

A 55 kW Three-Phase Automotive Traction Inverter with SiC Schottky Diodes

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Abstract- Silicon carbide (SiC) power devices are expected to have an impact on power converter efficiency, weight, volume, and reliability. Presently, only SiC Schottky diodes are commercially available at relatively low current ratings. Oak Ridge National Laboratory has collaborated with Cree and Semikron to build a Si IGBT– SiC Schottky diode hybrid 55kW inverter by replacing the Si pn diodes in Semikron’s automotive inverter with Cree’s made-to-order higher current SiC Schottky diodes. This paper shows the results obtained from testing this inverter and compares it to a similar all–Si inverter.

I. INTRODUCTION

There is a growing demand for more efficient, higher power density, and higher temperature operation of the power converters in the transportation area. In spite of the advanced technology, silicon (Si) power devices cannot meet some transportation requirements. Silicon carbide (SiC) has been identified as a material with the potential to replace Si devices in the near term because of its superior material advantages such as wider bandgap, higher thermal conductivity, and higher critical breakdown field strength. SiC devices are capable of operating at high voltages, high frequencies, and at higher junction temperatures. Significant reduction in weight and size of SiC power converters with an increase in the efficiency is projected [1-5]. SiC unipolar devices such as Schottky diodes, VJFETs, MOSFETs, etc. have much higher breakdown voltages compared to their Si counterparts which makes them suitable for use in traction drives replacing Si pn diodes and IGBTs [6-14].

Presently, SiC Schottky diodes are the most mature and the only commercially marketed SiC devices available. These diodes are commercially available up to 1200V/20A or 600V/20A.

SiC Schottky diodes have been proven to have better performance characteristics when compared to their equivalent Si pn diodes [1], especially with respect to the switching characteristics. SiC devices can also operate at higher temperatures and thereby resulting in reduced heatsink volume.

Oak Ridge National Laboratory (ORNL) has collaborated with Cree and Semikron to build a Si IGBT– SiC Schottky diode hybrid 55kW inverter by replacing the Si pn diodes in Semikron’s automotive inverter with Cree’s SiC Schottky diodes. This paper shows the results obtained from testing this inverter and comparing it to a similar all–Si inverter.

II. SiC SCHOTTKY DIODES

Semikron has built 55kW Automotive Integrated Power Modules (AIPM) for the U.S. Department of Energy’s FreedomCAR Program’s hybrid electric vehicle traction drives. These modules contain three-phase inverters with 600V/400A Si IGBTs and pn diodes.

For an ORNL project, Cree has developed 600 V/75A SiC Schottky diodes as shown in Fig. 1. Semikron has replaced each Si pn diode in their AIPM with two of these 75A SiC Schottky diodes.

After extensive testing, I - V characteristics of these diodes were obtained at different temperatures in the -50°C to 175°C ambient temperature range (Fig. 2). Considering the piece-wise linear (PWL) model of a diode, which includes a dc voltage, V_d and series resistor, R_d ; the diode I - V curves can be approximated with the following equation:

$$V_f = V_d + R_d \cdot I_f \quad (1)$$

where V_f and I_f are the diode forward voltage and current, and V_d and R_d are the diode PWL model parameters.

Fig. 3 shows R_d and V_d values of the 600V/75A SiC Schottky diodes with respect to temperature. As seen in these figures, V_d decreases with temperature and R_d increases with temperature. Decrease in R_d is a sign of the positive temperature coefficient the SiC Schottky diodes have, which implies that these devices can be paralleled easily. Equations

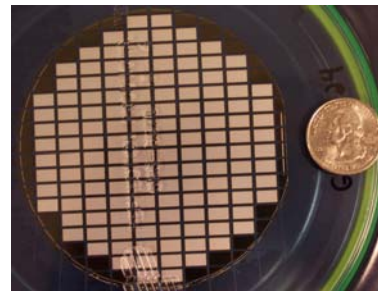


Fig. 1. The 600V/75A SiC Schottky diodes on a wafer next to a quarter.

