.

Fuji Electric uses design support tool for digital control software development. Design support tool generates code automatically by writing the program in block diagram format, enabling development of control software in a short period of time for various customer needs. Figure 4 shows a screen example of the software design support tool.

Figure 5 shows a waveform of output voltage and the output current when load is fluctuating between 100% and 75%. Fluctuation range is $\pm 1.5\%$, and good result can be obtained, which is no way inferior to ana-

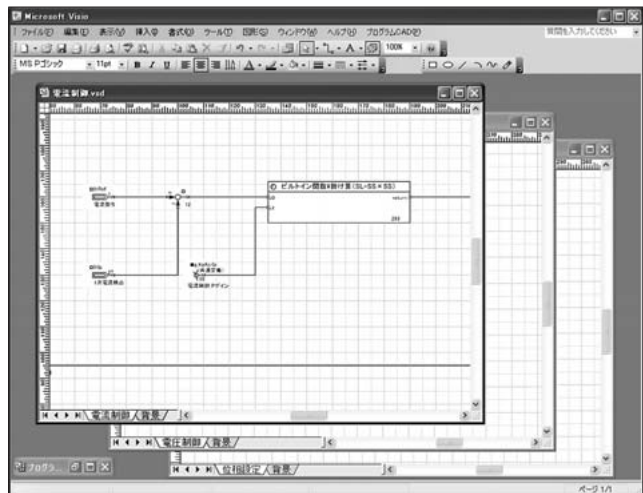


Fig.4 Screen example of software design support tool

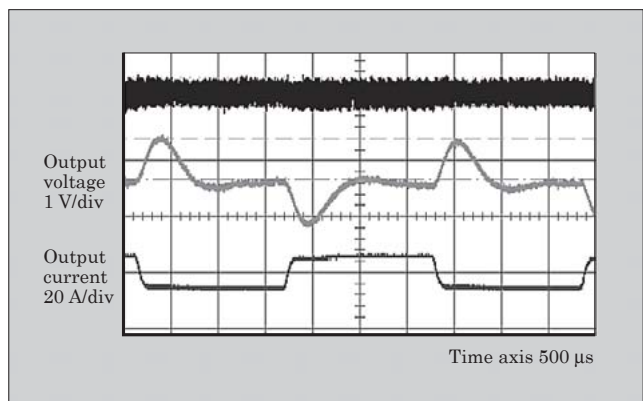


Fig.5 Load fluctuation waveform of "FH02500UAD"

log control.

4.2 Method of high efficiency

Engineering method which achieved high efficiency of Platinum rank is described below⁽³⁾.

- (1) One tier structure of rectifier circuit and PFC circuit

With the previous method, control was performed by straight two-tier structure of rectifier circuit and PFC circuit so that input current makes a sine waveform, and a stable direct-current middle voltage (input voltage of full-bridge insulation inverter circuit) was obtained. Meanwhile, in FH02500UAD, a method that put all these functions together was developed and the conversion tier was reduced to one tier (see Fig. 3: Section A).

- (2) Application of SiC diode and SJ-MOSFET

By applying silicon carbide (SiC) diode and super junction metal-oxide-semiconductor field-effect transistor (SJ-MOSFET) to the switching semiconductor of PFC circuit and full-bridge insulation inverter circuit, the switching loss and conduction loss were improved (see Fig. 3: Section A and B).

Figure 6 shows efficiency characteristic corresponding load factor. For load factor that 80 PLUS specifies,

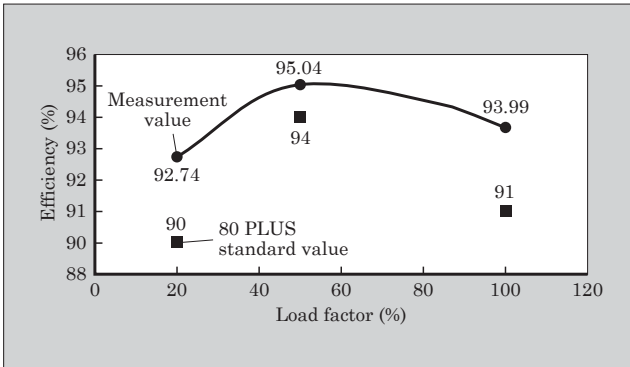


Fig.6 Efficiency characteristic corresponding load factor

it is possible to obtain 1 to 3 points higher efficiency.

- (3) Improvement of conduction loss of full wave rectifier circuit

Previously, diodes were used in full-wave rectifier circuit for power supply of 48 to 60 V class. As a result of recent progress in switching semiconductor, diodes were replaced with MOSFET for power supply of 48 to 60 V class, and conduction loss of semiconductor device was improved (see Fig. 3: Section C).

- (4) Change of switching method corresponding to load factor

Previously, switching losses of element was reduced and efficiency was improved by phase shift method operated by soft switching, which enables Zero Volt Switching (ZVS) operation of full-bridge insulation inverter circuit. However, phase shift method has a disadvantage that the soft switching operation becomes disabled at light-load and efficiency is lowered. By applying the aforementioned digital control, the disadvantage was improved as a result of changing to a hard switching method, which is more efficient than the phase shift method at light-load, and reduction of loss in all regions was achieved (see Fig. 3: Section D).

The front-end power supply, which utilizes these technologies were adopted by customers who focus on compactness and high-efficiency in the industrial field such as semiconductor manufacturing equipment, besides the information communication field.

In addition, currently, Platinum rank product having output voltage of 12 V with identical output power is being developed.

5. Front-End Power Supply “FH02100JAD” of 2,100 W Output

The external appearance of front-end power supply, “FH02100JAD” is shown in Fig. 7, and the main specification is described in Table 3.

Because output voltage is as low as 12 V, output current becomes 3.8 times of FH02500UAD that was explained in Chapter 4. Therefore, for secondary side of full-wave rectifier circuit in full-bridge insulation inverter circuit, MOSFET of surface mounting type that enables soldering directly on the printed board is used



Fig.7 Front-end power supply “FH02100JAD” of 2,100 W output

Table 3 Main specification of “FH02100JAD”

Item		Specification	
Input characteristic	Input voltage	100/200 V AC	
	Frequency	50/60 Hz	
	Inrush current	15 A or below	
	Efficiency	94% or higher (certified as 80 PLUS Platinum)	
	Power factor Harmonic current regulation	95% (load factor 50 to 100%) EN61000-3-2(compliant)	
Output characteristic		ch. 1	ch. 2
	Output voltage	+12 V	+5 VSB
	Rated current	175 A*	5 A
	Minimum current	0 A	0 A
	Ripple noise	120 mVp-p	50 mVp-p
	Total fluctuation	±3%	±5%
	Overvoltage protection	13.2 to 14 V	5.5 to 6 V
	Overcurrent protection	105 to 117%	110 to 120%
Environmental condition	Operational temperature/humidity	0 to +40 °C/5 to 90%RH	
	Storage temperature/humidity	-20 to +65 °C/5 to 95%RH	
	Vibration resistance	0.25 G, 5 to 55 Hz 1cycle/5 minutes×6	
	Heating protection	Yes	
Standard	Safety standard	UL/CSA/TÜV	
	Noise standard	CISPR/FCC Class A (compliant)	
Others	Dimensions	W112×D279×H47 (mm) (protruded section is not included)	
	Mass	2.0 kg or less	
	Output per unit volume	1.43 W/cc	
	Cooling condition	Forced air cooling	

* : 80 A for 100 V input

to reduce conduction loss of semiconductor device and switching loss as much as possible. In addition, in or-

der to reduce conducting loss of printed board, bus bar is used at the same time. Furthermore, for smoothing circuit coil, straight angle plates are used for windings to achieve efficient utilization of the space.

6. Postscript

In this paper, high efficient front-end power supplies certified as 80 PLUS were presented. Along with the rapid advancement of ICT in the society, information communication devices are becoming more high-density and power-saving style. Improvement of efficiency is also demanded for power supply of device along with this trend. In 2011, the rank called “Titanium” was set up for 80 PLUS. Compared to Platinum, which used to be the highest level so far, the maximum 4 points of efficiency improvement is required, and a new load factor, 10% was specified. Therefore, the hurdle for power supply manufacturers got higher.

While receiving support from customers, Fuji Electric is developing application technology on the latest semiconductor devices, such as SiC-MOSFET and GaN (gallium nitride)-MOSFET toward being certified as Titanium. In addition, magnetic components such as transformer and coil, and improving characteristic of printed wiring board that allows large current to be applied, are focused. Fuji Electric intends to promote further improvement in efficiency and increase in high power density.

Reference

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“FCPOP”: A Power Management Platform for UPS Products

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ABSTRACT

Fuji Electric has a wide lineup of UPS products and it is necessary to provide power control systems that integrate products from mid-to-high capacity UPS to mini-UPS.

To achieve this, Fuji Electric built “FCPOP” power management platform for UPS products. With this as a base, we developed a power management system with a new configuration in which sections corresponding to each UPS are stacked. The power management system comprises UPS monitoring software, integrated power management software, a network interface card, shutdown software, and more to provide the user with a unified product concept and operability.

1. Introduction

When an abnormality such as a power outage occurs in an electrical system, it is important to have a power control system for UPS operation in addition to installation of an uninterruptible power supply (UPS). There are various forms of power control systems, ranging from small ones that are comprised of a single UPS to large-scale systems that collectively control multiple UPS's via a network. Fuji Electric has a wide line-up of UPS products and it requires integrated power control systems for these products. Fuji Electric has already developed an integrated power control system in the field of mid-to-high capacity UPS, and mini-UPS is the current target. For such mini-UPS, in addition to a function to control the UPS, a power control system requires a shutdown function to stop the loading apparatus of the UPS when a power outage occurs, and such function and the system's interface differ depending on the intended purpose.

To achieve a comprehensive power control system, we built up “FCPOP”, a power management platform for UPS. Using this as the base, we developed a power management system with a new configuration by stacking up sections corresponding to each UPS.

FCPOP (Fuji common power platform) is made up of components such as hardware composing a power management system, common parts within software, a common processing section and a common user interface section etc. By adding UPS model-dependent function, it is possible to easily make the system compatible with various models.

2. Structure and Main Functions of “FCPOP”

2.1 Overall structure

Figure 1 shows the overall structure of FCPOP. For a single UPS, the UPS monitoring software operates on a computer connected to it and monitors the power supply and UPS, and shuts down loading apparatus (see Fig. 1 (a)). When there are multiple UPSs, a network interface card is mounted on the UPS and integrated power management software is used to collectively control them. The network interface card and shutdown software are used to shut down the devices in the event of a power outage (see Fig. 1 (b)).

Structures of the UPS monitoring software, network interface card, integrated power management software and shutdown software are shown in Fig. 1 (c). FCPOP operates on the Operating System and on that platform, a processing section, which differs depending on the series of UPS, is operated.

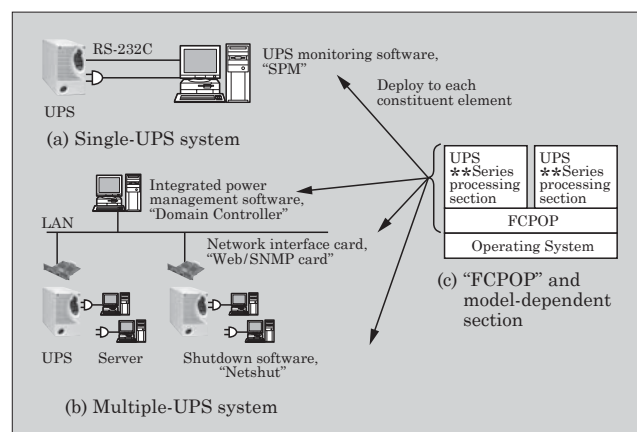


Fig.1 Overall structure of “FCPOP”

[†] Fuji Electric Co., Ltd.

2.2 Main function of component elements

(1) UPS monitoring software

UPS is used as a backup power supply for loads such as computers when an abnormality like a power outage occurs. However, only a finite amount of electrical energy can be accumulated in the battery of a UPS and it can only provide a backup power supply for a limited time. Meanwhile, if the predetermined procedures are not followed when shutting down a computer, data may be corrupted or a hard disk failure may occur. Therefore, our UPS monitoring software shuts down a computer before it becomes impossible to offer a backup power supply when a power outage lasts for a long time. In this manner, the UPS monitoring software operates on a computer connected to the UPS, monitors the UPS and power supply, and shuts down the computer and stops the UPS from providing power.

(2) Network interface card

A network interface card is mounted in an optional slot of the UPS to connect to the network.

In addition to the shutdown function, which is the same as the previously mentioned UPS monitoring software, there are extensive management functions during normal operation such as event notification using a network, remote power supply monitoring performed by a computer on the network, and scheduled operations.

(3) Shutdown software

This is software to be installed in advance on a server and personal computer that are to be backed up by the UPS, and it shuts down the computer by receiving commands from the network interface card. Prior to shutdown, it is possible to run a given user program on such computer.

(4) Integrated power management software

The range of backup functions provided by a UPS covers such various areas as an entire plant or group of floors, and our backup system has many installation modes to suit this range. In any event, it is important to have a device that offers backup power, and it must operate safely.

Such events as a power outage or UPS failure could significantly damage the operation of the load apparatus. Therefore, these events must be accurately notified to the user. On the other hand, it is often the case that multiple UPS are installed on the work floor, and managing each UPS individually is not efficient. Therefore, utilizing integrated power management software to manage multiple UPSs by means of a network reduces the man-hours required to manage them.

3. Characteristics and Technology of “FCPOP” Component Elements

3.1 “Web/SNMP card” for “EX100 Series”

(1) Shape and operability

This card is a network interface card for the mini-UPS “EX100 Series.” The shape of the EX100 Series

optional slot and interface specifications are adopted widely by overseas manufacturers and they are different from the card adopted in the existing “GX Series” or mid-to-high capacity UPS. Therefore, the mounted parts and functions are made uniform for the “Web/SNMP card” in products such as the GX100 Series, and the shape and interface specifications are adapted to the EX100 Series (see Fig. 2).

As a result, when a user who is utilizing the Web/SNMP card of a mini-UPS such as the GX Series and mid-to-high capacity UPS, introduces the EX100 Series, there is no need to learn new operations, and the product can be used in the same way as the existing ones (see Fig. 3).

In addition, for the shutdown software that is installed on a server in advance, it is possible to use “Netshut,” which is available for use on all UPSs manufactured by Fuji Electric, and the server can be shut down via the network. Hence, it is possible to shut down 200 or more servers, and easily accommodate a blade server and server virtualization system.

(2) Control function by segment unit

The output of the EX100 Series can control multiple output outlets called “segments” by group; there-

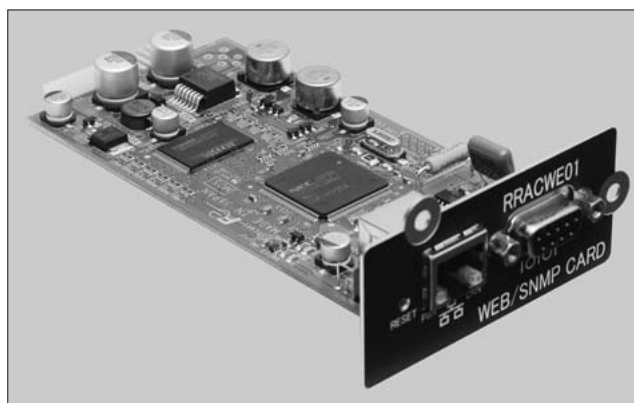


Fig.2 “Web/SNMP card” for “EX100 Series”

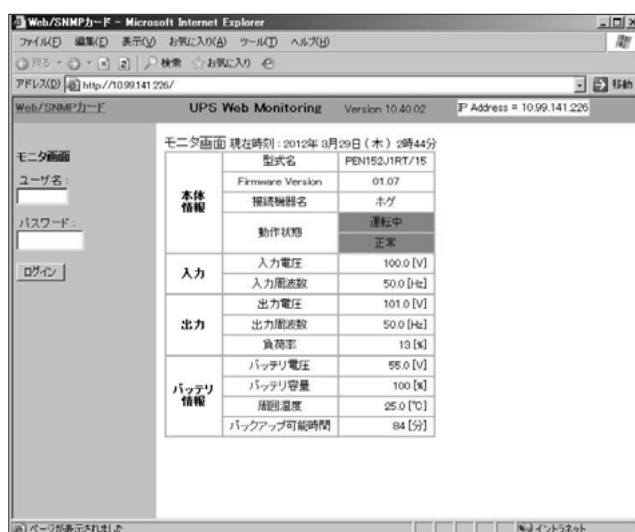


Fig.3 Monitoring screen

fore, it is possible to easily set up a time lag between the starting up and stopping of each device by using an information system that is comprised of servers and storages. This segment control function was newly mounted on the Web/SNMP card and in addition to startup and stop functions, new features such as OS shutdown and scheduled operations were linked. As a result, it has become unnecessary to use a power supply distribution unit for lag operation, which was necessary when a UPS was used for existing system that is comprised of the servers and storages, and the cost of the whole system can be reduced.

(3) Enhancement of security

For UNIX servers, it is sometimes difficult to introduce the aforementioned shutdown software because security measures are in place.

In addition, new software cannot be installed on a Linux-based appliance server for structural reasons. In order to shutdown such a server when there is a power outage, the server used to be controlled via a network card by using Telnet^{*1}. This time, security has been enhanced by introducing SSH^{*2} for information that flows on the network. Serial communication is also available in preventing data leaks, and the user can select the optimal shutdown method according to the environment.

