Energy-Saving Technologies of Power Electronics Using SiC Devices

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1. Introduction

The application of power electronics as a key energy-saving technology is expected to contribute to global environmental conservation. Advances in the performance of power devices has supported the development of power electronics equipment. Currently, the transistors used are mainly insulated-gate bipolar transistors (IGBTs). Silicon carbide (SiC) is a semiconductor material having excellent characteristics as a power device and is expected to be used for next-generation devices following Si. The bandgap of SiC is approximately three times that of Si and its breakdown electric field strength is approximately ten times higher. Mitsubishi Electric Corporation started developing SiC devices in the 1990s and has continuously released SiC products since 2010.

There are two methods for saving energy using SiC devices: One improves the power conversion efficiency by reducing the loss in the power electronics equipment themselves, and the other saves energy by reducing the loss of the entire system including the power electronics equipment. Photovoltaic inverters are a typical example of the former and railcar traction systems are a typical example of the latter. This paper describes SiC products used in these two methods.

2. Characteristics of SiC Devices

In a power electronics equipment, the power device switches the ON and OFF states to convert electric power. In power devices, power is lost during the ON state and during switching. During the OFF state, the voltage of power devices should be maintained at a high level, which is handled by the drift layers. As the withstand voltage of a drift layer increases, the impurity concentration needs to be lower and the thickness needs to be increased. In metal-oxide-semiconductor field-effect transistors (MOSFETs) and other unipolar devices, these are the main elements of the on-resistance. IGBTs are bipolar devices where holes are injected into the drift layers during the ON state and the carrier density increases by several orders of magnitude (conductivity modulation). Thanks to this characteristic, low ON-state voltage can be realized even for high-voltage devices. However, these bipolar devices have to discharge all the carriers that accumulated during the ON state at the time of turn-off, so the turn-off power loss is large. The IGBT's ON-state voltage has a trade-off relationship with the turn-off power loss. Using SiC, the concentration in the drift layers can be increased and the thickness can be reduced compared to Si, so even for high-voltage devices, MOSFETs with small switching loss can be used to achieve an ON-state voltage equivalent to that of Si-IGBTs. Currently, SiC-MOSFETs with a rated voltage of 3.3 kV are in practical use.

3. Photovoltaic Inverters with SiC

Photovoltaic inverters are equipment that convert the DC voltage output from PV cells to sine wave AC power. A photovoltaic inverter basically consists of a chopper that regulates the changing DC voltage output from the PV cells, an inverter that converts the DC voltage to AC, and a filter that converts the output from the inverter to sine wave output. Photovoltaic inverters are equipment for which power conversion efficiency is regarded as important. For that purpose, the loss in choppers, inverters, and filters needs to be reduced. Figure 1 illustrates a two-level pulse width modulation (PWM) inverter that is a basic configuration for photovoltaic inverters for home-use. For the two-level PWM inverter, the output voltage is a pulse voltage waveform as shown in the figure. The filter converts this voltage to sine wave output.

Figure 2 shows the configuration of a gradationally controlled voltage inverter adopting Mitsubishi Electric's method. Here, single-phase inverters with different voltages are connected in series, which allows voltage output closer to sine waves. Therefore, the loss in the filter can be significantly reduced. Applying this method achieved a power conversion efficiency of 97.5%, the highest at that time for PV inverters for home use. This efficiency value remained the highest until the introduction of photovoltaic inverters with SiC as described later.

Mitsubishi Electric has developed full SiC intelligent power modules (IPMs) and applied them to photovoltaic inverters.(3) An IPM contains a chopper circuit and a two-level inverter circuit. As shown in Fig. 3, the loss in the power device can be reduced by approximately 60% compared to Si and the power conversion efficiency is as high as 98% (at rated output), the highest in the industry as of 2015.

