

# Power Electronics: Current Status and Future Outlook

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## 1. Introduction

Power electronics and products based on power electronics technology have an indispensable role that penetrates every corner of our current society ranging from compact portable devices to social infrastructure represented by industrial plants and mega solar. Fuji Electric has combined its core technology of power devices and power electronics with its control technology and applications in order to concentrate its efforts on the development of products that efficiently and safely supply and use energy. Fuji Electric's power electronics products and their field of application are shown in Fig. 1. This paper describes the latest trends in power electronics technology, as well as Fuji Electric's activities and application products.

## 2. Market Needs and Technology Trends

### 2.1 Compactness and lightweight features

All types of products including those in the pow-

er electronics field are increasingly required to be smaller in size and lighter in weight. In particular, compactness is required when equipment for moving objects such as rolling stock needs to be installed in a limited space, and a lighter weight is needed to ensure acceleration and deceleration performance and to optimize the maximum loading capacity of vehicle bodies, since the weight of equipment adds to the overall mass of the vehicle body.

### 2.2 Energy conservation and high efficiency

The discharge of greenhouse gases needs to be suppressed in order to prevent global warming, and as such, great emphasis is being placed on the use of renewable energies and energy conservation.

Power electronics equipment has become indispensable in applications such as DC-AC conversion for connecting DC power generated by mega solar to transmission systems, as well as DC-AC inter-conversion in the storage facilities of smart grids used in providing a stable supply of highly variable renewable energies. The conversion efficiency of

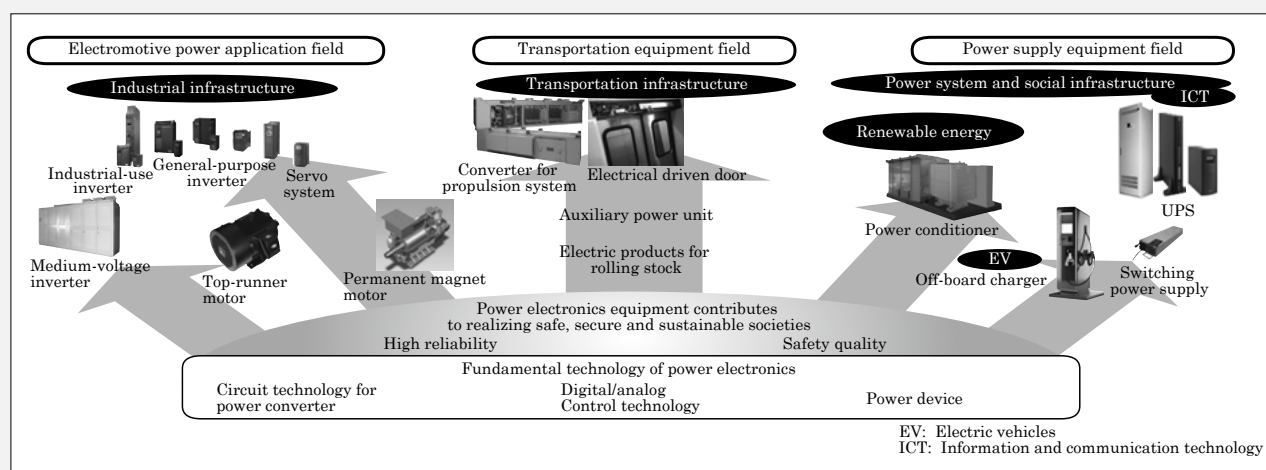


Fig.1 Fuji Electric power electronics products and their field of application

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the power electronics equipment in these types of facilities is directly related to the energy savings of systems, and from a business standpoint, this is the most important requirement for these products.

At the same time, utilization is expanding every year for data centers that support Internet based societies such as cloud services that provide social networks, and as a result, there is a growing need for large-capacity uninterruptible power systems (UPS) compatible with large-scale data centers. As increase in energy consumption for data centers attracts attention, attention has been given to the efficiency of UPS, especially in North America, and as a particular indicator, emphasis is placed on the selection of a UPS that has high efficiency under actual load. Furthermore, the time for renewal of IT equipment, for which there was heavy investment in the Japanese market around the year 2000, is approaching, and customers are requiring replacement with highly efficient new products that maintain compatibility with existing products.

