High Current SiC JBS Diode Characterization for Hard- and Soft-Switching Applications[†]

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ABSTRACT - **A newly developed high-current silicon carbide (SiC) junction barrier Schottky (JBS) diode with a 1200 V, 15 A rating was characterized and evaluated for both hard- and soft-switching applications. Experimental results indicate that the conduction characteristics are comparable with, but the switching characteristic is far superior to, its silicon diode counterpart. The SiC JBS diode exhibits nearly zero reverse-recovery time and associated losses. When applied to hard-switching choppers, it reduces not only the reverse-recovery loss, but also the main switch turn-on loss. Using the MOSFET as the main switching device, the combination of switch turn-on loss and diode reverse-recovery loss shows more than a 70% reduction. When applied to soft-switching choppers, the SiC JBS diode is used as the auxiliary diode to avoid the voltage spike during auxiliary branch turn-off. With the conventional ultra-fast reverse-recovery Si diode, a voltage spike exceeds the switched-voltage transition by 100%, and the auxiliary circuit requires additional voltage clamping or snubbing to avoid over-voltage failure. With the SiC JBS diode, however, the voltage spike is reduced to less than 50% of the switched-voltage transition, and the additional voltage clamping circuit can be eliminated. Savings in soft-switching choppers using SiC JBS diodes can be realized in size and weight reduction, energy loss reduction, and reduced packaging complexity.**

I. INTRODUCTION

The silicon carbide (SiC) Junction Barrier Schottky (JBS) diode has been reported as a near ideal diode for power supply and motor drive applications [1-3]. With an order of magnitude higher breakdown electric field than silicon and an electron mobility about 20% lower than silicon, the SiC power devices can have a thinner doped layer and higher voltage blocking capability. The JBS diode combines the best features of both Schottky and PiN diodes by obtaining low forward voltage drop and fast switching characteristics like the Schottky, and obtaining low off-state leakage and high temperature characteristics like the PiN diode. Thus, the SiC JBS diode can be built with the desired features for high voltage high power applications.

This paper presents performance data on a newly developed 3 mm × 3 mm SiC JBS diode rated at 1200 V, 15 A, designed for high power converter and inverter applications. Fig. 1 shows a photograph of the SiC JBS diode fabricated and used in this characterization work. The package design permits low inductance connections to the circuit.

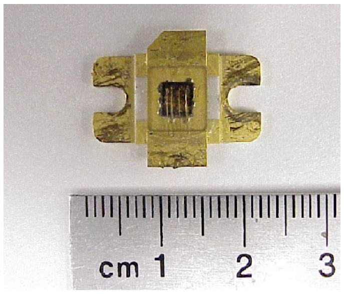

Fig. 1. Photograph of the newly developed high current SiC JBS diode.

Because the SiC JBS diode has nearly zero reverse-recovery time, it is well suited for power-switching applications. In this paper, we characterize the JBS diode, and show applications to both hard- and soft-switching converters. In hard-switching circuits, the reductions are mainly in device turn-on loss and associated electromagnetic interference (EMI) [1]. In soft-switching circuits, the main diode can be of a slower recovery type, such as the body diode of a power MOSFET, but the auxiliary diode should be extremely fast. Currently available high-voltage Si diodes are too slow to prevent over-voltage ringing during the auxiliary diode turn-off [4-8]. In a resonant snubber-based zero-voltage switching inverter [6–8], the over-voltage ringing is so severe that it requires an RC snubber to clamp the over-voltage; or, alternatively, a saturable reactor to slow down the auxiliary current turn-off to avoid over-voltage component failure [6]. The voltage clamping snubber or saturable reactor increases circuit complexity and losses that may offset the efficiency gains promised by soft switching.

For the above-mentioned resonant snubber-based soft-switching circuit, voltage overshoot due to the Si diode reverse recovery is more than 100% of the dc bus voltage. The ultra-fast reverse-recovery Si diode simply cannot be used without adding snubber or saturable reactor networks to the soft-switching inverter. In this work, we show that the SiC JBS diode reduces this voltage overshoot by 50%, and the conventional soft-switching inverter or converter that uses

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the new JBS SiC diode in the auxiliary branch does not need the dissipative snubber or saturable reactor.

