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Performance evaluation of SiC MOSFET in 5-level single phase converter

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Abstract

The use of silicon carbide (SiC) semiconductor power devices has been studied and evaluated in a wide variety of converters. The work presented in this paper shows the performance of C2M SiC MOSFETs compared to Si devices operating as switching elements in a 5-level, single phase, multilevel converter. The paper describes the multilevel converter platform used to undertake the evaluation study and experimental results for the operating temperature of the MOSFETs, and conversion efficiency are shown for frequencies ranging from 20 kHz to 80 kHz. Finally, a discussion of the results obtained to highlight the differences in the performance of the Si and SiC devices and the feasibility of using SiC in MLC.

1 Introduction

The impetus to reduce the use of electrical energy produced from fossil fuel resources, and the continued increased in electric powered equipment, has led to the increased deployment of alternative energy resources. A power converter is often required to ensure its energy is supplied to the load in the most efficient manner. A multilevel converter (MLC) is a DC to AC power electronic converter topology that is able to produce output waveforms featuring a much lower harmonic distortion when compared to the typical 2 level converter. In a MLC lower distortion is achieved by reducing the voltage step-size that occurs during a commutation event. Many different MLC topologies have been studied and all exhibit specific attributes which make them more suitable for certain applications. Indeed, some MLC use individual DC voltage sources whereas others split a single DC voltage into multiple levels using capacitor dividers and require ingenious control algorithms to ensure the capacitor voltage remain in balance so as not to affect waveform purity.

The work presented here is focused on a single phase 5-level Neutral Point Clamped (NPC) and is similar to system described [1], see Figure 1. Capacitor voltage balancing control ensures the voltage at the midpoint of C1 and C2 is stable and uses adapted form of space vector modulation typically employed in single phase drive systems [2].

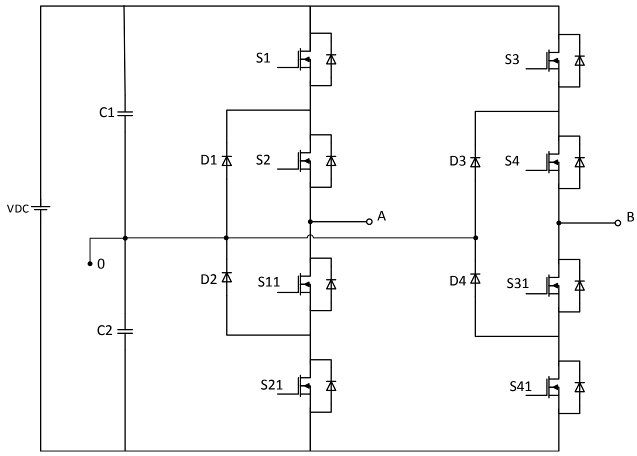

Figure 1: Circuit diagram for the 5-level single-phase converter

To reduce filtering requirements it is desirable to operate the MLC at higher frequencies, however, this can reduce efficiency due to switching losses. Emergent semiconductor devices, such as Silicon Carbide (SiC) MOSFETs, enable high switching frequency and high temperature operation thereby reducing filter size and cooling requirement compared to their silicon (Si) counterparts.

Previous work has been reported in [3] to [7] comparing the performance of SiC over Si devices in multilevel topologies. In [3] and [7] a modular multilevel converter comparison simulation study was undertaken to evaluate the performance of Si IGBT and diode over SiC MOSFET and SiC JFET respectively. In reference [4] a study comparing the efficiency and operating temperatures of a medium power 3-level switched neutral point converter was undertaken by replacing the Si IGBT and Si antiparallel diode with their SiC counterparts. The work presented in references [5] and [6] examine improvement that can be achieved with a 3-level NPC topology. Reference [5] uses simulation to evaluate the performance of SiC diodes (antiparallel and clamping) by comparing the average junction temperature and losses differences with an all Si converter. Reference [6] focuses on a 3-phase converter, and uses simulation to evaluate a variety of PWM methods and the Total Harmonic Distortion (THD) for different gate resistances.

