Three-level Inverter with 60 A, 4.5 kV Si IGBT/SiC JBS Power Modules for Marine Applications

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***Abstract*— Semiconductor modules with medium-voltage (MV) Si IGBTs and anti-parallel silicon-carbide (SiC) junction-barrier Schottky (JBS) diodes are of interest in commercial and naval converters as they allow for significantly reduced switching losses and at present are more cost-effective than an all-SiC switch [1][2][3]. A three-level converter is being built and tested using custom modules made with 60A (120A pulsed), 4.5kV Si IGBTs and SiC JBS diodes. This work provides a platform to de-risk and evaluate the integration of SiC JBS diodes at MV using commercial modulation strategies and gating electronics with standard industry topologies for a range of switching frequencies. A comparison of SiC JBS diodes for MV, such as the decrease in turn-on IGBT losses and the elimination of snappy or avalanche recoveries is reviewed, and ways to make SiC more cost effective via topology and packaging choices are discussed.**

I. INTRODUCTION

Naval power systems are demanding greater amounts of electrical power on relatively small platforms. To control and distribute such large amounts of power the move to medium-voltage (MV) power converters is essential. SiC JBS diodes are attractive at MV as they significantly reduce IGBT turn-on switching losses as compared to Si PiN diodes [4]. Additionally, Si PiN diodes may necessitate slower turn-on speeds of the IGBT, in order to prevent avalanche or snappy recovery in the diode.

Recent work has shown 6.5kV SiC diodes in a neutral-point clamped (NPC) topology significantly improves efficiency [2]. Other work with lower voltage Si IGBT/SiC JBS diodes in an NPC topology shows that the SiC JBS diodes of the complement switches can be replaced with Si diodes to reduce system cost while still maximizing the use of the SiC and achieving a high efficiency [5]. This approach is not directly applicable to the neutral-point piloted (NPP) topology since NPP does not have asymmetric switching losses in the rail devices like NPC. The NPP topology does not improve system efficiency over the NPC, but does allow for increased current throughput and potentially higher switching frequencies due to the more even distribution of losses [6][7].

These two advantages of the NPP topology coextend benefits of SiC, and additionally, in a given application, could reduce the number of phase-legs and therefore the number of SiC devices needed; however, the NPC in some cases may benefit most from higher voltage utilization of devices that SiC JBS diodes may allow.

This work reviews SiC JBS diodes at 4.5kV as anti-parallel diodes co-packaged with Si IGBTs. The non-snappy behavior of the JBS potentially allows for higher voltage utilization of a 4.5kV IGBT/SiC JBS package versus a Si IGBT with PiN diode. An example of how higher utilization may be beneficial in the NPP and NPC topologies to reduce device count are given.

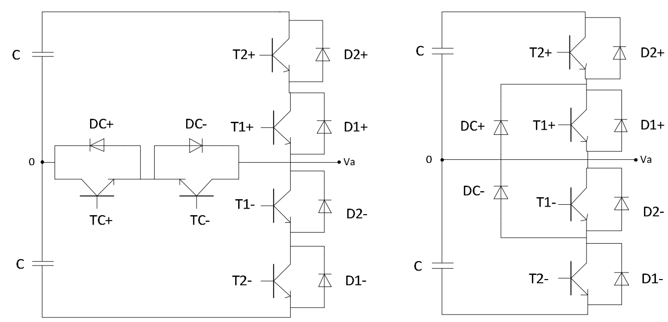

Figure 1: NPP (left) and NPC (right) topology

II. SI PIN VERSUS SIC JBS DIODE

The merits of the SiC JBS diode at MV have been evaluated versus Si PiN to demonstrate their improvement in the turn-on losses when used as the free-wheeling diode for a Si IGBT [4]. A second improvement over MV Si PiN diodes is in reducing the likelihood of snappy and avalanche recoveries during diode turn-off due to the JBS and SiC characteristics, respectively [8].

