Mega Solar PCS Incorporating All-SiC Module "PVI1000AJ-3/1000"

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ABSTRACT

In recent years, solar power generation has come to need greater power generation performance. Power conditioning sub-systems (PCSs) are the core of the generation, and they require high efficiency, reliability to continue to generate electricity, and a reduction of total cost. Fuji Electric has developed a highly efficient PCS for mega-solar plants by incorporating an All-SiC module consisting of silicon carbide metal-oxide-semiconductor field-effect transistors (SiC-MOSFETs) and SiC Schottky barrier diodes (SiC-SBDs), which are the next-generation semiconductors.

1. Introduction

The steady growth in energy demand worldwide has been a factor in big environmental problems such as CO_2 based global warming, and to counter this trend, renewable energy sources, such as photovoltaic cells, have been gaining wider adoption. The "Feed-in Tariff Scheme for Renewable Energy," which was in enacted in Japan in 2012, has created a construction boom for commercial-use photovoltaic power generation stations, also known as mega solar*1. There has also been a growing demand for larger-capacity power conditioning sub-systems (PCSs) in order to realize reduced prices and higher efficiency for power equipment.

In order to correct the voltage fluctuation of photovoltaic cells in residential-use PCS and traditional small- and medium-sized PCS, power conversion is performed twice by means of a configuration composed of a booster circuit equipped with a silicon insulated gate bipolar transistor (Si-IGBT) and an inverter circuit that converts the boosted DC voltage into AC. Since photovoltaic cells produce a high output voltage in the winter when the surface temperature of photovoltaic panels is low and a lower output voltage in the summer when the surface temperature is high, a booster circuit needs to be utilized to maintain a consistent output voltage.

On the other hand, in order to avoid increases in loss by performing power conversion twice, equipment for the PCS for mega solar is generally configured so as to maximize the power generation efficiency of the PCS near the lower limit of the output voltage of photovoltaic cells without the use of a booster circuit. As a result, a situation of uneconomic usage occurs since inverter efficiency decreases between autumn and spring when the output voltage of photovoltaic cells is high.

Therefore, an All-SiC module for the DC booster circuit has been utilized, as well as a reverse-blocking IGBT (RB-IGBT) 3-level power conversion circuit for the inverter, which performs DC-AC conversion. This type of PCS corrects the voltage fluctuation of photovoltaic cells with high efficiency, while enabling high-efficiency inverter operation throughout the year. The All-SiC module that utilizes silicon carbide metal-oxide-semiconductor field-effect transistors (SiC-MOSFET) and SiC Schottky barrier diodes (SiC-SBD), which are the next-generation semiconductors developed under the joint efforts of Fuji Electric and

Fig.1 "PVI1000AJ-3/1000"

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*1: Mega solar refers to a large-scale power station in excess of 1 MW according to the facility-certified power generation scale.

the National Institute of Advanced Industrial Science and Technology. This paper describes the features of the mega solar PCS incorporating an All-SiC module "PVI1000AJ-3/1000" (see Fig. 1).

2. PCS Related Issues

Up until now, power stations have often been set up utilizing a design that configures the total output power of photovoltaic panels and the amount of power capable of being generated by PCS so that they are on the same level. However, feed-in tariff schemes for renewable energy, which are being enacted in countries such as Japan, have facilitated cost reductions in photovoltaic panels, and as a result, there has been an increasing number of power stations that generate power at 1.2 to 1.4 times the generating capacity of PCS by increasing the number of photovoltaic panels arranged in parallel as a method of increasing the capacity factor. In this type of power station, photovoltaic panels produce more power by operating in a state in which current is lower and voltage is higher than the optimal operating point. As a result, a PCS is required that can perform high-efficiency power conversion at a voltage higher than the optimal operating point.

