3.3-kV All-SiC Module with Trench-Gate MOSFETs for Electric Distribution Equipment

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ABSTRACT

Fuji Electric has participated in the project of the New Energy and Industrial Technology Development Organization (NEDO) and is developing electric distribution equipment and control systems to stabilize the power grid when the massive introduction of distributed energy sources, such as photovoltaic power generation. In this regard, we have developed a 3.3-kV All-SiC module equipped with SiC trench-gate MOSFETs for electric distribution equipment. The module reduces inverter loss by 60% and achieves higher power density compared with modules equipped with conventional SiC planar-gate MOSFETs.

1. Introduction

To cope with environmental problems such as global warming, emission of greenhouse gases such as CO_2 needs to be reduced. To realize this task, it is necessary to aggressively utilize renewable energy and save energy on power electronics. A power semiconductor plays an important role in power conversion of power electronics. Conventional mainstream silicon (Si) devices have been improved, but they are currently approaching the performance limit based on physical properties. Under such circumstances, a silicon carbide (SiC) device, which is a next-generation semiconductor realizing even greater reduction in power dissipation, is expected to contribute to size reduction and weight saving of power electronics.

Since September 2014, Fuji Electric is working on the "Demonstration Project for Constructing a Distributed Energy Next-Generation Electric Power Network" as a project of New Energy and Industrial Technology Development Organization (NEDO). We have been developing the next-generation voltage regulator (power distribution devices), such as a static var compensator (SVC) that utilizes a SiC power semiconductor, and control systems to expand the adoption of renewable energy like photovoltaic power generation and to maintain and improve Japan's international competitiveness in the electric power equipment and systems industry.

2. All-SiC Module for Power Distribution Devices

In the "Demonstration Project for Constructing a Distributed Energy Next-Generation Electric Power Network" of NEDO, we are developing power distribution devices and control systems that deal with many technical challenges such as generation of surplus power, insufficient frequency trimming, and voltage increase in power distribution lines, which are caused when distributed energy such as photovoltaic power generation is largely adopted to distribution systems (see Fig. 1). Particularly in Japan, when the introduction amount of photovoltaic power generation of ordinary homes becomes larger than it is currently, there would create challenges such as power loss caused by reverse power flow at the time of voltage increase in 6.6-kV distribution systems and output suppression of

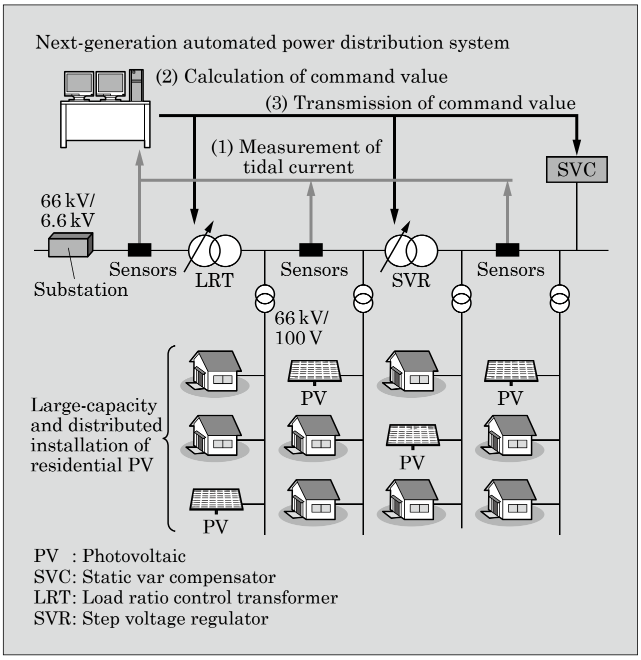

Fig.1 Outline of "Demonstration Project for Constructing a Distributed Energy Next-Generation Electric Power Network" of NEDO