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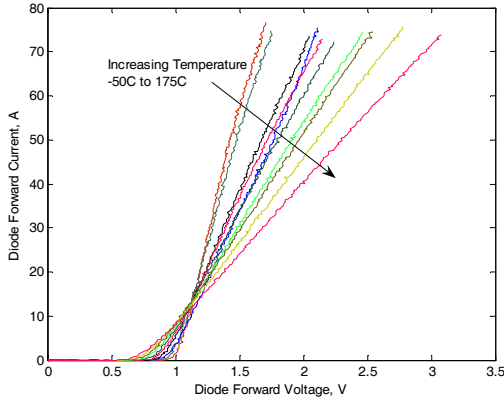


Fig. 2. Experimental I-V curves of the 75A SiC Schottky diode.

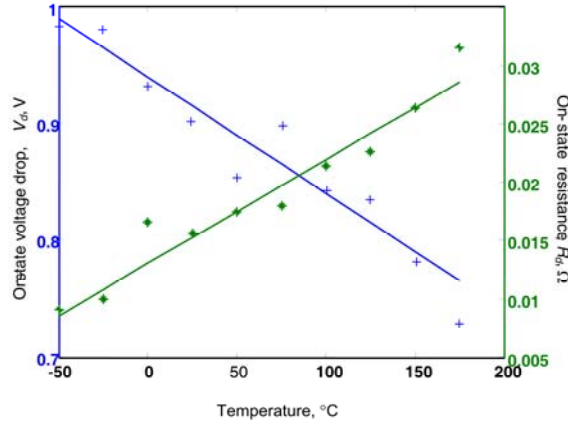


Fig. 3. R_d and V_d obtained from the experimental data in Fig.2.

below show the temperature dependence of the SiC Schottky diode PWL model parameters.

$$V_d = -0.001 \cdot T + 0.94 \quad (2)$$

$$R_d = 8.9 \times 10^{-5} \cdot T + 0.013 \quad (3)$$

where T is the temperature in °C.

III. INDUCTIVE LOAD TEST

Both the Si-SiC hybrid and the all-Si inverters were tested with an inductive load and a dyne set with the same procedure and the same conditions.

For the inductive load test, the output leads of the inverter are connected to a three-phase star connected variable resistor bank with a three phase inductor in series. The dc inputs are connected to a voltage source capable of supplying the maximum rated operating voltage and current levels for the inverter. The test setup is shown in Fig. 4.

The dc link voltage was varied from the minimum operating voltage of 200V to the maximum bus voltage of 450V. The bus voltage trip fault occurs for voltages beyond 450V.

The load resistance was set to the minimum value and the output current was varied. The inverter was operated with a 20°C coolant at a flow rate of 9.46 liters per minute. The open loop frequency of operation and the PWM frequency (10 kHz) were fixed and the current command was varied for a particular dc link voltage. For each value of the current



Fig. 4. Inductive load test set-up.

command and open loop frequency, the dc link voltage, dc link current, input/output power, efficiency, and output line currents and voltages were recorded. The three-phase power was measured using the two wattmeter method.

The command current was increased in steps of 10A without exceeding the power rating of the inverter or the power rating of the load. The procedure was repeated by increasing the open loop frequency in steps of 25Hz.

The coolant temperature was changed to 70°C and the above procedure was repeated to observe the operation at higher temperatures.

The operating waveforms, for two specific operating conditions of the Si-SiC hybrid inverter are shown in Fig. 5.

The data obtained for both of the inverters were analyzed, and the corresponding efficiencies were calculated. The efficiency versus output power plots for several operating conditions are shown in Fig. 6.