Figure 4 shows the improvement in efficiency of

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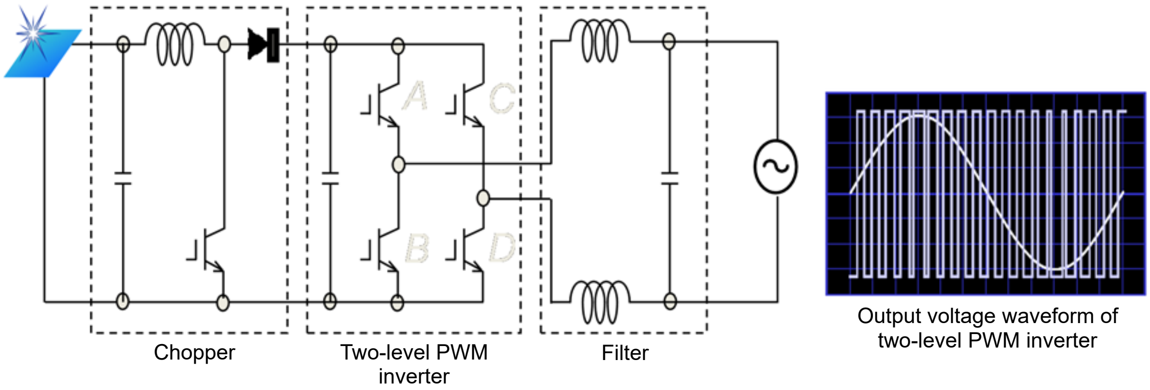

Fig. 1 Two-level PWM inverter

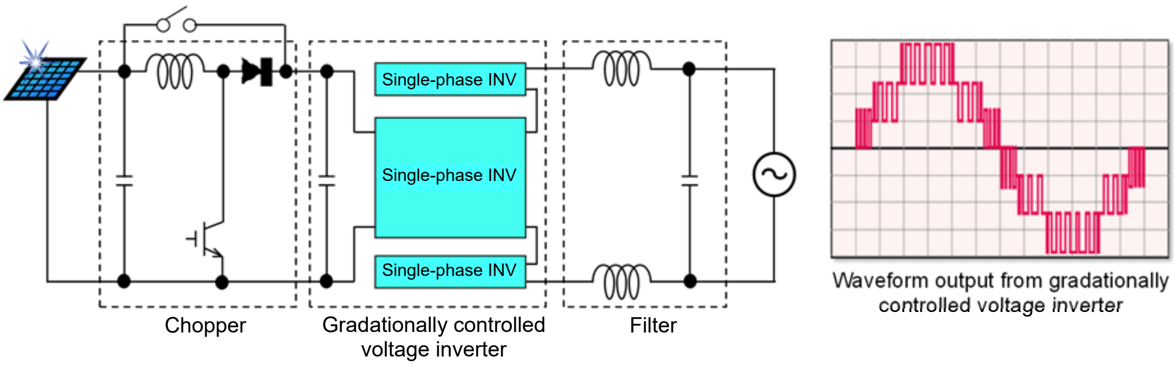

Fig. 2 Gradationally controlled voltage inverter

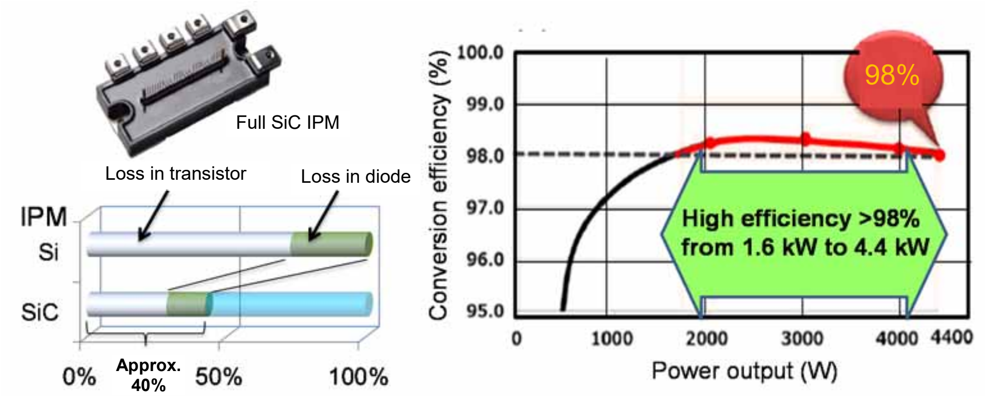

Fig. 3 Power conversion efficiency of PV inverter with SiC devices

Mitsubishi Electric's photovoltaic inverters for home-use. Thanks to the advances made in the Si devices' performance and innovations in the converter circuits, the power conversion efficiency has been improved. The application of SiC devices in 2015 achieved a conversion efficiency exceeding the limit of Si devices.

4. Railcar Traction Systems with SiC

Railcar traction systems are systems that convert the power from catenaries to AC power and control the main motors. When a train is accelerating, the inverter converts the power from the catenaries and supplies the converted power to the motor powering. At the time of deceleration, it converts the vehicles' kinetic energy and supplies the converted power to the catenaries regenerating. The regenerated energy is supplied to other railway vehicles.