In addition, in the field of variable speed driving devices, which have always placed importance on functionality and performance, there is a growing global trend toward the need for energy savings, and as a result, high-efficiency motors that utilize the Top Runner Approach<sup>\*1</sup> are continuing to penetrate the Japanese market. Overseas markets have seen the enactment of European standards that regulate the efficiency of inverter systems that drive motors of 1,000 kW or less. These regulations are scheduled to take effect as an International Electrotechnical Commission (IEC) standard in 2018.

## 2.3 Diversification of needs

As products that utilize power electronics technology continue to gain popularity, market needs are diversifying for power electronics products. Take general-purpose inverters as an example. Up until now, the product line-up for these has mainly been based on functionality and performance, but recently, products have been required to meet specific application and installation environment of each customer. For example, inverters for driving mid-to-low level elevators of machine-roomless type,

which have become mainstream, are now required to be smaller and thinner in dimension. In addition, products are required to be equipped with a diverse range of functions according to users and their applications.

## 2.4 Power devices

For over 50 years, power devices manufactured from silicon (Si) semiconductor materials have been used for power electronics equipment. Currently, mainstream insulated gate bipolar transistor (IGBT)<sup>\*2</sup> have been advancing in their device structure, processing technology and wafer technology, and as a result, power loss is now less than half of what it was initially as these devices continue reducing loss as shown in Fig. 2. At the same time, however, we have just about reached the limits of Si semiconductor performance, and since greater performance improvements cannot be expected in the future, there has been increased anticipation for the debut of power devices that are capable of achieving dramatic characteristic improvements.

In light of this, anticipation is mounting for wide band gap semiconductors as semiconductor materials capable of achieving dramatic low-loss performance, high-frequency operation and high-temperature operation. In recent years, silicon

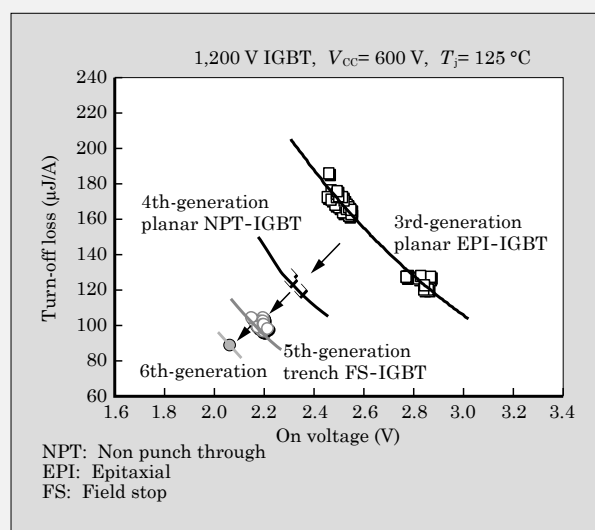


Fig.2 Si-IGBT generation and feature changes

### \*1: Top Runner Approach

This is a Japanese unique system based on the “Act on the Rational Use of Energy,” in which a target criteria of energy-saving performance for products is defined higher than that of the best energy-saving equipment (Top Runner) as of the definition. This program was introduced based on the revised Act on the Rational Use of Energy in 1999. As of FY2014, there are 28 products subject to the system, which include air

conditioners, TVs, electric refrigerators, and fluorescent and LED lighting equipment. In addition, 3-phase induction motors (industrial-use motors) became part of the Top Runner Program in October 2013.

### \*2: IGBT

This is an acronym for an insulated gate bipolar transistor. This is a voltage control device that has a gate insulated with an oxide insulated film, having the same

structure as MOSFET. Self-turn-off power devices such as GTO and power transistors were current driven. The IGBT, however, is voltage-driven, and as such, they have gained instant popularity because of its simple drive circuit, easy control, and high-speed switching capabilities. It is currently used by almost all power electronics equipment, with the exception of low-voltage, small-capacity equipment such as switching power supplies.

carbide (SiC)<sup>\*3</sup>, as one type of wide band gap semiconductor, has finally become a practical technology, and there is increasing expectation that SiC power devices and their application equipment will gain popularity.

## 2.5 International standardization

As borderless markets continue to progress, international standardization has been increasing in its importance. The need for power electronics products to be compliant with international standards has steadily increased, and they have covered many fields, such as insulation, electromagnetic compatibility (EMC) as well as data transmission, functional safety [Supplemental explanation 1] and efficiency characteristics. Furthermore, the development of standards has been progressing, starting with EMC emission limit values, and now targeting the expansion of frequency ranges, as well as the latest technologies which include grid connected power converter (GCPC) and wireless power transfer (WPT)<sup>\*4</sup>.