The average loss reduction resulted in using SiC Schottky diodes instead of Si pn diodes was calculated as:

$$\% \text{loss reduction} = \frac{P_{loss}^{Si} - P_{loss}^{SiC}}{P_{loss}^{Si}} \times 100. \quad (4)$$

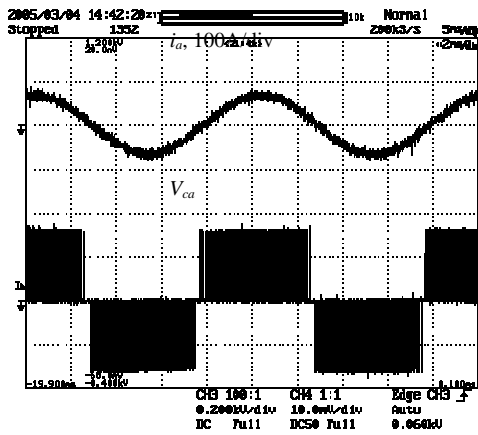
The Si-SiC hybrid inverter losses are up to 33.6% less than the all-Si inverter.

IV. DYNAMOMETER TEST

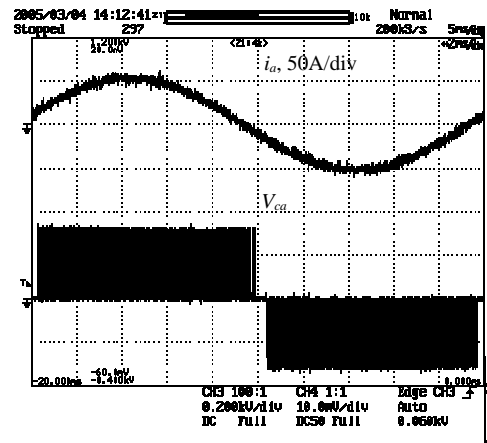
The inverters were connected individually to an induction machine set up in a dynamometer test cell to test them for their dynamic performance in the motoring and regeneration modes. The induction motor used was a four-pole induction motor with a base speed of 2500 rpm and the dynamometer had 100-hp capacity. The tests were performed with the inverter being supplied with 70°C coolant and a flow rate of 9.46 liters per minute.

A. Motoring Mode

In this mode, the speed set point, the magnetizing current, the direction of rotation, and the current limit were the parameters that could be adjusted. The dc voltage input to the inverter was set at the nominal battery operating voltage (325V dc). The closed loop speed controller gains were adjusted for a given magnetizing current value and current



(a) $V_{dc}=325V$; $i_{a,peak}=80A$; $f_c=50Hz$



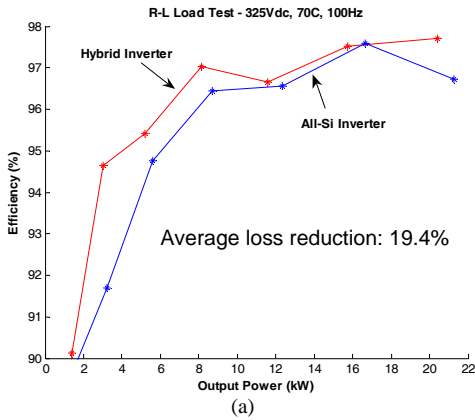
(b) $V_{dc}=325V$; $i_{a,peak}=60A$; $f_c=100Hz$

Fig. 5. Inverter output voltage and current during the inductive load test for two different conditions

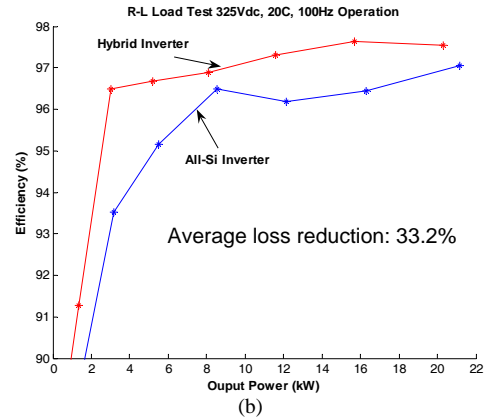
limit to achieve a stable operation of the system for wide range of speeds. The direction of rotation was set to forward and the motor speed was increased from 750 rpm to the rated base speed for a specific continuous load torque. The load torque was varied gradually from zero to the required torque and then decreased to zero. The data was obtained for a wide range of speed and torque values by changing the load torque (100,150, 200 Nm) using the dynamometer controller. The following information was recorded at each speed increment: motor shaft speed, motor torque, input and output voltages,

and currents.

