

Silicon Carbide Inverter for EV/HEV Application featuring a Low Thermal Resistance Module and a Noise Reduction Structure

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ABSTRACT

This paper presents the technologies incorporated in an electric vehicle (EV)/hybrid electric vehicle (HEV) inverter built with power semiconductors of silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs) instead of conventional silicon (Si) insulated gate bipolar transistors (IGBTs). A SiC inverter prototype of 2.9 L in size for driving an 80-kW motor was fabricated and evaluated on a motor test bench. The SiC inverter prototype attained average efficiency of 98.5% in the Worldwide harmonized Light-duty Test Cycle (WLTC) driving mode. The two main technologies achieved with this SiC inverter prototype are described. The first one is a new direct-cooled power module with a thick copper (Cu) heat spreader located under the semiconductors that improves thermal resistance by 34% compared with a conventional direct-cooled power module. The SiC chip size is smaller than that of Si IGBTs, so this technology solves the problem that cooling characteristics typically worsen with a smaller chip cooling area. The second technology is an inverter structure that reduces transmission of generated noise to the inverter case. This structure makes it possible to take advantage of the inherent characteristic of SiC MOSFETs that their switching speed is faster than that of Si IGBTs. As a result, switching loss is reduced and efficiency is improved. The fabrication and evaluation of this SiC inverter prototype have confirmed that these key technologies elicit the advantages of SiC MOSFETs and compensate their drawbacks, thereby reducing the size and improving the efficiency of the SiC inverter.

CITATION: Numakura, K., Emori, K., Okubo, A., Shimomura, T. et al., "Silicon Carbide Inverter for EV/HEV Application featuring a Low Thermal Resistance Module and a Noise Reduction Structure," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 10(1):2017, doi:10.4271/2017-01-1669.

1. INTRODUCTION

The downsizing and improving efficiency are required of inverters to convert battery direct current (DC) voltage to alternating current (AC) voltage for driving traction motors. Si power semiconductors are used in inverters. And the characteristics of inverters are advanced by the improvement of component parts (e.g. power semiconductor, power module and capacitor) [1] [2]. In addition, inverters that use SiC power semiconductor are being researched and developed for the further downsizing and improving efficiency [3] [4].

Improvement of fuel efficiency has been reported in driving tests of a hybrid electric vehicle (HEV) equipped with an inverter built with a SiC chip in place of a Si module [3]. A reduction of surge voltage during switching and improvement of SiC inverter efficiency at a maximum current of 130 Arms have been reported by using an air-cooled power module to reduce stray inductance [4].

This paper focuses on the application of water cooling to downsize and improve the efficiency of a SiC inverter with large current output. The objective of this work was to develop inverter technologies for eliciting the advantages of SiC MOSFETs and compensating their

drawbacks. Attention was focused specifically on technologies in two areas. Firstly, power module technologies are described for improving cooling characteristics to facilitate downsizing, while simultaneously increasing the output current of the inverter by applying a small die size of semiconductor like a SiC chip. Making the switching speed faster improves inverter efficiency, but it worsens inverter noise. The technologies of a noise reduction structure for addressing this issue are then described.

2. SiC INVERTER PROTOTYPE

2.1. Outline of SiC Inverter Prototype

The SiC inverter prototype developed in this work is shown in [Figure 1](#). A schematic diagram of the prototype SiC inverter is shown in [Figure 2](#). It is a three-phase water-cooled AC inverter consisting of SiC MOSFETs, a gate driving circuit, capacitors and a cooling structure. External diodes are eliminated because the built-in diodes of the MOSFETs are utilized. The specifications of the SiC inverter prototype are shown in [Table 1](#). It is 2.9 L in size and can drive an 80-kW motor.