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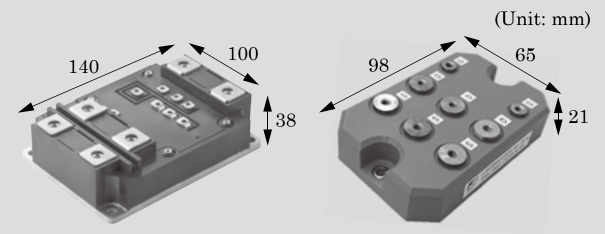
photovoltaic power generation. To solve this issue, it is necessary to adopt power distribution devices such as SVCs and step voltage regulators (SVRs) to regulate voltage of 6.6-kV power distribution systems. The power distribution devices to be adopted must be small and lightweight so that they can be mounted to existing electric poles (single poles) and must be self-cooling because water-cooling and forced air-cooling cannot be supported.

Si power semiconductors dissipate large amount of power and require large heat sink for releasing heat generated in the module. Therefore, it is difficult to develop small and lightweight power distribution devices, and they need to be installed to a frame provided on the dedicated adjacent 2 utility poles[1]. Thus, the power distribution devices are not being adopted very much in terms of installation places and costs. By having an All-SiC power semiconductor module developed in the 2017 NEDO project, power distribution devices became small and lightweight, and they can now be installed on a single pole. High-frequency operation also became available, and it is expected that power distribution devices will be operated at the high-frequency (13 kHz or higher), which is higher than the audible frequency of humans, thus making possible to install in residential areas. In 2017, we developed an All-SiC 200-A 1-in-1 module with a withstand voltage of 3.3 kV for power distribution devices and a SVC equipped with this module[2].

For further size reduction and weight saving of power distribution devices, we are developing modules with larger rated capacity. The package that is being developed is equipped with a SiC trench-gate metal-oxide-semiconductor field-effect transistor (MOSFET) having both low on-state resistance and high-speed switching characteristics. This article describes the structure and characteristics of the All-SiC 400-A 2-in-1 module with a withstand voltage of 3.3 kV that is being developed for power distribution devices (see Fig. 2).

Four 200-A 1-in1 modules are necessary to make the same circuit configuration as the 400-A 2-in-1 module. Compared to this figure, the footprint size of the All-SiC 400-A 2-in-1 module is reduced by 45%.



(a) All-SiC module (2-in-1) with a withstand voltage of 3.3 kV and rated value of 400 A

(b) All-SiC module (1-in-1) with a withstand voltage of 3.3 kV and rated value of 200 A

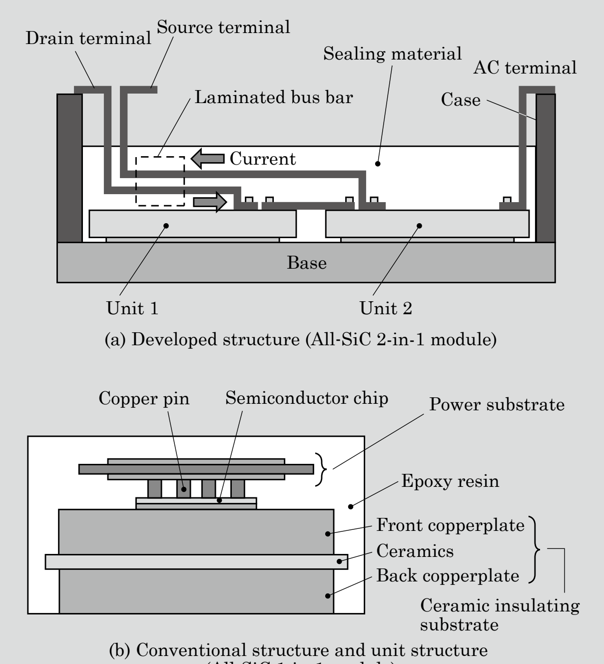
Fig.2 All-SiC module with withstand voltage of 3.3 kV

An All-SiC module is a combination of SiC-MOSFETs and SiC-Schottky barrier diode (SBD) chips. Since the on-state resistance per unit area becomes higher as the withstand voltage becomes higher, an insulated gate bipolar transistor (IGBT) is mainly used for a withstand voltage of 600 V or higher in the case of Si. The on-state resistance of IGBT modules is reduced by conductivity modulation in which positive holes serving as minority carriers are injected into the drift layer. However, accumulation of minority carriers generates tail current at the time of switching, causing large switching loss. On the other hand, SiC has lower drift layer resistance compared with Si devices because of a wide bandgap and can reduce the on-state resistance without conductivity modulation. Therefore, both high withstand voltage and low power dissipation can be achieved with a MOSFET.

