3.3-kV All-SiC Modules for Electric Distribution Equipment

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ABSTRACT

Fuji Electric has partnered with the New Energy and Industrial Technology Development Organization (NEDO) in a project to develop electric distribution equipment and control systems that contribute to power grid stabilization when distributed energy sources such as solar power generation are massively introduced. For electric distribution equipment, an All-SiC module with a withstand voltage of 3.3 kV has been developed in that purpose. Compared to conventional Si-IGBT modules, it reduces the generated loss of inverters by 64%. As a result, our electric distribution equipment becomes so small and lightweight that they can be mounted to a single utility pole, which was not possible for conventional Si-IGBT modules due to size restrictions.

1. Introduction

There has been growing demand to reduce emission of greenhouse gases such as CO_2 in order to mitigate global warming. To achieve this, it is necessary to use renewable energies actively and adopt energy-saving power electronics equipment. Playing a major role in power conversion for power electronics equipment is power semiconductors. Up until now, the technological advance of silicon (Si) devices has made them widely popular, but they are already nearing the performance limit of their physical properties. Against this backdrop, it is expected that next-generation silicon carbide (SiC) semiconductor devices will enable even greater reductions in power loss while simultaneously contributing to energy savings and the reduction of size and weight of power electronics equipment.

In September 2014, Fuji Electric began working with the New Energy and Industrial Technology Development Organization (NEDO) in the "Demonstration Project for Constructing a Distributed Energy Next-Generation Electric Power Network." We have been developing next-generation voltage regulators (electric distribution equipment) and applicable control systems such as a static var compensator (SVC) that uses SiC power semiconductors. This development is aimed at supporting the expanded installation of renewable energies such as photovoltaic power generation and also support to maintain and improve Japan's international competitiveness in the electric power equipment and systems industry.

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2. All-SiC Power Semiconductor Modules for Electric Distribution Equipment

In the "Demonstration Project for Constructing a Distributed Energy Next-Generation Electric Power Network" that we have been participating in with NEDO, one of the goals has been to facilitate the large-scale adoption of distributed energy sources such as photovoltaic power generation to electric distribution systems. In this regard, we have been developing electric distribution equipment and applicable control systems to deal with many technological challenges, such as the generation of surplus power, lack of power for frequency adjustment and voltage rise in distribution wires (see Fig. 1). Particularly in Japan, the increased adoption of household photovoltaic power generation would create challenges such as power loss caused by reverse power flow at times of voltage rise in 6.6-kV distribution systems and output suppression of photovoltaic power generation. Therefore, it is necessary to utilize electric distribution equipment for these 6.6-kV distribution systems. In this respect, it would be necessary for them to be compact and lightweight so that they could be mounted to existing utility poles (single poles) and be self-cooling because they would not be able to support water or air based cooling systems.

Electric distribution systems with conventional Si power semiconductor were susceptible to large amounts of loss and required large heat sinks for dissipating heat generated by the module, thus making it impossible to achieve size reductions and weight savings. Therefore, it was necessary to install dedicated infrastructure for double utility poles,[1] and as a result, the adoption of these systems was infeasible due to the problem of installation space and cost factors.

However, size reduction, weight savings and single pole mounting can be achieved for electric distribution