In this paper we present the findings of an experimental study on the performance of SiC MOSFETs and SiC anti-parallel diodes operating within a 5-level NPC MLC. The performance of the MLC operating with SiC devices is compared with that of Si devices, which is based on the temperature rise of the devices and the total efficiency of the converter. A description of the complete system and converter is presented in Section 2 and then the semiconductor devices used in the evaluation are described in Section 3. In Section 4 the experimental evaluation of the switching devices is discussed, highlighting the differences in efficiency and operating temperature of the switching components.

2 5-level NPC Converter

The evaluation platform for this work was a 5-level NPC intended for use in a Vehicle to Grid (V2G) application. The block diagram of the complete system is presented in Figure 2. The work presented here concentrates on the DC to AC 5-level converter. The entire system is designed to provide bi-directional power flow and the control of the system is implemented in LabVIEW, with a FPGA providing gate control signals to the MOSFETs.

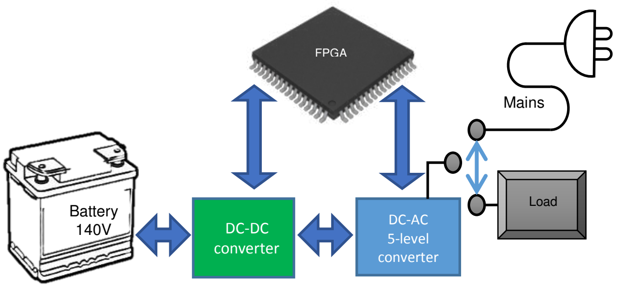

Figure 2: Block diagram of MLC system

The 5-level MLC is based on utilising 2 phases of the 3-level Half-Bridge Neutral Point Clamped (3L-HB-NPC) proposed in [8]. The DC-link is composed of two capacitors C1 and C2 where the input voltage (V) is divided in 2 discrete levels (V/2 and -V/2), Figure 1. Considering a single leg, the output is taken from A and 0, where 0 is the neutral point between the 2 capacitors. The leg output voltage V_{A0} can take on one of three levels -V/2, 0, or V/2 and is produced using the switching states (S_1,S_2) listed in Table 1 where '1' means the switch is ON and '0' indicating the switch state is OFF.

V_{A0} or V_{B0}	S_1	S_2	S_{11}	S_{21}
$V_{dc/2}$	1	1	0	0
0	0	1	1	0
$-V_{dc/2}$	0	0	1	1

Table 1: Switch states 3-level NPC

Although there are different implementations of the NPC topology reviewed in [8], for a single phase system, a topology with an additional leg or phase can be added, taking the output from nodes A and B making the 5-level Full-Bridge NPC (5L-FB-NPC) topology with output voltage levels defined as V, V/2, 0, -V/2 and –V. By using redundant switching states to generate the output voltage the individual divider capacitor voltages maybe balanced.

3 Si and SiC evaluation devices

Wide bandgap (WBG) semiconductor materials such as SiC is enabling an unprecedented performance to be obtained with power electronic switching devices allowing power electronic converters to operate with higher voltage stress, higher temperatures and with reduced size.

Reference [9] presents a review of a series of SiC and Gallium Nitride (GaN) devices including SiC MOSFETs in the range from 1.2kV to 10kV and provides details on the latest improvements in the technology including the MOSFETs in the 1.2kV range from CREE and ROHM. It has been demonstrated in [10] that the 2nd generation of Cree MOSFETs (C2M) can provide long term reliability, based on a stress of 1000 hours and 150°C and 175°C for a V_{GS} of -15V and 20V respectively.

The power electronic devices evaluated in this study are listed in Table 2. The silicon MOSFET N95 was chosen as its ratings are comparable to the range of the SiC devices being evaluated. MOSFETs SiC 040 and SiC 280, were chosen for comparison due to their low $R_{DS(on)}$ and low current rating respectively.