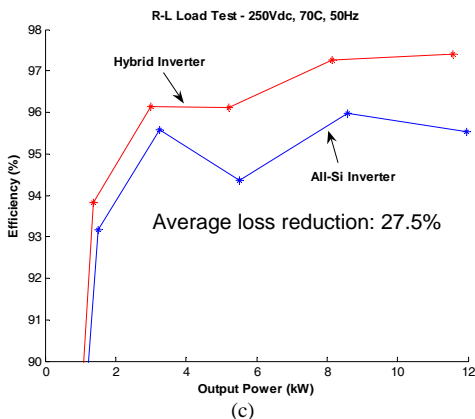
The operation waveforms for two different load conditions are shown in Fig. 7. The efficiency plots for various speed and load torque are shown in Fig. 8. The average loss reduction was obtained as described in the previous section. In this case, up to 10.7% reduction in the losses is observed.



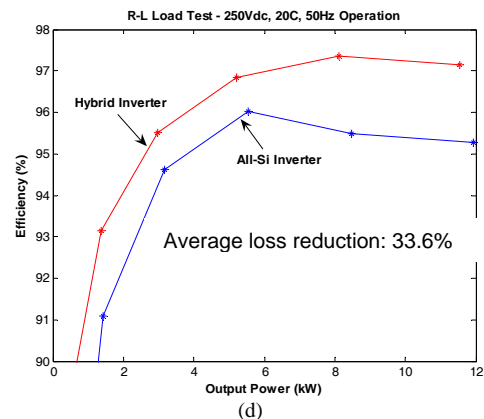
(a)



(b)

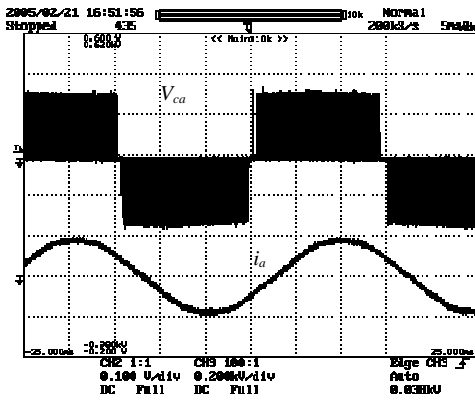


(c)

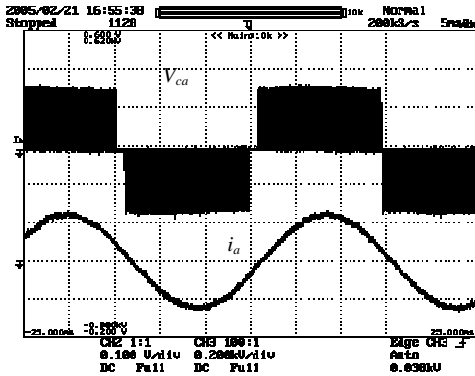


(d)

Fig. 6. R-L load test efficiency curves for various load conditions.