II. THE STATIC CHARACTERISTICS

The measured temperature dependence of the on-state characteristics for a 1200-V, 15-A rated SiC JBS diode is shown in Fig. 2. The increase in on-state voltage with respect to the temperature is indicative of the reduction of mobility with temperature for a majority carrier device. Although this positive temperature coefficient of resistance increases the on-state loss at high temperatures, it is beneficial for paralleling and large-area current sharing.

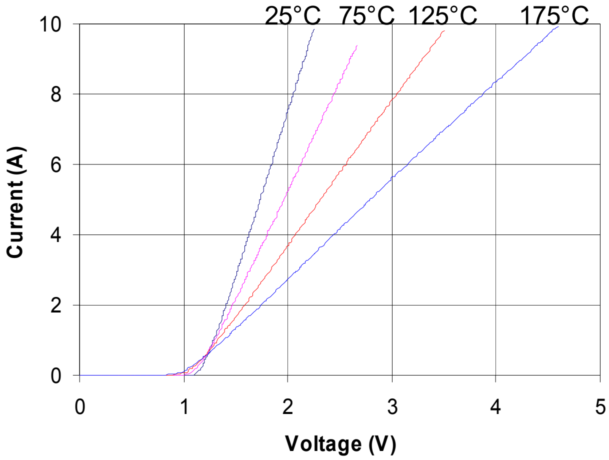


Fig. 2. Measured temperature dependence of the on-state voltage for 1200-V, 15-A rated SiC JBS diode.

III. SWITCHING CHARACTERISTICS IN HARD SWITCHING APPLICATIONS

Fig. 3 shows a hard-switching chopper test circuit. The circuit consists of two branches of switch-diode pairs. Both switches S_1 and S_2 are turned on and off simultaneously. Diodes D_1 and D_2 provide a freewheeling path when both switches are turned off. Such a chopper has been widely used in magnetic levitation, magnetic bearing, and switched reluctance motor drives. The bottom devices serve as the devices under test (DUT) and the current measurement is implemented with low-inductance current-sensing resistors, R_D and R_S. Major circuit components used in this circuit are listed as follows: S_1, S_2: 600-V, 20-A MOSFET; D_1, D_2: 600-V, 20-A fast recovery Si diode, or alternatively for comparison, the above-mentioned SiC JBS diode; and L: 2 mH. The measured switch voltage and current are: S_2 drain-source voltage, v_S; source current, i_S; D_1 cathode-anode voltage, v_D; and anode current, i_D.

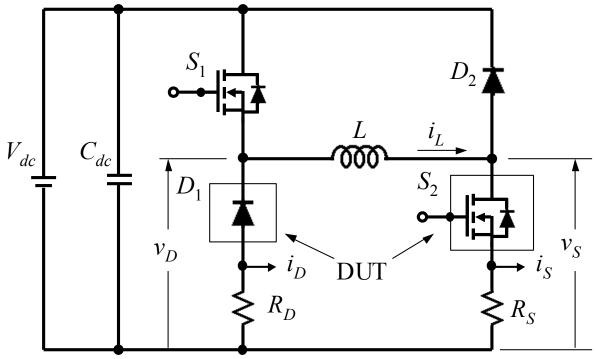
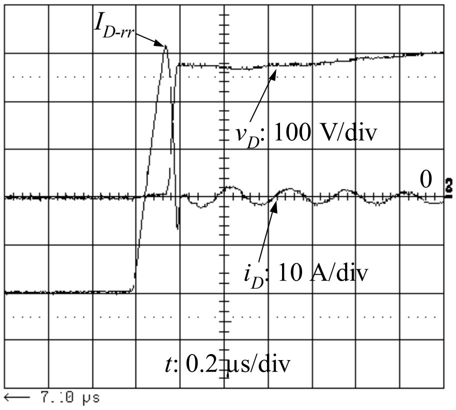