Name	MOSFET	Manufacturer	V_{DS} (V)	I_{DS} (A)	$R_{DS(on)}$ (mΩ)
Si N95	Si	ST	950	10	680
Si FDP	Si	Fairchild	100	164	4.5
SiC 040	SiC	CREE	1200	60	40
SiC 280	SiC	CREE	1200	10	280

Table 2: Switching devices for performance evaluation in 5-level single phase converter

4 Experimental evaluation

In order to effectively evaluate the performance of the switching devices, an external antiparallel SiC diode and a blocking diode was used to minimize the effect of the body diode of the MOSFETs were used as shown in Figure 3, the diode characteristics are detailed in Table 3. The diodes were selected to match the specification of the converter and they were mounted on the same heatsink as the switching devices. The terminals shown as G, D and S in Figure 3, represent the actual terminals connected to the converter topology presented in the previous section.

For each device under test its temperature was measured by using thermocouples attached to the heatsink. The ambient temperature in a laboratory was also measured and subtracted from the measured device temperatures to provide measurements for the temperature rise caused by the losses. The efficiency is determined by measuring the input and output power of the converter.

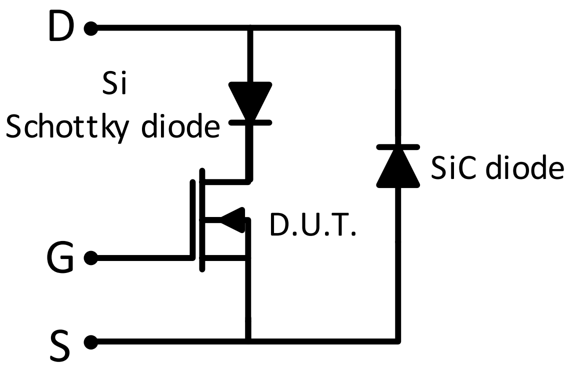

Figure 3: MOSFET with external SiC antiparallel diode and blocking diode.

Name	Device	Manufacturer	V_{RRM} (V)	I_F (A)
Blocking Diode	Si Schottky diode	IXYS	600	50
Antiparallel diode	SiC Diode	CREE	1200	11

Table 3: Characteristics of blocking diode and antiparallel diode

The experimental apparatus, Figure 4, is housed inside an enclosure with forced air provided by fans blowing from the S1 and S3 devices to S21 and S41. Since S1 and S3 are located closest to the fans they receive greater cooling. Labels S1-4 and S11-41 show the locations of the heatsinks fitted with the power devices and C1, C2 are the DC capacitors. The heatsinks have a thermal resistance of R_{th}= 4°C/W. The operating conditions for the experiments are the same, with the evaluation MOSFETs being the only change made during the experiments.

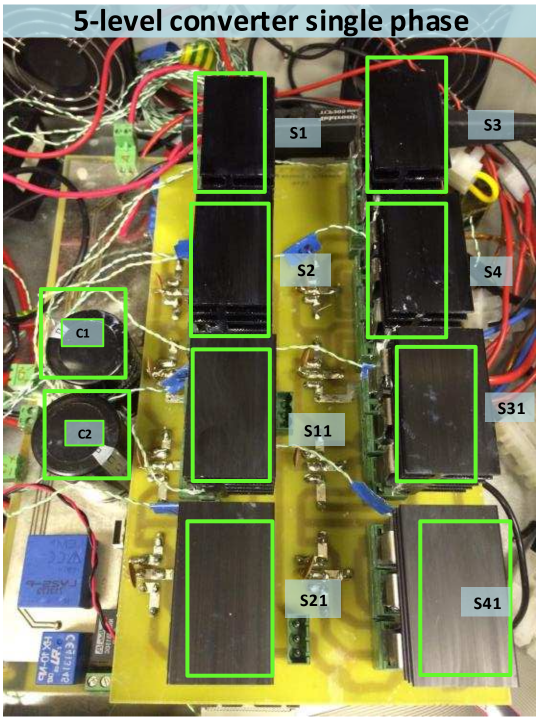

Figure 4: Hardware of converter evaluated

The results for the Si devices evaluated in the experiments is depicted in Figures 5 and 6 shows that for the N95 the temperature rise fluctuates in the range from 50°C to 110°C and for the FDP from 15°C to 37°C, for the range of frequencies tested.