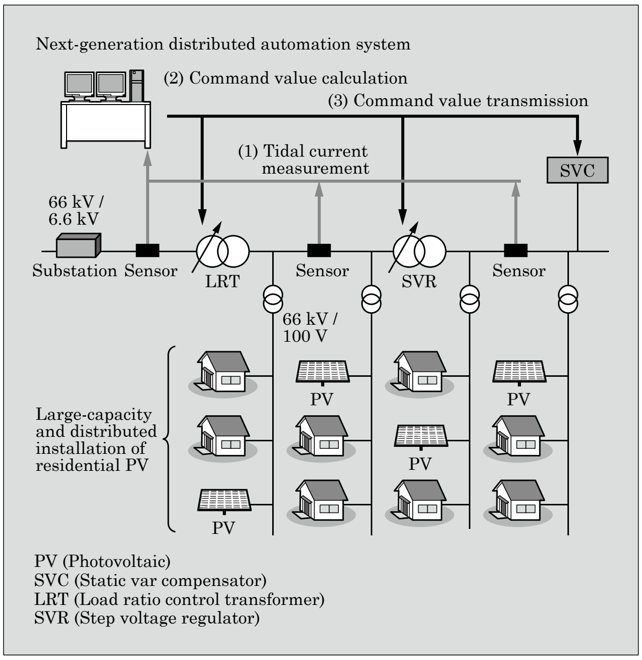

Fig.1 Overview of NEDO's "Demonstration Project for Constructing a Distributed Energy Next-Generation Electric Power Network"

equipment equipped with our newly developed All-SiC power semiconductor modules. Furthermore, they can be operated at high-frequency (13 kHz or higher), which is higher than the audible frequency of humans, thus making it possible to install the equipment in residential areas and accelerate adoption of them. Figure 2 shows the recently developed 3.3-kV All-SiC module for electric distribution equipment and the external appearance of an SVC mounted with the module. This paper describes the structure and characteristics of the 3.3-kV All-SiC 1-in-1 module developed for electric distribution equipment.

The All-SiC module contains SiC metal-oxide-semiconductor field-effect transistor (SiC-MOSFET) and SiC Schottky barrier diode (SiC-SBD) chips. Since

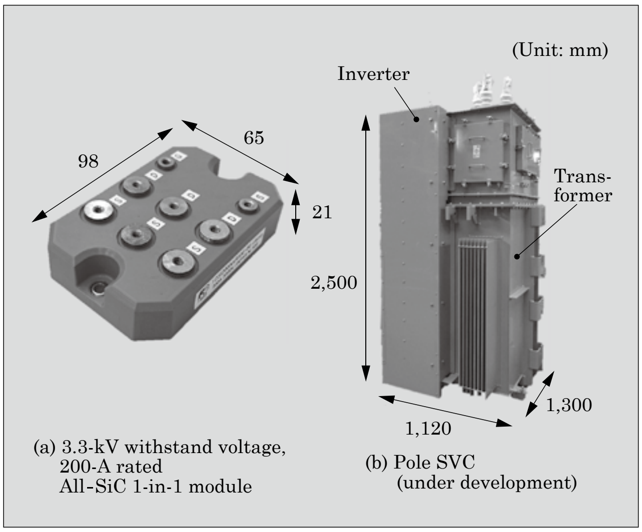

Fig.2 3.3-kV All-SiC module and pole-mount SVC

on-resistance per unit area increases in proportion with increases in withstand voltage, insulated gate bipolar transistor (IGBT) mostly utilized for voltages of 600 V and higher in Si devices. IGBTs reduce on-resistance through conduction modulation that minority carrier holes are injected into the drift layer. However, this also becomes a cause of large switching loss, because tail current occurs during switching due to an accumulation of minority carriers. In contrast, SiC devices exhibit lower drift layer resistance than Si devices, and as a result, are characterized by low on-resistance even without conduction modulation. SiC MOSFETs thereby establish both high withstand voltage and low loss.

3. Module Structure

Figure 3 shows a comparison of the schematic structures of the cross-section of conventional and new modules. The structure of the 3.3-kV All-SiC module follows the design principles for the structure of the 1.2-kV All-SiC module for mass-produced power conditioning systems (PCSs), and thus has a structure that is vastly different from conventional Si-IGBT modules.[(2),(3)] The structure of the All-SiC module utilizes copper pin wiring on the power board instead of the conventional aluminum bonding wire. This enables large current flow and facilitates high-density mounting of SiC devices. The insulating substrate on which the chips are mounted utilizes a high-strength silicon nitride (Si_3N_4) insulating substrate bonded with thick copper plates instead of conventional aluminum nitride (AlN) as a design feature for improving resistance to epoxy resin sealing stress. Furthermore, by adopting epoxy resin