The All-SiC 200-A 1-in-1 module developed in 2017 is equipped with SiC planar-gate MOSFETs. To reduce the on-state resistance per unit area of a SiC planar-gate MOSFET, miniaturization of the cell pitch is generally effective. However, excessive miniaturization increases the resistance of the junction field-effect transistor (JFET) and stops the decrease of the on-state resistance. The SiC trench-gate MOSFET can suppress the increase in JFET resistance components due to miniaturization, and thus, low on-state resistance can be achieved.

3. Module Structure

Figure 3 shows the comparison of schematic struc-



(a) Developed structure (All-SiC 2-in-1 module)

(b) Conventional structure and unit structure (All-SiC 1-in-1 module)

Fig.3 Comparison of schematic structures of cross sections of modules tures of cross sections of modules. The All-SiC module with a withstand voltage of 3.3 kV follows the structure of the All-SiC module with a withstand voltage of 1.2 kV for power conditioning systems (PCS) that are being mass-produced(3),(4). The structure of the All-SiC modules is wired with copper pins formed on the power substrate. Thus, a large current can be supplied, enabling high-density mounting of SiC devices. For the insulating substrate equipped with a chip, a high-strength insulating substrate that is made of silicon nitride (Si_3N_4) and has a thick copperplate bonded is adopted to improve the resistance to residual stress of the epoxy resin sealing. Further, epoxy resin is used as the sealing material in the module to suppress deterioration of solder and insulation performance during high-temperature operation. Thus, high reliability is secured. However, increasing the capacity of this module structure caused a problem that the package becomes large because sufficient insulation distance needs to be secured.

Therefore, the developed module has a 2-in-1 circuit configuration that uses a bus bar and has plastic molded units allocated on the base. The module has a laminated structure in which units, a bus bar and the joint part thereof are further sealed with a sealing material. Thus, the capacity of the module has been increased with the insulating property secured without increasing the size of the unit. The module has same appearance as the large capacity power module "HPnC" (High Power next Core) to secure attachment compatibility with modules of other companies(5). For the base material, a composite material of magnesium and silicon carbide (MgSiC) having a low coefficient of thermal expansion and excellent thermal conductivity is adopted to secure high reliability for power distribution devices.

The structure of a laminated bus bar, which is a wiring between units and terminals such as the drain terminal and the source terminal, has the characteristics described below. Thus, the insulation property is secured and the internal inductance of the module is reduced to 10 nH as with the HPnC.

Figure 4 shows the analysis result obtained by simulating the wiring inductance of the bus bar. Points for reducing the wiring inductance are to shorten the current pathways, increase the cross-sectional area of the current pathways, and utilize the mutual inductance. Among these, utilization of mutual inductance is important for package design. The influence of mutual inductance becomes larger as the interval between bus bars is narrower. The influence becomes significant when the interval reaches 3 mm or less. Regarding the developed module, the bus bar between the drain terminal or the source terminal and the unit is further sealed with a sealing material to narrow the interval while securing the insulation property. The directions of currents flowing through the bus bars are caused to face each other, thus realizing the module internal inductance that is equivalent to the inductance of the HPnC.