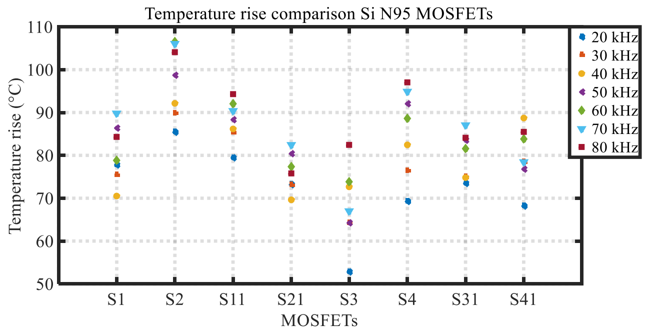

Figure 5: Temperature rise of Si N95 MOSFETs in MLC

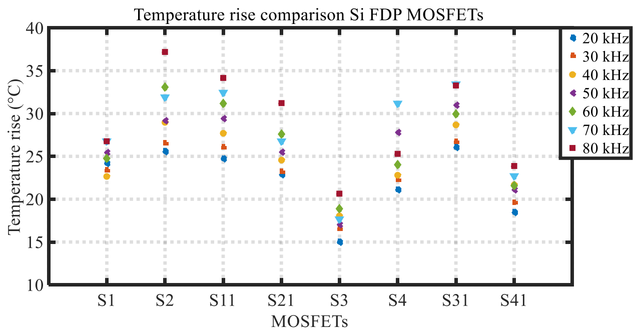

Figure 6: Temperature rise of Si FDP MOSFETs in MLC

The results presented in Figure 7 and 8 correspond to the SiC devices 280 and 040 respectively. The temperature rise is in the range from 25°C to 55°C for 280 MOSFETs and from 12°C to 40°C for the 040 MOSFETs.

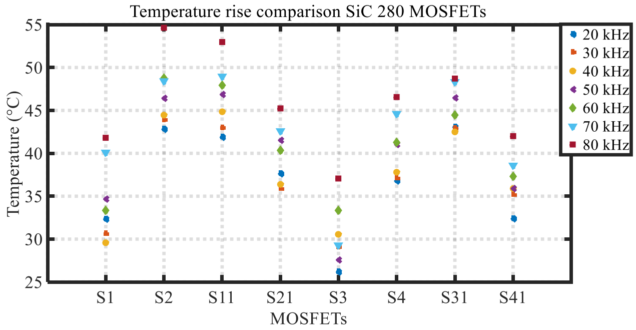

Figure 7: Temperature rise of SiC 280 MOSFETs in MLC

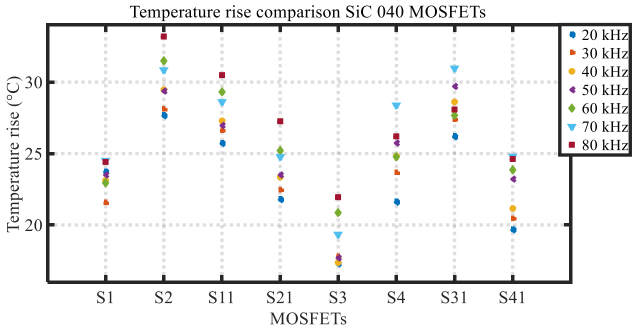

Figure 8: Temperature rise of SiC 040 MOSFETs in MLC

Despite the distribution of the temperatures between the devices, the average temperature rise of all the devices increases with frequency. In Figure 9 the mean temperature of all the devices for a given frequency is taken and plotted to show the average temperature rise as a function of frequency for the Si and SiC devices.