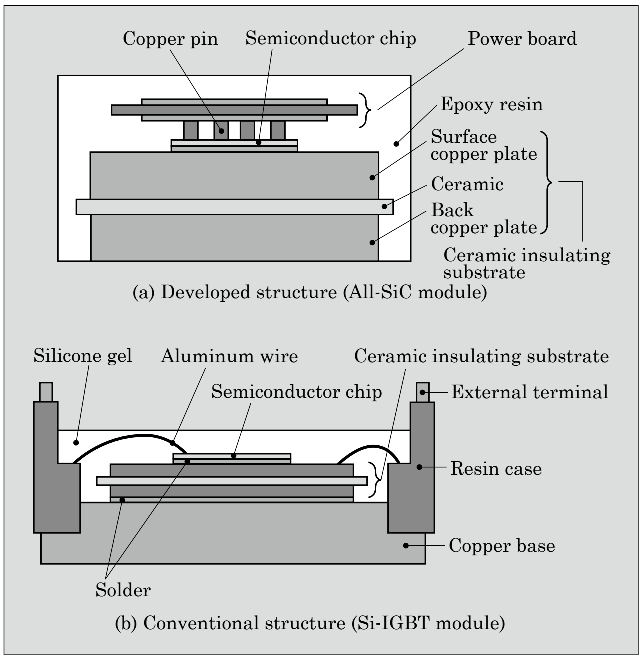

Fig.3 Comparison of modules' cross-sectional schematic structures

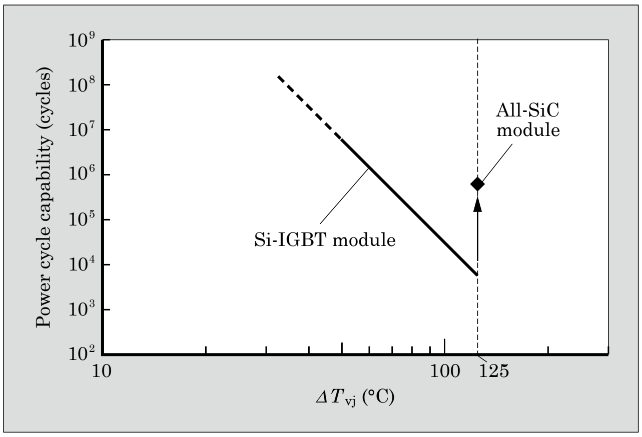

Fig.4 ΔT_{vj} power cycle test results at room temperatures

instead of the conventional silicone gel as the sealing material for the inside of the module, we were able to suppress solder degradation and insulation performance reduction during high-temperature operation while also securing high reliability and achieving weight savings without using a metal base nor case.

Figure 4 shows the results of a ΔT_{vj} power cycle test for the All-SiC module and conventional 3.3-kV Si-IGBT module at room temperature. The All-SiC module exhibited a power cycle capability of at least 120 times greater than that of the Si-IGBT module at ΔT_{vj} = 125°C. Electric distribution equipment is required to have a service life of at least 20 years, which is twice that of general industrial machines, which is 10 years. In this respect, the product has a sufficient power cycle capability to support this requirement.

4. Characteristics

The newly developed 3.3-kV All-SiC 1-in-1 module has a rated current of 200 A. We compared its characteristics with that of a same rated 200-A Si-IGBT 1-in-1 module that we made by replacing the SiC-MOSFETs with Si-IGBTs and the SiC-SBDs with Si free wheeling diodes (Si-FWDs).

4.1 *I-V* characteristics during conduction

The *I-V* characteristics determine the amount of steady-state loss, the loss generated at the time of conduction in the module. Figure 5 shows the *I-V* characteristics of an All-SiC module and Si-IGBT module at T_{vj} = 25 °C and T_{vj} = 150 °C. Compared with the Si-IGBT module, the All-SiC module had a smaller drain voltage by 48% at 25 °C and 20% at 150 °C at a rated current of 200 A. The SiC-MOSFET has lower steady-state loss than Si-IGBT due to the lower on-resistance.