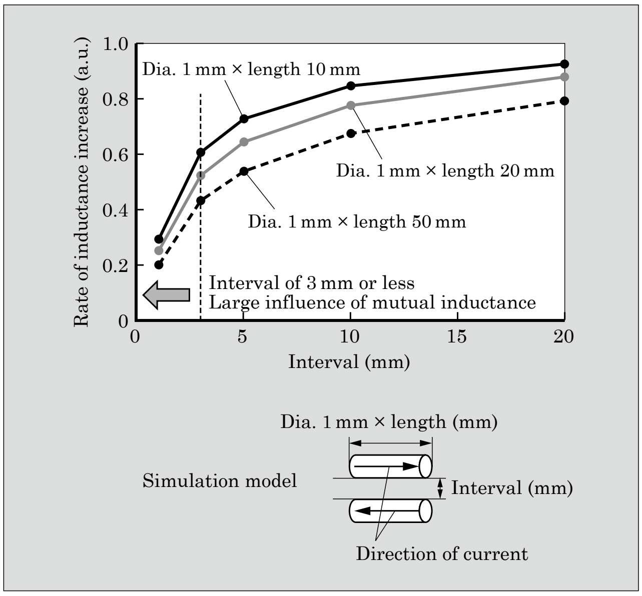


Fig.4 Wiring inductance (simulation)

4. Characteristics

The rated current of the newly developed All-SiC 2-in-1 module with a withstand voltage of 3.3 kV is 400 A, and the module is equipped with SiC trench-gate MOSFETs. Therefore, the characteristics were compared with the characteristics of a 200-A 1-in-1 module equipped with SiC planar-gate MOSFET.

4.1 *I*-*V* characteristics during conduction

The loss generated at the time of module conduction (steady-state loss) is determined by the *I*-*V* characteristics. Figure 5 shows the *I*-*V* characteristics of an All-SiC 400-A 2-in-1 module and an All-SiC 200-A 1-in-1 module at T_{vj} = 25 °C and T_{vj} = 150 °C. The drain voltage of the All-SiC 400-A 2-in-1 module equipped with SiC trench-gate MOSFETs remained equivalent even after the drain current is doubled

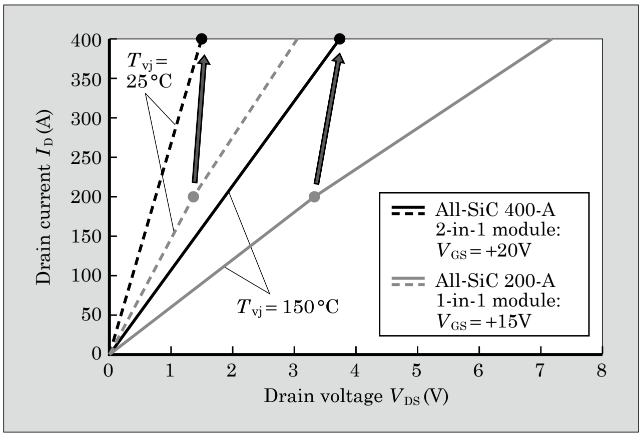


Fig.5 Comparison of *I*-*V* characteristics

at 25 °C and 150 °C when compared with the All-SiC 200-A 1-in-1 module equipped with SiC planar-gate MOSFETs. This is because the SiC trench-gate MOSFET has smaller on-state resistance than the SiC planar-gate MOSFET.

4.2 Switching characteristics

The switching loss can be divided into 3 different types: turn-on loss, turn-off loss, and reverse recovery loss. Figure 6 shows turn-on loss and Fig. 7 shows turn-off loss at T_{vj} = 150 °C. In addition, Fig. 8 shows total switching loss.

With respect to the All-SiC 200-A 1-in-1 module, the turn-on loss and turn-off loss of the All-SiC 400 A 2-in-1 module are reduced when the gate resistance is 4.7 Ω. This reduces the total switching loss by 20%. The SiC trench-gate MOSFET has faster switching characteristics compared with the SiC planar-gate MOSFET; therefore, the total switching loss is low even if the rated current is doubled.