MV Si power diodes are usually PiN, which means they have an additional lightly doped intrinsic region which is required for higher blocking voltages. Low carrier lifetimes are used to ensure a rapid removal of charge and quick

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14. ABSTRACT

Semiconductor modules with medium-voltage (MV) Si IGBTs and anti-parallel silicon-carbide (SiC) junction-barrier Schottky (JBS) diodes are of interest in commercial and naval converters as they allow for significantly reduced switching losses and at present are more cost-effective than an all-SiC switch [1][2][3]. A three-level converter is being built and tested using custom modules made with 60A (120A pulsed), 4.5kV Si IGBTs and SiC JBS diodes. This work provides a platform to de-risk and evaluate the integration of SiC JBS diodes at MV using commercial modulation strategies and gating electronics with standard industry topologies for a range of switching frequencies. A comparison of SiC JBS diodes for MV, such as the decrease in turn-on IGBT losses and the elimination of snappy or avalanche recoveries is reviewed, and ways to make SiC more cost effective via topology and packaging choices are discussed.

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recovery times; however, this can lead to the space charge region occupying the whole drift region before the reverse-recovery current is zero, which causes the reverse-recovery current to snap to zero and cause damaging overvoltages on the diode due to the high dI/dt [9]. The effect is particularly exacerbated at low forward currents.

As described in [8], a damping factor can be defined for the PiN diode during turn-off such that values greater than one for the damping factor, ζ, indicate a soft recovery, and a damping factor less than 1 and approaching zero indicate the possibility of a snappier recovery. The damping factor is defined below.

$$\xi = \frac{C_T + g_D \cdot L_C}{2\sqrt{L_C \cdot C_T (1 + g_D)}}$$

Where g_D is the conductance of the diode, C_T is the capacitance across the diode, and L_C is the commutation inductance. From the parameters that define the damping factor, the most easily influenced by a converter design perspective is the commutation inductance. From the damping factor it can be shown that larger values of commutation inductance, L_C lead to a softer recovery as shown in Figure 2 for generic constant values of g_D and C_T.

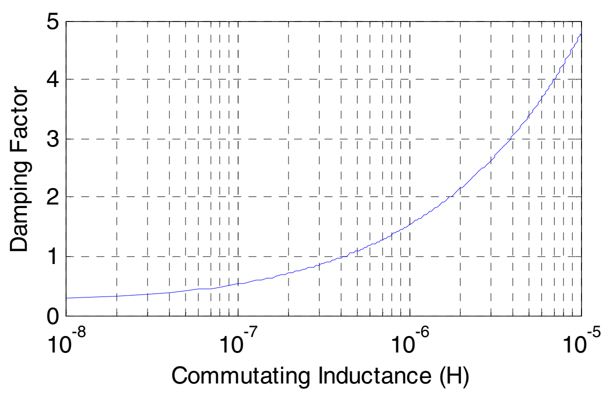

Figure 2: Example of increased damping with increasing commutation inductance

Increasing commutation inductance may ensure a softer recovery; however, it has several implications. First, it can slow down the turn-on and turn-off of both the IGBT and diode which can lead to larger switching loss. Secondly, it increases the overshoot of Vce during the IGBT turn-off as shown in the equation below.

$$V_{CE\_peak} = V_{CE\_steadystate} - L_C \cdot {dI}/{dt}$$

Should the V_{CE_peak} reach dangerous levels due to the additional inductance, overvoltage snubbers, such as parallel resistive-capacitive circuits, may be sized to limit the V_{CE} overshoot at IGBT turn-off and the diode overvoltage at diode turn-off. Regardless, the device may need to be switched at only a portion of its nominal rating to confirm the avoidance of damaging overvoltages; therefore, the snappiness can drive system level design decisions such as the amount of commutation inductance, snubber size, or a voltage derating of the semiconductor devices.

Example results for a 1.5kA, 4.5kV IGBT and Si PiN FWD without any form of snubber are shown below for a commutation inductance of approximately 300nH during turn-off at different levels of current.