On the other hand, there is a movement toward setting international standards as regional standards based on the World Trade Organization/Technical Barriers to Trade (WTO/TBT) agreements. A good example of this is seen in China's product safety certification system, the China Compulsory Certification (CCC). Therefore, compliance with international standards and regional standards is considered to be an essential condition in expanding products for the global market. Furthermore, third-party certification for standards also plays a role in establishing evaluation criteria for product quality and performance. As a result, the activities and timing surrounding the acquisition of self-declaration or third-party certification for standard compliance have carried a huge weight in the development of products in recent years.

On the other hand, it is gathering momentum to actively pursue international standard compliance, which has been somewhat of a passive activity in the past, as part of one's global strategy and intellectual property strategy.

## 3. Fuji Electric's Efforts in Technology Development

### 3.1. Development and application of new power devices

Fuji Electric has set its focus on SiC based power devices and has been carrying out research development while participating in the Tsukuba Power Electronics Constellations (TPEC), a project being led by the National Institute of Advanced Industrial Science and Technology. Currently, we have reached the stage where 1,000 V class SiC power devices are developed to a practical level, and in April 2014, we started operations of a continuous production line at the Matsumoto Factory that utilizes our 6-inch wafers in pre-process and post-process work.

Fuji Electric is now supplying the market with a line-up of compact and lightweight products that feature low-loss and high-frequency operation, both of which are advantages of SiC power device. In addition, we are continuing to develop technologies and products that fully leverage the potential of SiC, which includes high-temperature operation and a high blocking voltage.

Fuji Electric is one of only a few companies worldwide that deals in both power devices, which form the backbone of power electronics equipment, and their application products. Fuji Electric has taken advantage of this by forming an alliance between our device and application divisions to further facilitate the development of new technologies and new products. Besides the above mentioned SiC power devices, our device and application divisions are working hand-in-hand in development at all stages starting at the product planning stage for products that also include our Si power devices.

### 3.2 Platform

In order to supply an increasingly diversified line-up of products that meet the various needs of globalization and the market, there has been an increasing need to develop power electronics technologies and products, and this requires that emphasis

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#### \*3: SiC

This is a compound of silicon (Si) and carbon (C).

SiC exists in many structural polymorphisms of crystal, such as 3C, 4H and 6H. Due to its structure, it is known as a wide-gap semiconductor, having a band-gap between 2.2 to 3.3 eV. Since SiC possesses physical characteristics that are advantageous as a power device, such as a high dielectric breakdown voltage and high thermal conductivity, it has been advancing in its practical applications by enabling devices to

have high blocking voltage, low loss and high-temperature operation characteristics.

#### \*4: WPT

This is an acronym for wireless power transfer. This is a technology to transfer electrical energy in a contactless manner. It converts electric power into medium-frequency AC with a device such as an inverter, and then convert this into medium-frequency electromagnetic waves by use of the primary coil. This, in turn, is propagated to the secondary coil by using the physical

phenomena described below and received energy is converted to AC power. The utilized physical phenomena include electromagnetic induction, magnetic resonance, electric field coupling, electric field resonance and radio frequency radiation according to electromagnetic-wave frequency. These have traditionally been used in home appliances and mobile devices, but they are now expected to be used in the charging systems of electric vehicles.

be placed on securing development personnel and speeding up the development process. Fuji Electric has developed, as a platform, a commonality between product groups, which includes main circuits, which are composed of power devices, as well as their control circuits, and based on this, we have been able to expand the product family and capacity series of new product groups. We have been working to expand this platform, as well as product development based on this platform, in all areas of power electronics such as general-purpose inverters, which are composed of various product groups, UPS and equipment installed in rolling stock.

### 3.3 Improvement of development environment

In order to improve speed and integrity in the development of power electronics technology, Fuji Electric has been actively making use of simulation technology.

Traditionally, control system simulations and simulations dealing with individual physical phenomenon, such as can be found in thermal cooling and the unwanted emission of electromagnetic noise, have been the mainstream. In power electronics equipment, there is a mutual and close relationship between several aspects of power devices including the wiring structure design for achieving a specified operation, drive conditions [Supplemental explanation 2] and generated loss [Supplemental explanation 3] (input to the cooling system), as well as phenomena related to the unwanted emission of electromagnetic noise. Therefore, the results of combination tests make it impossible to avoid development backtracking, such as performing a redesign due to tradeoffs in operating conditions.