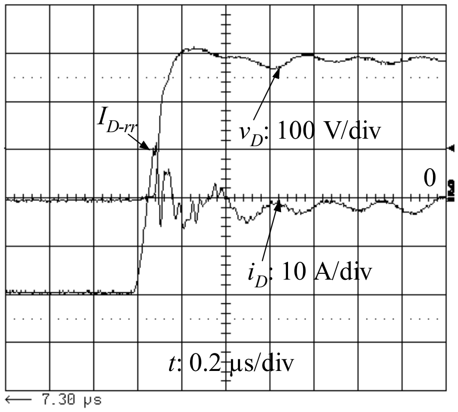
Fig. 3. Circuit diagram of hard-switching chopper.

A. Diode Reverse Recovery Characteristics

Fig. 4 shows the measured diode current, i_D, and voltage, v_D, under 300-V dc bus voltage and 20-A load current conditions. With the Si diode, the reverse-recovery time t_{rr} is about 160 ns, and the peak reverse-recovery current $I_{D\text{-}rr}$ is 30 A, or 1.5 times the load current I_L. With the SiC JBS diode, the reverse-recovery time is about 80 ns, and the peak reverse-recovery current is 10 A, or half the load current.



(a) with Si diode



(b) with SiC diode

Fig. 4. Diode voltage and current waveforms under the switch turn-on and diode turn-off condition.

Once the switching device voltage reaches its on-state value, the diode current starts returning to zero, and the switching loss due to this part of the diode reverse recovery can be expressed as $P_{D-rr} = f_{sw} \cdot E_{D-rr}$, where E_{D-rr} is the diode switching energy associated with the diode reverse recovery. Fig. 5 shows the diode reverse-recovery energy, E_{D-rr}, of the SiC JBS diode and the Si diode under different load conditions. With the Si diode as the DUT, E_{D-rr} is 0.2 mJ at a 20-A load condition. With the SiC diode as the DUT, the E_{D-rr} is 0.02 mJ at a 20-A load condition. The energy loss with the Si diode is a function of the load current. However, the energy loss with the SiC diode during the reverse-recovery period tends to be constant over the entire load range. This indicates that the small amount of the energy loss or the intersection of voltage and oscillating current is likely caused by the parasitic components, but not the reverse recovery.

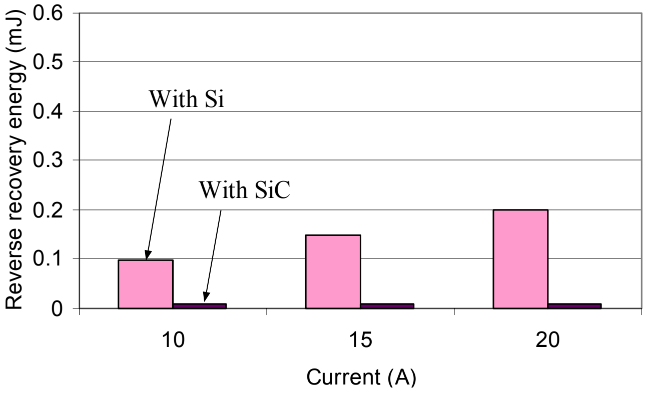


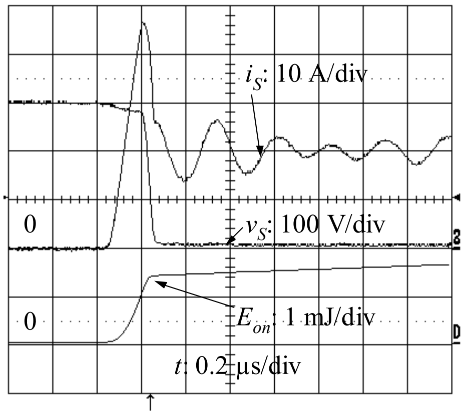
Fig. 5. Reverse recovery energy of SiC JBS diode and fast Si diode under different load conditions.