(a) 1000 rpm and 50 Nm



(b) 1000 rpm and 150 Nm

Fig. 7. Inverter output voltage and current during the dyne test for two different conditions

B. Regeneration Mode

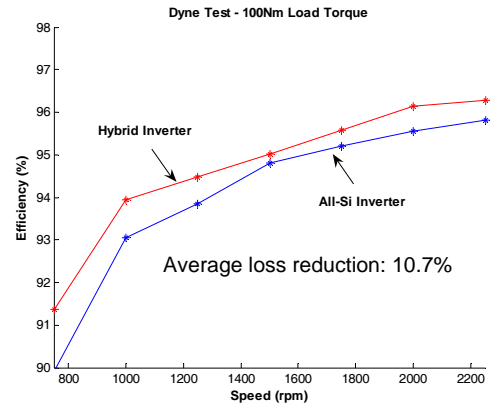
In this mode, the torque limit and the operating current can be adjusted. The dc voltage input to the inverter was set at the nominal battery operating voltage. The direction of rotation was set to be forward. The dynamometer controller was adjusted to control the speed while the inverter controller controlled the current. Data has been collected for 100, 150, and 200 Nm torque produced by the drive.

The procedure was repeated to obtain the data for a wide range of speed and torque values. The following information at each speed increment: motor shaft speed, motor torque, input and output voltages, and currents were recorded.

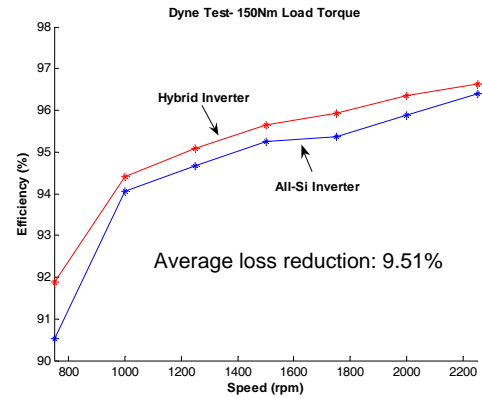
The operating waveforms for the regeneration mode are shown at two different speeds in Fig. 9. The curves comparing the efficiency of the inverters at 70°C are shown in Fig. 10. In this mode, the reduction in the losses is comparable to the motoring case.

V. CONCLUSION

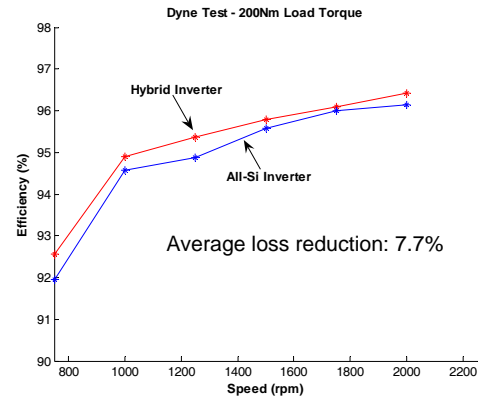
The testing of both the Si-SiC hybrid and all-Si inverters was completed successfully. The inverters were able to operate at peak power levels with efficiencies greater than 90%. The inverters were tested for a peak power of 47 kW and continuous rating of up to 35kW.



(a)



(b)

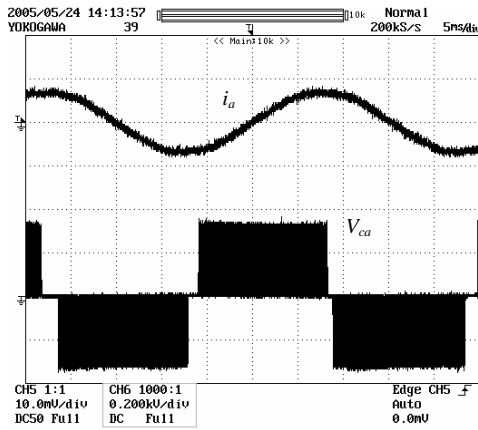


(c)

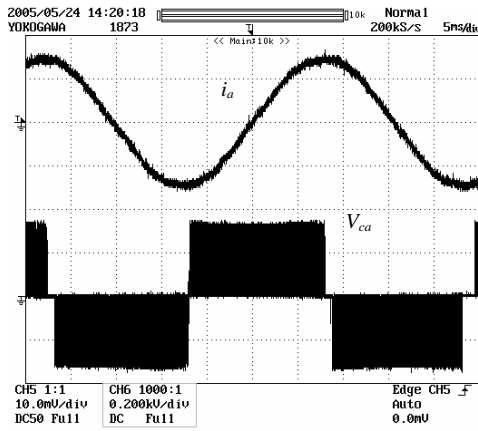
Fig. 8. Dynamometer test – motoring mode efficiency plots at 70°C with a) 100 Nm, b) 150 Nm, c) 200 Nm load torques.

