Comparative PSCAD and Matlab/Simulink Simulation Models of Power Losses for SiC MOSFET and Si IGBT Devices

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***Abstract*—Silicon carbide devices have several advantages, including high blocking voltage, lower conduction losses, and lower switching losses, when compared to silicon-based devices. This paper demonstrates high power and high frequency operation of the SiC MOSFETs compared to conventional Si IGBT with a similar power rating. The commercial SiC MOSFET QJD1210007 (1200V/100A) from POWEREX and Si IGBT CM100TF-24H (1200V/100A) from Mitsubishi were used in this study. PSCAD and Matlab/Simulink models were used to analyze the power losses of the devices. The following studies were carried out: (i) a comparison between PSCAD and Matlab/Simulink simulation results for a push-pull converter and boost converter, (ii) switching power loss calculations via Matlab/Simulink and accurate loss measurements, and (iii) finally a prototype was built to gather physical measurements to compare with the simulation results. The SiC MOSFET model has been verified by comparing the simulation results with experimental switching waveforms. Based upon the experimental and analytical results, our results show that Matlab/Simulink provides better simulation capability for computing switching losses of the semiconductor devices under investigation. The characterization and modeling processes are generic enough so that these methods can be applied to study new SiC devices.**

Keywords- SiC, MOSFET, switching loss, Semiconductor, PSCAD, Matlab/Simulink, simulation

I. INTRODUCTION

Megawatt power applications require efficient and high power-density converters that are capable of operating at elevated temperatures. The performance of Si-based power transistors is limited due to low junction operating temperatures and low blocking voltage. With the improved performance available from wide band-gap semiconductor materials such as SiC, devices composed of such materials will make the present power converter constraints less of a burden. SiC switching devices have been studied [1-9] and developed in the power electronics industry throughout the last decade. Some commercial power supplies using SiC diodes are already available in the market. [10]

Cree, Inc. has introduced 1,200V, 100A dual SiC MOSFET modules for high-frequency power conversion applications. The devices are capable of operating at a junction temperature of 200°C, which is a 50°C increase over the operating temperature of silicon based power modules. The devices also exhibit low switching and conduction losses, higher voltage operation (1200 Volts), high power dissipation (maximum power dissipation at 880 W), and the ability to operate at high current density for short periods. The research staff has reported, when compared to a silicon IGBT module of equal rating and operating at a junction temperature of 150°C and 20 kHz, the SiC MOSFET module has 38% lower conduction loss and 60% lower switching loss. [10] However, there are significant power losses in SiC MOSFET devices operating at high voltage.

The objective of this study was to compare the power losses of a commercial SiC MOSFET device to a conventional Si IGBT module with a similar power rating. The commercial SiC MOSFET QJD1210007 (1200V/100A) from POWEREX [11] and Si IGBT CM100TF-24H (1200V/100A) from Mitsubishi Electric [12] were selected in this study. Various simulations were carried out to calculate the power loss of SiC MOSFET, and the results were compared to those from experimental measurements. The experiments were performed on a basic push-pull converter and the DC-DC boost converter, and both circuits were used to verify not only the transistors' conduction losses, but also their switching losses.

II. CIRCUIT DESIGN FOR MEASURING TRANSISTOR POWER LOSSES

A. Push-Pull Converter Design Circuit Analysis

The simplified one-line diagrams of the designed circuits representing as a push-pull converter are shown in Fig.1 and 2.