B. Switch Turn-on and -off Characteristics

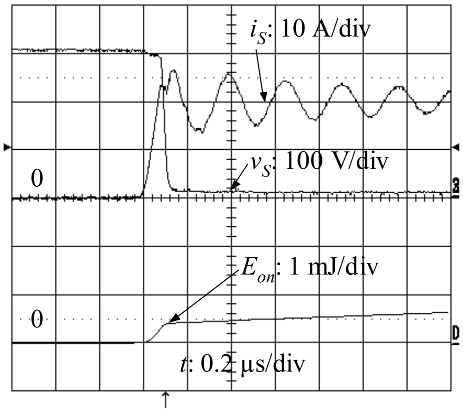
Fig. 6 shows the turn-on current and voltage waveforms of the MOSFET switch at the 300-V bus voltage and 20-A load current condition. Switch current, i_S, contains the load current and the diode reverse recovery current. With the Si diode, a 27-A current overshoot is observed, along with parasitic ringing associated mainly with the sensing resistor for the measurement. With the SiC diode, i_S contains negligible overshoot, but parasitic ringing similar to that with the Si diode remains.

The turn-on energies, E_{on}, of main switches, S_1 and S_2, are influenced by the reverse recovery of the freewheeling diodes D_1 and D_2. With a nearly zero reverse-recovery characteristic, the SiC JBS diode significantly reduces the switch turn-on energy as compared to the Si diode counterpart.

Fig. 7 compares the turn-on energy of S_2. With the Si diode as the freewheeling diode, D_2, the turn-on energy is 1.5 mJ at the 20-A load condition; while, with the SiC diode as the freewheeling diode, E_{on} is 0.4 mJ at the 20-A load condition. The use of SiC JBS diodes reduces the switch turn-on-related losses by more than 70%.



(a) MOSFET turn-on with fast Si diode



(b) MOSFET turn-on with SiC JBS diode

Fig. 6. Comparison of MOSFET turn-on with SiC JBS diode and fast Si diode as the freewheeling diode.

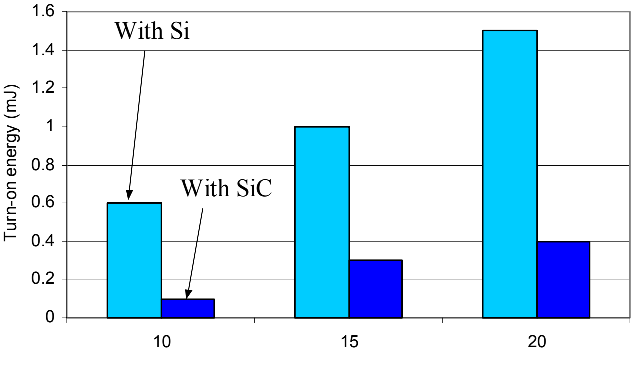
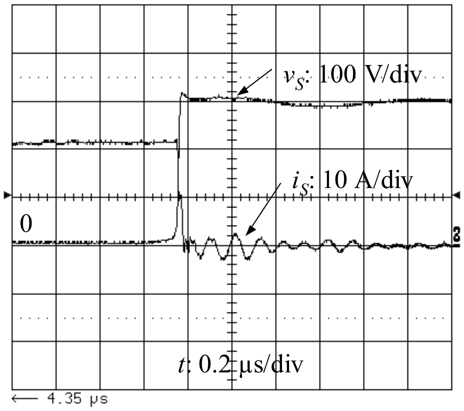
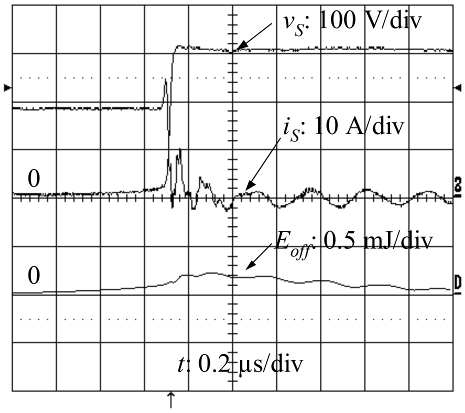


Fig. 7. Turn-on energy of MOSFET with SiC JBS diode and ultra fast Si diode under different load currents.