In general, a PCS supplies power to systems by implementing maximum power point tracking control (MPPT control) to control DC voltage and current so that power can be generated at the optimal operating point based on the output characteristics of the photovoltaic panels. When the power generation capabilities of photovoltaic panels and PCS are the same, maximum generating power occurs during the day when sunshine is the strongest. On the other hand, increasing (i.e., accumulation of) the number of photovoltaic panels arranged in parallel creates a situation in which power generation capabilities are higher than the maximum power generation of the PCS. The output characteristics and accumulation of photovoltaic panels in such a case are shown in Fig. 2. Furthermore, maximum generating power would be attained earlier than the time of the day when sunshine is the strongest (see Fig. 2 (a)). By accumulating a large number of photovoltaic panels, the amount of daily power generation can be increased by extending the period in which maximum power can be generated. Photovoltaic panels are in a state of open-circuit voltage V_{oc} early in the morning before power generation begins. Since MPPT control causes operation to move away from V_{oc} and toward the optimal operation voltage V_{pm}, photovoltaic panels enter an operating state that is always higher than the optimal operating point. (see Fig. 2 (b)).

The converter experiences 2 types of loss, namely, conduction loss and switching loss. For the inverter circuit, switching loss is increased in proportion with the DC intermediate voltage of the inverter. Since conduction loss does not change when the output voltage and current for the inverter are the same, switching loss increases and conversion efficiency decreases as the DC intermediate voltage increases. Up until now, PCS for mega solar have suffered from the problem of decreased efficiency as a result of inverter-only conversion. This is due to several factors including the following: direct connection of the output of photovoltaic panels has often been made to the DC intermediate of the inverter circuit; accumulation of more photovoltaic panels creates more opportunities to generate power at a voltage higher than the optimal operating point of the photovoltaic panels; and there is a voltage increase, including open-circuit voltage and optimal operating voltage, for the photovoltaic panels between autumn and spring when daytime temperatures are not very hot.

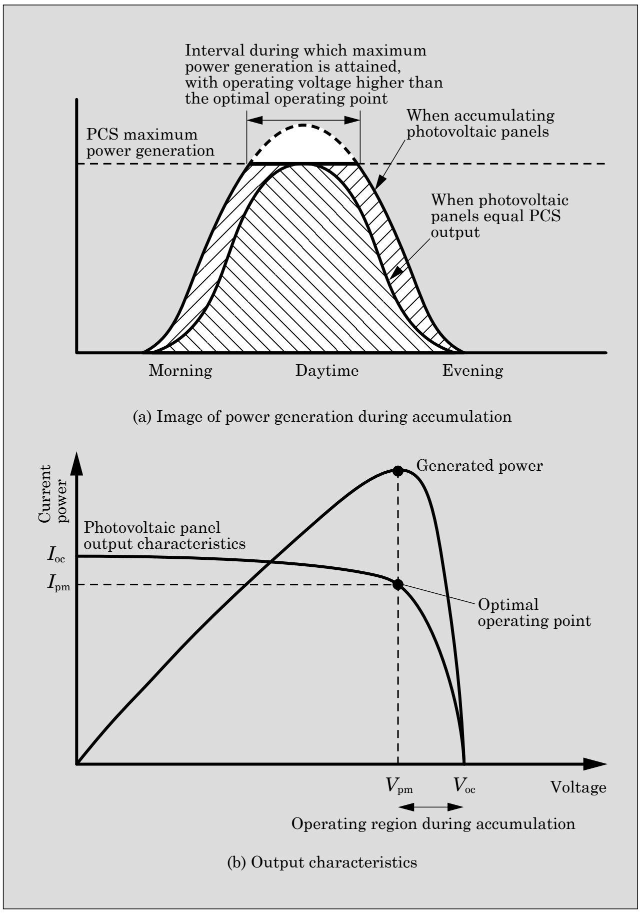

Fig.2 Accumulation of photovoltaic panels and output characteristics

3. Features of the "PVI1000AJ-3/1000"

There is an increasing demand for highly reliable PCS capable of continuous power generation, without bringing about significant losses to power generation businesses, which include the issues mentioned in Chapter 2. Therefore, the following 3 features are required of PCS.