3.2 Integrated power management software, “Domain Controller”

“Domain controller” is software to collectively manage multiple mini-UPSs that exist on a network. For management objects, a group concept called UPS domain was introduced.

When multiple UPSs exist within an information system, they are regarded as the same group in the UPS domain, which is a different group from viewed from the existing power supply side, and this is the information-system-centric concept. By introducing this, when multiple information systems exist on a network and multiple UPSs are included in each information system, it becomes easy to have such power supply management centered on individual information systems as scheduled operations on an information system basis and grasp the area of influence in the event of a power outage.

To allow the domain controller to be used with the Web/SNMP card, we adopted a structure where each UPS-corresponding section was piled up on FCPOP, which is a common base as previously mentioned. This will not only add the GX Series and EX100 Series to the target model, but also make it easy to add future

*1: Telnet⁽¹⁾ (Telecommunication network): Communication protocol that supports virtual terminal connection via network.

*2: SSH⁽²⁾ (Secure Shell): A type of communication protocol for which ciphers or authentication technology is used. Login and commands are executed via network.

models.

3.3 UPS monitoring software, “SPM”

“SPM” (stand power monitor) is software that operates on a personal computer or server that is backed up by UPS and communicates with the UPS via a serial interface.

This software gathers information on UPS and power supply, notifies the user of events such as power outages, and performs a coordinated operation of shutdown and UPS output stoppage.

(1) Decrease in degree of OS dependence

There are currently various types of OS installed in personal computers or servers and each of them is frequently updated. SPM is required to correspond to these OSs and in general, if the degree of dependence on an OS is large, it takes time for release because operation verification work needs to be conducted when a new OS released or the existing OS is updated.

Therefore, SPM was designed so that its dependence on the OS is as low as possible. It has been designed to lessen the degree of dependence at each section. For example, when there is communication between tasks, SPM can handle such communication by using its own resources inside the SPM without the API provided by the OS. This makes it possible to promptly handle a new or updated OS.

(2) Common platform and model depending module

As for the structure within the software of the SPM, an interface section with UPS is regarded as a model depending module, and it becomes independent from the common platform including the event handling processing section, and communication between tasks is used to exchange data between these modules. Because the interface between SPM and UPS differs in the GX Series and EX100 Series, the connecting UPS is identified when the SPM is started, and the interface to be supported is switched according to the type of UPS.

This allows the SPM to connect to a UPS of both the GX Series and EX Series, and it has given a struc-

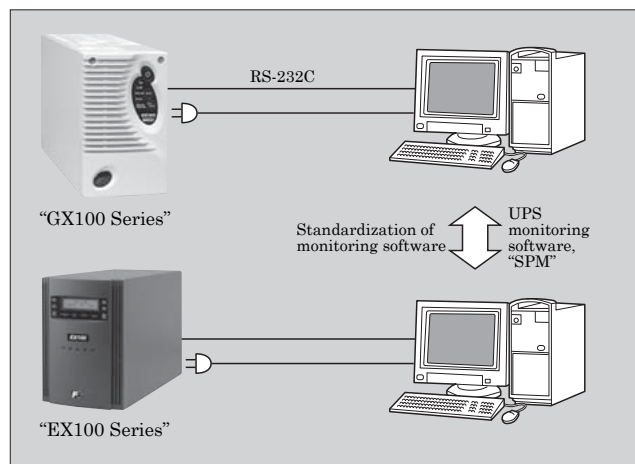


Fig.4 Standardization of UPS monitoring software

ture to allow expansion of the supporting models in the future easily (see Fig. 4).

Users can mutually use monitoring software regardless of the UPS type that is used, and the operability will not change.

Figure 5 shows a screenshot of the SPM. Because



Fig.5 Screenshot of “SPM”

of the simple display method using an icon, which is set up in the task tray and changes depending on the status of UPS, it is easy to grasp the status of the UPS and the power supplies.

4. Postscript

This paper presented “FCPOP,” a platform to manage power supplies for a UPS that can provide the user with a unified product concept and operability. Fuji Electric will continue working to offer more benefits to users by expanding the supporting models and rapidly updating products so that they can run on a latest OS.

Reference

- (1) RFC854: Telnet Protocol Specification (IETF).
- (2) RFC4250: The Secure Shell Protocol (IETF).

Evaluation and Application Technology of New Batteries in UPS Products

NAKAZAWA Hiroshi[†] HAMADA Ippei[†]

ABSTRACT

In consideration of the environment, Fuji Electric is developing a UPS with a new type of battery to replace lead-acid batteries, which use environmentally regulated materials. We are also developing storage devices and investigating application technology for lithium-ion batteries installed in electric vehicles and hybrid cars in partnership with battery manufacturers. We evaluated olivine-type lithium iron phosphate batteries, which have received attention in Japan as a new type of battery, and are considering adding them to our UPS products. We also launched UPS products equipped with the manganese lithium-ion batteries by evaluating with the similar method.

1. Introduction

An uninterruptible power supply (UPS) is a device that provides a stable power supply regardless of the power-supply variation in the AC input, and numerous UPSs are used to ensure the stable operation of network devices that support advanced information society. In general, UPSs contain a lead-acid battery as a storage medium, which is separated from a commercial power supply, in order to supply power during a power outage.

In consideration of the environment, Fuji Electric is developing a UPS with a new generation battery to replace lead-acid batteries that use environmentally regulated materials. In addition, in order to promptly respond to market changes, we are also developing storage media in addition to a conversion circuit necessary for UPSs.

This paper describes the technology of a lithium-ion battery as a secondary battery to replace lead-acid batteries, and reports on olivine-type lithium iron phosphate batteries, which have received attention in Japan as a new type of battery. Furthermore, as an example of a product, we will present a UPS equipped with a manganese lithium-ion battery.

2. Environmental Changes Surrounding UPS and Need for Battery Evaluation

Amid concerns about natural disasters and energy shortages, UPSs are gaining attention for general household use, not only for commercial purposes, and recently, they have come to be sold in electrical appliance retailers.

In general, UPSs are used to prepare for a rela-

tively short power outage due to disasters or unforeseen circumstances. Meanwhile, as a countermeasure against a planned power outage, there is increasing demand to use UPSs as a backup power supply for longer hours.

Under such circumstances, lithium ion batteries are attracting attention as they do not contain environmentally regulated materials, they are excellent for periodic use and they can provide a backup power supply for long hours.

The properties of lithium-ion batteries change significantly depending on the constituent materials of parts such as the positive-electrode material.

Table 1 shows a comparison of the characteristics

Table 1 Comparison of characteristics of cathode material

Positive-electrode material	Manganese system LiMn ₂ O ₄	Cobalt system LiCoO ₂	Nickel system LiNiO ₂	Ternary system LiNi/Co/MnO ₂	Iron phosphate system LiFePO ₄
Structure	Spinel structure	Layer structure	Layer structure	Layer structure	Olivine structure
Nominal voltage (V)	3.7	3.7	3.5	3.7	3.2
Discharge potential curve	Flat	Flat	Slope	Slope	Flat
Capacity (Ah/kg) [Theoretical value/practical value]	148/110	274/150	274/190	278/160	170/150
Thermal decomposition temperature (°C)	355	225	180	300	400 or more
Thermal stability	○	△	×	○	◎
Raw material cost (ratio)	1/8	1	1/6	1/6	1/10
Recoverable reserves (Mt)	680	4	47	4/47	83,000

[†] Fuji Electric Co., Ltd.

Table 2 Comparison of characteristics of secondary battery for mounting on mini-UPS

Type of battery	Electrode material		Battery capacity	Voltage range	Maximum current		Usage environment	Cycle life (20°C)	Output density Power density	Characteristics
	Positive electrode	Negative electrode			Battery charge	Discharge				
Electric double-layer capacitor	Activated coal	Activated coal	350 to 3,000 F	0 to 2.5 V	1,000 A	1,000 A	−20 to +70 °C	1 million times or more	6,700 W/kg 4 Wh/kg	○ Enables discharge up to 0 V ○ Long cycle life ○ High output density → Peak cut use
Lithium-ion capacitor	Activated coal	Carbon material (Li dope)	1,000 to 2,000 F	2 to 3.8 V	100 A	100 A	−20 to +70 °C	100,000 times or more	3,300 W/kg 12 Wh/kg	○ High working voltage → Few serial connections ○ Used in intermediate range between battery and the capacitor ○ High safety
Lithium-ion battery	Lithium compound	Lithium titanate	4.2 Ah	1.5 to 2.8 V	12 CA	10 CA	−30 to +50 °C	6,000 times or more	1,250 W/kg 65 Wh/kg	○ Enables fast charge → Can be charged in a short time ○ High thermal stability
	Lithium compound (Olivine-type iron phosphate)	Carbon material	3 Ah	2 to 3.6 V	2 CA	6 CA	−20 to +60 °C	5,000 times or more	113 Wh/kg	○ Low material cost → Low-price battery ○ High safety
	Lithium compound (Spinel-type manganese acid)	Carbon material	3.5 Ah	2.5 to 4.2 V	2 CA	5 CA	−20 to +50 °C	5,000 times or more	2,380 W/kg 136 Wh/kg	○ High energy density → Provides backup power for long hours ○ High working voltage → Few serial connections
Lithium-ion (polymer) battery	Lithium compound	Carbon material	4.7 Ah	2.5 to 4.2 V	1 CA	5 CA	−20 to +50 °C	5,000 times or more	158 Wh/kg	○ High energy density due to polymer product ○ Good degradation resistant characteristics at high temperature ○ Little capacity changes due to temperature and high-rate discharge

The contents of this table show extracted pro forma values in order to compare the characteristics of a single cell.

of lithium-ion batteries depending on the positive-electrode material, and Table 2 shows a comparison of the characteristics of a secondary battery to be mounted on a mini-UPS.

Many accidents have been reported with lithium-ion batteries such as those where heat is generated and the battery catches fire. The cause of these accidents is not only the batteries but also the equipment that controls them. Therefore, ensuring safety of the lithium-ion battery mounted equipment has become a big issue.

For that reason, it is necessary to select a battery that is suitable for the purpose, and design the device to ensure safety while maximizing the characteristics of the battery. In order to do so, it is important to evaluate the battery and understand its characteristics.

3. Characteristics and Evaluation of Batteries Required for UPS

The performance requirements for UPS include backup time, charging time and life. The characteristics of a battery that influence this performance are battery capacity, maximum discharge rate and maximum charge rate^{*1}. From these characteristics, UPS backup time and charging time can be determined,

and both the battery capacity characteristic and the maximum discharge rate characteristic of the battery change according to conditions such as ambient temperature, charging voltage, cut-off voltage and discharge rate. In other words, it is necessary to understand the battery characteristics under these conditions in order to maximize UPS performance.

Fuji Electric performs the following evaluation and selects the optimal battery for a UPS to develop a UPS by pursuing high performance and safety.

(1) Evaluation of characteristics

We confirm the changes in characteristics of the battery with ambient temperature, charging voltage, cut-off voltage, discharge rate and charging rate as parameters, and optimized the UPS design.

(2) Evaluation of safety

We confirm the safety of a UPS at abnormal times and determine countermeasures and a function to protect UPS.

(3) Evaluation of reliability

We predict battery degradation such as cycle degradation and storage degradation and battery life.

^{*1}: Battery capacity, discharge rate, and charging rate: See “Explanation 2” on page 217

Table 3 Features and issues of olivine-type lithium iron phosphate batteries

	Battery	Precautions for use of battery	Features
Features	No environmentally restricted materials are used	RoHS-compliant	Environment friendly
	Excellent in heat stability in terms of material	Hard to generate heat due to olivine-type crystal structure	High safety
	Good high-rate characteristics	Constant capacity irrespective of discharge current	Long hours of backup power by high-capacity discharge
	Good thermal characteristics	Little capacity change from 0°C to 60°C	Backup time does not fall even at low temperature
	Flat discharge curve	Easy to predict capacity, No capacity change due to cut-off voltage setting	Easy to predict remaining backup time, Easy to design UPS (possible to set up narrow converter control range)
	Voltage suddenly increases at charging terminal stage	Easy detection of full charge and overcharge	High safety at abnormal times
	No change in discharge capacity regardless of charging voltage	Can set low charging voltage	Easy to design UPS charger
	No resource restriction on the materials	Stable production Low material cost	Possible to secure stable supply in the future Possible to reduce price
	Popular overseas (China)	Easy to deploy overseas Cost of battery itself is low.	Possible to be used globally Possible to reduce cost
Issues	Low energy density	Low cell voltage (3.2 V)	Large number of mounted batteries (factor of price increase) Complicated protection function (factor of unbalance)
	Large IR drop at discharge start	Large drop in voltage at stand-by Large self-discharge (under examination and investigation)	Influence on management man-hours when stored

4. Characteristics of Olivine-Type Lithium Iron Phosphate Batteries

Because olivine-type lithium iron phosphate batteries use iron-based material for the positive electrode as shown in Table 1, there is no restriction on resources such as cobalt material, which is used in a general way. Therefore, the batteries have attracted attention in Japan as a new type of battery.

4.1 Characteristics and issues with olivine-type lithium iron phosphate batteries

The main characteristics of olivine-type lithium iron phosphate batteries are lower material cost, no oxygen release or heat generation until 400°C, and good thermal stability. The reason why this battery is called an “olivine-type” is that the crystal structure of the iron phosphate is the same as olivine.

Table 3 shows the features and issues of olivine-type lithium iron phosphate batteries. UPSs that are equipped with olivine-type lithium iron phosphate batteries are very safe compared to general lithium-ion batteries. In addition, there is a potential for them to be low cost, which is one of the issues to solve before UPS can be more widely used in the home to cope with planned outages.

4.2 Characteristic evaluation of olivine-type lithium iron phosphate batteries

Fuji Electric performs tests such as a thermal characteristic test, discharge characteristic test, and discharge capacity test by charging voltage, and is

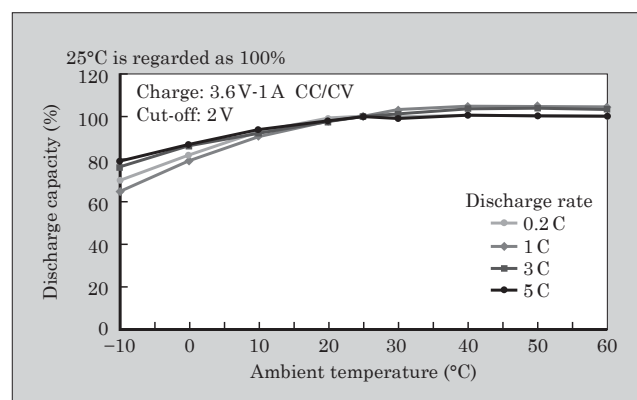


Fig.1 Thermal characteristics of olivine-type lithium iron phosphate batteries

evaluating the characteristics of the olivine-type lithium iron phosphate batteries.

As mentioned in Chapter 3, UPS backup time is influenced by battery capacity. The usable battery capacity is dependent on the using ambient temperature, discharge rate, cut-off voltage and charging voltage, and it is evaluated in the characteristics test.

(1) Thermal characteristics

Figure 1 shows changes in discharge capacity against ambient temperature at various discharge rates. Even at the lowest supported ambient temperature (0°C) of the UPS, which assumes it is used in a normal interior location, the test results show that the UPS maintains 80% or more capacity at all rates. Because the backup time of a normal UPS that uses a lead-acid storage battery shortens enormously, only

a backup time at 25°C is guaranteed in the specifications. However, we can expect a stable backup time with this battery because there is little change in the discharge capacity of the battery even if the using environment changes.

(2) Discharge characteristics

Figure 2 shows changes in the discharge capacity at various discharge rates. From data on discharge characteristics, it is possible to predict the expected discharge capacity; and therefore, this is a fundamental characteristic for judging the performance of the battery. Rated capacity is equivalent to discharge capacity at the condition of 0.2C and the figure shows that the rated capacity of the battery is 3.05 Ah.

In general, if the discharge rate increases, the amount of possible discharge capacity decreases. Even with a high-rate discharge up to 5C, a capacity of 90% (approx. 2.75 Ah) or higher can be maintained, proving good high rate discharge characteristic. Therefore, it is possible to secure a stable backup time even if the UPS load changes.

(3) Discharge capacity characteristics due to charging voltage

The speed at which a lithium-ion battery degrades depends on charging voltage, terminal voltage during storage and using ambient temperature, and it is said that the higher the voltage is, the faster the battery degrades. Therefore, it is possible to reduce the battery's degradation and extend its life by lowering the charging voltage as much as possible. However, when the charging voltage is lowered, the chargeable capacity is naturally reduced and the backup time will be shortened. Therefore, there is a trade-off relationship between backup time (which depends on charging voltage) and life.