Fig. 8 shows the current and voltage turn-off waveforms of the MOSFET with Si and SiC JBS diodes at 300-V bus voltage and 20-A load current. The turn-off energy, E_{off}, with SiC JBS diode was evaluated with integration of the voltage and current product. It appears that the speed of the diode does not influence the turn-off energy. Fig. 9 indicates that the turn-off energy of the MOSFET is a function of the load current but is invariant whether the freewheeling diode is Si or SiC JBS. At 20-A load current, the turn-off energy, E_{off}, is 0.2 mJ using either diode.



(a) turn-off with Si diode



(b) turn-off with SiC diode

Fig. 8. Comparison of MOSFET turn-off with Si and SiC JBS diodes as the freewheeling diode

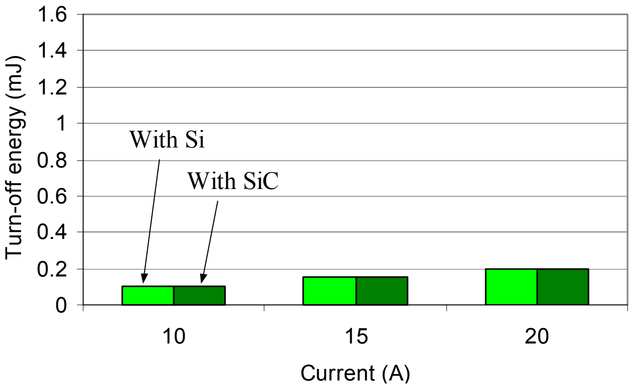


Fig. 9. Turn-off energy with SiC JBS diode and ultra fast Si diode under different load currents.

Based on the switching energy obtained above, the total switching losses using the SiC JBS diode and the fast Si diode can be compared. The total device switching loss for each switch-pair can be expressed as $P_{Q\text{-}sw} = f_{sw}(E_{on} + E_{off})$, and the diode reverse-recovery loss can be expressed as $P_{D\text{-}rr} = f_{sw} \cdot E_{D\text{-}rr}$, where f_{sw} is the switching frequency. Fig. 10 compares the total switching losses ($=2P_{Q\text{-}sw} + 2P_{D\text{-}rr}$) for a chopper using the SiC JBS diode and the fast Si diode under different switching frequencies. The calculation here is for a 6-kVA chopper with a bus voltage of 300 V and a load current of 20 A. It can be seen that the use of a SiC JBS diode cuts switching losses more than 60%, thus reducing size and cooling requirements.

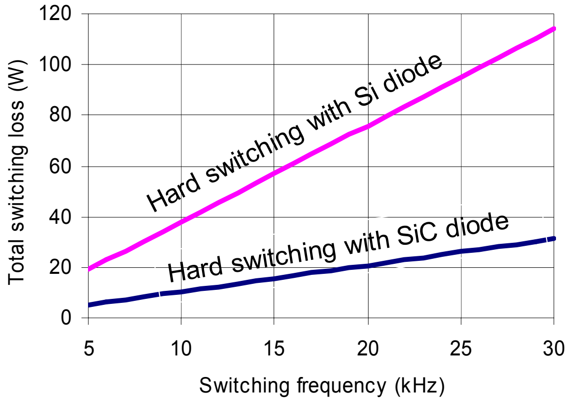


Fig. 10. Comparison of the total switching loss as a function of switching frequency for a 6-kVA chopper using Si and SiC JBS diodes.

IV. SWITCHING CHARACTERISTICS IN SOFT SWITCHING APPLICATIONS

Fig. 11 shows the soft-switching test circuit using an auxiliary resonant snubber chopper (ARSC). The basic circuit structure is similar to that shown in Fig. 3 with two main switches, S_1 and S_2, and two main freewheeling diodes, D_1 and D_2. The lossless snubber capacitors are connected across the main switches and diodes. With soft switching, the main diode can have a slow reverse recovery [9]. An auxiliary resonant circuit that consists of an auxiliary switch, S_r, diode, D_r, and resonant inductor, L_r, is connected across middle points of the two chopper legs. With proper resonant circuit design and control timing, this type of converter can achieve near zero-voltage turn-on and avoid the loss due to diode reverse recovery [7, 8].