In order to overcome this situation, Fuji Electric has developed a simulation technology for power electronics equipment based heavily on device simulations. By using this technology, it is possible to assess efficiency and size of the power electronics unit in the very early stages of development, and this makes it possible to reduce the development period by cutting down on the man-hours needed in creating and evaluating prototypes. (Refer to "Simulation Technology for Power Electronics Equipment" on page 63.)

### 3.4 Globalization and international standards

Power electronics equipment developed for the global market must be compliant with international standards. It is becoming more common to establish compliance with the UL standard in the United States and EMC requirements for the CE marking in Europe. In addition to these, the functional safety standard (IEC 61508) has become a very important standard in recent years, and it is going to be a critical requirement in meeting the efficiency regulations of motors and inverters. In particular, compliance with functional safety regulations is not limited to the assessment of technology and quality of individual products, but also relates to the development processes of such products.

In order to conform to international standardization of products, Fuji Electric promotes improvements in its own technology development and in-house systems so as to comply to the regulations of standards before they come into effect, and by doing this, we are working to provide compliant products and services even before enforcement of regulations begin. Furthermore, we have established targets and are promoting activities to strengthen the contributions of human resources in international standardization activities such as deliberation on standards creation in IEC.

## 4. Product Development

### 4.1 SiC applicable products

In concert with putting SiC power device to practical use, we started out by equipping 200-V series and 400-V series general-purpose inverters with a hybrid module consisting of Si-IGBT and SiC-Schottky barrier diode (SiC-SBD)<sup>\*5</sup>. After this, we have introduced a power conditioning sub-system (PCS)<sup>\*6</sup> for mega solar mounted with a 1,200-V withstand-voltage All-SiC module, as well as a 690-V series inverter equipped with a 1,700-V rated voltage SiC hybrid module (see Fig. 3). Following this, we worked to expand the voltage class and current capacity of our SiC power devices, while also promoting development for expanding SiC based application technologies and applicable products.

#### \*5: SBD

This is an acronym for Schottky barrier diode. This diode has rectification characteristics utilizing a Schottky barrier that is created by bonding metal with a semiconductor. Because of its excellent electrical properties, application of SiC-SBDs for free wheeling diodes is becoming popular. Compared to PIN diodes that use minority carriers, SBD, which has fast reverse recovery and low reverse recovery loss, must operate

via the usage of majority carriers.

#### \*6: PCS

This is an acronym for power conditioning sub-system. This piece of equipment converts power from DC voltage generated by a photovoltaic cell or fuel cell into AC power. In general, it is configured with an inverter for converting DC into AC. It works in order to implement control that maximizes power output according to the output characteris-

tics that photovoltaic cells have toward solar radiation or the operating characteristics of fuel cells. This system also comes equipped with a power failure detection function that prevents electric shock accidents caused by continuous stand-alone use during black-outs, as well as a function that supports continuous operation during short-term voltage drops (instantaneous drop).

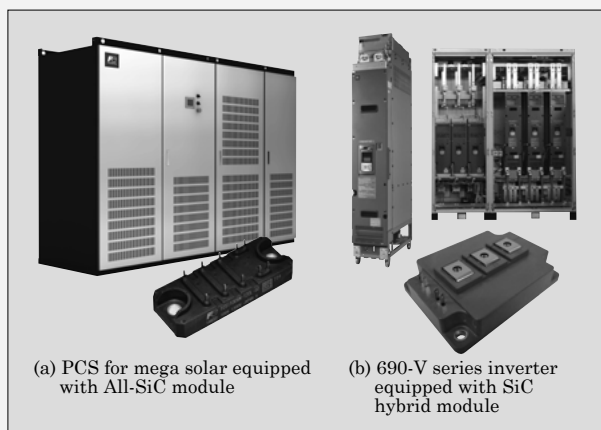


Fig.3 SiC module and SiC module equipped products

#### 4.2 Electromotive power based equipment field

There is a diverse range of product groups for the electromotive power based equipment field, and we have from the very early stages created a development policy based on a platform for developing new products in accordance with market characteristics. This has allowed us to speed up the development of products, and thereby, release them earlier to the market. The “FRENIC-HVAC/AQUA Series” has been released as a solution to air conditioning and pump applications that require usage without a storage panel, which is quite common in the North American and Asian markets. The series is characterized by being compatible with IP55 [Supplemental explanation 4], which has enhanced the dust-proof and waterproof structure. We have developed a stack-type inverter as a product model suited for markets that are expected to grow in the future, such as those for cranes, molding machines and automatic testing machines. (Refer to “690-V Inverters Equipped with SiC Hybrid Module ‘FRENIC-VG Stack Series’” on page 27.) In addition, we have developed products equipped with SiC power devices and expanded our series of medium-voltage inverters so that we can continue to offer optimized solutions based on the various application and usage environments of our customers.

