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The Impact of Silicon Carbide Technology on Grid-Connected Distributed Energy Resources

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Abstract— Distributed Energy sources can be connected to the electrical grid using power electronic converters traditionally implemented in silicon insulated gate bipolar transistors (IGBTs), gate turn-off thyristors (GTOs) and PiN diodes. However, recently developed SiC technology can improve energy conversion efficiency as well as power density. To investigate the benefits provided by SiC technology, experimentally calibrated SiC MOSFET models have been modeled in multilevel voltage sourced converters (VSCs) to analyze the generated harmonics, converter temperature rise, switching losses and filtering requirements. Models show that converters implemented in SiC MOSFETs operate at 25-75% less temperature compared with silicon IGBTs, potentially simplifying cooling. Also, SiC MOSFETs generate ~2% less THD for the same switching frequency and can reduce the switching loss by up to 82% compared to silicon devices.

Index Terms-- Silicon Carbide FETs, Voltage Source Converters, Total Harmonics Distortion, Switching Losses

I. INTRODUCTION

RECENT advances in wide band-gap semiconductors have opened up new possibilities in the efficiency of power conversion. Silicon carbide (SiC) by virtue of its wider bandgap, higher critical field and higher thermal conductivity can block higher voltages, switch faster and deliver better electrothermal performance under harsh conditions [1]. SiC technology has therefore been studied extensively. The switching performance of SiC power devices in converters has been studied in [2-8] and the combination of SiC power devices and Schottky barrier diodes (SBDs) have been studied in [9-12].

To this end, SiC schottky diodes and MOSFETs have become commercially available at 1.2 kV break-down with increasing current ratings. SiC devices with breakdown voltage ratings as high as 10 kV have been demonstrated in literature with excellent switching characteristics. Researchers have already reported power modules in SiC

with at least 19% less switching losses compared with silicon IGBTs. [13] Other researchers have reported a 25% increase in energy density for SiC modules compared with modules implemented in silicon devices for the same frequency. [14-15] An important advantage of SiC devices is the fact that thinner epitaxial layers can block higher voltages thereby delivering high voltage devices with low conduction losses. Furthermore, enabling unipolar devices at higher blocking voltages where bipolar devices are dominant means higher switching frequencies can be used. Unlike bipolar devices like PiN diodes and IGBTs, where charge storage from conductivity modulation means slow switching speeds, unipolar devices (e.g. FETs) are capable of fast switching.

The use of SiC devices for high efficiency and compact power conversion in renewable energy systems is a very promising prospect. Voltage Source Converters (VSCs) are among the most important converters used to integrate power electronics to power systems. VSCs can be applied in HVDC systems as well as flexible AC transmission systems like static VAR compensators. Currently, VSCs are implemented in silicon IGBTs and PiN diodes. Since IGBTs and PiN diodes have limited switching speeds due to long tail currents and high reverse recovery charge, there are limits to the switching frequencies of the VSCs. In some applications, high switching speeds are desirable so that filter sizes can be reduced especially where weight/space come at a premium e.g. off-shore converters in wind energy systems. Filters are an important part of power converters because they mitigate harmonic injection into the grid [16-18]. However, faster switching causes higher base temperatures from higher losses and possibly reduced reliability from increased electro-thermal and thermo-mechanical stress cycling.

In this paper, experimentally measured SiC FET/SBD and silicon IGBT/PiN diode clamped inductive switching results are fed into a 3-level neutral point clamped VSC model. The impact of the technologies on generated harmonics and operating temperature is analyzed. Section II discusses the experimental set-up, section III discusses the measured results while section IV discusses the converter model.

II. EXPERIMENTAL MEASUREMENTS

Fig. 1 shows the circuit diagram of the clamped inductive switching test rig with the transistor and diode part numbers. Fig. 2 shows a picture of the rig and equipment used to set up the experiments. The test rig is a standard one that emulates current commutation between a high side diode and a low side transistor and the testing is performed as a quasi-clamped inductive switching.

Fig. 1. Schematic of the Test Rig

Fig. 2. Test Rig Components: 1- Thermal Chamber
2-Function Generator 3- Digital Oscilloscope 4- Main Power Supply
5- Interlock Power Supply 6,7- Gate Drive Supplies 8- Capacitors
9-Inductors 10-Gate Drive System inside rig 11-Current Probe
12- Safety Voltmeter 13- Power Breakers

III. DISCUSSION OF MEASUREMENT RESULTS

The switching energies of the transistors (IGBT and SiC MOSFET) were calculated over a wide range of switching speeds and temperatures. The switching speeds were modulated by using different gate resistances while the temperature was set using the thermal chamber. Fig. 3 and Fig. 4 shows the percentage reduction in switching energy of the SiC MOSFETs compared to silicon IGBTs at turn-on and turn-off respectively for different switching rates and temperatures. It can be seen from Fig. 3 and Fig. 4 that up to 82% reduction in switching energy is achieved by using the Silicon Carbide MOSFET and that the performance enhancement over the IGBT increases with increase in the temperatures and switching rate.