Figure 3 shows changes in cell voltage against discharge capacity due to charging voltage. When charging voltage (voltage at discharge inception) and cut-off voltage (voltage at stop of discharge) change, the dischargeable capacity changes. Figure 3 shows that the discharge capacity is dependent on charging voltage and this characteristic is an important data to consider

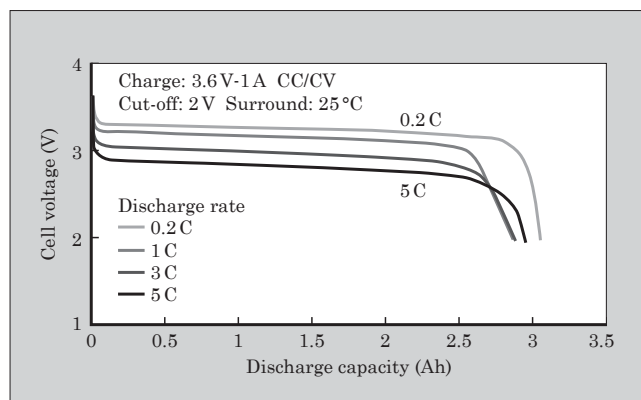


Fig.2 Discharge characteristics of olivine-type lithium iron phosphate batteries

when setting a charging voltage by considering also the battery life.

From Fig. 3, which shows the result of changing the charging voltage within the range of 3.6 V to 3.4 V of recommended charging voltage, it can be found that if charging is performed within the recommended charging voltage, there is no big change in discharge capacity due to changing voltage. Therefore, it is possible to reduce battery degradation if the battery is used by lowering the charging voltage to 3.4 V.

In addition, it can be confirmed from Figs. 2 and 3 that the discharge curve is flat and IR drop (cell voltage depression) is large immediately after discharge inception. This is also a characteristic of olivine-type lithium iron phosphate batteries in terms of material.

Because the discharge curve is flat, even if the cut-off voltage is lowered to a certain degree, it does not affect the discharge capacity. By increasing the cut-off voltage and making the depth of the discharge smaller, it is possible to reduce the degradation of the battery. This is a big advantage in extending battery life.

(4) Charging characteristics

Figure 4 shows temporal variations in charging voltage and discharge current with various charging currents.

A battery's charging characteristic has charging

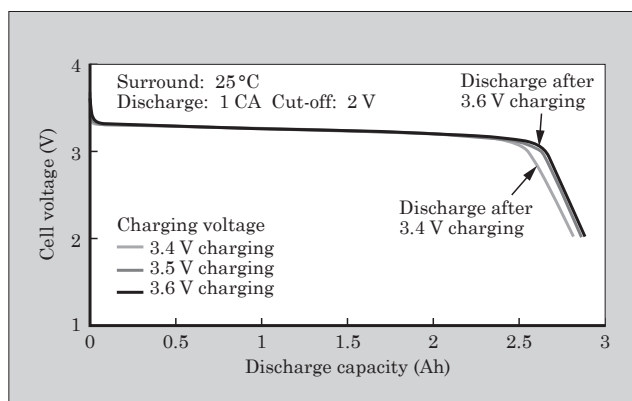


Fig.3 Charging voltage characteristics of olivine-type lithium iron phosphate batteries

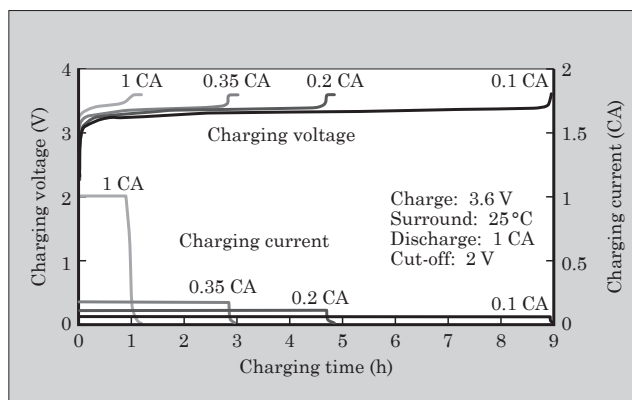


Fig.4 Charging characteristics of olivine-type lithium iron phosphate batteries

current as a parameter and charging time and shift of charging capacity can be confirmed. With this characteristic, the output capacity of the charger can be calculated from the charging time that the customer requires.

The charging characteristic of olivine-type lithium iron phosphate batteries shows an exponential voltage rise at the charging terminal stage. By determining this voltage rise as fully charged, a charging capacity approximate to 95% of the battery is made possible with the existing constant-current charging mode. In addition, because the battery is within the range of constant-current charging until it becomes almost fully charged, it becomes easy to predict the charging time from the charging rate. This is a big advantage when designing devices.

4.3 Issues of olivine-type lithium iron phosphate batteries for mounting

Compared to cobalt acid and manganese acid lithium-ion batteries, the cell voltage of olivine-type lithium iron phosphate batteries is as low as 3.2 V. In order to compensate for this lower energy density, more batteries need to be mounted (number of series connections) in a device. Therefore, the issue is to reduce the price of the UPS safety circuit and battery unit.

In addition, because of the large number of series connections, it is necessary to assume there will be an imbalance between cells. This issue of imbalance is expected to be resolved by battery management system (BMS).

5. Issues and Measures in Evaluation of Lithium-ion Batteries

There are two issues with all lithium-ion batteries, not only olivine-type lithium iron phosphate batteries: evaluation and measures for safety, and evaluation and prediction of life.

(1) Evaluation and measures for safety

Because lithium-ion batteries have a high cell voltage, a non-aqueous organic solvent is used for the electrolyte. This is inflammable liquid classified under hazardous material Class 4 Petroleum No. 2 of the "Fire Service Act", the same type of liquid as kerosene, light oil and xylene. Accordingly, if the battery is used incorrectly, there is a risk of catching fire and many accidents have been reported. Evaluation and measures for safety are the highest-priority issue for devices in which lithium-ion batteries are mounted.

Fuji Electric has been promoting verification of safety jointly with a battery manufacturer before these accidents began to be reported, and it complies with a common basic safety standard and has been ensuring safety for UPS by setting up our own safety standard.

The most important two items are safety in terms of short circuits within the cell and safety in terms of overcharging.

An investigation on the cause of accidents that actually occurred showed that accidents with a short circuit within the cell were caused by two overlapping factors; the primary factor was contamination, and the secondary factor was the discharge method. Because an internal short circuit is an issue concerning the battery's main body, the battery manufacturer that is the joint developer with us has taken measures and Fuji Electric is also internally conducting a test by assuming that an internal short circuit occurs and confirming safety.

A challenge for device manufacturers is to ensure safety against overcharging, and evaluation was performed and measures were taken for safety with a single-body battery. First, it is considered that knowing the behavior of overcharging increases the safety of the device. Fuji Electric internally analyzed the behavior and mechanism of overcharging after conducting an in-house safety test and receiving advice from the battery manufacturer, and it was possible to significantly improve safety with the battery pack.

Figure 5 shows a hazardous zone in which there is a risk of causing a thermal runaway at the charging voltage and charging current of the battery pack after measures are taken, and the safe zone. Even if an abnormality occurs in the charger, if there is enough margin taken for the lower limit of this hazardous zone, it is possible to provide a safe UPS.

Electrical protection by BMS is the secondary measure, and it is important to design devices that use lithium-ion batteries with a safety margin instead of just relying on electrical measures.

(2) Prediction of life

Factors that cause degradation of secondary batteries include degradation of the active material itself, growth of electrode surface membrane, and degradation of electrolytic solution. Furthermore, the factors that accelerate degradation further are related to cell voltage, discharge depth, operating ambient temperature, number of charging and discharging times, and usage period of batteries. It depends on the intended purpose of the device and working conditions, and the materials of the battery also make the difference.

As just mentioned, while many factors are inter-

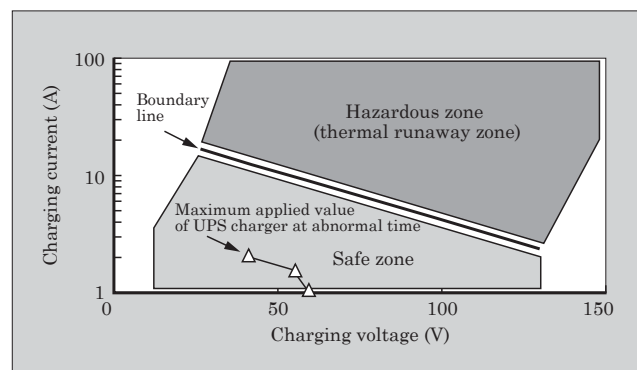


Fig.5 Safe zone of lithium-ion battery

twined, predicting degradation (life) is a big challenge. Currently, each manufacturer is narrowing down the working conditions and performing evaluations while assuming certain operating conditions.

Fuji Electric also predicts battery life based on data from a battery manufacturer and in-house life test data after UPS working conditions are narrowed down and test conditions are clarified.

Also in the future, we must have a cooperative relationship with a battery manufacturer so that we can improve our prediction accuracy. Currently, for a UPS equipped with olivine-type lithium iron phosphate batteries, we are aiming to carry out further evaluations toward commercialization while considering the above advantages and challenges.

6. Case Example of UPS Equipped with Lithium-Ion Battery

In this section, a mini-UPS (1.5 kVA online UPS) equipped with a manganese acid lithium-ion battery, for which the same evaluation was performed as olivine-type lithium iron phosphate batteries as presented in Chapter 5, is presented as a product example (see Fig. 6).

Table 4 shows the result of comparing a lead-acid

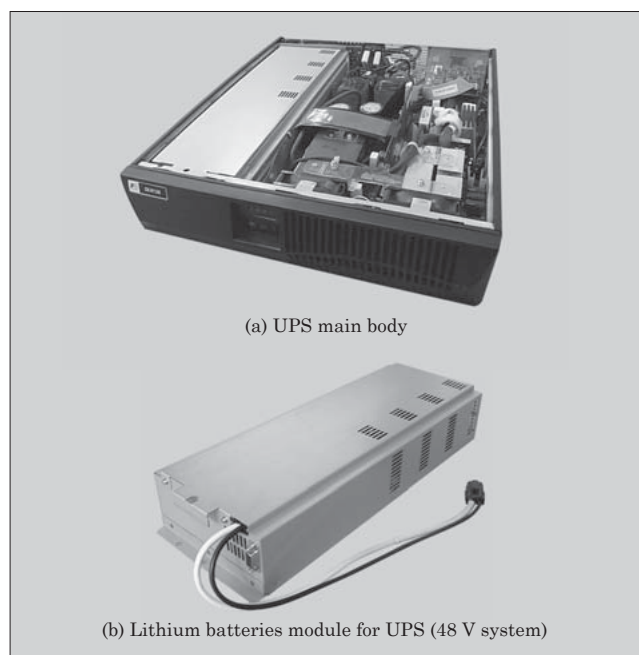


Fig.6 UPS equipped with lithium-ion batteries (1.5 kVA)

Table 4 Comparison of lead-acid battery and lithium-ion battery

Battery type		Lead-acid battery	Lithium-ion battery
Rated output capacity		1,500 VA/1,050 W	
Rated output voltage		100 (110 V, 120 V)	
Feeding system		Normally with inverter	
Outer shape		432×87×494 (mm) (2U)	
Backup time (25 °C)		6 minutes	11 minutes (83% increase)
Mass	UPS unit	22.5 kg	17.0 kg (24% decrease)
	Battery unit	11.3 kg	5.9 kg (48% decrease)
Battery replacement period (25 °C)		4.5 years	8 years or more (maintenance-free)

battery and manganese acid lithium-ion battery when mounted on the UPS.

Compared to the existing lead-acid battery, the backup time is roughly doubled, and the mass of UPS unit decreased by 24%. In addition, the battery life became 8 years or more and maintenance-free was realized. Furthermore, considering the case where a device that can provide many hours of backup is needed, we prepared an expanded battery unit that was half as thick and wide as the main body.

Existing lead-acid batteries have a restriction on the number of battery expansions due to issues with safety and mass. Therefore, there was a limit to the number of hours of backup they could provide. Meanwhile, lithium-ion batteries are fundamentally compact and lightweight without any restriction on the number of parallel connections, and it became possible to connect expanded batteries to the UPS main body and many hours of backup became possible.

7. Postscript

This paper presented an evaluation and application technology of a new battery for UPSs. As a result of the Great East Japan Earthquake, the time has come to consider how energy ought to be and how it is used, not only within companies but also at home. With such rapid changes in the environment, we consider that a UPS that can stably supply power even during a power outage has a major role to play in contributing to society. In order to achieve such UPS, Fuji Electric intends to work on developing products that can provide improved safety and security in the future.

“LX Series”: Mini-UPS Products with NIMH Batteries for Data Centers

OSHIMA Masafumi † MORITO Yujiro † SHIINA Hiroyuki †

ABSTRACT

To increase power usage efficiency, data centers continue to reduce the power usage of their cooling equipment and use outdoor temperatures for their cooling methods. This has increased the demand for longer life of devices used inside in high-temperature environments. Fuji Electric has developed and released the “LX Series” of Mini-UPS products, which use nickel-metal hydride batteries and are intended for data centers. This uses Fuji Electric’s unique dual conversion method to increase battery life in high-temperature environments, decreases equipment size, and realizes high-performance through high-frequency PWM control. A wide range of optional products is available and the series complies with the RoHS directive.

1. Introduction

In recent years, the growth of the information services has led to a rapid increase in the volume of information processed. This has resulted in efforts to increase the processing capacity at data centers and the power consumption of ICT equipment such as servers is increasing. In addition, in order to achieve stable operation of the servers, air-conditioning systems have been introduced to maintain the ambient temperature environment at 25°C. The electricity consumption by these air-conditioning systems is also increasing because of the increasing amount of heat generated by the servers. The raising of a data center's power usage effectiveness (PUE^{*1}) is essential as a measure for energy conservation and environmental problems. As the ratio of electricity consumption in air-conditioning systems is high, the method of avoiding their use as much as possible is being considered. For ICT equipment, this will lead to demands for operation and longer service life in even higher temperature environment.

At data centers, uninterruptible power supplies (UPS) are used to avoid the halting of services, for example, through system malfunction caused by power failure. In addition to conventional demands for higher efficiency of these UPS, there are demands for space-saving through miniaturization and for longer service life in high-temperature environments (at ambient temperature 35°C). However, one key component is the storage battery, and the lead storage batteries conventionally used only have a short lifespan in a high-temperature environment, and they could not satisfy the demands of data centers.

*1: PUE: See “Explanation 3” on page 217

† Fuji Electric Co., Ltd.

Based on the highly efficient “GX200 Series” of mini-UPS, Fuji Electric has developed and released the “LX Series” of low profile, rack-mountable UPS using nickel-metal hydride batteries to achieve miniaturization of the equipment and longer service life of the battery in high-temperature environments.

2. Characteristics

Figure 1 shows the external appearance of the LX Series. The LX Series uses Fuji Electric's unique dual conversion method, which combines both the voltage stability of a normal inverter type UPS and the high efficiency of a line interactive type. It has the five characteristics of space-saving miniaturization, high performance, longer service life, support for a wide range of options and support for environmental measures.

2.1 Space-saving miniaturization

Figure 2 shows the external appearance when mounted on a 19-inch rack. This device was designed



Fig.1 “LX Series”



Fig.2 LX Series mounted on 19-inch rack

as a model specifically for mounting on 19-inch server racks in data centers.

Compared with the output power of 10 kVA/ 8 kW of the standard model GX200 Series (M-UPS100 AD2B), there is approximately a 12% increase to 10 kVA/9 kW with load power factor 0.9. As the energy density per volume of nickel-metal hydride batteries is twice or more than that of lead storage batteries, it is possible to miniaturize compared to lead storage batteries of equivalent capacities. It was possible to reduce the volume to 85% and the mass to 70% compared to standard models. As a 10 kVA class uninterruptible power supply, it realizes first-rate high output power, miniaturization and weight reduction. When mounting on a 19-inch rack, it can be mounted in a space of 5 U (1 U $\approx$ 44.5 mm), realizing space-saving when it is mounted on a rack.

2.2 High performance

During normal operation, the LX Series suppresses power supply fluctuations and supplies the load with a low distortion sine wave voltage through high-frequency pulse width modulation (PWM) control at a switching frequency of approximately 16 kHz using insulated gate bipolar transistors (IGBT). It achieves an output voltage accuracy of 2% or less and a distortion factor of 4% or less for rated linear load. Figure 3 shows an example of the output waveform when the input power supply voltage to the device is fluctuating. For the input current, the use of the high power factor control system means that the outflow of harmonic current and reactive current generated by the load equipment is suppressed. Furthermore, as shown in Fig. 4, when a power failure occurs, the unusual input voltage is judged instantaneously and a switching of the output voltage without interruption is achieved. When the power returns, the operation is switched from the battery to normal operation once the input voltage has stabilized, and the output voltage is switched with-

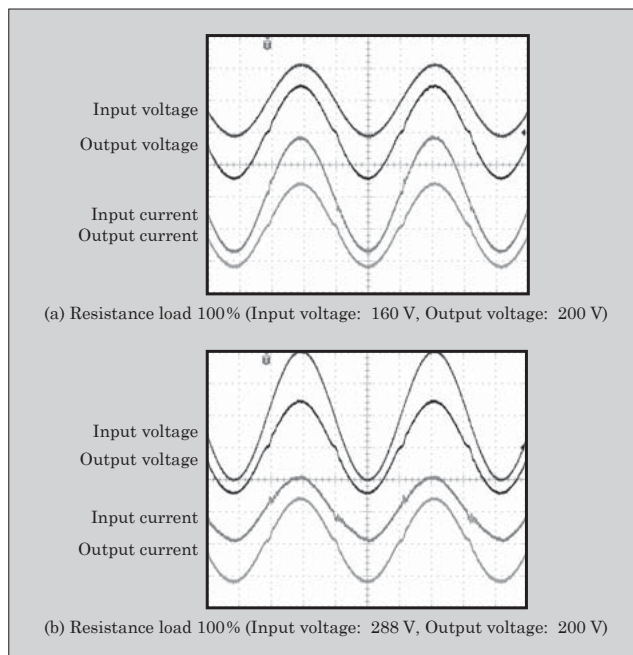


Fig. 3 Input and output waveforms (200 V/div, 50 A/div, 4 ms/div)

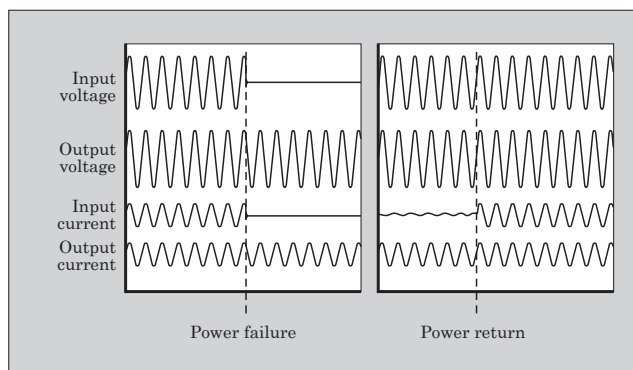


Fig.4 Switch-over waveforms at power failure and power return

out instantaneous interruption to the same voltage as when the power failure occurred. It is also equipped with various alarm output functions, including for input voltage abnormalities and battery abnormalities.