In terms of switching timing, the gating signals of the main devices with a fixed time period corresponding to the desired load current is the same as that used in the hard-switching test circuit. The gate signal of the auxiliary switch is added before the main switch is turned on to ensure zero-voltage turn-on of S_2. The basic operating principle of the zero-voltage switching for this ARSC test circuit was described in detail in [7, 8]. The major advantage of this soft-switching operation over conventional hard-switching operation is the provision of a zero-voltage condition before the MOSFET turns on. The MOSFET turn-off voltage is snubbed by the capacitors across the main devices.

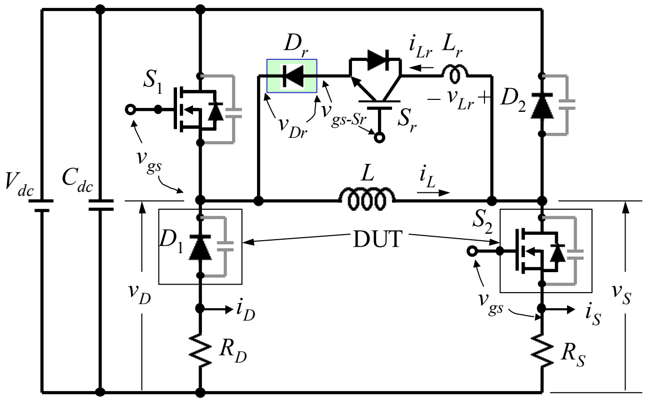


Fig. 11. The auxiliary resonant snubber chopper test circuit.

Fig. 12 shows the gate timing and key operating waveforms of the soft-switching test circuit. The main switches turn on between t_1 and t_2 and between t_4 and t_6, which correspond to the conventional pulse width modulation (PWM) signal. From t_1 to t_2, the MOSFETs are turned on, and the device current increases linearly. Between t_3 and t_5, the auxiliary switch, S_r, turns on to provide the resonant current to divert the load current away from the freewheeling diodes and to allow the devices to be switched under zero-voltage conditions. The resonant current, i_{Lr}, rises from t_3 to a value higher than the load current with sufficient energy to charge and discharge the added resonant capacitors and then drops back to zero before t_5. Thus, the auxiliary switch is turned off under zero-current conditions.

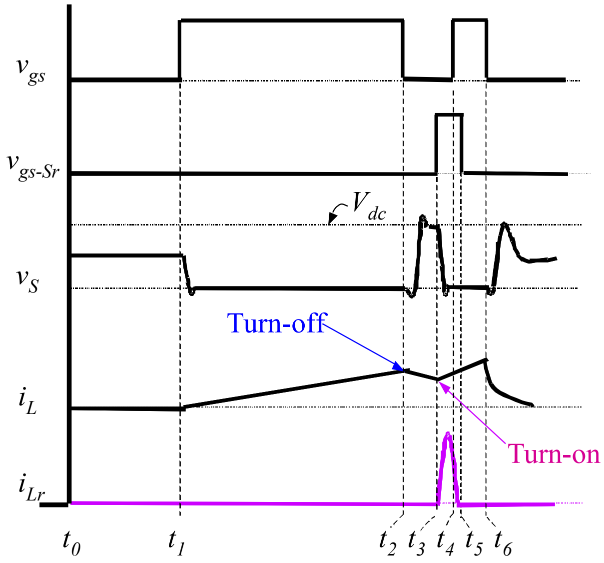


Fig. 12. Corresponding gating signals and waveforms of the test circuit.

The main problem with this circuit operation is the reverse recovery of the auxiliary branch diode, D_r. When the resonant current drops to zero and is blocked by D_r, the reverse-recovery current creates an oscillation, which induces an over-voltage condition for the auxiliary diode.