Fig. 3. Reduction of SiC FET switching loss compared with Si IGBT

Fig. 4. Reduction of SiC FET switching loss compared with Si IGBT

Fig. 5.Reduction of SiC SBD switching loss compared with Si PiN

Fig. 6.Reduction of SiC SBD switching loss compared with Si PiN

Fig. 5 and Fig. 6 show the percentage reduction of switching energy of the SiC SBD compared to the PiN diodes at turn-on and turn-off. It can be seen from Fig. 5 and 6 that there is significant performance improvement with the SiC SBD showing up to 90% reduced losses compared to the IGBT at turn-off. Fig. 7 shows the switching energies of the transistors as functions of temperature for both turn-on and turn-off. It can be seen from Fig. 7 that the SiC MOSFET switching energy is nearly temperature invariant (especially in lower gate resistances) whereas that of the IGBT increases with temperature. Fig. 8 shows the switching energies of the diodes as function of temperature for both turn-on and turn-off. It can also be seen from Fig. 8 that at turn-off, the SiC diodes performance improves with increasing temperature whereas that of the PiN diode rises significantly with increasing temperature. Hence, like the transistors, the performance of the SiC diode improves with increasing temperature and is significantly better than the PiN diode.

Fig. 7. Switching energy as a function of temperature for the SiC FET/Si IGBT at 15Ω gate resistance

Fig. 8. Switching energy as a function of temperature for the SiC SBD/Si PiN at 15Ω gate resistance

IV. CONVERTER MODEL

Using 2 or 3 level converters is convenient because of the simple gate drive control however this is at the cost of producing large output harmonics which require large filters. Increasing the number of levels of the converters improves the AC waveforms by reducing the harmonics. This is achieved by introducing more steps hence producing more sinusoidal waves. The main advantage of multi-level converters is that less filtering is required, hence, the size of

the filters are more compact. However, the cost of this is the increasingly complex control algorithms required for the gate drives. Another technique that increases energy density is the maximization of the switching frequency and using energy efficient semiconductors like SiC to minimize the switching losses. In conventional three-level diode-clamped converters, silicon IGBTs are used as the switching devices. Using SiC MOSFETs will maintain the voltage blocking capability while adding enabling higher frequency switching. This will have two important impacts:

- Reduce harmonics (THD) by around 2%
- Shifts the core of harmonics to higher orders

Fig. 9 shows the 3-level NPC VSC model that is under investigation. The devices in the converter are parameterized using the switching characteristics measured in Fig. 7 and Fig. 8. The converter is operated as a voltage source inverter connected a DC energy source. The respective datasheets of the devices are also used in the parameterization of models.

A. Impact of Switching Frequency and Device Technology on Converter Temperature

The switching frequency of the devices in the converter ultimately determines the cooling systems, EMI and long-term reliability of the converter. Higher switching frequencies will reduce filtering requirements, at the expense of higher operating temperatures. Fig. 10 shows the impact of increasing the switching frequency on operating temperature of converter for constant dI_{DS}/dt where dI_{DS}/dt is determined by the gate resistance of the driver circuitry.

Fig. 9. Three-Level Three-Phase NPC VSC

Fig. 10. Temperature rise at $dI/dt=99A/\mu s$ as a function of different switching frequencies of the SiC MOSFET/SBD pair

It can be seen from Fig. 10 that higher switching frequencies cause significant temperature rises. This switching rate in dI_{DS}/dt of the device can be modulated by changing the gate resistance. The maximum switching rate will be determined by the semiconductor technology itself since parasitic capacitances also limit the switching rate. Fig. 11 shows the operation temperature of the converter as a function dI_{DS}/dt for a fixed switching frequency. It can be seen in Fig. 11 that the temperature increases as dI_{DS}/dt reduces for a fixed switching frequency. This is due to the fact that longer switching durations generally cause larger switching energy since the latter is the product of the switching power and duration. Fig. 12 shows converter operation temperature at 2 kHz and 10 kHz for the SiC MOSFET and silicon IGBT. The SiC MOSFET shows lower operation temperatures because of the lower switching energy. Hence, the benefits of SiC MOSFET are clear since lower switching energy of technology translates to reduced cooling costs as a result of smaller temperature rises.