2.3 Longer service life

In order to extend the service life of nickel-metal hydride batteries to be used in high-temperature environments (at ambient temperature 35°C), optimal charge/discharge control is essential. A long-service life performance cannot be expected on nickel-metal hydride batteries if the same charging method is used as that for lead storage batteries.

On nickel-metal hydride batteries, a continuation of the charging after the full charge is reached results in an over-charged state and heat generation. The rise in temperature due to this heat generation has a great effect on the lifespan of the battery. For this reason, it is important to have full charge detection to stop

the charging before this over-charged state is reached. Furthermore, because capacity is lost due to the self-discharging which occurs on nickel-metal hydride batteries when the charging is stopped, it is essential to perform supplementary charging periodically.

In order to implement optimal control of the charging and discharging of the battery, dedicated control circuits were built in to monitor the voltage, the temperature and the charge-discharge capacity, providing communication links with the UPS control. This realized charge/discharge control which prevents over-charging and over-discharging. Furthermore, in order to suppress the degradation due to internal heat generation during the charging and discharging of the battery, a cooling fan was installed on the battery part to suppress the increase in internal temperatures. As a result, whereas lead storage batteries used in an environment of ambient temperature 25°C have a lifespan of 4 years, a lifespan of 8 years was achieved for these nickel-metal hydride batteries used in the same temperature environment. A lifespan of 4 years was also achieved for an environment of an ambient temperature 35°C. For the cooling fan too, a long-service life in a high-temperature environment was realized with the use of a long-service life fan.

2.4 Support of extensive options

(1) Optional cards

(a) Standard interface card

As an external interface, an interface card using D-SUB 9 pin connection is provided as standard. This card supports the output of abnormality information signals and UPS automatic shut-down signal and also the input/output of RS-232C serial communication, etc.

(b) USB card

An example of USB card in use is shown in Fig. 5. With this USB card, the connection of a USB cable makes it possible to perform shutdowns and stop the UPS during a blackout from a standard

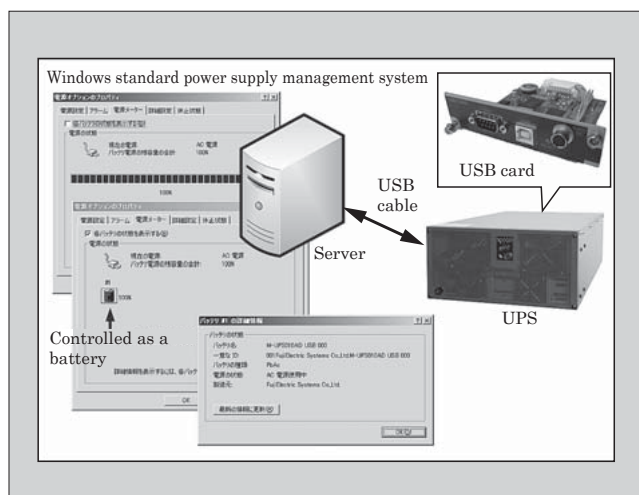


Fig.5 An example of USB card in use

power supply control system in Windows, without needing to install applications and drivers on the server. There is also a function for storing the UPS event log and data log into internal memory. By simply connecting a card to the server, this memory is allotted to a drive, and the log data can be easily retrieved.

(c) “Web/SNMP card”

The Web/SNMP card makes it possible to use a Web browser, etc., to perform power supply management and operations of multiple servers from a remote location.

(i) Real-time monitoring function

Through the Web/SNMP card connected to a network, it is possible to manage the status of the UPS with a general purpose browser from client PC without needing to install any special software.

(ii) Multi-server shutdown function

When performing a backup of the entire network, multiple servers are connected to the UPS load. When stopping these multiple servers during a power failure or in accordance with a schedule, it is essential to shut down them safely.

When a power failure occurs, the Web/SNMP card sends a shutdown instruction via the network to multiple servers which have the shutdown instruction software module “Netshut” installed. The servers which receive the shutdown instruction then transfer the shutdown instruction to other servers. Using this shutdown instruction, it is possible to safely shut down each server which is receiving a power supply from the UPS.

By repeating this transfer, it is possible to configure a system to shut down multiple servers.

(2) Step-down transformer box

Figure 6 shows the external appearance of the step-down transformer box. Some servers and peripheral equipment mounted on the racks require a 100 V power supply. The 200 V output from the UPS is converted to 100 V using a step-down transformer and used as the power supply for 100 V equipment. The output apparent power is 2 kVA and there are 5 electrical outlets for 100 V. The transformer load is displayed on indicators on the front of the device.

For mounting on a 19-inch rack, the transformer box is extremely low profile and uses a high efficiency transformer. It therefore achieves an occupied height of 2 U (86.25 mm) on a 19-inch rack. It also has various alarm outputs such as excessive load warnings and



Fig.6 Step-down transformer box

a ground fault alarm.

2.5 Support for environmental measures

The standard model complies with the RoHS directive*2 as it uses components which comply with the RoHS directive and lead-free solder is used in the printed circuit board assembly. This device uses nickel-metal hydride batteries instead of small valve regulated lead storage batteries, and the entire device is a lead-free product.

3. Product Specifications

Table 1 shows the LX Series specifications. The device supports a wide range of AC input voltages, from 160 to 288 V. The output voltage can be easily set to 220, 230 or 240 V from the outside using a dip switch, and the device can support the power supply circum-

Table 1 "LX Series" specifications

Model		M-UPS100AN2V
Operation method		Dual conversion method
Cooling method		Forced air-cooling
Input	Voltage	160 to 288 V
	Number of phases/wires	Single phase/ 2 wires
	Frequency	50/60 Hz
	Maximum current	50 A
Output	Output power	10 kVA/9 kW
	Number of phases/wires	Single phase/ 2 wires
	Voltage	200/208/220/230/240 V
	Voltage accuracy	±2%
	Waveform	Sine wave
	Switch-over time at power failure	Uninterrupted
	Distortion factor	6% or less
Switching to commercial power		Uninterrupted (thyristor switching method)
Efficiency		96%
Battery	Type	Nickel-metal hydride battery (NiMH battery)
	Backup time	5 minutes
	Nominal voltage	259.2 V
External dimensions		W436.4×D780×H212 (mm)
Space occupied in 19-inch rack		5U
Mass		89 kg
External connections	Input	Terminal block (M6)
	Output	Terminal block (M6) NEMA L6-30×2
Usage environment	Ambient temperature	0 to 40 °C
	Sound noise	55 dB (A) or below
	Relative humidity	20 to 95%

*2: RoHS directive: An EU (European Union) directive restricting the use of limited hazardous substances in electrical and electronic equipment

stances in both Japan and overseas.

4. Circuit Structure and Operation

Figure 7 shows a comparison among the conventional normal inverter type UPS, the line interactive type and Fuji Electric's original dual conversion method.

With the dual conversion method, even if there is fluctuation in the AC input voltage, the fluctuating part of the power supply voltage is compensated with a series converter. As a result, a stable voltage is supplied to the load. At this time, whilst the parallel converter is compensating just for the energy used by the series converter in the voltage compensation, it controls the DC intermediate voltage to a constant value. Compared with the line interactive type, on which voltage compensation for the input voltage is done with a transformer and others, the voltage is steadier with the dual conversion method because the output voltage is compensated with the series converter. Also, compared with the on-line type, in which all the power output is converted with converters and inverters, in the dual conversion method, only the energy needed for the voltage compensation is converted in the parallel converter part, and the conversion losses are greatly reduced and a higher efficiency is achieved which is equivalent to that on line interactive types.

If a power failure occurs in the AC power supply, at the same time as the input side is opened, the series converter is used to supply stable power continuously

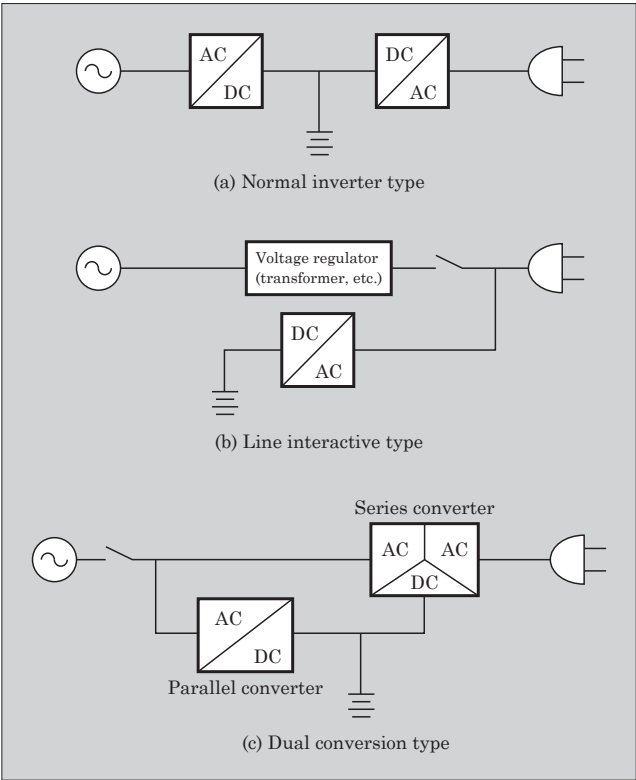


Fig.7 Comparison of main circuit block diagrams

from the battery to the load. Furthermore, there is also a built-in bypass circuit which makes it possible to switch without interruption to the AC input power supply if there is excessive load or a UPS abnormality.

5. Postscript

The “LX Series” mini-UPS for data centers with nickel-metal hydride batteries was presented. Both a longer battery service life in high-temperature environments and miniaturization of the equipment were

achieved with this product and it is capable of responding to the environment demanded in data centers. Furthermore, by making use of the fact that this UPS is a 200 V system, it is expected that it will not only be used in data centers, but will also be extended to embedding in various types of manufacturing equipment. We will continue to work on an expansion of the range of capacity models and further improvements to reliability, and we will make efforts to develop and commercialize UPS to reply to a wide range of customer requirements.



“PVI1000”: Outdoor High-Efficiency Power Conditioners for Mega Solar Projects

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ABSTRACT

The solar power market ranges from home power generators to large-scale installations for Mega Solar projects. Fuji Electric developed an 1 MW power conditioner (PCS) that is optimal for these Mega Solar projects. This PCS achieves world-class efficiency through use of an AT-NPC 3-level IGBT module. In addition, setup costs are reduced as the high-voltage transformers and the PCS are integrated on the same stage into a sub-station. Furthermore, it achieves highly reliable solar power generation through Fault-ride-through capability and unit parallel redundancy when connecting to a power system.

1. Introduction

The global demand for energy continues to grow and global warming caused by CO₂ is becoming a major problem. With this as a background, there are increasing expectations for electricity generation using renewable energy sources such as solar cells. The size of the global market for solar cells exceeded 10 GW in fiscal 2010 and is predicted to exceed 35 GW in 2015. Furthermore, the demand is not just for residential applications. In various locations around the world, there are rapidly increasing actual records and plans for installations exceeding 1 MW, what we call mega solar power plants. The market for solar cells is also expanding rapidly, not only in Europe, but also in places such as China, the U.S.A., Southeast Asia and India.

Meanwhile, there are multiple mega solar power plants being planned around Japan, on consideration of the start of “Feed-in Tariff System for Renewable Energy” from July 2012. Fuji Electric developed a highly efficient power conditioner (PCS) for outdoor installation which is optimal for mega solar applications. This PCS uses a new circuit system using advanced t-type neutral-point-clamped (AT-NPC) 3-level IGBT module⁽¹⁾ employing the latest, Fuji Electric proprietary switching device, reverse-blocking insulated gate bipolar transistor (RB-IGBT)⁽²⁾. It realizes an operating efficiency at the highest level in the world. This paper explains the characteristics, functions and performance of high-efficiency, outdoor installation PCS “PVI1000” for mega solar applications.

2. Characteristics

In mega solar systems, there are demands not only for reduction of the unit price per watt for solar cells, but also for the simultaneous achievement of both reductions of the electricity generation unit price and improvements of reliability concerning the PCS, which is a major element of the systems. This means that the following three points are necessary:

- (a) The power generating efficiency must be high
- (b) The total cost must be low
- (c) The reliability must be high, because they are connected to the grid

Fuji Electric developed the PVI1000 that achieves all these. Figure 1 shows its external appearance.

2.1 High Efficiency

- (1) Use of RB-IGBT and new circuit system

This is the first practical application in the world of the AT-NPC 3-level IGBT module (see Fig. 2), which

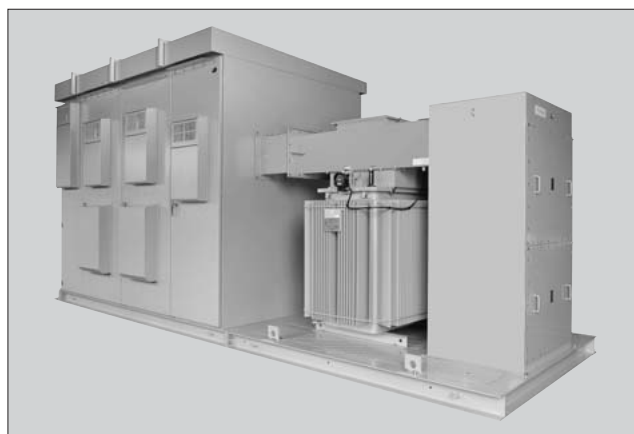


Fig.1 “PVI1000”

[†] Fuji Electric Co., Ltd.



Fig.2 AT-NPC 3-level IGBT module

is equipped with the RB-IGBT and conventional IGBT in one package. By using this module for a 3-level conversion circuit, it is possible to simultaneously achieve a great reduction in both power losses and the number of components.

(2) Achievement of world-leading 98.5% efficiency

By applying the 3-level IGBT module to the new power conversion technology (AT-NPC 3-level conversion circuit), the switching loss in the IGBT device is greatly reduced. Furthermore, the filter loss is reduced because the harmonic content included in the PWM waveform output voltage from the inverter is reduced to half of the conventional devices. This results in the achievement of a world-leading high efficiency of 98.5% (IEC 61683 efficiency tolerance, not including internal power supply). It also achieves 98.2% for Euro efficiency, which considers the partial load efficiency and is in a situation close to the actual efficiency of PCS used for solar power generation.

2.2 Reduction in Total Costs

(1) Single unit capacity of 1 MW

A large capacity of 1 MW per single unit is realized. For use in large-scale mega solar systems, increasing the capacity per single unit means that fewer PCS are necessary, which leads to the reduction of the space required for installation.

(2) Outdoor substation type

The PCS panel is suitable for installation outdoors, and there is no need for a container to cover the PCS panel and air conditioning. Furthermore, fuses for a direct current branch can be built-in inside the PCS panel as an option, and the output of the solar cells collected at the connection box can be connected directly to the PCS.

A substation type has been adopted for the structure of the PCS, where switchgear necessary between PCS and the grid, and a high voltage transformer (corresponding to outdoor use) are built together on a common base. It can be delivered as it is from the factory

to the customer's site, and installation costs can be reduced.

2.3 High Reliability

(1) FRT function

A fault ride through (FRT) function, which is becoming essential on PCS for mega solar, is included as standard in the PVI1000. With the FRT function, even when there occurred a three-phase short-circuit or a two-phase short-circuit accident in the grid, the inverter outputs a three-phase current within the regulated range (the momentary power dip time and the extent of the voltage drop required in each country), working to suppress the fluctuation in the grid.

(2) Units in parallel

The single unit of 1 MW capacity inverter is constructed from four 250 kW inverter units. Even if one of the component units fails, the electricity generation can be continued with the remaining units. Even if one of the inverter units can not operate during the daytime, the electric power generated by 1 MW of solar cells (maximum 750 kW) can be output until its maintenance at night. The availability factor can therefore be better than the systems using separate PCS for each 250 kW.

2.4 Global Standard

The product supports the connection of grid voltages from 4.15 to 34.5 kV, and the direct current input voltage is possible up to the global standard of a maximum 1,000 V DC. Furthermore, the IEC 62109 is supported as the electrical safety standard (with the acquisition of 3rd party authentication planned), and, as an option, the IEC 61000-6-2 and CISPR11 EMC specifications can also be supported.