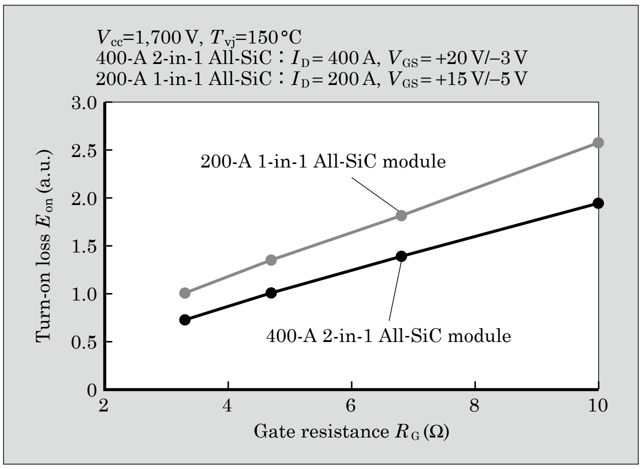


Fig.6 Turn-on loss

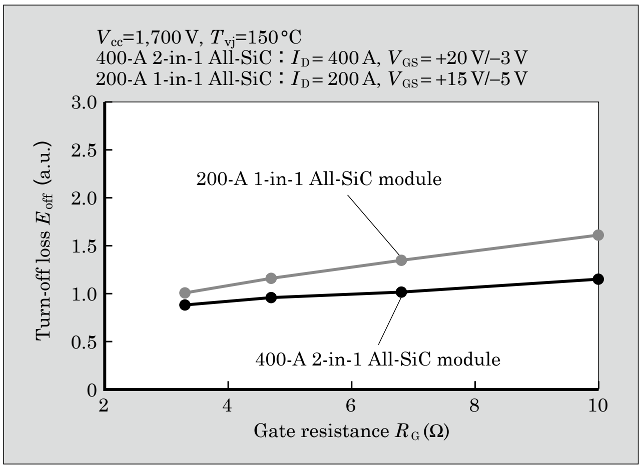


Fig.7 Turn-off loss

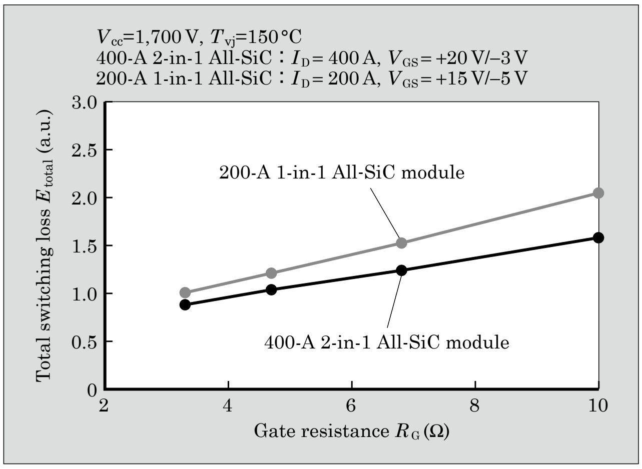


Fig.8 Total switching loss

4.3 Simulation of inverter generated loss

The inverter for the power distribution device SVC that is being developed is a 3-level inverter, and Fig. 9 shows its circuit configuration. Figure 10 shows simulation results of inverter loss of the All-SiC module equipped with SiC trench-gate MOSFET and All-SiC module equipped with SiC planar-gate MOSFETs under the operating condition of the 3-level inverter for a SVC. The loss of the 3-level inverter of the SVC depends more on switching loss than steady-state loss. Therefore, the All-SiC module equipped with SiC trench-gate MOSFETs and having low switching loss showed 60% lower inverter loss at a carrier frequency of 13 kHz with respect to the All-SiC module equipped with SiC planar-gate MOSFETs.