Fig. 13 shows the experimental results using one of the best available ultra-fast reverse-recovery Si diodes, rated at 50 A and 600 V, as the auxiliary diode. The diode turns off naturally as i_{Lr} goes to zero, with a small reverse-recovery current. The reverse recovery current follows a parasitic ringing that is caused by the junction capacitance of the diode and the resonant inductance, and this introduces a large reverse voltage peak on the diode, which is more than twice the dc bus voltage. In this case, the dc bus voltage is 200 V, and the voltage peaks at 420 V. For a 300 V dc bus voltage, a 600-V Si diode simply cannot be operated without exceeding the diode rating in this soft-switching circuit.

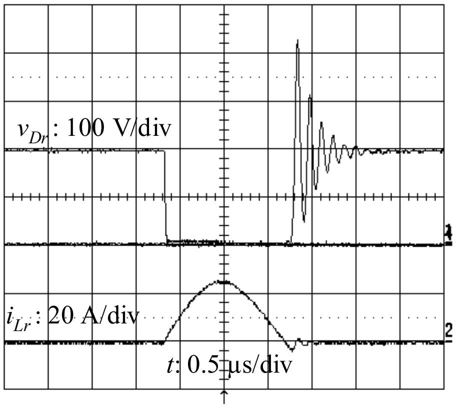


Fig. 13. Resonant branch diode voltage and current with Si diode.

To reduce the ring-excitation effect of the reverse recovery of the auxiliary resonant branch diode, it is common to add an RC snubber across the switch to reduce the voltage rise rate and peak voltage or a saturable reactor (SR) in series with the inductor so that the diode current can be turned off with much reduced di/dt slope. Fig. 14 shows the experimental result using a SR to reduce the di/dt slope. The SR causes the effective inductance of L_r to become large as the current nears zero at the point of diode recovery. This phenomenon can be seen from the i_{Lr} waveform. With the slow falling rate of the resonant current, the peak diode voltage is reduced to 350 V. This approach has been widely used in many soft-switching circuits to resolve the diode reverse recovery problem that has been hindering the use of the zero-voltage switching inverter. The result indicates that overshoot voltage is reduced to less than 20%.

The use of the SR is not without problems. Fig. 14 indicates that a non-trivial switching energy of 0.5 mJ is associated with the SR. If the switching frequency is 20 kHz, the SR consumes 10 W. This additional loss not only reduces the system efficiency, but also causes difficulties in cooling and packaging a small-footprint magnetic core. With a total switching loss of about 60 W, the SR loss represents more than 16% of the total loss.

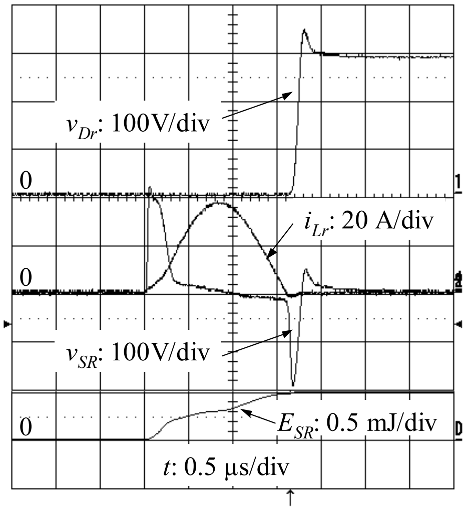


Fig. 14. Resonant branch diode voltage and current with Si diode and saturable reactor.

To avoid the use of the SR, or other voltage-clamping means, the reverse recovery of the auxiliary diode must be fully eliminated. This prompts the use of the SiC JBS diode to eliminate reverse recovery, and thus to reduce the voltage overshoot. Fig. 15 shows the experimental voltage and current waveforms using the high current SiC JBS diode with the 300 V DC bus. As compared to the resonant current, i_{Lr}, waveform shown in Fig. 13, the diode reverse recovery is clearly reduced. However, the diode junction capacitance tends to ring with the resonant inductor and results in a voltage spike about 45% higher than the dc bus voltage. As compared to the circuit with the Si diode, the voltage overshoot is largely reduced, and a 600-V device can be comfortably used in a 300 V dc bus system with the SiC diode. More importantly, the circuit does not need the SR, or other voltage clamping means, and additional associated losses and costs are eliminated.