Multi-language display functionality for the operation panel of products has become an indispensable feature of products developed for the global market. As such, our products make it easy to display several different languages by simply downloading language data, created by a personal computer based language creation tool, to the operation panel.

Furthermore, we have also released the “FRENIC-Ace Series” equipped with customized logic functions that support our customers’ various application needs in plant facilities and processing machines. Customers are able to make their own inverter control programs based on their applica-

tion needs by themselves. As a component that facilitates programming, the unit comes equipped with a wealth of logic timers, an analog computing unit and digital/analog mixed components. (Refer to “General-Purpose Inverters Meeting Global Standards ‘FRENIC-HVAC/AQUA Series’ and ‘FRENIC-Ace Series’” on page 22.) In future models, we are also planning on improving convenience by diversifying the types of components and expanding the maximum number of steps.

We are working to promote compliance with the functional safety standard (IEC 61508), which aims at ensuring safety in equipment and systems, and in this respect, we have developed an inverter compatible with safety integrity level (SIL) 3 [Supplemental explanation 5], which is the standard for representing the safety performance of a system. We improved the probability in diagnosis and enhanced the development process at the time of moving up to SIL3 from SIL2. In the future, we plan to further expand our safety-function compatible models, as well as introduce safety bus compatibility.

#### 4.3 Rotating machine field

In overseas markets, emphasis is placed on the efficiency class of single motors that is regulated by IEC standard. In North America, most motors are of the IE2 (high efficiency) and IE3 (premium efficiency) class, and even in Europe, the IE2 class has been gaining popularity. In Japan, emphasis has been placed on the efficiency of the system in combination with an inverter. As a result, most motors are of the IE1 (standard efficiency) class, while the IE2 and IE3 classes have lacked popularity. Fuji Electric has developed an IE3 compatible “Premium Efficiency Motor” based on the Top Runner Program. (Refer to “Fuji Electric’s Top Runner Motor—Loss-Reduction Technology of ‘Premium Efficiency Motor’” on page 31.)

Inverter control for conserving energy in air-conditioning systems has been increasing in demand, and as a result, securing inverter installation space has become an issue. Fuji Electric has been working to develop an inverter equipped motor based on the synergy of our specialized power semiconductor technology and power electronics technology. (Refer to “Inverter-Integrated Motor” on page 36.)

#### 4.4 Transportation equipment field

In the field of equipment to be mounted on rolling stock, the demand for small and lightweight equipment that can be mounted on moving objects has become one of the most important issues.

The traction converter<sup>7</sup> of the propulsion system for Shinkansen (bullet) trains is always an application for which the most advanced tech-

nology available is needed. The newest series of Shinkansen trains operated by Central Japan Railway Company is the N700A model, and it has achieved higher efficiency and a lighter weight by utilizing a low-loss snubber-less system, while also achieving a smaller and more lightweight design for the traction converter with a traveling wind self-cooling (blower-less) system. Compared to the Series 300 Shinkansen train, cubic volume has been reduced 42% and weight by 59%.

Increased compactness and lightweight features are also being required for the auxiliary power unit<sup>\*7</sup>, which converts high-voltage power received from feeding system such as overhead lines or third rail in order to supply low-voltage power to on-car equipment such as the air conditioning and lighting systems. Up until now, it has been common to adopt a system to supply power that uses a transformer to insulate the power of the commercial frequency output from the converter in the auxiliary power unit. Fuji Electric has made full use of its power electronics technology to develop an auxiliary power unit based on a medium frequency link technology with a medium frequency transformer to insulate medium frequency AC power of the kHz order, and then convert this to the commercial frequency and DC power so that it can be supplied. This unit has achieved significant compactness and weight reduction improvements (see Fig. 4).



Fig.4 Auxiliary power unit with medium-frequency link

The field of rolling stock is one of the most highly anticipated fields with regards to the practical use and popularization of SiC power devices. Fuji Electric is carrying out development work to meet the expectations of miniaturization and weight reduction improvements of cooling structures through the reduction of generated loss, as well as the size and weight reduction improvements of filter reactors and insulation transformers through increase of switching frequency. (Refer to “Technologies to Reduce Size and Weight of Power Electronics Equipment for Rolling Stock” on page 41.)