4.2 Switching characteristics

Switching loss can be classified into three different types: turn-on loss generated during turn on, turn-off loss generated during turn off and reverse recovery loss generated during reverse recovery. Figure 6 shows turn-on loss, Figure 7, turn-off loss, and Figure 8, reverse recovery loss at T_{vj} = 150 °C. Similarly, Fig. 9 shows total switching loss.

Compared with the Si-IGBT module, the All-SiC module reduces turn-on loss by 80%, turn-off loss by 78% and reverse recovery loss by 85% when gate resistance is 4.7 Ω. As a result, total switching loss was

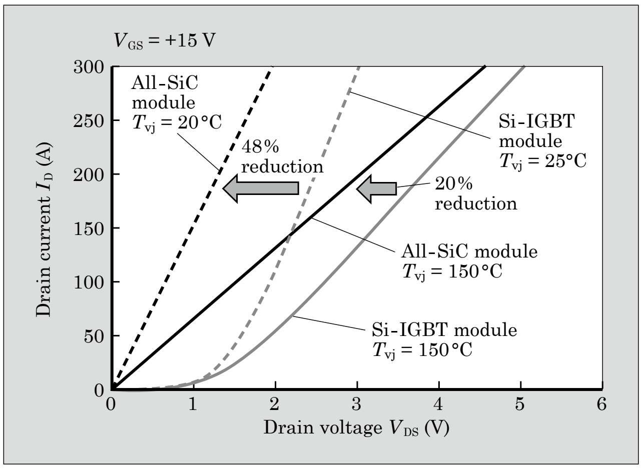

Fig.5 *I-V* characteristics

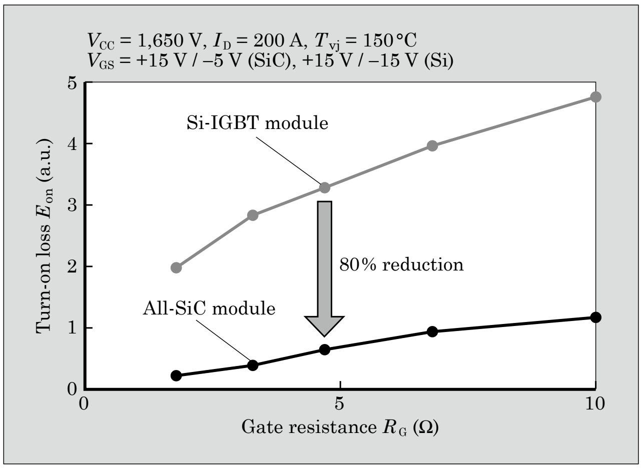

Fig.6 Turn-on loss

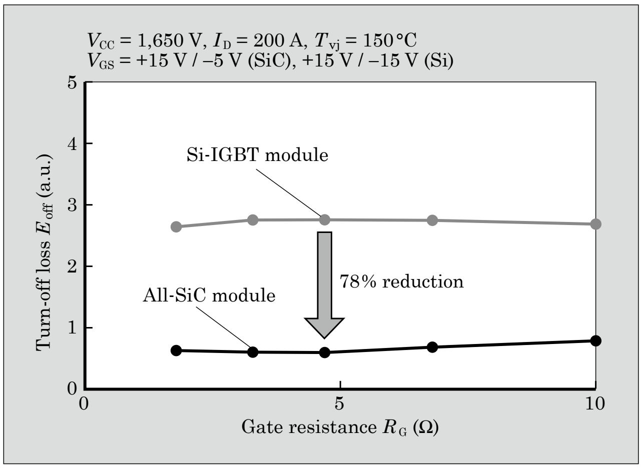

Fig.7 Turn-off loss

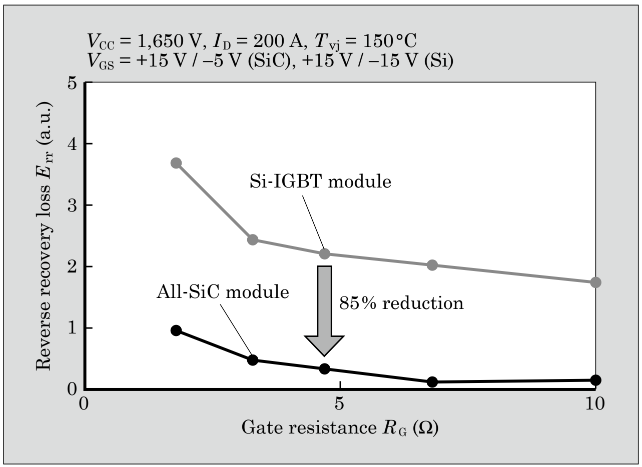

Fig.8 Reverse recovery loss

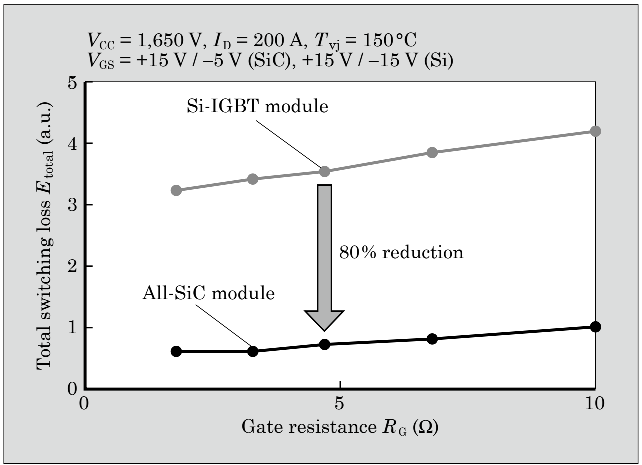

Fig.9 Total switching loss

reduced by 80%.

4.3 Loss simulation of Inverter generated

Figure 10 shows the circuit configuration of the 3-level inverter in the SVC of electric distribution equipment under development. Figure 11 shows simulation results of the inverter generated loss for the All-SiC module and Si-IGBT module under the operating condition of the 3-level inverter for SVC. As the operating conditions of 3-level inverters for SVC, a carrier frequency was set at 13 kHz, which is higher than that generally used for Si-IGBT modules, and thus a steady-state loss occupied only several percent. The inverter generated loss was almost entirely dependent on switching loss. The simulation result showed that inverter generated loss for the All-SiC module was lower by 64% comparing with the Si-IGBT module. This low generated loss resulted in a simplified product design that adopts a self-cooling system for the cooling structure for the SVC inverter while also facilitating size reduction and weight savings and enabling single pole mounting of the distribution system.

Figure 12 shows the carrier frequency dependence for the generated loss of the inverter. Under condi-