Fig. 11. Temperature rise as a function of dI_{DS}/dt for a fixed Switching Frequency

Fig. 12. Effect of Si/SiC Devices Technology on Power Loss and Temperature increase in different switching frequencies

Increase of gate resistances and switching frequencies normally leads to increased temperature in the converter; however this is much more of a concern when silicon IGBTs and PiN diodes are used due to their significant higher losses. As can be seen in Fig. 12, the rate of temperature increase with increasing switching frequency is lower for the SiC based converter compared with the silicon based converter i.e. increasing the switching frequency in the SiC converter from 2 kHz to 10 kHz increases the operation temperature by 65% whereas it is 350% for the silicon converter.

B. Impact of Switching Frequency and Device Technology on Harmonics

An important metric for measuring power quality out of a grid connected converter is the THD which is a measure of the harmonics generated by the converter. Harmonics ultimately determine the specifications of the filter needed for the converter. The requirement for filtering increases with the level of harmonics. Since this will significantly impact the cost, weight and losses in filters, the reduction of filter size is a very important goal as passive elements (inductors and capacitors) used in filters are one of the biggest challenges ahead in converter design. As Fig.13 shows, the THD of the converter based on SiC MOSFETs is around 2% lower than that of the Si IGBT devices with the same frequency and gate resistance. This is due to the fact that IGBTs switch slower than MOSFETs and are in the transient condition for a longer period. Hence the waveform resulting from the converter based on SiC MOSFET switching is closer to the ideal waveform compared to the converter based on IGBTs.

Fig. 13. THD as a function of the switching rate (dI_{DS}/dt) for SiC FET and silicon IGBT showing better performance of the SiC FET

Fig. 14. The graph shows Silicon Carbide MOSFETs can act in a wider range of frequencies especially in case of higher R_G s

The reduction in harmonics distortion in the output of SiC-based converters compared to silicon-based converters is due to the higher reaction speed of SiC devices to gate signal, resulting in a more ideal output compared to the slow reaction of the IGBTs.

Another important factor is the location of the harmonic peaks. Results of converter simulations clearly show that increasing the switching frequency results in the harmonic peaks being shifted to higher orders. This will simplify the task of filter design, since the dominant harmonics have shifted to higher frequencies although the total THD remains relatively the same. This is not achievable in IGBTs since

their switching frequency capability is limited and hence cannot switch as fast as MOSFETs. The switching frequency is ultimately limited by the maximum dI_{DS}/dt of the device, and since MOSFETs have higher dI_{DS}/dt , they can operate at higher frequencies. Fig. 14 shows the calculated theoretical and practical maximum switching frequencies of the SiC MOSFETs and silicon IGBTs. This has been calculated for each gate resistor by using the delays measured during the switching experiments. The on-state conduction duration is assumed to be 10 times the sum of the turn-on and turn-off switching transients. The difference between the theoretical and practical switching frequencies is the allowable THD in the converter output. It can be seen from Fig. 14 that the SiC device has 40%-800% higher maximum switching frequency depending on what gate resistance is used. Given that the modeled SiC based converter exhibits a smaller temperature rise for the same switching frequency and gate resistance, SiC has been shown to have the potential to deliver more energy dense power electronics at reduced cooling costs.

V. CONCLUSION

Voltage source converters (VSCs) will be indispensable in future smart grids since they will be required to interface distributed energy sources (like photovoltaic sources and wind energy) to the grid as well as FACTS technologies and energy storage. These VSCs will be implemented by transistors. In this paper, SiC MOSFETs and silicon IGBTs have been compared in experimental switching test rigs. The switching energies have been measured for a range of temperatures and switching rates. The measurements were used to parameterize device models in a 3-level neutral point clamped VSC model. The SiC devices showed significantly lower switching energies over different temperatures and switching rates compared with the silicon IGBT.

According to the converter simulations, the performance enhancements at the device level translated into lower converter operation temperatures and higher energy conversion efficiency. For a given switching frequency, the models show that the converter implemented in SiC MOSFETs will operate at lower junction temperatures hence, will require less cooling. The THD of the AC voltage output was also positively impacted by SiC technology. Simulations showed that converters based on SiC MOSFETs will generate less harmonics compared with those of silicon IGBTs for a given filtering capacity and switching frequency. This is an important advantage because it means smaller and more compact filters can be used with SiC technology devices in use since switching frequencies can be increased without a high temperature price.

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