In the field of electrical driven doors for rolling stock, we have, in addition to our service-proven linear motor driven door, developed and released a door equipped with a rotary type flat motor, Flat Cup Permanent Magnet Motor (FCPM) superior in energy-saving and lightweight features. This door is now available in the Japanese, Southeast Asian and North American markets. The opening and closing operation of doors and maintaining the door at the closed position are directly connected to passenger safety, which is considered to be of the highest importance for the electrical driven doors of rolling stock. Fuji Electric has been offering highly reputable and industry recognized doors to overseas markets, especially the North American market, and we are working on achieving an even higher level of safety, while conforming to international and regional standards. (Refer to “Latest Trend and Safety and Reliability Technology of Rolling Stock Doors” on page 45.)

#### 4.5 Power supply equipment field

In the field of power supply equipment such as UPS, reliability and functionality have always been emphasized, but in recent years high efficiency and energy savings have become the most important need. Fuji Electric has utilized its control technology and newest technology, which combines the latest device technology and circuit technol-

#### \*7: Traction Converters and Auxiliary Power Units

In the field of electrical rolling stock, equipment is sometimes labeled according to its application, with equipment related to the propulsion system of the rolling stock being indicated by the Japanese character for “main” and equipment used for other purposes being indicated by the characters for “auxiliary”. In trains that utilize an inverter drive system, such as the Shinkansen train, the traction motor used for propelling the train is called the main motor, and the converter and inverter used to drive the traction motor is called the main converter. Furthermore, the converter, which converts the high-voltage power received from over-

head lines or third rail into a commercial frequency low-voltage power used in the air conditioning and lighting equipment of the train, is an independent piece of equipment, but in order to distinguish it from the traction converter for propulsion system, it is referred to as the auxiliary power unit.

#### \*8: RB-IGBT

This is an acronym for reverse-blocking insulating gate bipolar transistor. It is also called a reverse blocking IGBT. It is an IGBT that has blocking voltage in the reverse direction (between the emitter and collector). Regular IGBT devices do not have blocking voltage in the reverse application direction, and they need to insert a diode.

In contrast, the RB-IGBT has the blocking voltage of the same level as the forward direction, and it does not require a diode.

#### \*9: New 3-Level Inverter

Three-level power conversion represents one of the new types of multi-level conversion circuits that greatly reduce the power loss of the power converter. Advanced T-type neutral-point-clamped (AT-NPC) new 3-level inverter uses this 3-level power conversion method. For more details, refer to “3-Level Power Conversion” on page 71 [Supplemental explanation 6].



ogy in devices such as the reverse-blocking IGBT (RB-IGBT)\*<sup>8</sup> based advanced T-type neutral-point-clamped (AT-NPC) new 3-level inverter\*<sup>9</sup>, to supply the market with highly efficient and space-saving products.

Large-capacity UPS for the North American market are highly efficient, utilizing Fuji Electric's originally developed RB-IGBT. The small size of the UPS footprint is in the top class, and the units are characterized as having high medium-load efficiency when operating in practical-use regions. (Refer to "Large-Capacity, High-Efficiency 3-Level UPS for North America '7000HX-T3U'" on page 17.)

Our All-SiC module equipped PCS are highly efficient and we have achieved a smaller unit size by optimally utilizing the current and voltage ratings of the power devices. Furthermore, it is now possible to send 1 MW class units as a single integrated unit, whereas in the past we needed to send the unit in sections and then re-assemble them at on-site facilities. By doing this, we have streamlined overall costs including those for installation. (Refer to "Mega Solar PCS Incorporating All-SiC Module 'PVI1000AJ-3/1000'" on page 11.)

In addition, we have been promoting the use of a platform that facilitates the quick development and

supply of products that meet customer needs.

## 5. Postscript

This paper outlined the situation and trends surrounding power electronics, as well as described Fuji Electric's power electronics technology and the state of its applicable product development.

Power electronics have undergone a dramatic evolution with the advance of power devices that make up main circuits as well as control devices such as microprocessors. SiC have become increasingly practical, and it is expected that it will be a key device in creating the next technological revolution. At the same time, the trend in globalization is represented in international standardization, and we believe that standards have the hidden potential for revolutionizing a concept for power electronics technology, as well as business models.

Fuji Electric will continue to offer products and services that meet the diverse needs of society so that we can help build an environmental-friendly and prosperous society.

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For "Supplemental Explanation 1 to 5" in this paper, refer to "Supplemental Explanation" on page 68 to 70.



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