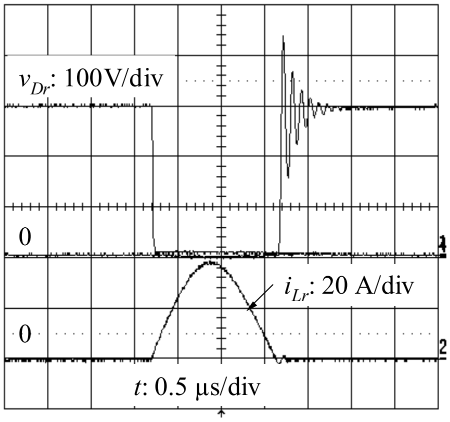


Fig. 15. Resonant branch diode voltage and current with SiC JBS diode.

It should be noted that the 15-A SiC JBS diode operates at a 39-A peak resonant current quite comfortably. The diode turns on and off under zero-current conditions, and the only loss comes from the on-state voltage drop. Fortunately, the auxiliary diode conduction period is only 1.5 µs over a 50-µs period. The diode conduction loss is less than 1 W for the m 6 kVA system, and its body temperature can be maintained near room temperature without heat sinking.

To demonstrate the advantage of the SiC JBS diode in soft-switching applications, the turn-on loss comparison is made for the following three cases in Fig.16: (1) hard-switching chopper with the Si diode, (2) soft-switching chopper with the Si diode and the SR in the auxiliary resonant circuit, and (3) soft-switching chopper with the SiC JBS diode in the auxiliary resonant circuit. For a 6-kVA chopper operating at a 20-kHz switching frequency, the use of the SiC JBS diode, or case (3), cuts the turn-on loss of the soft-switching chopper by more than 50%, as compared to the use of an ultra-fast reverse-recovery Si diode and SR, or case (2). As compared to the hard-switching chopper, or case (1), the use of the SiC JBS diode cuts the turn-on loss from 52 W to 8 W, about an 86% percent loss reduction.

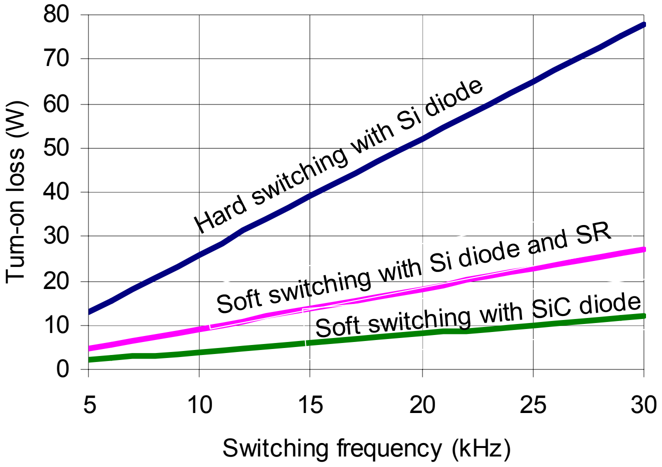


Fig. 16. Turn-on loss comparison for three different cases

V. CONCLUSIONS

In this paper, the use of a high current SiC JBS diode in both hard-switching and soft-switching circuits has been evaluated. Experimental results indicate that, in hard-switching applications, the use of the SiC JBS diode almost eliminates the reverse recovery and the associated transistor turn-on current overshoot as compared to its Si diode counterpart, thus reducing the transistor turn-on losses more than 70%.

In soft-switching applications, the use of a SiC JBS diode in the auxiliary branch reduces voltage ringing by more than 50% compared to ringing caused by the recovery of an ultra-fast Si diode. With the Si diode, the ringing is too high to allow the auxiliary branch network to be used without special suppression techniques such as snubbers or saturable reactors.

When compared with the use of the Si diode and saturable reactor, the use of the SiC diode reduces the power loss associated with the auxiliary branch by 50%. Compared to hard switching, the use of the JBS SiC diode in the soft-switching circuit can reduce transistor turn-on losses more than 86%.

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