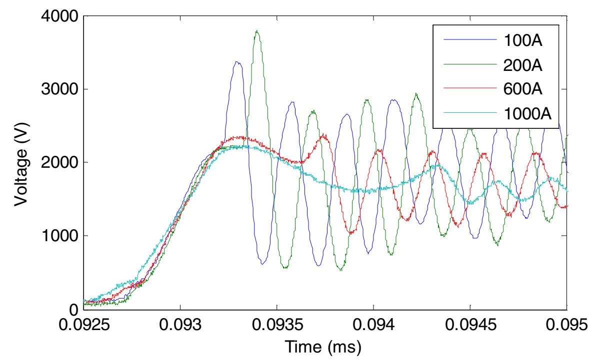

Figure 3: 4.5kV Si PiN Diode turnoff with approximately 300nH commutation in inductance at varying current

This result is compared with the 60A, 4.5kV SiC JBS diode package in a set-up with a commutation inductance of 1.4uH. Likewise there is no snubber used. The result is shown below in Figure 4.

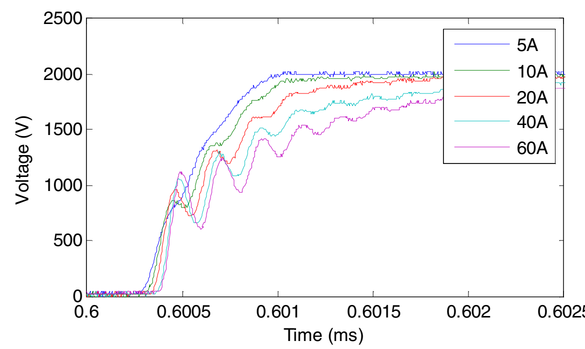

Figure 4: 4.5kV Si PiN Diode turnoff with 1.4uH commutation in inductance at varying current

Due to the JBS there is no additional intrinsic region and therefore the turn-off exhibits no snappy behavior although there is a considerable oscillation in the diode voltage and reverse recovery current (not shown). Another example of the same JBS SiC diode at 2kV with significantly less commutation inductance is shown in Figure 5, where the commutation inductance is reduced to around 300nH.

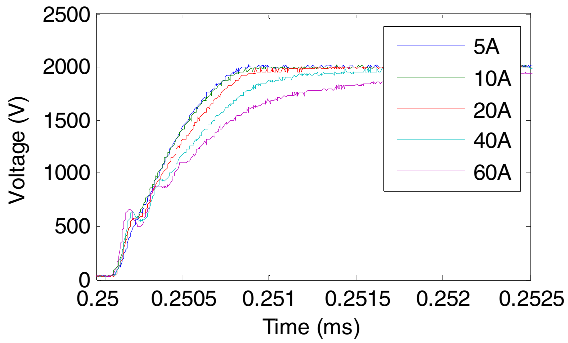

Figure 5: 4.5kV Si PiN Diode turnoff with approximately 300nH commutation in inductance at varying current

Finally, with the low commutation inductance of 300nH, it is shown in Figure 6 that at 3kV there is still almost negligible voltage overshoot.

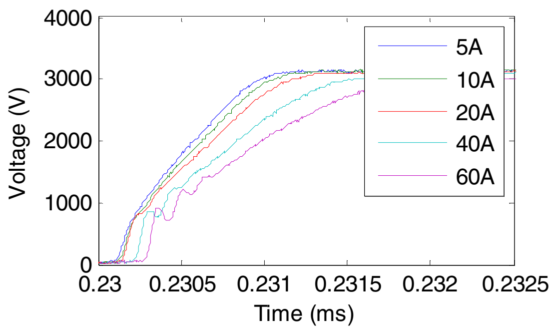

Figure 6: 4.5kV Si PiN Diode turnoff at 3kV with 300nH commutation in inductance at varying current

While this test set-up was limited, it is likely that with a low commutation inductance the switch can operate over 3kV.