3. Specifications

Table 1 shows the PVI1000 specifications. The direct current voltage range supports the 1,000 V DC

Table 1 "PVI1000" specifications

Item	Specifications
Capacity	1 MW
DC voltage range	450 to 1,000 V
MPPT range	460 to 850 V
Maximum input current	2,440 A
AC voltage	270 V (−12 to +10%)
Frequency	50/60 Hz
Power factor	0.99
Total harmonic distortion in current	5%
Maximum efficiency*	98.5%
Euro efficiency*	98.2%
Internal power supply capacity	2,000 W or less
Stand-by loss	200 W or less

*IEC-61683 efficiency tolerance indication, excluding internal power supply

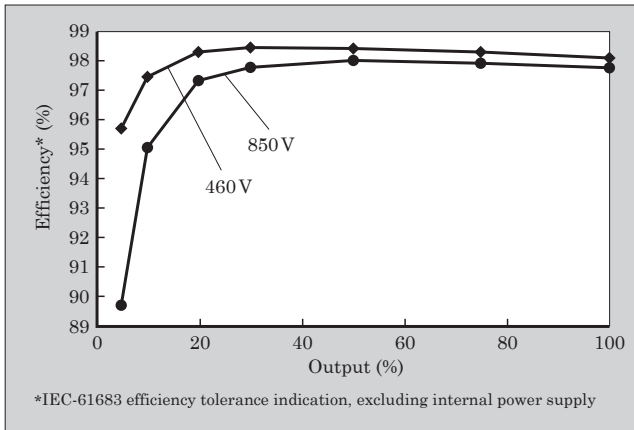


Fig.3 Efficiency curves

which is becoming standard in Europe and the U.S.A. The maximum power point tracking (MPPT*) range for the rated output is 460 to 850 V. The alternating current voltage is 270 V and the voltage is transformed to the grid voltage at each site with the transformer connected. The maximum efficiency and the Euro efficiency which is partial load efficiency are the figures at the time when the DC open circuit voltage is 460 V.

Figure 3 shows the efficiency curves when the solar cell voltage is 850 V and 460 V. The efficiency will vary depending on the value of the solar cell voltage, and the efficiency curves for the upper limit values and lower limit values are shown.

4. PCS Structure and Operation

4.1 Circuit Configuration

As shown in Fig. 4, the circuit configuration of the PVI1000 is composed of four 250 kW units. The DC input is drawn as four inputs in the figure, but these can be increased to a maximum of 24 inputs. Two inputs are connected to a single breaker and the outputs from 2 breakers are connected to one DC link. This makes the four inverters operate on the same DC voltage and no circulating current is generated among

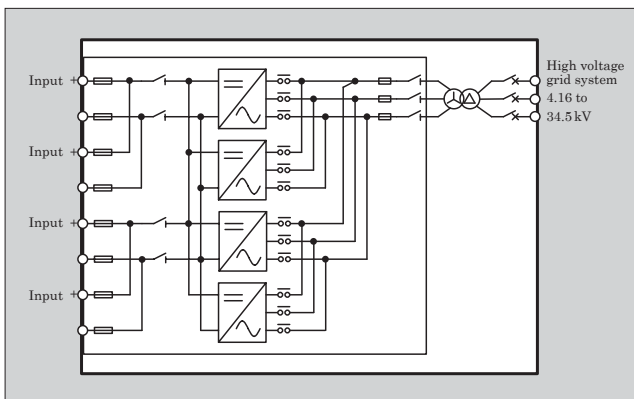


Fig.4 Circuit Configuration

*1: MPPT: See "Explanation 4" on page 218

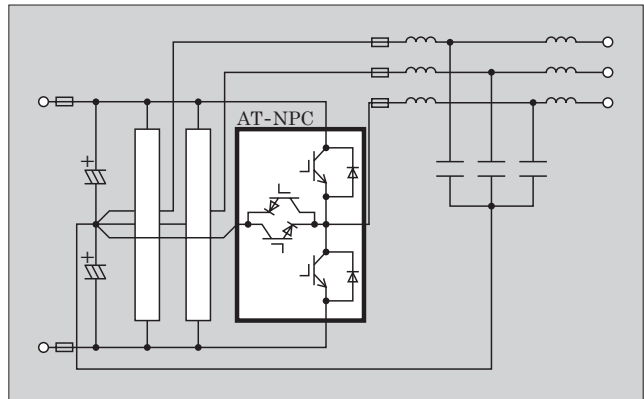


Fig.5 Power unit and filter circuits

units because each unit is switched on the same carrier. Moreover, when starting up, as the connection to the grid is performed so that the contactor switched on in the state each inverter outputting voltage synchronized with the grid, the start-up can be completed without any generation of a rush current to the grid.

Each unit which realizes the inverter is composed of a 3-level inverter, fuses and LCL filters (see Fig. 5). This kind of 3-level circuit had already been proposed in the 1980s⁽³⁾, but inability to lower the withstand voltage of the IGBT device prevented widespread of its use. However, in an inverter, where the connection of devices in series is not necessary, as it is possible to reduce the number of devices that the output current passes, there is the merit that the conduction losses can be reduced. Fuji Electric therefore has developed the practical application of a 3-level IGBT module using an RB-IGBT as the switch for connecting the AC output and DC midpoint where a reverse withstand voltage is necessary. Using this, it is possible to realize 3-level inverters with the same number of modules as conventional 2-level inverters. The practical application of highly efficient inverters is therefore achieved without any increase in circuit cost.

4.2 Outdoor Panel Structure

Up until now, when power electronics equipment with forced air cooling was placed outside, it was often the case that an indoor panel was stored inside a container for outdoor use and cooling was done using an air conditioner. However, with this method, as the air conditioner accounts for roughly 1/2 to 1/3 of the generated loss, it is disadvantageous for PCS, for which operating efficiency is considered an important factor. Furthermore, when the storage in a container is not done and a filter for outdoor use is placed on an ordinary indoor panel, as the replacement cycle for the filter becomes extremely short, there is the problem that the maintenance cost would increase.

We therefore used the double structure shown in Fig. 6. The power unit (PWU), which is made up of the dust intolerant printed circuit board and IGBT module, is placed in an airtight area and isolated from

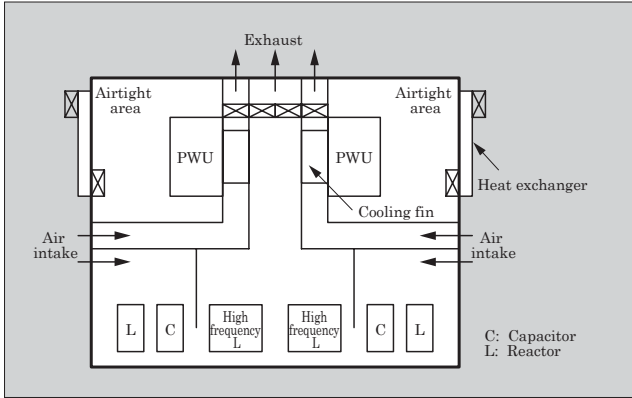


Fig.6 Outdoor panel structure

the outside air. The cooling fins and filter circuits are cooled using outside air. With this method, as the filter on the part taking in the outside air can just be wire netting sufficient to prevent garbage and small animals from entering, maintenance becomes unnecessary. Furthermore, by using a filter like this, it is possible to increase the air flow for the forced air cooling, and the miniaturization of the equipment as a whole becomes possible.

Also, the structure is designed so that the heat generated by the PWU in the airtight area is exhausted to the outside with a heat exchanger using a heat pipe. This makes the dust in the outside air completely blocked from the airtight area, and the PCS can be protected from malfunctions caused by dust.

4.3 FRT Function and Inverter Control method

An FRT function is demanded of PCS in preparation for large-scale introductions to the grid. This FRT function is already mandatory in Europe and the U.S.A., and will become mandatory in Japan for equipment introduced from fiscal 2013. Furthermore, the levels demanded for the FRT function (residual voltage and duration) vary from one country to another. We balanced the costs with the required specifications by making continued operation possible with 0% residual voltage and offering an option for a backup method of the control power supply for improving the duration. The system was designed so that the control power supply can be selected from either an external grid supply or from self-supply within the system. If a supply from the grid is selected, a power dip of 1 s or shorter is backed up with an internal capacitor. If a backup is required for a long period of time, it is decided to install an external UPS.

Furthermore, as shown in Fig. 7, to support the FRT function, the current phase reference $\cos\theta$ and the voltage base (equivalent to the grid voltage at the connection point), which were previously generated in the phase-locked loop (PLL), are changed to be referenced from the grid voltage⁽⁴⁾. Ordinarily, if the grid voltage is referenced directly, then system resonance and output current distortion can sometimes occur. A band-

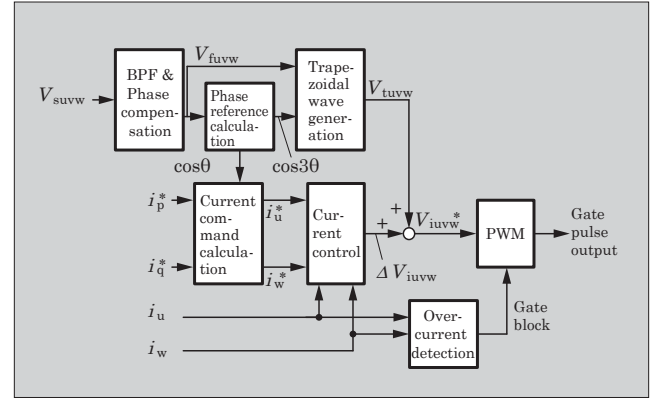


Fig.7 Block diagram for control logic of inverter

pass filter (BPF) is therefore used to remove the high frequency component from the grid voltage detected, to realize a high-speed response to grid abnormalities and a countermeasure to grid resonance. From this BPF output, the compensated value of the output filter phase delay is taken as V_{iuvw} and we determine the current phase reference $\cos\theta$ and trapezoidal wave voltage base V_{tuvw} which are necessary for converting the dq axis current command i_p^* , i_q^* into three-phase current commands from this value. Furthermore, in order to prevent any overcurrent caused by rapid changes in the voltage, a mechanism is adopted to perform a gate block as soon as any overcurrent is detected.

The operation resulting from these improvements to the control was verified using control verification equipment (20 kW). With a residual voltage of 0%, it becomes a continuous gate lock state, and the output current becomes 0 A. However, as shown in Fig. 8, it was confirmed that when the residual voltage is 20%, an intermittent gate lock stops occurring 6 ms after the power dip occurs, and after roughly 2 cycles, the rated current can be output. In this way, it was confirmed that even when power dips occur, the PCS can continue operating.

Furthermore, there is also an option for a grid compensation dynamic voltage support (DVS) function. The DVS is a function to stabilize the grid voltage when a power dip occurs and when the power returns. Reactive current decided by the user is output according to the grid voltage level. Even if the grid phase be-

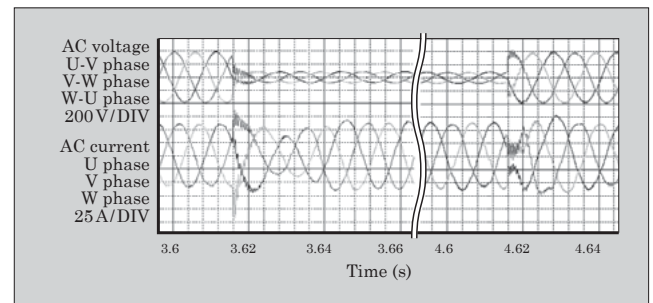


Fig.8 FRT verification waveforms

comes into an unbalanced state such as with a two-line short circuit, by putting the V_{tuvw} shown in Fig. 7 to an unbalanced state in accordance with the grid, it is possible to output a balanced three-phase current.

When the FRT function operates, it is sometimes the case that the rapid change in the grid voltage causes mistaken detection of islanding mode operation*2. As for the PVI1000, a method of actively detecting islanding mode operation with reactive current fluctuations and a method of passively detecting islanding mode operation with frequency deviations were applied. This makes it possible to both continue operation when there occurs a short-circuit in the grid and to stop quickly when the grid is open.

4.4 Units in Parallel

As shown in Fig. 5, the reason why fuses are installed in the DC and AC parts of the power unit is to cut off short circuit current from other units if the IGBT or the electrolyte capacitor inside the unit fails. If temperature abnormalities, contactor abnormalities or a continuation of overcurrent protection occur in a unit, the operation is stopped and then a start-up is done automatically with the other, problem-free units. However, when there are abnormalities which involve destruction, such as fuses blowing or component device abnormalities, this is judged to be a major failure and the operation is stopped to prevent a spreading of the

*2: Islanding mode operation: a state in a system isolated from commercial power supply where electricity flows the power line using only power from the distributed power supply

abnormality.

By using this structure of units with fuses in parallel, even if one of the component units fails, as long as the solar cells are generating 750 kW or less of electricity, it is possible to output the amount of maximum power determined in the MPPT to the grid, and this leads to improved reliability for the equipment.

5. Postscript

The “PVI1000” high-efficiency PCS for installation outdoors is an optimal PCS for mega solar power plants. This is because of its characteristics such as reduction in system cost due to the large capacity of a single unit, reduction in installation cost due to substation type, and increase of generated electricity output due to its high efficiency.

We will continue to make a contribution to the realization of a low-carbon society by promoting even further increases in capacity and efficiency.

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“UPS 7000HX Series” of High-Efficiency, Large-Capacity UPS Products Using AT-NPC 3-Level for Data Centers

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ABSTRACT

In recent years, as ICT expands, the building market exemplified by data centers has focused on environmental performance and economy, and the demands for high efficiency, high reliability, and compactness from power supply equipment are increasing. Fuji Electric developed a large capacity high efficiency UPS, “UPS 7000HX Series” (400 V 500 kVA) to meet these needs. Maximum efficiency is as high as 97% and the installation area is 30% less than conventional models. In addition, the parallel operation provides a stable power supply. To achieve this, we set the power conversion circuit construction to three levels and used a three-level dedicated module equipped with the RB-IGBT that we developed in the switching element.

1. Introduction

Networks and communications infrastructure making use of the rapid development of information and communications technology (ICT) are not only used in businesses, but are also improving the convenience of civic life, into which they have penetrated deeply and become an essential feature in the same way as utilities such as electricity and waterworks.

The volume of data handled by information processing systems is also growing each year, and the electricity those systems consume is increasing. Information processing systems were conventionally managed separately at each company, but there is now an increasing trend towards outsourcing the system construction and operation. This is based on efforts to reduce installation and operating costs, high level ICT introduction plans and business continuity plans for disasters or other unforeseeable situations. The data centers that this work is outsourced manage everything from the construction to the operation and maintenance of information processing systems, air-conditioning systems, power management systems, etc.

As a result, the amount of power consumption becomes huge in the data centers where the information processing systems are concentrated. There are therefore strong demands for improved machine efficiency of the uninterruptible power supplies (UPS) which supply stable electric power to the systems.

In this paper, we present the 400 V 500 kVA model of a large capacity, high efficiency UPS product, “UPS 7000HX Series,” which features the AT-NPC 3-level conversion technology. This UPS for data centers has reduced power loss by using the advanced t-type neutral-point-clamped (AT-NPC) 3-level conversion circuit

and Fuji Electric’s original new devices.

2. Characteristics

Figure 1 shows the external appearance of the UPS 7000HX Series 400 V 500 kVA model.

2.1 High Efficiency

The equipment efficiency has been improved by 2% from the conventional model, achieving an industry-leading level of 97%. The improvement in the equipment efficiency also reduces the heat generation due to UPS power loss, and there is also the merit that the electricity consumption of the air conditioner used for the UPS system can also be reduced.

Equipment duplication and redundancy are used at data centers to improve the reliability of individual system. This means that in some cases the load factor during normal operation is low, and this equipment also reduces power loss in the low load range (20 to



Fig.1 “UPS 7000HX Series” (400 V 500 kVA)

[†] Fuji Electric Co., Ltd.

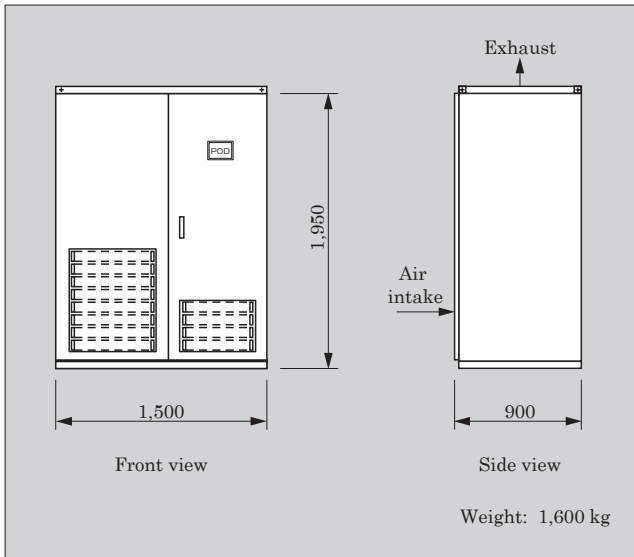


Fig.2 External appearance and weight

50%).

