The First 4H-SiC BJT-based 20 kHz, 7HP PWM DC-to-AC Inverter for Induction Motor Control Applications

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Abstract. This paper reports the design, fabrication and testing of the first 4H-SiC BJT-based, PWM DC-to-AC inverter at a record high power (7.4HP) and PWM frequency of 20 kHz with a bus voltage of 330V. Six 4H-SiC BJT switches and six 4H-SiC MPS diodes are used to form an all-SiC power board which is driven by a Si base driver, interfaced with a Si-based voltage source driver. The inverter has been used to control a GE three-phase AC induction motor of 7.5HP and has run up to an input power of 7.4HP (5.5kW). The SiC BJT I-V characteristics, the inverter switching waveforms and the inverter efficiency at different input power levels are presented.

Introduction

SiC-based inverters are of substantial interest because they promise a large reduction in system size and weight with improved efficiency. Motor control inverter at 45V-1.3A was first reported in 1999 [1] based on normally-off junction-controlled SiC thyristors. Normally-off Si switches are desirable for high power inverters because they provide fail-safe protection. Among SiC power switches being developed, SiC BJT switches are attractive for inverters because they do not have the thermal runaway and slow switching problems associated with Si BJTs. In addition, they are free of the gate oxide-related reliability problems, able to provide higher power, and can permit the development of soft-switching reliability transistors [2] in comparison to SiC MOSFETs at high temperatures. SiC BJTs also have higher power capability in comparison to SiC VJFETs when operating at high temperatures. However, there is no SiC based high-temperature gate driver and control chip available. And, although the Si BJT was introduced decades ago, there is no mature base driver technology available today. Si IGBTs and MOSFETs are now the dominant technologies. Therefore, the base driver capable of handling current controlled devices such as the SiC BJTs needs to be designed and developed. Because the Si-based driver to be developed will not be able to operate at high temperatures, it would have to be thermally separated from SiC power board in order for the SiC BJTs to operate at high temperatures. This paper reports the development of the first 4H-SiC BJT-based power inverter capable of a record high output power of 5kW and a pulse-width-modulated (PWM) frequency of 20 kHz.

Inverter Design and Fabrication

To overcome the aforementioned limitations, we have designed and developed an intermediate board which serves as the base driver interfacing between the voltage source gate driver and the high temperature SiC BJT power board. Fig.1 shows one phase leg of the base driver with a Si N-MOSFET for turn-on and P-MOSFET for turn-off, interfacing with the voltage source gate driver and the SiC BJT power board. The intermediate base driver board is physically separated from the high temperature SiC power board by a thermal buffer, and thus requires minimum cooling. With this approach, the SiC BJTs can operate at high temperature, providing the desired advantages of
reduced thermal cooling size and weight. A saturable inductor is inserted between the BJT collector and N-MOSFET to limit the rate of the base current rise as well as to reduce the turn-on switching loss in the N-MOSFET.

Fig. 1 Base driver structure for one phase leg.

Fig.2: All-SiC power board for 7HP applications (photo courtesy of Rick Griffiths).

Fig.2 shows the fabricated all-SiC power board. Low inductance current sensors have been embedded into the design to allow direct monitoring of the switching waveforms of both BJTs and diodes. The SiC BJTs and MPS diodes are capable of 40A and 600V. The room-temperature DC I-V characteristics of a 4H-SiC BJT are shown in Fig.3. It is seen that the BJT conducts 30A ($I_c \sim 240A/cm^2$), limited by DC I-V set-up, with a forward voltage drop of $V_F = 4.1V$. The 4H-SiC BJT has a current gain of $\sim 29$. The BJTs are capable of high ambient temperature operation. Fig.4 shows the DC I-V curves measured at an ambient temperature of 150°C. In order to see the details, the leakage currents have been magnified 10,000X for both Fig.3 and Fig.4. The power dissipation in the blocking mode at a bus voltage of 320V is therefore negligible.

Fig.3 4H-SiC BJT I-V curves at RT.

Fig.4 4H-SiC BJT I-V curves at 150°C.

Fig.5 shows the dynamometer serving as the load of a three-phase 7.5HP GE AC induction motor. Fig.6 shows a set of switching waveforms during start-up at lower bus voltage using SPWM at 10 kHz. The waveforms are, from top to bottom, phase current, switch current, gate voltage and switch voltage. Fig.7 shows the switching waveforms when $V_{bus}$ is increased to 300V. Fig. 8 depicts detailed waveforms and Fig.9 presents a single switching cycle waveforms showing <0.2μs turn-on and turn-off time for the SiC BJTs. Fig.10 shows the inverter operating at increased SPWM frequency of 20 kHz. The waveforms are, from top to bottom, bus voltage, switch current, phase currents for two of the three phases. Another mode of PWM used for achieving higher inverter efficiency is the space vector modulation (SVM). Fig.11 shows the waveforms for the inverter with 5.5kW power input at $V_{bus} = 330$V with a SVM-PWM frequency of 20 kHz. The waveforms are, from top to bottom, bus voltage (200V/div), phase current (46A peak-peak), switch current.
Fig. 12 shows the SVM inverter multi-cycle switching waveforms. The waveforms, from top to bottom, are switch voltage and switch current. Fig. 13 shows the detailed turn-on waveforms (330V, ~24A) as well as the turn-on energy loss and power loss spectrum. It is seen that the turn-on power has a peak value of 10kW while the turn-on energy loss is about 2mJ. The conduction loss is noticeable also because of forward voltage drop $V_F > 3$V at this high current level as shown by the DC I-V curves in Fig. 3. Fig. 14 shows the detailed turn-off waveforms (330V, ~24A) as well as the turn-off energy loss and power loss spectrum. It is seen that the turn-off power has a peak value of ~3kW while the turn-off energy loss is about 0.4mJ. The inverter has been tested from an input power of 297 W to 5511W with the corresponding output power, motor shaft power, and BJT case temperature recorded. The SiC inverter efficiencies at different power levels are shown in Fig. 15.
Fig. 11 SVM switching waveforms of SiC BJT-inverter at 5.5kW input power ($V_{dc}=330V$, $I_{dc}=16.6A$) and 20kHz.

The inverter efficiency decreases from 95% at 3,500W to 91% at 5,511W input, largely due to the conduction loss because, as shown in Figs. 13 and 14, the total SiC BJT switching energy loss is less than 1% at 5,511W input.

Summary

The first 4H-SiC-BJT based high power inverter has been demonstrated at 20kHz with a record high output power of 5kW, surpassing any type of all-SiC power systems reported to date.

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Fig. 12 Multi-cycle switching waveforms of the inverter at 5.5kW input power ($V_{dc}=330V$, $I_{dc}=16.6A$) and 20kHz.

Fig. 13 Detailed inverter waveforms showing BJT turn-on energy loss.

Fig. 14 Detailed inverter waveforms showing BJT turn-off energy loss and conduction loss.

Fig. 15 SiC inverter efficiency vs. input power.

Reference