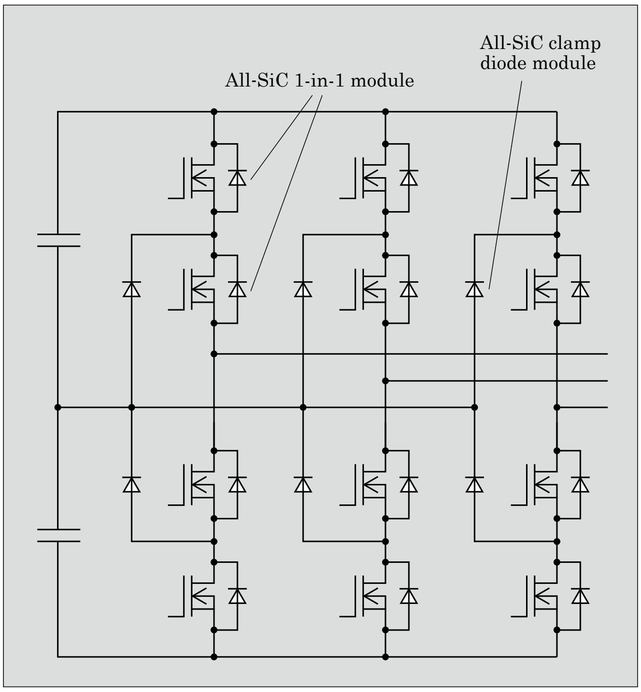

Fig.10 SVC 3-level inverter circuit

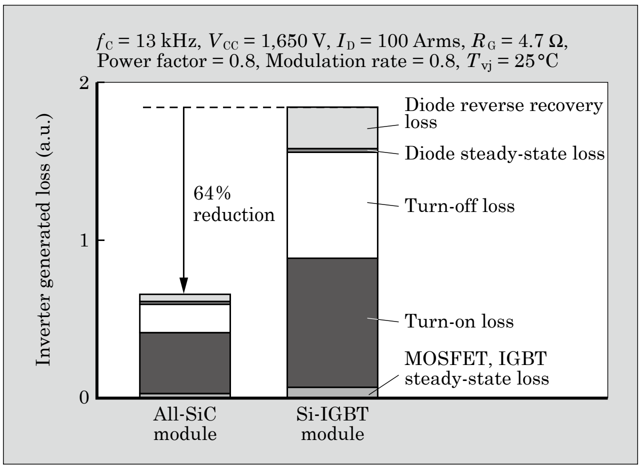

Fig.11 Inverter generated loss simulation

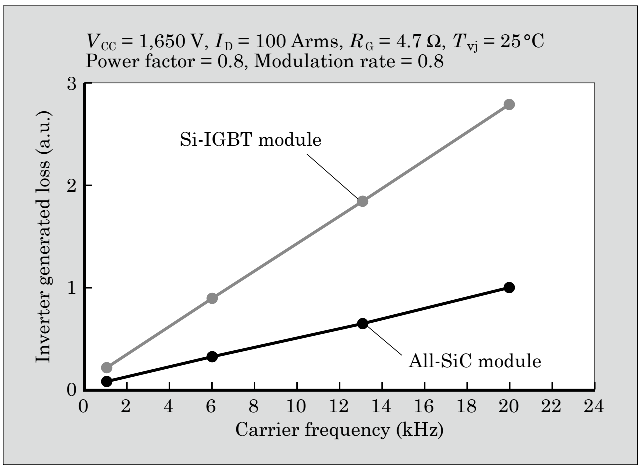

Fig.12 Carrier frequency dependence of inverter generated loss

tions of 3-level inverter operation for SVC, the difference in generated loss between the All-SiC module and the Si-IGBT module grew in proportion with carrier frequency. Based also on this result, it can be said that the All-SiC module is superior when operated at high frequency.

5. Postscript

This paper introduced the 3.3-kV All-SiC modules for electric distribution equipment. This module has high reliability, which follows the design principles of the structure of the 1.2-kV All-SiC module for power conditioning systems. It is characterized by its low loss and high-frequency operation, and those characteristics contribute to the development of smaller and lighter SVC, the electric distribution equipment that can be mounted on a single pole.

We plan to accelerate the development of All-SiC 2-in-1 modules and large-capacity All-SiC modules for rolling stock and achieve even greater size reduction and weight savings in electric distribution equipment so that we can further contribute to the development of power electronics technology and help realize of a low-carbon society.

The content of this paper is based on the results 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 conclude by expressing our appreciation to all those involved in this project.

References

(1) Kojima, T. et al. Distribution Static Var Compensators and Static Synchronous Compensators for Suppressing Voltage Fluctuation. FUJI ELECTRIC REVIEW. 2017, vol.63, no.1, p.36-40.

(2) Nashida, N. et al. All-SiC Module for Mega-Solar Power Conditioner. FUJI ELECTRIC REVIEW. 2014, vol.60, no.4, p.214-218.

(3) Nakamura, H. et al. All-SiC Module Packaging Technology. FUJI ELECTRIC REVIEW. 2015, vol.61, no.4, p.224-227.

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