2.2 Miniaturization and Space-saving

Compared with conventional models, the size of

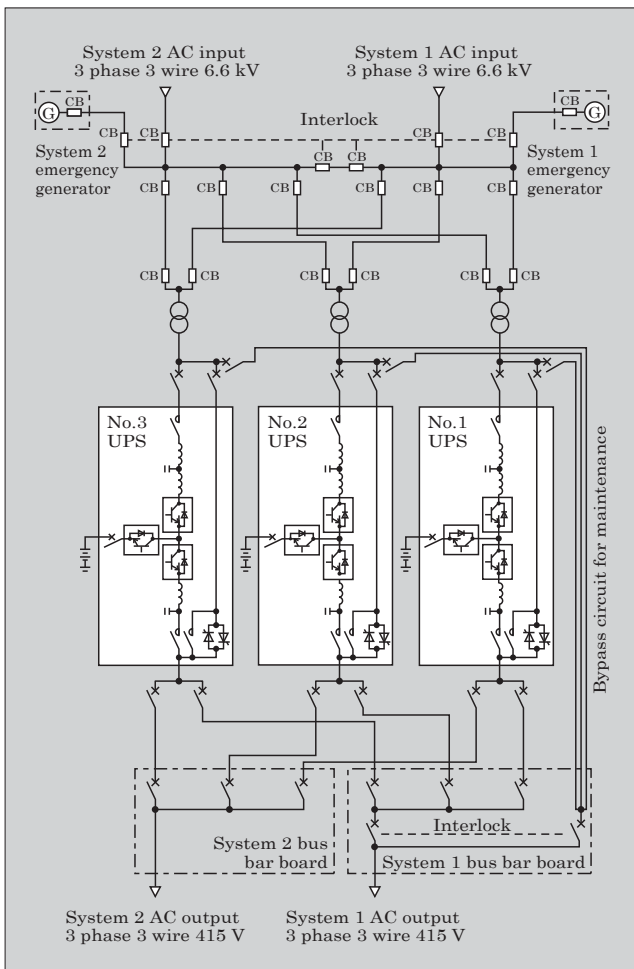


Fig.3 Parallel redundant system
(Completely independent double bus method)

the equipment has been reduced by approximately 30% and the weight is also approximately 30% lighter, to 1,600 kg (see Fig. 2). The merit of any space-saving done with equipment and devices such as UPS etc. is that there can be more space for installing servers and other equipment.

2.3 High Reliability

Data centers need a power supply which continues 24 hours a day for 365 days a year. Even during maintenance and any failures that may occur unexpectedly, this is supported with systems such as parallel redundant systems and stand-by redundancy systems, with a continued electricity supply from a UPS. Representative system configurations are shown in Figs. 3 and 4.

2.4 High Performance and High Functionality

(1) Support for high power factor load

In the conventional 500 kVA equipment, support range was only up to a load power factor of 0.9 (450 kW), but the UPS 7000HX Series achieves an output up to a load power factor of 1.0 (500 kW). Therefore, for high power factor loads such as information pro-

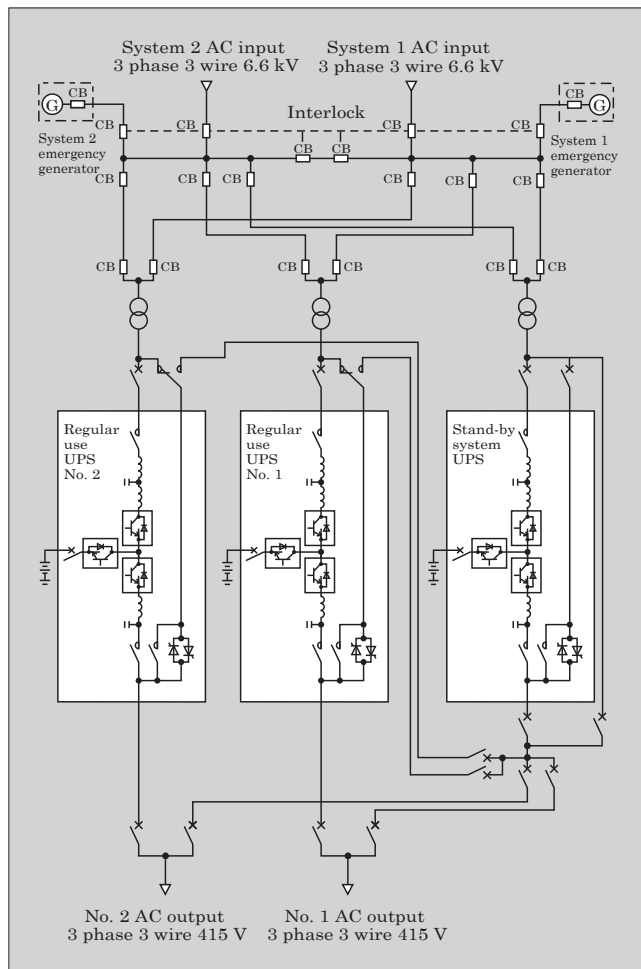


Fig.4 Stand-by redundancy system

cessing systems using power-factor correction circuits (PFC) on their power supply inputs, the product supplies 11% more electric power compared with conventional models.

(2) Power walk-in function

When the UPS switches over from the power supply from the battery (in operation at blackout) to the power supply from the emergency generator, by employing a function to gradually transfer from the battery discharge power to the emergency generator power (a power walk-in), voltage fluctuation or hunting on the emergency generator due to a rapid change in load can be suppressed.

(3) Network function

By connecting to a network using the “Web/SNMP card” the operating status of the UPS can be monitored using a standard browser and notification of failure information can be sent by e-mail. In addition, by using the dedicated monitoring software, it is possible to

monitor items such as trends in the output power and the operation history and failure history of the UPS.

3. Specifications

Reduced losses and miniaturization of the filter circuits were realized with the use of a 3-level conversion circuit. As a result, the equipment as a whole was made smaller and lighter. Table 1 shows the performance and specifications of the UPS 7000HX Series.

4. Circuit Structure and Operation

4.1 Outline of the Configuration and Operation of Main Circuit

Figure 5 shows the main circuit block diagrams. We adopted a normal inverter feeding method, made up of an inverter which converts direct current to alternating current and a rectifier which converts alternating current to direct current. There is also a chopper connected on the DC input, which performs charge/discharge control for the storage battery.

In the normal operating state, where the AC input is within the normal range, a stable power supply with a constant voltage and constant frequency is supplied to the load using the inverter. The rectifier controls the UPS AC input current to be a sine wave with power factor ≈ 1.0 , and the chopper charges the storage battery. When a power failure occurs in the AC input, the chopper boosts up the storage battery voltage to the appropriate DC voltage and the inverter converts it

Table 1 Performance and specifications of the “UPS 7000HX Series”

Item		Performance and specifications
UPS method		Normally inverter feeding
Rated output apparent power		500 kVA/500 kW
Equipment maximum efficiency		97%
Switch-over time at power failure		Uninterrupted
AC input	Number of phases	3 phase 3 wire
	Voltage	415/420 V $\pm 10\%$
	Frequency	50/60 Hz $\pm 5\%$
	Power factor	0.98 or more
	Current harmonic distortion factor	5% or less
Bypass input	Number of phases	3 phase 3 wire
	Voltage	415/420 V $\pm 10\%$
DC input	Nominal voltage	480 to 528 V (Equivalent to 240 to 264 lead storage battery cells)
AC output	Number of phases	3 phase 3 wire
	Voltage	415/420 V
	Frequency	50/60 Hz
	Load power factor	0.7 (delay) to 1.0
	Voltage tolerance (at steady state)	Within $\pm 1\%$
	Transient voltage regulation	Within $\pm 3\%$ (Load: 0 to 100%)
	Settling time	50 ms or less
	Voltage waveform distortion	2% or less (linear load), 5% or less (rectifier load)
	Frequency precision	0.01% or lower (when internal oscillation)
	Range of external synchronization	Within $\pm 5\%$
	Overload capability	125%: 10 minutes, 150%: 1 minute, 200%: 2 seconds

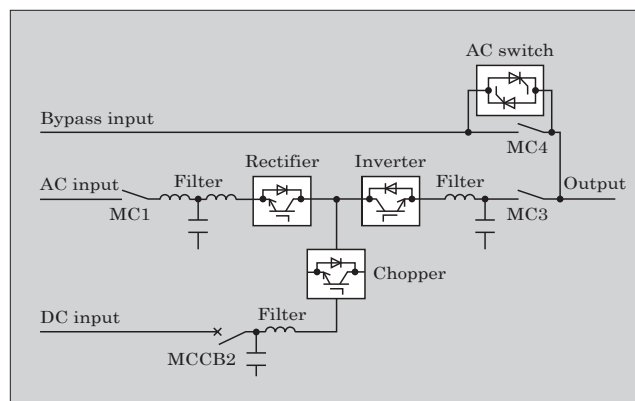


Fig.5 Main circuit block diagram

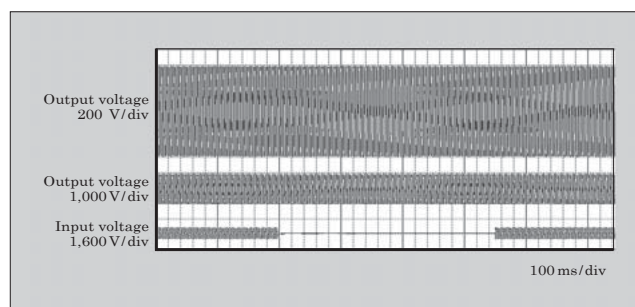


Fig.6 Waveforms at the time of power failure and recovery

to a stable alternating current and supplies it. Figure 6 shows the waveform data at the time of a power failure and power recovery. Even if power failure occurs in the input voltage, the output continues to supply a stable voltage.

4.2 Application of AT-NPC 3-level Conversion Circuit

AT-NPC 3-level conversion circuit as shown in Fig. 7 was adopted for the rectifier and inverter part. The characteristics of an AT-NPC 3-level conversion circuit are as below.

- (1) As the switching voltage is half that in a 2-level conversion circuit, the switching loss in the converter is reduced and it is possible to improve the power conversion efficiency, to achieve energy conservation, and to achieve miniaturization of the converter.
- (2) As the switching waveform is a staircase waveform as shown in Fig. 8, the harmonic voltage is reduced compared to that in a 2-level conversion circuit. In addition, because the losses are also reduced from the filter circuits accounting for a high proportion of the volume and mass, such as the reactor and capacitors, miniaturization of the equipment is possible.
- (3) The noise generation from the switching can be reduced comparing 2-level conversion circuits.

4.3 Application of AT-NPC 3-level IGBT Module

The AT-NPC 3-level insulated gate bipolar transistor (IGBT) module developed by Fuji Electric is used in the 3-level conversion circuit (see Fig. 9). This module

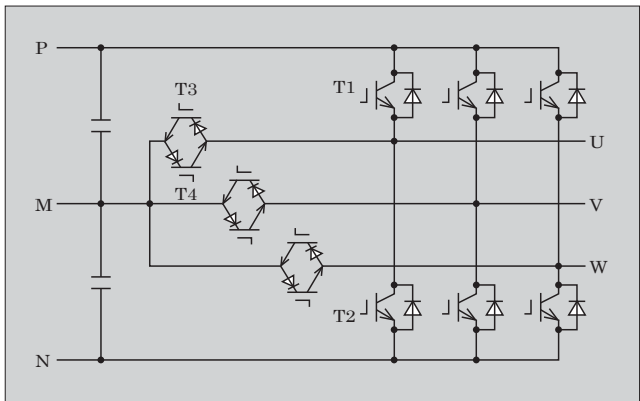


Fig.7 AT-NPC 3-level conversion circuit

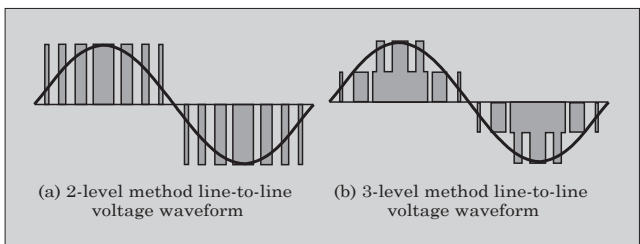


Fig.8 Comparison of switching waveforms between 2-level and 3-level conversion circuits

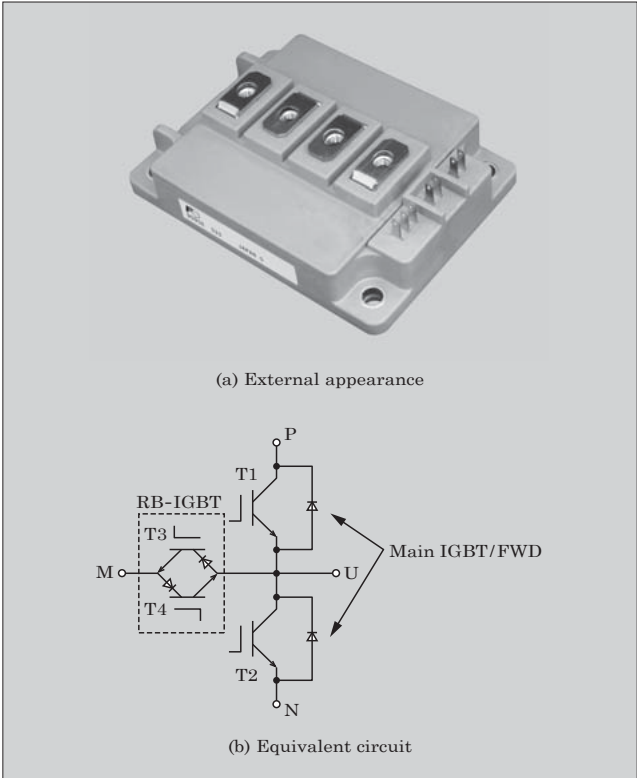


Fig.9 AT-NPC 3-level IGBT module

uses a reverse-blocking IGBT (RB-IGBT) as the neutral point clamped element and the four semiconductor switching elements required for a single 3-level arm are packaged in one device.

The merits for the use of this module are as described below.

- (1) Compared with a generally available diode clamped NPC, the number of conducting elements are reduced by half, and the conduction loss can be suppressed.
- (2) The use of a single package module makes it possible to use 3 sheet conductors corresponding to P, M and N as shown in Fig. 7 for the connections between elements. This reduces the inductance of the switching circuit and the surge voltage can be suppressed, and it becomes possible to suppress noise and to streamline circuits through a reduction in the devices needed as countermeasures to surge voltage.

4.4 Efficiency and Losses

Figure 10 shows the efficiency characteristics of this machine during AC-AC operation. In the range where the load factor is between 20% and 100%, the maximum efficiency is 97.1% and the minimum efficiency is 95.9%. Since the efficiency is also good even when the actual operation load is low, a large energy conservation effect can be obtained.

Figure 11 shows a comparison of losses for the conventional 2-level conversion equipment and for the AT-NPC 3-level conversion equipment. For the AT-NPC

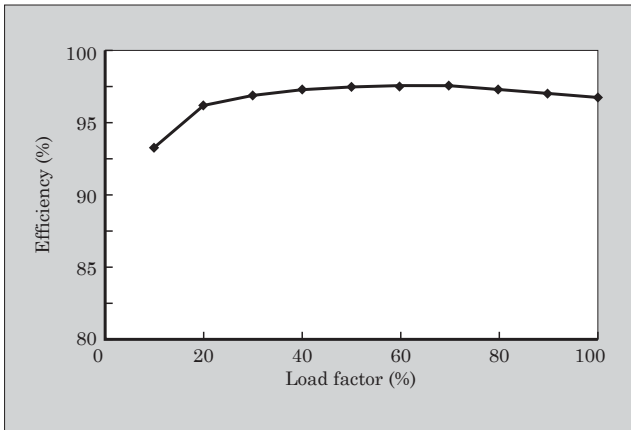


Fig.10 Efficiency characteristics

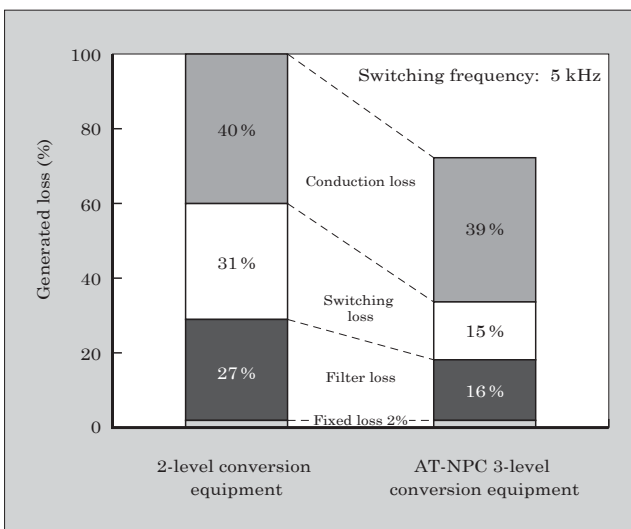


Fig.11 Comparison of loss between 2-level conversion equipment and AT-NPC 3-level conversion equipment

3-level conversion equipment, losses are reduced by about 30% compared with those for the conventional 2-level conversion equipment. The figure clearly shows that there is a great reduction in switching loss and filtering loss. As written above, this is because the switching voltage is reduced by half.

4.5 Control Technology

The control equipment carries out PWM waveform control, sequence control, communication reliability, availability, serviceability (RAS) management and man-machine control.