(a) High efficiency (higher than optimal operating

point)
(b) Low total cost
(c) High reliability (power generation continuity)

The PVI1000AJ-3/1000 is a PCS for mega solar that achieves all of these.

3.1 High efficiency

The unit has utilized a booster circuit to raise equipment efficiency in relation to the accumulation of photovoltaic panels. If there is no change in the load for the booster circuit, a low DC input voltage for the booster circuit will create conduction loss and switching loss, but since there is a decrease in current when there is an increase in voltage, there will also be a decrease in conduction loss and switching loss. By optimizing the relationship between loss characteristics and inverter efficiency in the boosted state, the equipment is characterized as having increased efficiency in proportion with increases in the DC input voltage. The DC input voltage of the booster circuit corresponds to the output voltage of photovoltaic panels, and as a result, it is possible to apply this characteristic to the accumulation of photovoltaic panels and seasonal changes.

The product has raised the efficiency of the chopper by mounting an All-SiC module (see Fig. 3) on the booster circuit, as well as makes use of an advanced T-type neutral-point-clamped (AT-NPC) 3-level IGBT for the T-type 3-level power conversion circuit of the inverter[1].

A comparison of loss characteristics for PCS (existing models) that do not utilize a booster circuit and PCS that do utilize an SiC booster circuit is shown in Fig. 4. If the sum of the total conduction loss and switching loss of existing models at a 460 V DC input voltage is taken to be 100%, there is no change in conduction loss when the DC input voltage rises to 850 V, but switching loss increases from 40% to 68% and total loss increases to about 128%. In PCS equipped with our newly developed SiC booster circuit, loss increases by about 17 points compared with PCS with no booster circuit when the DC input voltage is 460 V, but when the DC input voltage rises to 850 V, loss improves by

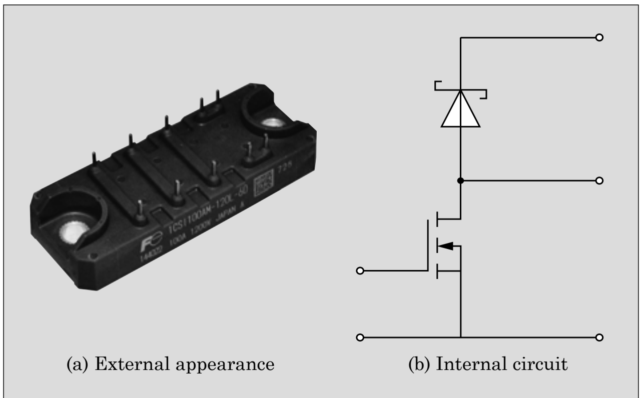

Fig.3 All-SiC module

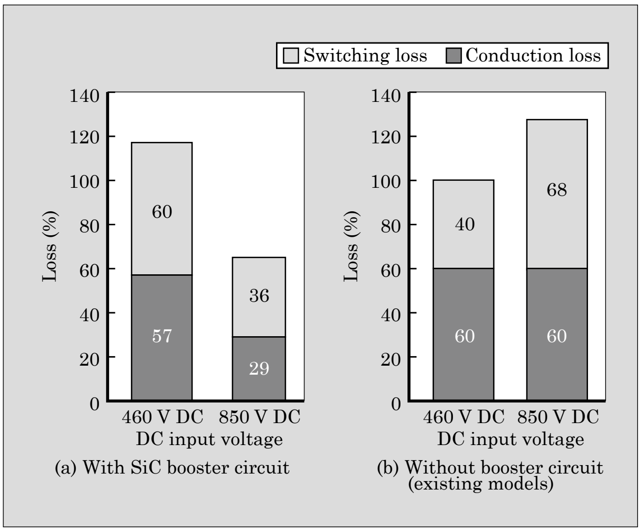

Fig.4 PCS loss comparison

35 points.

As a result, equipment can achieve a maximum efficiency of 98.8% (IEC 61683 efficiency tolerance, not including internal power supply).