According to the analysis results of electrical power consumed by the main circuits of railway vehicle systems, the loss in inverters is small at 2% of the total loss. The main elements of electrical power consumption are the loss in motors and the loss due to mechanical brakes. We considered reducing such loss by utilizing the performance of SiC. First, we considered how to reduce the loss in motors. In conventional control methods, the switching loss in Si devices is large, so the switching frequency is limited and the harmonic loss is large. On the other hand, the switching loss in SiC devices is small,

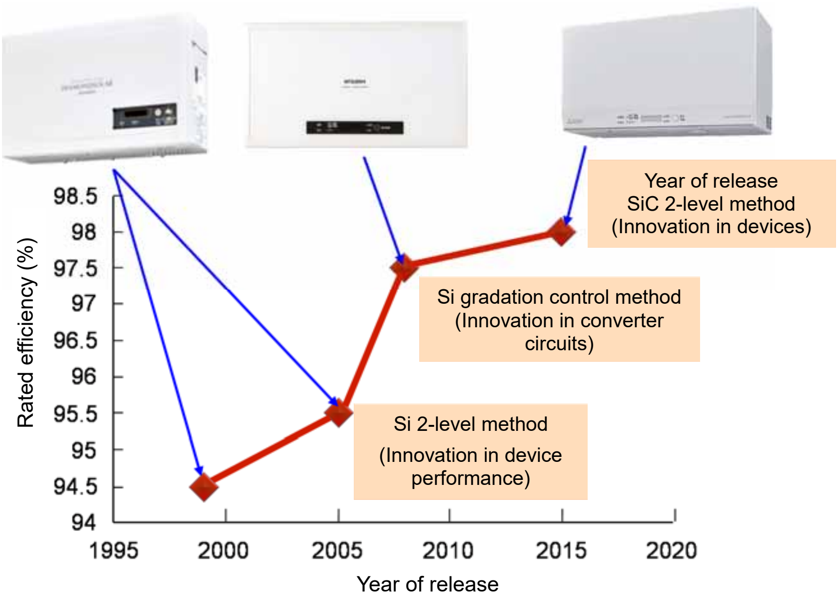

Fig. 4 Improvement of power conversion efficiency

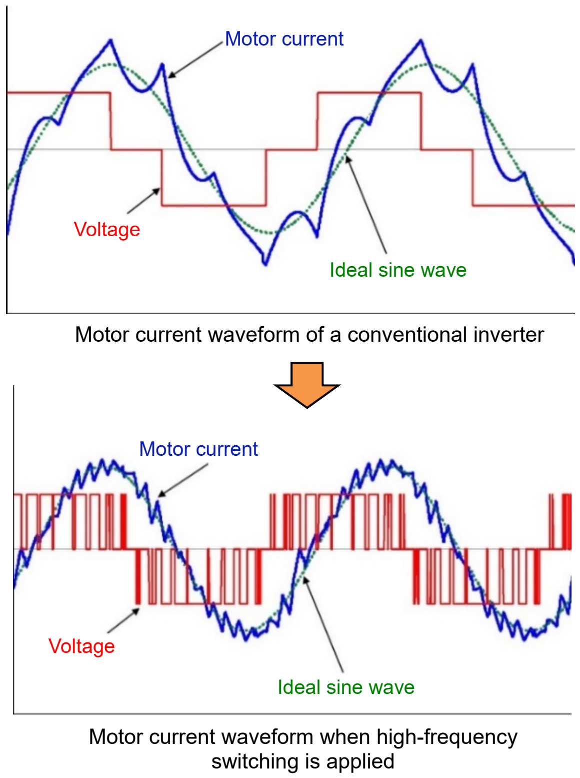

Fig. 5 Motor loss reduction using high-frequency switching

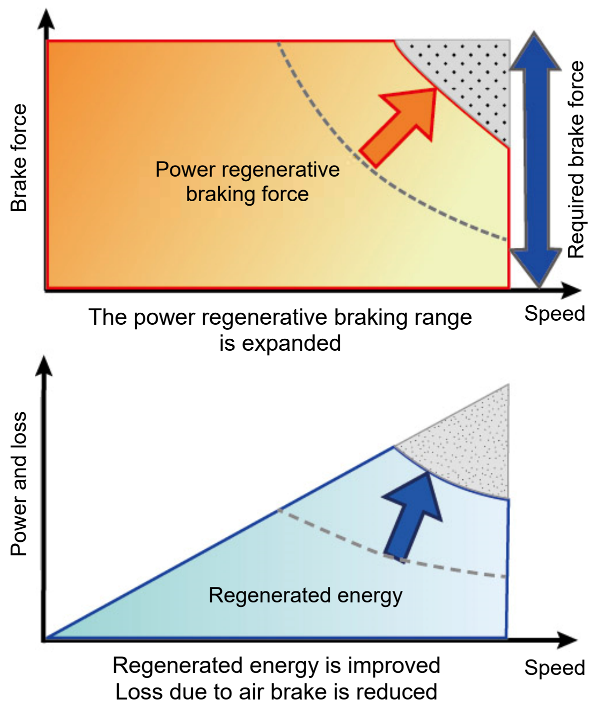

Fig. 6 Mechanical brake loss reduction

which enables high-frequency switching, so the motor currents include less harmonics (Fig. 5).

Next, we considered how to reduce the loss due to mechanical brakes. In the conventional method, the regenerative braking force decreases in the high-speed range, so mechanical brakes are used. With mechanical brakes, the vehicles' kinetic energy is converted into heat, causing a loss. Expanding the power regenerative braking range to the high-speed range can reduce the loss due to mechanical brakes (Fig. 6), but for this, the motor currents need to be increased, which increases the loss in inverters. Making the most of the SiC devices' low loss performance can reduce the increase of the loss in inverters and expand the regenerating brake range.