In addition to the instantaneous voltage waveform control in the inverter, this control equipment also performs instantaneous current control. This makes it possible to perform shock-less changeovers between

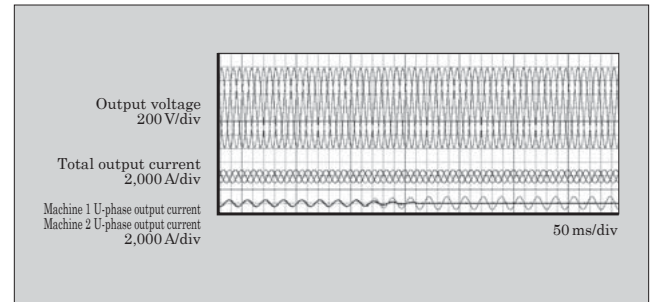


Fig.12 Waveform at one unit stopped during two unit operation

the inverter power supply and bypass power supply and also parallel operation of the UPS. It realizes a steady and high-quality supply of electric power, both in normal and transient states.

In parallel operation, the current is balanced by control so that the current in each UPS is equal. Furthermore, when one of the units in parallel operation is stopped and removed, for example, for maintenance work, and when a UPS that has been stopped is started up and connected in parallel with an operating UPS, the share of the current is controlled so as to change slowly, so that there is no disturbance in the output voltage and it is possible to supply a stable voltage to the load.

Figure 12 shows the waveforms when one of two units in parallel operation is stopped and separated off. There is no disturbance in the output voltage and the current from the UPS which is to be stopped gradually decreases to zero and the current from the UPS to be continued operation gradually increases.

5. Postscript

We presented a large capacity, high-efficiency UPS product, “UPS 7000HX Series” which is intended for data centers and features AT-NPC 3-level conversion technology. By using the AT-NPC 3-level conversion circuit and Fuji Electric's proprietary IGBT module dedicated for 3-level circuits, high efficiency of maximum 97% and miniaturization by 30% can be achieved compared to conventional models. Furthermore, the equipment also supports various power management systems, and it is expected that it will be used for a wide range of power supply equipment in addition to data centers, in applications where a reduced environmental burden and high reliability are demanded.

We will continue to incorporate new technologies and to work to develop and commercialize power supply equipment which meets the expectation of customers.

Power Electronics Equipment Applying SiC Devices

MATSUMOTO Yasushi [†] KONDO Yasushi [†] KIMURA Hiroshi [†]

ABSTRACT

To achieve innovative compactness, light weight, and low loss in power electronic equipment, it is beneficial to use power semiconductors that use wide bandgap materials such as SiC and GaN. By installing hybrid modules using Si-IGBT and SiC-SBD semiconductors into general-purpose inverters, Fuji Electric can reduce inverter loss by 25%. In addition, by installing all-SiC modules in power conditioners for solar power generation, we demonstrated that it can increase main circuit efficiency to 99% while also reducing the overall equipment volume to 1/4 of conventional models, which is a substantial size reduction.

1. Introduction

In order to achieve innovative miniaturization, weight reduction and lower power dissipation on power electronics equipment, the progress of power semiconductors including their packages is essential. We are now approaching the limits of what is possible for the performance of devices using Si, which is currently the mainstream material for power semiconductors. Product development is proceeding for power semiconductors using wide band gap materials such as SiC (silicon carbide) and GaN (gallium nitride), which have a high blocking voltage and low losses and can operate at high frequencies and elevated temperatures.

This article describes the characteristics of hybrid modules of SI-insulated gate bipolar transistors (IGBTs) and SiC-schottky barrier diodes (SBDs) and All-SiC modules of SiC-metal-oxide-semiconductor field-effect transistors (MOSFETs) and SiC-SBDs, and explains the characteristics of general-purpose inverters mounting these hybrid modules. Also the characteristics of prototype power conditioner equipment for solar power generation which mounts this All-SiC module are presented.

2. Characteristics of SiC Power Semiconductor Modules

2.1 Hybrid Si-IGBT and SiC-SBD modules

Figure 1 shows the external appearance and internal circuits of a power integrated module (PIM) which is a hybrid of Si-IGBTs and SiC-SBDs.

For the SiC-SBDs, we used the chips⁽¹⁾ shown in Fig. 2, which were developed jointly with the National Institute of Advanced Industrial Science and

Technology, and applied them to the free wheel diodes (FWDs). For the IGBTs, we used the 6th generation “V-Series” chips. There are a total of 6 types of the hybrid module: 3 types of 50 A, 75 and 100 A for 600 V, and 3 types of 25 A, 35 A and 50 A for 1,200 V⁽²⁾. The profile of the hybrid module product performance and characteristics given hereinafter will take the 1,200 V/50 A type as a representative example.

Figure 3 shows the forward characteristics of the

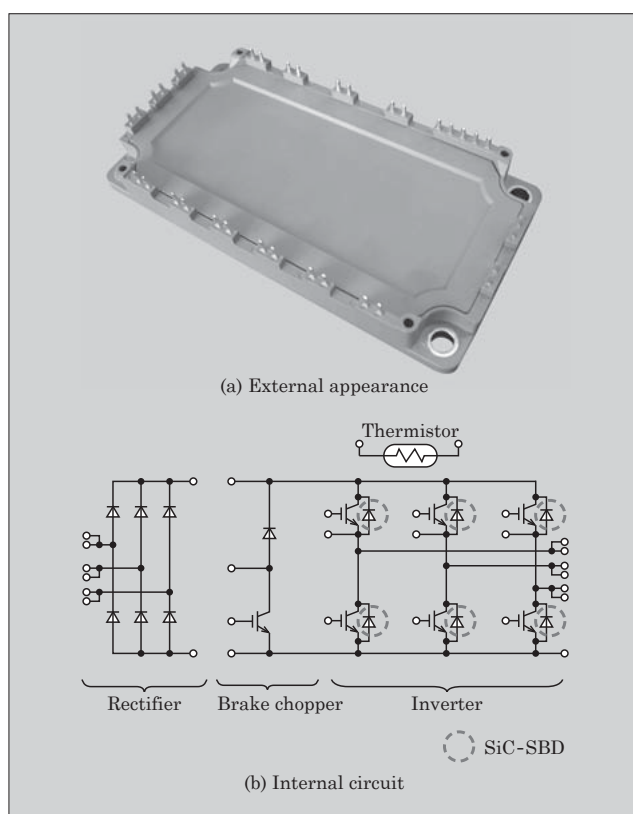


Fig.1 Si-IGBT and SiC-SBD hybrid PIM

[†] Fuji Electric Co., Ltd.

SiC-SBD and V-Series P-N junction diode (V-Series PND). They have almost identical characteristics within the range of currents for actual use. Also, the

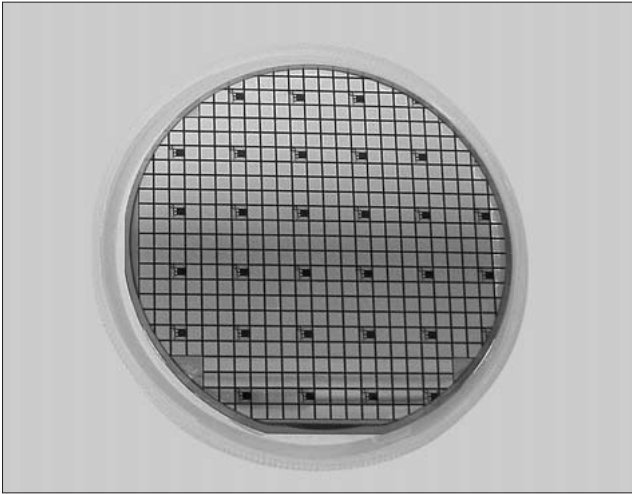


Fig.2 SiC-SBD chips

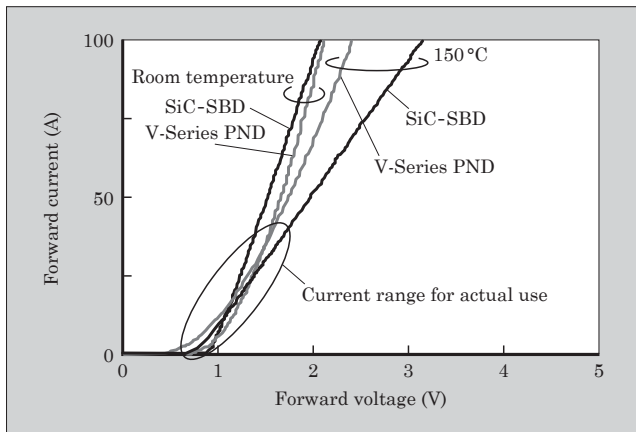


Fig.3 Comparison of forward characteristics

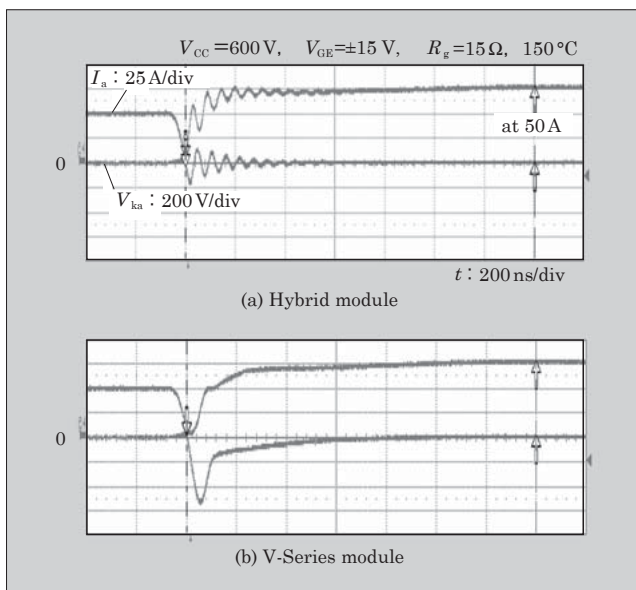


Fig.4 Comparison of FWD reverse recovery waveforms

SiC-SBD shows a strong positive temperature coefficient such that the ON-state voltage rises with a rise in temperature, and the current can be easily balanced even in multi-parallel use.

Figure 4 shows the waveforms during reverse recovery of the hybrid module and V-Series module using V-Series PND as the FWD. Figure 5 shows the IGBT turn-on waveforms. Because the SiC-SBD is a unipolar device not injecting minority carriers, it is possible to suppress the generation of peak current at the FWD reverse recovery. Furthermore, by suppressing the peak current at the FWD reverse recovery, it is also possible to suppress the turn-on peak current of the IGBT. As a result of this, compared to the values for the V-Series PND, at rated current 50 A, the reverse

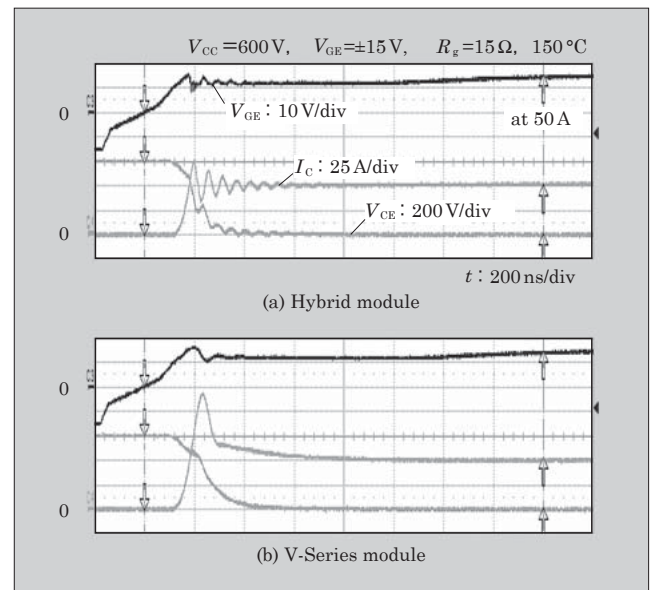


Fig.5 Comparison of IGBT turn-on waveforms

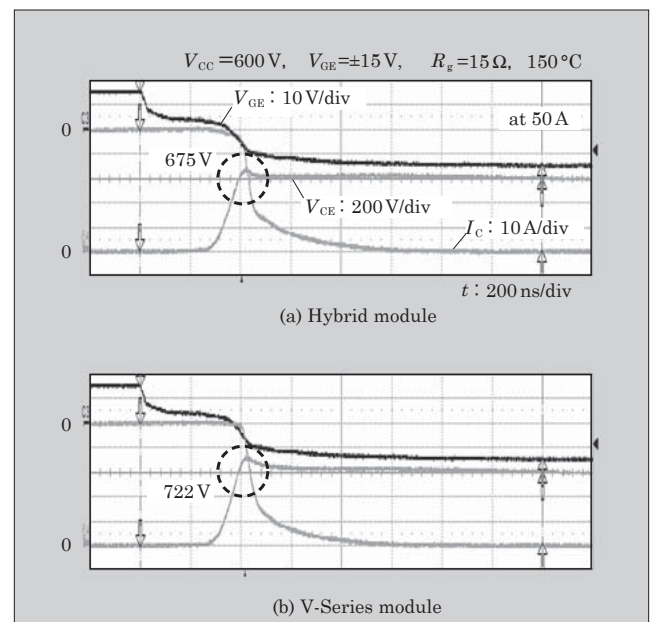


Fig.6 Comparison of IGBT turn-off waveforms

recovery loss is reduced significantly to 30% and the turn-on loss is reduced to 46% respectively.

Figure 6 shows the IGBT turn-off waveforms. As the turn-off surge voltage at a rated current of 50 A is kept to 47 V lower than that on the V-Series PND, the turn-off loss can also be reduced.

2.2 All-SiC module

For the SiC-MOSFETs, we used the implantation and epitaxial metal oxide semiconductor (IEMOS) chips⁽³⁾ shown in Fig. 7, which was developed jointly with the National Institute of Advanced Industrial Science and Technology.

Figure 8 shows the forward characteristics of the chip and Fig. 9 shows the temperature characteristics of the on-resistance $R_{on} \cdot A$ and gate threshold voltage V_{th} . The SiC MOSFET also has a positive temperature coefficient, in the same way as the SiC-SBD, and balancing the current is easy even in multi-parallel use. Furthermore, it realizes a low on-resistance on a normally-off type, and the normally-off characteristics are maintained even at a high temperature state of 200 °C.

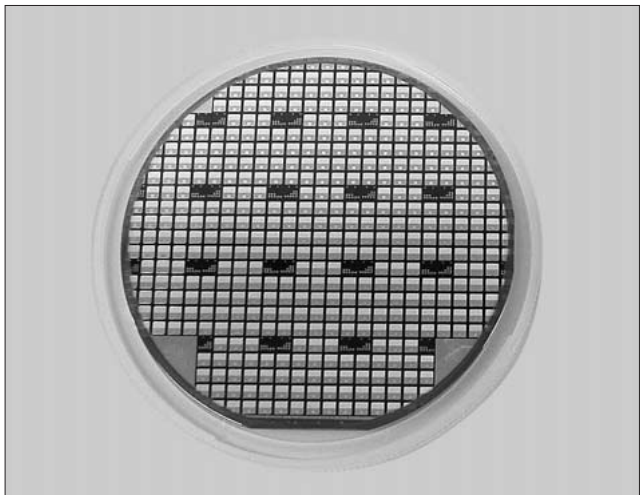


Fig.7 SiC-MOSFET chips

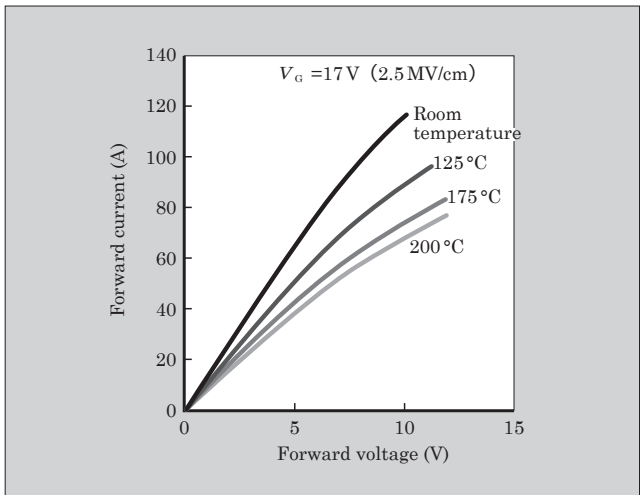


Fig.8 Comparison of forward characteristics

Figure 10 shows the SiC-MOSFET turn-off and turn-on waveforms at 200 °C. Both at the turn-off and turn-on, the time required for the switching is around 100 ns, which is greatly reduced to around 250 ns comparing Si-IGBT. Furthermore, the temperature causes little change in the switching characteristics, and the turn-off loss and turn-on loss show almost no dependence on the temperature. The turn-off loss and turn-on loss at 150 °C are 40% and 31% of those losses of Si-IGBT.