3.2 Total cost reduction

Conventional PCS for mega solar have often directly connected the DC voltage of photovoltaic panels with the DC intermediate of the inverter circuit, and as a result, fluctuations in the voltage of the photovoltaic panels would also cause fluctuations in the DC intermediate voltage of the inverter circuit. On the other hand, since the voltage of photovoltaic panels fluctuates between the open-circuit voltage and the optimal operating voltage, the low temperatures in winter months raise the open-circuit voltage, whereas the high temperatures in summer months lower the optimal operating voltage. Therefore, the inverter circuit needs to operate regardless of whether the optimal operating voltage is low or the open-circuit voltage is high.

For example, if the DC intermediate voltage (optimal operating point for photovoltaic panels during summer months) of the inverter is around 340 V, it can only output 200 V (282 V peak) of AC voltage. The output power of the inverter circuit depends on the AC output voltage and current of the inverter, but if the DC intermediate voltage of the inverter can rise from 340 V to about 800 V, the AC output voltage will rise to 400 V, thus enabling output power to achieve a twofold increase using a conventionally used inverter circuit.

Therefore, a booster circuit can be used to increase the DC intermediate voltage of the inverter circuit, and thereby, increase the output voltage and output power of the inverter, which, in turn, improves the capacity factor of the inverter circuit. Furthermore, by increasing the output capacity to 1 MW, total cost reductions can be achieved since it will be possible to reduce the number of PCS used for the mega solar, as well as the amount of equipment used to implement medium-voltage linkage.

3.3 High reliability

The main circuit for the chopper consists of 12 units, each with a 83 kW output. If any of the units fails, the faulty unit automatically shuts down, while operation for the system can continue to operate. This type of functionality improves power generation continuity by making it possible to avoid the complete shutdown of the system. The faulty unit can be identified through the monitoring or main body display screen, and since the system is based on a plug-in design, it is easy to replace the unit and quickly restore full capacity. Furthermore, if a serious failure occurs such as a blown fuse, operation can continue at a degraded level after the faulty unit is removed manually.

3.4 Generated power improvements

(1) MPPT control based on 2 systems

PCS for mega solar have conventionally implemented MPPT control in a collective manner for multiple DC inputs. This product has been designed to improve the amount of power generation by the chopper circuit performing MPPT control for 4 inputs in units of 2 inputs (500 kW).

(2) Rated output power with an output load power factor between 0.9 and 1.0

Increases in power generation through the use of renewable energies, including photovoltaic power generation, can cause fluctuations in system voltage, and as a result, there needs to be a method for properly maintaining the system. In particular, photovoltaic power generation equipment is often installed at locations far away from the area of power consumption, and if the amount of power sent to the system is larger than the amount consumed, it will cause the system voltage to rise. Therefore, in order to suppress increases in distribution system voltage, it is recommended by power companies to suppress the voltage by injecting a reactive power into the system from a PCS. For example, in the case of Fuji Electric's conventional PCS (1,000 kVA, 1,000 kW), if the power factor is 0.9, PCS capacity becomes 1,000 kVA, 900 kW, which means that the rated power of 1,000 kW cannot be output. Our new product enables the suppression of voltage rise in distribution systems without degrading the amount of generated power by setting the output rating at 1,111 kVA, 1,000 kW so that the rated output power can be generated at an output load power factor between 0.9 and 1.0.

3.5 Indoor type structure and miniaturization of equipment

(1) Indoor type structure

When this product is installed outdoors, it adopts an indoor type structure that is used while mounted to a container. By changing the specifications to correspond to the container, the unit is capable of being installed in coastal areas (areas susceptible to salt damage), which is something that was not possible for our outdoor type PCS "PVI1000."

(2) Compact equipment

By integrating the choppers into the unit structure and optimizing the inverter circuit, we have been able to reduce the outer dimensions (footprint) by about 60% compared to installations that adopt 2 of our conventional "PVI750-3/500-T" (500 kW output PCS) units. Interleaved control is possible for each of the chopper units, and the size of the main circuit has been reduced. Furthermore, the switching frequency has been set to 20 kHz in consideration of balancing switching loss[2]. These enhancements have decreased switching ripple, and we have achieved compact size for the chopper unit by reducing the size of the filter.