In 2011, Mitsubishi Electric commercialized inverters to which 1.7-kV power modules with SiC diodes and Si-IGBTs were applied for railway vehicles for DC 600-V/750-V overhead lines. Inverters with 3.3-kV SiC-MOSFETs for railway vehicles for DC 1,500-V overhead lines started commercial operation after the completion of running tests in 2014.(2) The energy-saving effect was

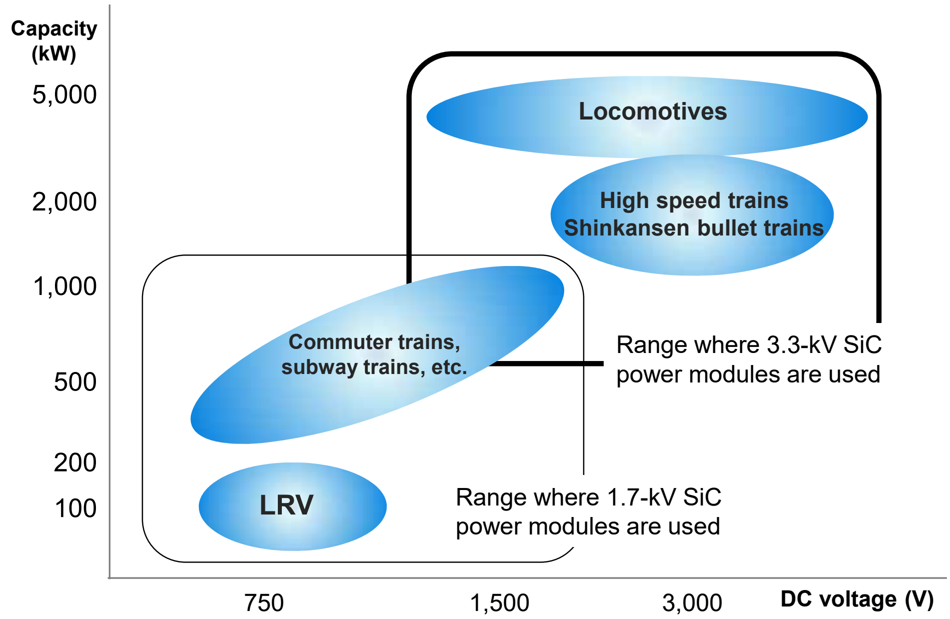

Fig. 7 SiC application range

tested for approximately four months: the energy saved was approximately 40% for the entire main circuit system compared to the previous models. In 2015, Mitsubishi Electric developed main converters with SiC for Shinkansen (bullet) trains. They were installed in Shinkansen trains and checked in running tests.(6)

As shown in Fig. 7, SiC devices have been applied in the railway field, from subway trains to Shinkansen trains, contributing to energy-saving in railway vehicle systems.

5. Conclusion

The practical use of SiC devices began as key energy-saving devices in power electronics devices after a long development period. We will introduce these devices to all sectors in power electronics including automobiles and high-voltage equipment (e.g. power electronics equipment for utility grids) to contribute to energy-saving on a global scale. To that end, technologies will be developed to further enhance the performance, and reliability of SiC devices and equipment to which such SiC devices are applied and to reduce the prices.

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