The test results show that by merely replacing Si pn diodes with their SiC Schottky diode counterparts, the losses of an inverter decrease considerably.

Note that both of the inverters were tested in the exact same conditions with the same controller. Since SiC Schottky diodes have negligible reverse recovery, they do not stress the main switches as much as Si pn diodes. Therefore, it is possible to operate the Si-SiC hybrid inverter at higher switching frequencies than the one used in these tests.



(a) 1000 rpm and 50 N.m.



(b) 1000 rpm and 150 N.m.
(c)

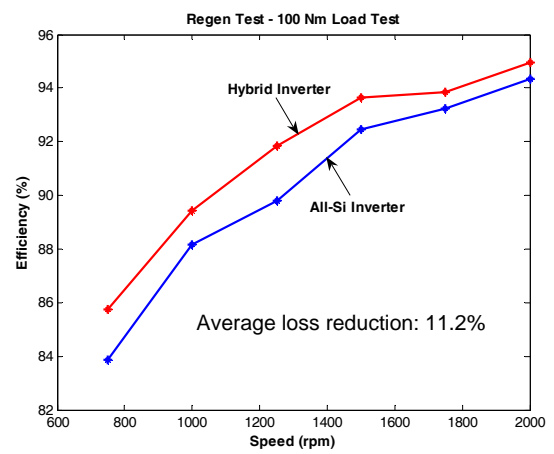
Fig. 9. Inverter output voltage and current during the regeneration test for two different conditions

ACKNOWLEDGMENT

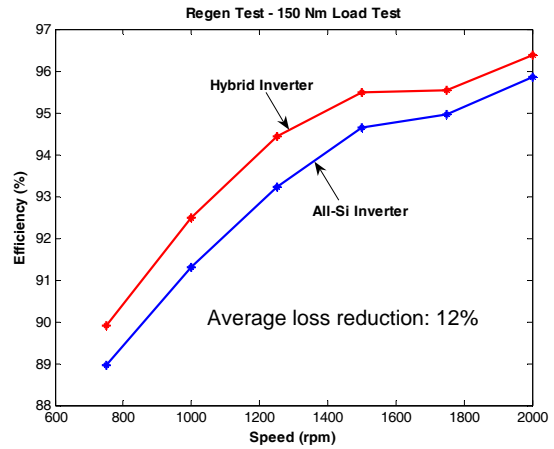
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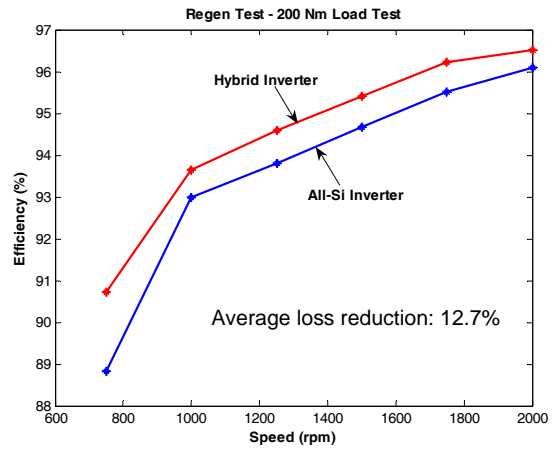
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(a)



(b)



(c)

Fig. 10. Dynamometer test –regeneration mode efficiency plots at 70°C with a) 100 N.m, b) 150 N.m, c) 200 N.m load torques.

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