3.6 Specifications

Table 1 lists the specifications for the PVI1000AJ-3/1000. The DC voltage range corresponds to 1,000 V DC, and the maximum power point tracking range at rated output is 460 to 850 V. The AC output voltage is 480 V, and the interconnection transformer increases the system voltage at each site.

Table 1 "PVI1000AJ-3/1000" specifications

Item	Specification
Output capacity	1,111 kVA/1,000 kW
DC voltage range	450 to 1,000 V
MPPT range	460 to 850 V
Maximum input current	2,440 A
AC voltage	480 V (±10%)
Frequency	50/60 Hz
Power factor	0.9 to 1.0 (rated output) 0.8 to 0.9 (output reduction)
Harmonic distortion rate	5%
Maximum efficiency	98.8%
EURO efficiency	98.5%
External dimensions	W2,980 × D900 × H1,950 (mm)
Mass	2,850 kg

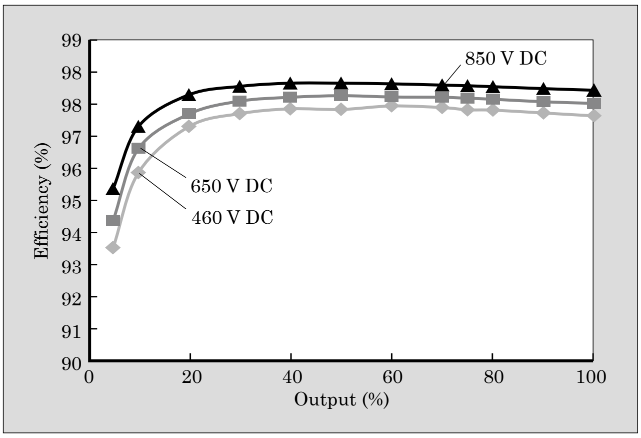

Fig.5 Efficiency curve

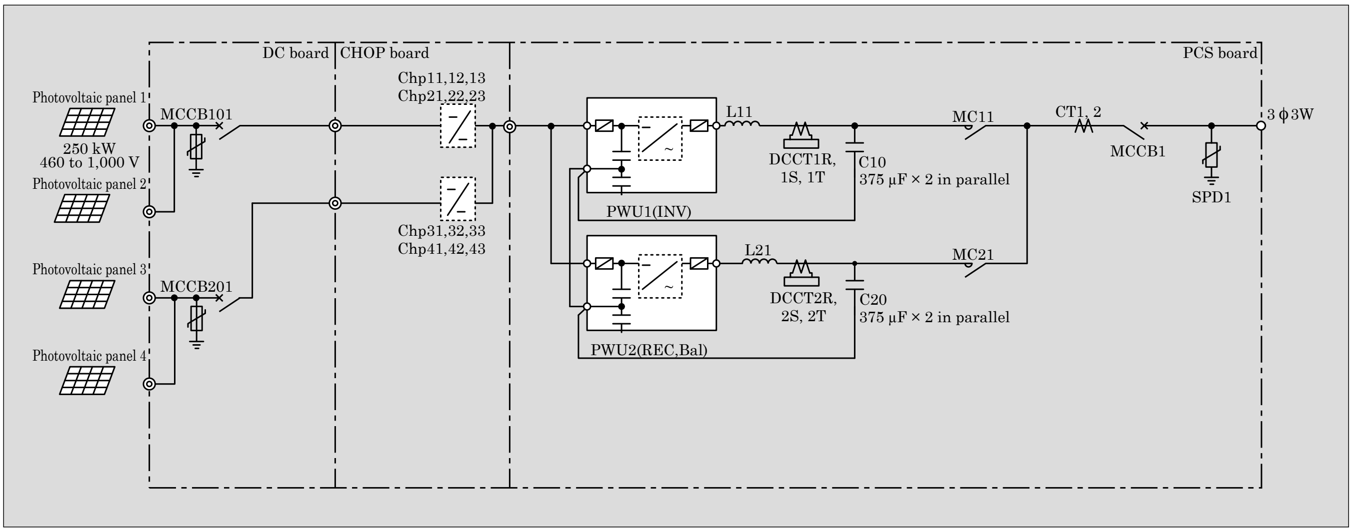

Fig.6 “PVI1000AJ-3/1000” circuit configuration

Maximum efficiency is 98.8% and EURO efficiency (stipulated in the European Union as being closer to actual operation efficiency) is 98.5% when the DC voltage is 850 V. The relationship between output power and efficiency is shown in Fig. 5. Efficiency increases as the input voltage rises.

3.7 Circuit configuration

The circuit configuration for the PVI1000AJ-3/1000 is shown in Fig. 6. It consists of twelve 83 kW chopper units and two 500 kW inverter units. The figure shows a set up of 4 circuits for the DC input, but an optional DC input panel makes it possible to have up to 24 circuits.