Figure 1. SiC inverter prototype

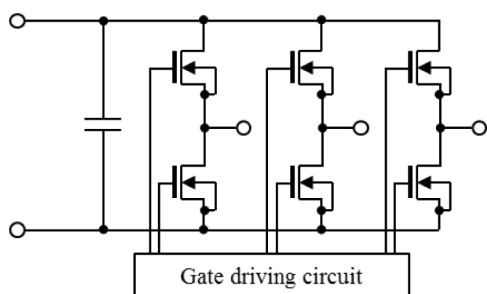


Figure 2. Schematic diagram of SiC inverter prototype

Table 1. Specifications of SiC inverter prototype

Parameter	Specification	Unit
Typical DC input voltage	360	V
Max. motor output	80	kW
Size	2.9	L
Cooling method	Water cooling	-

2.2. Motor Test Bench Evaluation and Estimation of Driving Range Improvement

The fabricated SiC inverter prototype was evaluated on a motor test bench. Turn-on and turn-off waveforms are shown in Figures 3 and 4, respectively, at the rated voltage of 360 V and inverter output current of 550 A as one example of the motor test bench results. I_{ds} characteristics show a switching time within 100 nsec at turn-on and turn-off. The SiC inverter prototype achieved average efficiency of 98.5% in the WLTC driving mode by power module cooling technologies and noise reduction technologies.

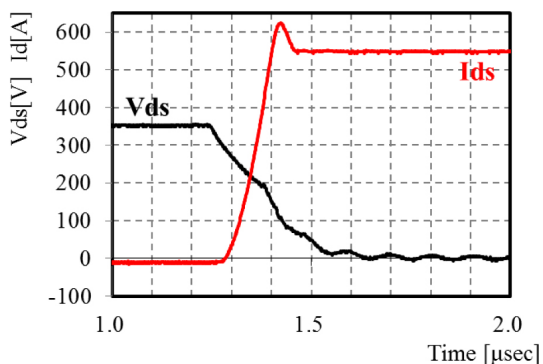


Figure 3. Turn-on waveforms of SiC inverter prototype in a motor bench test

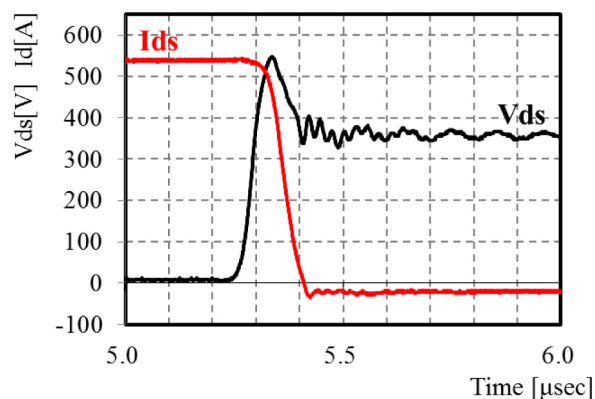


Figure 4. Turn-off waveforms of SiC inverter prototype in a motor bench test

3. DIRECT-COOLED POWER MODULE FOR LOW THERMAL RESISTANCE

3.1. Outline of Direct-Cooled Power Module Prototype

Firstly, the power module cooling technologies for facilitating inverter downsizing are described. The direct-cooled power module prototype fabricated in this work is shown in Figure 5. Six plastic mold packages (1-in-1 type) and the water jacket are soldered via insulated substrates. One plastic mold package consists of one arm of the inverter.

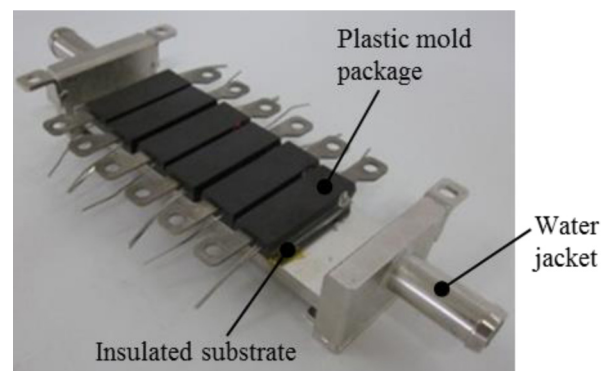


Figure 5. Direct-cooled power module prototype

The plastic mold package features a thick Cu heat spreader located under the chip for lower thermal resistance. Thermal resistance can be reduced by using a thick Cu heat spreader because the heat generated by the chip spreads not only directly under the chip but also laterally. However, stress is increased due to differences in the coefficient of thermal expansion of the soldered parts. To address this issue, a thin closed aluminum (Al) water jacket was adopted to suppress stress. Thermal resistance and stress simulation results and evaluation results of the fabricated prototype are presented below.

3.2. Simulation Results: Thermal Resistance

A conventional direct-cooled module (e.g. the module having pin-fin type water jacket [5] [6]) and the direct-cooled module prototype with a thick Cu heat spreader are shown in Figure 6.