III. Reducing SiC Device Count

While the benefits of SiC may be apparent, the semiconductor is at present more expensive than Si; therefore, topologies and die ratios that reduce the cost, but still exploit the benefits of the SiC JBS diodes are of interest for commercial applications. While Si semiconductor devices do not make up an overwhelming percentage of the cost of a commercial drive, the introduction of SiC to increase efficiency or switching frequency can quickly make the converter less cost competitive. One way to reduce this cost is to still exploit the benefits of the SiC, but reduce the number of SiC devices.

As mentioned before, the NPP topology allows for better current utilization of the semiconductor devices than the NPC as the losses are more evenly distributed. This loss distribution is demonstrated in a thermal simulation with the 4.5kV devices in an NPP versus an NPC configuration in Figure 7. The NPP topology on the left has the same loss on T1+ and T2+ in Figure 1, while for the NPC, T2+ has significantly more loss than T1+. As a result the phase-leg is limited by the temperature of T2+ and cannot go as high in current or switching frequency as the NPP for the same operating conditions.

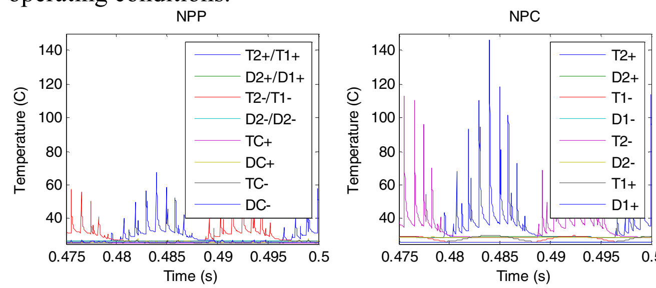

Figure 7: Thermal simulation of NPP (left) and NPC (right) for the same operating conditions.

made up of the comparable number of devices, the NPP will have a higher overall wattage rating than the NPC and therefore may allow less phase-legs, and less SiC devices, per an application.

Another interesting point of comparison is the voltage utilization of the devices in the NPP and NPC. The main difference between the two topologies in this case is that the rail devices must switch and block Vdc/2 in the case of the NPC. In the case of the NPP they must block Vdc/2 but must only switch at Vdc/4 (assuming two series devices).

An analysis is done below in Table 1 for a DC link voltage at 7kV, i.e. nominally a 4160V AC interface, and assuming the 4.5kV IGBT/SiC JBS diode devices. At a 1.8kV allowable device switching voltage, the NPP clearly has an advantage in terms of device count; however, while a higher switching voltage is advantageous for both the NPP and NPC topology as shown in Table 1, a 4.5kV rated (or higher) device capable of switching at 3.5kV allows for the same number of SiC JBS diodes as the NPP and 6 less IGBTs per a three-phase converter. This coupled with the fact that series device matching or voltage sharing snubbers may not be needed for the NPC make the NPC with devices capable of switching at 3.5kV devices an attractive solution for a 4160V interfaced converter.

Table 1: Device Count for NPP and NPC per 3-phase Converter, Vdc = 7kV, at 1.8 kV versus 3.5 kV switching

	NPC				NPP			
Switch Group	Block	Switch	# per SG 1.8kV	# per SG 3.5 kV	Block	Switch	# per SG 1.8kV	# per SG 3.5 kV
T2/D2	3.5 kV	3.5 kV	2	1	3.5 kV	1.75kV	1	1
T1/D1	3.5 kV	3.5 kV	2	1	3.5 kV	1.75kV	1	1
TC/DC*	3.5 kV	3.5 kV	2*	1*	3.5 kV	3.5 kV	2	1
# per rail			6	3			4	3
Total			**36**	**18**			**24**	**18**

*For NPC there is no complement transistor (TC)

The results of Table 1 are particular to the DC link, switching, and blocking voltages; however, the analysis demonstrates the advantage of device voltage utilization.

IV. CONCLUSION

The 4.5 kV SiC JBS diode co-packaged with a Si IGBT has potential to provide improved performance for medium-voltage three-level voltage source converters. The possibility of improved voltage utilization due to the non-snappy recovery in particular can help bring down the cost of use of the SiC modules.

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