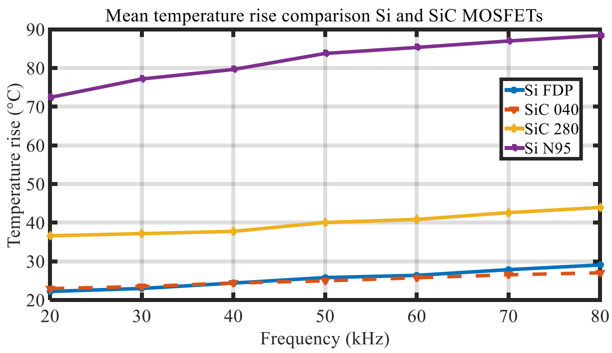

Figure 9: Average temperature as a function of frequency for the Si and SiC devices

It can be seen that the device having the larger temperature increase is the Si N95, followed by the SiC 280 but there is a difference of approximately 40°C. This is to be expected since the $R_{DS(on)}$ of these devices is quite large which leads to higher conduction losses. Comparing SiC 040 and Si FDP reveals some interesting behaviour. At low-frequencies the FDP devices provide better performance due to their lower on-state resistance. However, at higher frequencies the 040 devices give slightly better performance where the switching losses incurred by the Si FDP devices begin to take effect. Indeed, one can observe the gradient is shallower for the 040 devices indicating superior high-frequency behaviour.

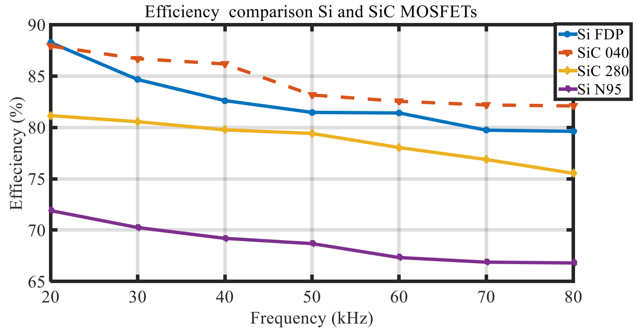

Figure 10: Efficiency comparison as a function of frequency

Efficiency measurements for the MLC fitted with the four types of MOSFETs is shown in Figure 10. As expected the converter with the SiC 040 devices installed performs the best with efficiencies of 88% to 83%, then the Si FDP gives the next highest efficiency with 88.5% to 80% . SiC 280 gives an overall efficiency of 81% to 75% and finally the device giving the lowest efficiency is the N95 with 72% to 66%.

The results clearly show the impact that $R_{DS(on)}$ and operating frequency on the performance of the converter. This is clearly seen in the efficiency measurements as the converter fitted with the 040 devices exhibits the highest efficiency for the range of frequencies considered.

5 Conclusions and future work

The evaluation of performance of SiC compared to Si devices in the 5-level MLC presented in this paper shows the effect of the $R_{DS(on)}$ on the temperature rise of the devices and efficiency. The second generation of SiC MOSFETs and Si MOSFETs evaluated were chosen for their low $R_{DS\ on}$ (SiC 040 and Si FDP) and for the similarity in current and voltage ratings (SiC 280 and Si N95).

The overall performance of SiC devices evaluated in the converter is significantly higher, the low temperature rise with SiC devices would allow the reduction of size as the cooling systems required by these devices are smaller and operating at higher frequencies implies a reduction in filter component's dimensions. Although the temperature rise with Si FDP and SiC 040 appears to be close, the SiC competitor gives lower temperature rise at higher frequencies. Furthermore, the reliability of the SiC devices should be greater as the Si N95 operates at 85% of its voltage rating compared to less than 10% of SiC 040 rating.

It should be noted that the control and modulation scheme remained unchanged for the experiments presented here. It may be possible to modify the control to decrease switching losses for the different frequencies considered which could reduce the temperature rise in the devices and improving the overall efficiency and is currently under investigation.

Acknowledgements

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