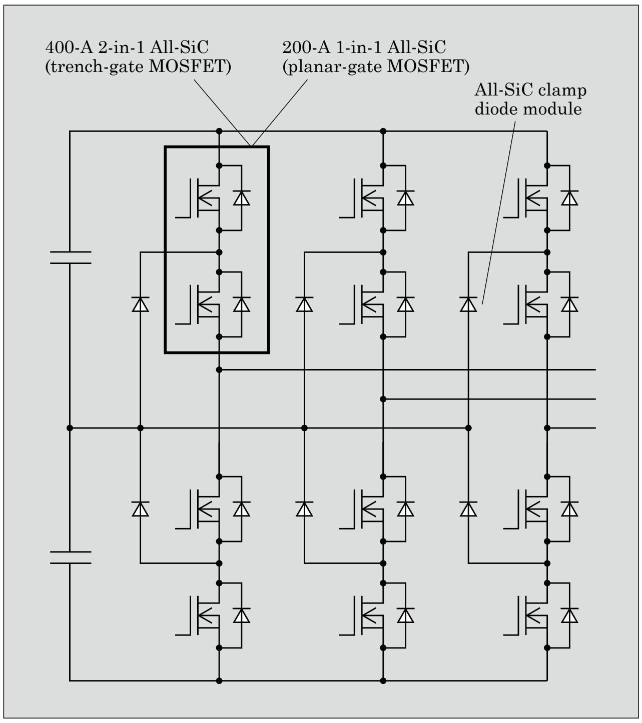


Fig.9 Circuit of 3-level inverter of SVC

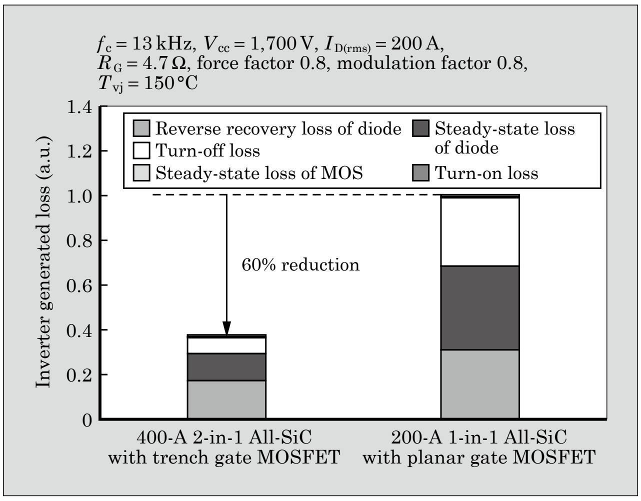


Fig.10 Simulation of inverter generated loss

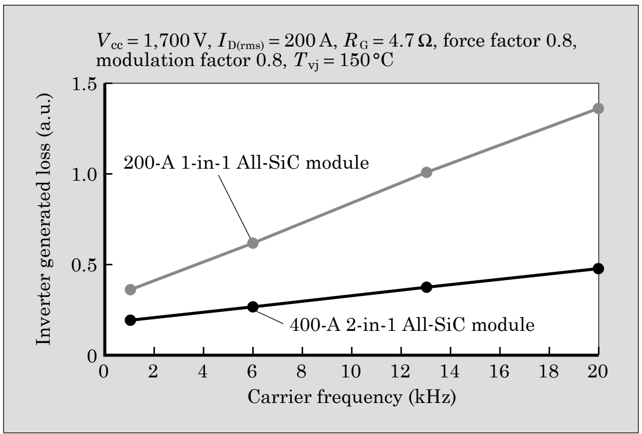


Fig.11 Carrier frequency dependence of inverter generated loss

Figure 11 shows the simulation results of carrier frequency dependence of a 3-level inverter loss. Under the operating condition of the 3-level inverter of a SVC, as the carrier frequency becomes higher, the difference in the generated loss becomes larger between the All-SiC module equipped with SiC trench-gate MOSFETs and the All-SiC module equipped with SiC planar-gate MOSFETs. The result shows that the All-SiC module equipped with SiC trench-gate MOSFETs is superior at a high frequency.

5. Postscript

The 3.3-kV All-SiC module equipped with trench-gate MOSFETs for power distribution devices has been described. The module follows the structure of the All-SiC module with a withstand voltage of 1.2 kV for power conditioners and has high reliability. The module also contributes to the development of small and lightweight power distribution devices SVC that can be self-cooled and mounted on a single pole utilizing features such as low power dissipation and high-frequency drive.

With respect to further size reduction and weight saving of power distribution devices, we will be accelerating the development of large capacity All-SiC modules and contribute to the development of power electronics technology and realization of the low-carbon society.

The results has been obtained from the "Demonstration Project for Constructing a Distributed Energy Next-Generation Electric Power Network" implemented by the New Energy and Industrial Technology Development Organization (NEDO). We would like to express our appreciation to all those involved in this project.

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