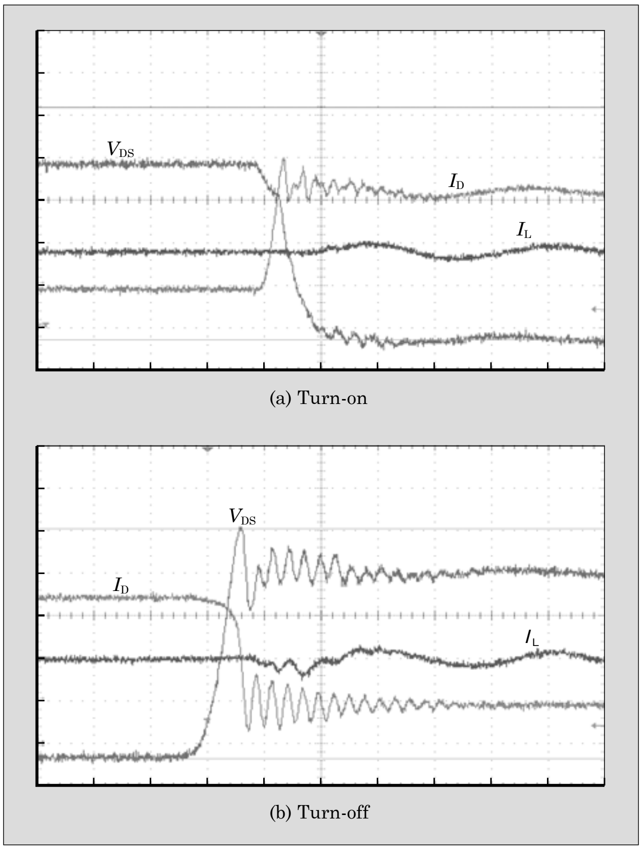

Fig.7 SiC-MOSFET switching waveform

3.8 Reduced induction

Since the All-SiC module eliminates the need for the bonding wire between the chip and the terminal[(3)], inductance is lower than previous models. Furthermore, a printed circuit board is used to configure the main circuit terminal, and this has a lower inductance than screw terminal type connection methods. These enhancements make switching speed faster than previous models, while also suppressing bouncing voltage during turn-off. The switching waveform of the SiC-MOSFET with a DC voltage of 850 V and switching current of 100 A is shown in Fig. 7. Turn-off time is within 100 ns, which is less than 10% of that of Si-IGBT as a result of reduced induction, and bouncing voltage is on the same level as Si.

4. Postscript

The “PVI1000AJ-3/1000”*2 achieves high-efficiency power generation as the first PCS for mega solar to utilize an All-SiC module. This PCS is optimized for mega solar, reducing system costs through its single-unit high capacity, while also increasing the environmental resistance of the unit through the use of a storage container.

In the future, we will continue to work to develop products with higher efficiency and capacity in order to contribute to the realization of a low-carbon society.

*2: “PVI1000AJ-3/1000” is eligible for the “FY2015 (64th) Electrical Industry Technology Achievement Award” of the Japan Electrical Manufacturers’ Association

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