Figure 11 shows the module structure of SiC-

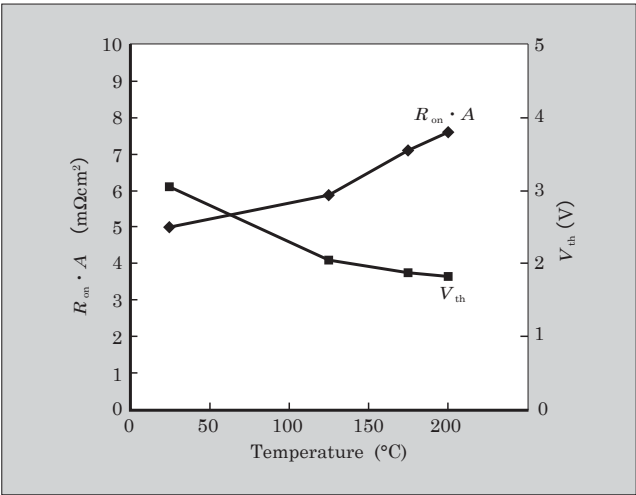


Fig.9 Temperature characteristics of the on-resistance and gate threshold voltage

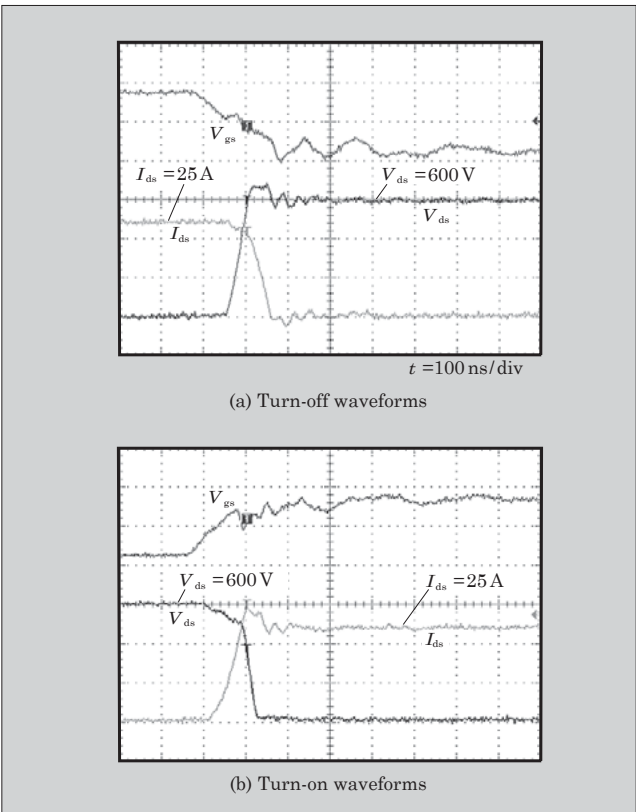


Fig.10 SiC-MOSFET turn-off and turn-on waveforms

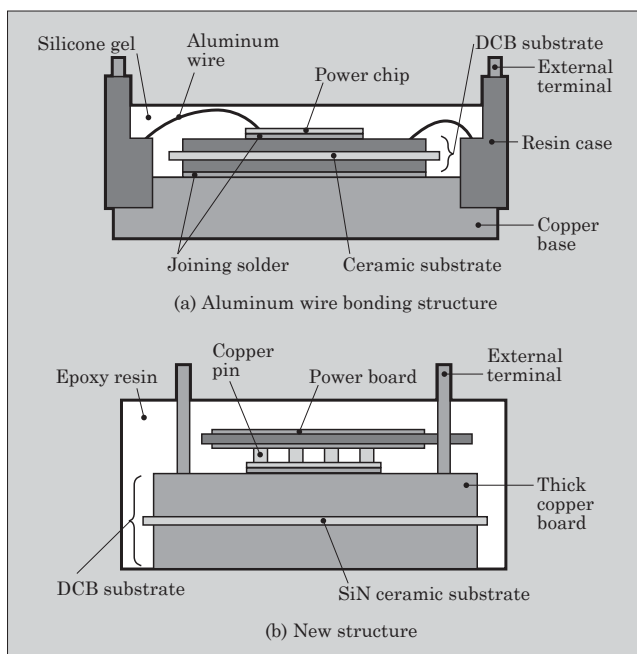


Fig.11 Comparison of the module structures

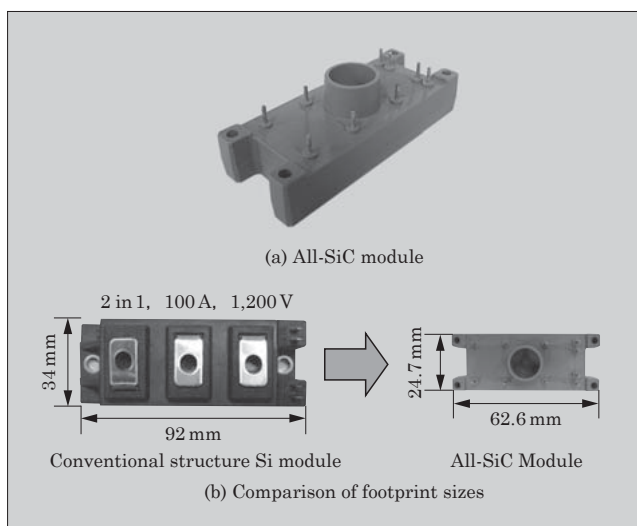


Fig.12 External appearance of All-SiC module and comparison of footprint sizes

MOSFETs and SiC-SBDs⁽⁴⁾⁽⁵⁾ developed for All-SiC module. In the package developed, a Fuji Electric proprietary copper pin connection structure was used in place of the aluminum wire bonding structure used conventionally, and miniaturization and high power density were realized. Furthermore, by using a direct copper bonding (DCB) substrate made from copper plates and SiN ceramic substrate, the thermal resistance was reduced and the rise in the chip temperature T_j due to power density rise was suppressed. Also, by using an encapsulation structure using highly heat resistant epoxy resin in place of silicone gel, the warping which occurs at the points of connection around the chips has been eased and the reliability of the device has been improved. With this, it is possible to increase

the capacity of modules with the parallel connection of multiple small SiC chips, and also to achieve miniaturization of the package. Figure 12 shows the external appearance of a 2 in 1 type All-SiC module rated 1,200 V/100 A and a comparison of footprint sizes (floor area). The footprint is half comparing that of a conventional structure Si module of the same rating.

3. Power Electronics Equipment Applying SiC

3.1 SiC-SBD mounted general-purpose inverters

The “FRENIC-MEGA GX-SiC” general-purpose inverter mounted Si-IGBT and SiC-SBD hybrid module was developed with the aim to raise further the efficiency of the inverters used for motor drives in air-conditioning systems and production equipment in factories. In the FRENIC-MEGA Series, this is a new GX Series specifically designed for synchronous motor drives. There are 6 models of three phase input devices, including 5.5, 7.5 and 11 kW for 200 V, and 5.5, 7.5 and 11 kW for 400 V. Figure 13 shows the external appearance of the 400 V/11 kW model and the external appearance of its major circuit part. The use of a hybrid model makes the switching losses such as turn-on

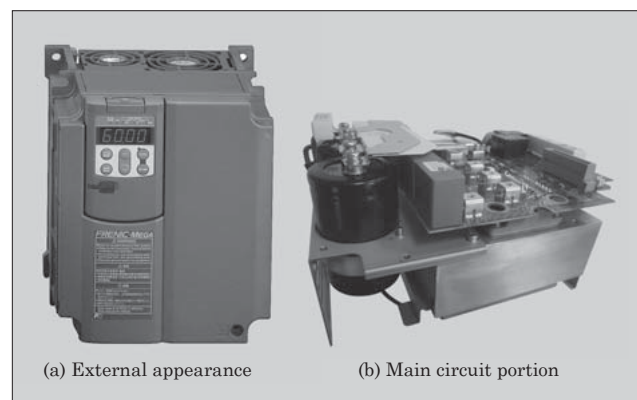


Fig.13 “FRENIC-MEGA GX-SiC”

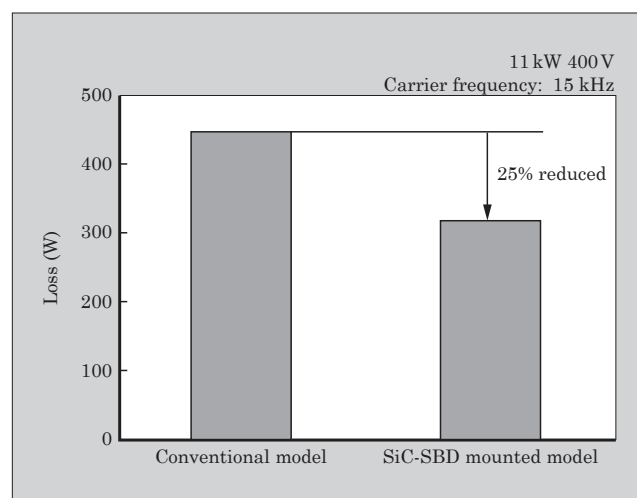


Fig.14 Comparison of generated loss of general-purpose inverters

& turn-off losses and the reverse recovery loss reduce. It was possible to reduce the generated loss in the general-purpose inverter by 25% compared to conventional models using Si devices (see Fig. 14). As a result, when used in combination with the highly efficient “GNS Series” and “GNP Series” of IPM motors, it was possible to achieve an even more efficient drive system.

3.2 All-SiC module mounted power conditioner

We produced a power conditioner for solar power generation which made miniaturization and improved efficiency possible with the use of the All-SiC module. The circuit structure chosen for the equipment was the AT-NPC 3-level circuit shown in Fig. 15. On consideration of the balance between the miniaturization of the filter and the switching losses, the switching frequency was set to 20 kHz. Figure 16 shows the external appearance of the 20 kW machine and the ex-

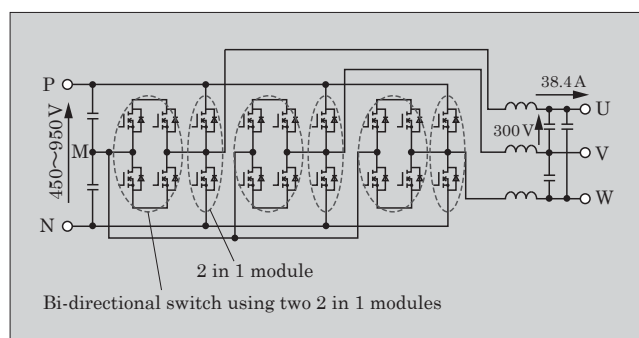


Fig.15 Circuit structure of All-SiC power conditioner

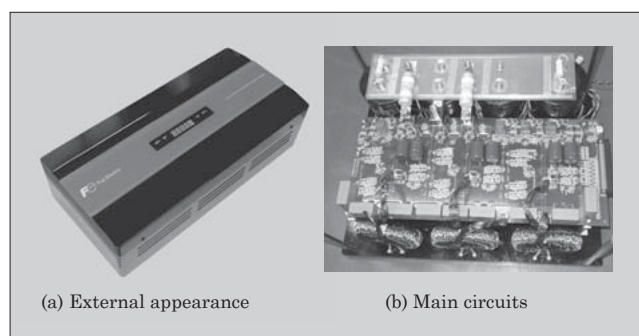


Fig.16 All-SiC power conditioner

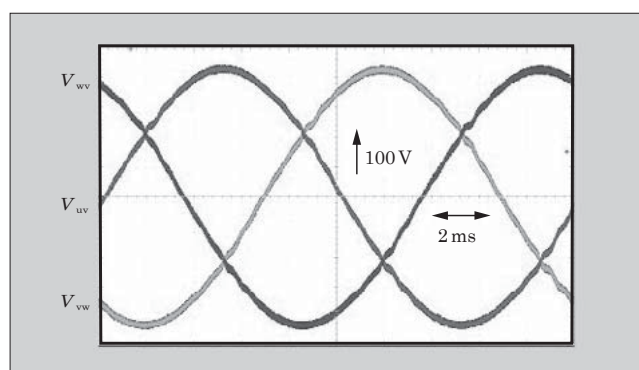


Fig.17 Power conditioner output waveform

ternal appearance of its major circuit part. The use of All-SiC module made miniaturization of the filter and cooling fin possible, and it was possible to reduce the volume of the power conditioner equipment as a whole to a quarter of that of conventional models. Figure 17 shows the three phase output voltage waveform when the equipment is operated independently. Even with the switching frequency raised and the filter miniaturized, the waveform has little distortion or ripple. Furthermore, the efficiency of the main circuit part is 99%, and a great improvement in efficiency was realized.

4. Postscript

We developed a general-purpose inverter product using hybrid modules of Si-IGBT and SiC-SBD. We also produced a power conditioner for solar power generation using an All-SiC module. By mounting power semiconductor modules using SiC on power electronics equipment, it becomes possible to improve the efficiency of the equipment and to achieve miniaturization further. We will continue to contribute to the rapid progress of power electronics equipment by continuing the development of circuit technologies and package technologies which utilize the characteristics of SiC as much as possible.

We are very grateful to the members of the Advanced Power Electronics Research Center at the National Institute of Advanced Industrial Science and Technology for their cooperation in the development of the SiC chip. Some of this development was carried out as a part of “Experimental demonstration of the prototype mass production of SiC devices” in the National Institute of Advanced Industrial Science and Technology's Industrial Transformation Research Initiative.

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Supplemental Explanation

Supplemental explanation 1 80 PLUS

80 PLUS is a guideline promoted by 80 PLUS Program for reduced electricity consumption on electrical appliances. It indicates that the efficiency of conversion from alternating current to direct current is 80% or higher. Using the 80 Plus certified power supply is a requirement for information equipment (workstations and personal computers) to adapt ENERGY STAR*.

The guidelines of 80 PLUS contain input voltages of 115 V AC and 230 V AC. Products are given the certification when they satisfy the condition of an 80% or greater conversion efficiency for each of the load fac-

*: International ENERGY STAR Program (ENERGY STAR): An international environmental labeling system for energy saving of electrical equipment. It is operated with the mutual recognition of the Ministry of Economy, Trade and Industry and the United States Environmental Protection Agency. A wide range of products are subject to the labeling, ranging from household electrical products to industrial machinery and computers.

tors 20%, 50% and 100%. The six ranks of Standard, Bronze, Silver, Gold, Platinum and Titanium are defined for the specification, in ascending order of efficiency. However, the top rank of Titanium is only defined for 230 V AC, so this rank is not found on power supply units for general personal computers. Power supply units with improved power conversion efficiency by complying with this 80 PLUS can reduce heat generation, and thereby decreasing the rotation speed of a cooling fan to suppress its noise as well as reducing the thermal degradation of electronic components. This results in noise reduction, and a reduction of the thermal degradation of electronic components is also possible. This has an effect on the comfortableness of the machine and its energy saving, and also has a good effect on the lifespan of the product.

Reference

80PLUS Program, <http://www.80plus.org>. (accessed 2012-04-10).

Supplemental explanation 2 Battery capacity, discharge rate and charge rate

The battery capacity means the amount of electricity which is taken out a battery from starting discharge to a discharge final voltage. The units used are Ah (ampere hours). For example, a battery with a battery capacity of 10 Ah has enough electricity for a 10 A current to flow for 1 hour. It is also possible to have a 2 A current flowing for 5 hours.

Battery capacity is defined by JIS. The rated capacity is defined as the capacity with a current at which discharging will be completed in 5 hours at 20°C. This is called 5 hour rate capacity.

The discharge rate is the relative ratio of the current at which a battery is discharged against its ca-

capacity. This is a method of description to equalize the characteristics conditions for different batteries. The units used are C.

A discharge rate of 1 C means the current value for discharging to be completed in exactly one hour when a cell with the nominal capacity value is discharged at a constant current. For example, on a battery with a rated capacity of 10 Ah, it will be 10 A for 1 C. If it is discharged with a current of 20 A, it is said that it was discharged at 2 C, and at 2 A it is said that it was discharged at 0.2 C.

The charge rate is defined in the same way.

Supplemental explanation 3 PUE

Power usage effectiveness (PUE) is an index expressing the energy efficiency of data center equipment. It is the value resulting when the electricity consumed by an entire data center is divided by the electricity consumed by IT equipment such as servers. The electricity consumed by an entire data center includes the electricity consumed by the IT equipment

such as servers, storages, routers and control terminals, and also the electricity consumed by other equipment such as air conditioning equipment, power equipment, lighting and monitoring equipment.

$$\text{PUE} = \frac{\text{Electricity consumption of entire data center}}{\text{Electricity consumption of IT equipment}}$$

Supplemental explanation 4 MPPT

Solar cells have I-V characteristics like those shown on the figure. The current flowing when in a short circuit state is called I_s . The voltage when in an open state is called V_{oc} . In between these short circuit and open states, there is a maximum power point where a solar cell generates maximum power. This maximum power point changes according to the change in the amount of sunlight, so a power conditioner (PCS) is controlled to search for this operating state during operation. This is called maximum power point tracking (MPPT) control.

When operations start, the PCS gradually lowers its operating voltage in order to find the maximum power point from the V_{oc} state. At this time, the PCS measures the generated output of the solar cell and decrease the solar cell operating voltage whilst the generated power is increasing. When the generated output

falls, the PCS increases the operating voltage. In this way, the PCS can maximize the power generated by solar cells through this MPPT control changing the operating voltage of solar cells.

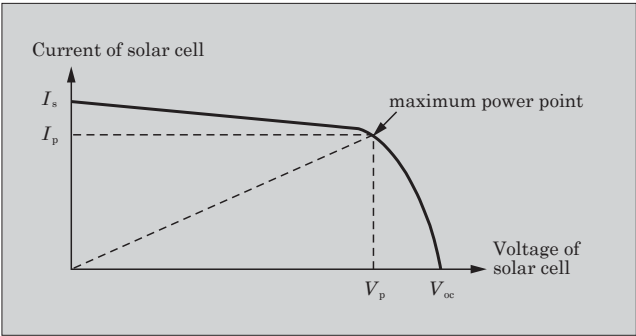


Figure I-V characteristics of solar cell

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