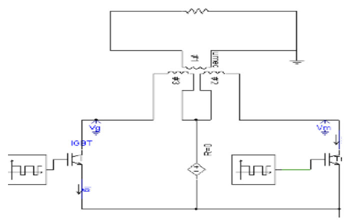

Figure 1. PSCAD model of design circuit

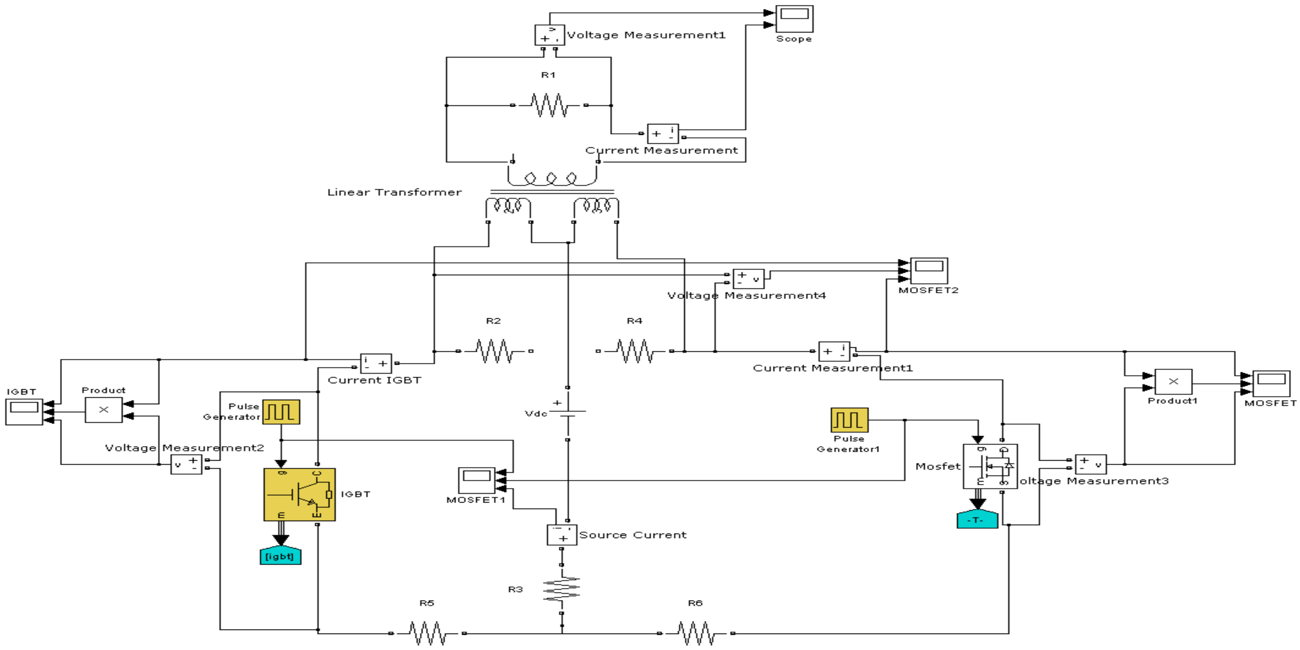

Figure 2. Matlab/Simulink model of design circuit

Fig. 1 represents the designed circuit in the PSCAD environment and Fig. 2 shows the same circuit designed in Matlab/Simulink. A 50V battery is to be used to power a 100Ω load. The gate drive circuit is operating at 20 kHz switching frequency and 50% duty cycle. The advantage of a push-pull converter is its ability to scale up the voltage for high power applications. The push-pull converter design allows one to perform a fair comparison between both devices. The diagrams also show the parameters of the power supply, transformer ratio, and load resistance. When the transformer was inserted into the simulation, excessive currents were recorded through the semiconductor devices. To mitigate this, extra resistances were added, preventing the back flow of current. The transistor parameters for both simulation models were obtained from the commercial SiC MOSFET and Si IGBT data sheets.

Fig. 3 and 4 provide the transistor voltage and current waveforms which were obtained from simulating the circuits in Fig. 1 and 2.

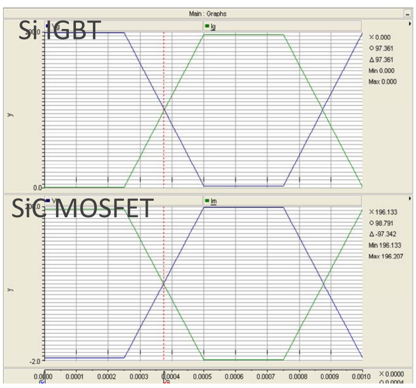

Figure 3. PSCAD simulation results—Voltage and current waveform obtained from the circuit in Fig1

Fig. 3 presents the simulation results from the PSCAD model circuit. The top plot presents the voltage (blue line) and current (green line) of the Si IGBT module, the bottom plot presents those of the SiC MOSFET module. The waveforms show that both transistors demonstrate the same value of maximum voltages and currents.

The transistor voltage and current results obtained by PSCAD simulation show the same results for both the Si IGBT and SiC MOSFET modules, indicating that both devices exhibit the same losses.

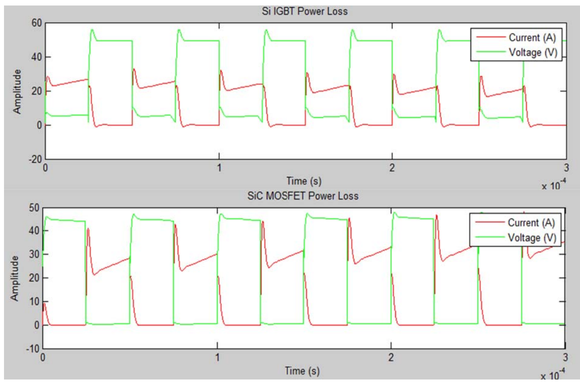

Figure 4. Matlab/Simulink simulation results-- Voltage and Current waveforms

The Matlab/Simulink results, as shown in Fig 4, demonstrate the switching loss of the SiC module was less than that of the Si module. The results show that SiC module has better performance at high switching frequencies operation than the SiC module.

B. Boost Converter Circuit Analysis

A boost converter was also used to evaluate the losses of both semiconductor devices as shown in Fig 5(a) and (b). The boost converter of this experiment was designed to operate in the continuous conduction mode. The boost converter is a good test case since all losses, such as copper loss, diode loss, inductor loss, and capacitor loss, can easily be accounted for. When comparing the losses in the SiC MOSFET and Si IGBT, the copper, diode, inductor, and capacitor losses would be constant from trial to trial. The specific semiconductor in the circuit would strictly cause the difference between the overall circuit loss for the SiC MOSFET case and the Si IGBT case.

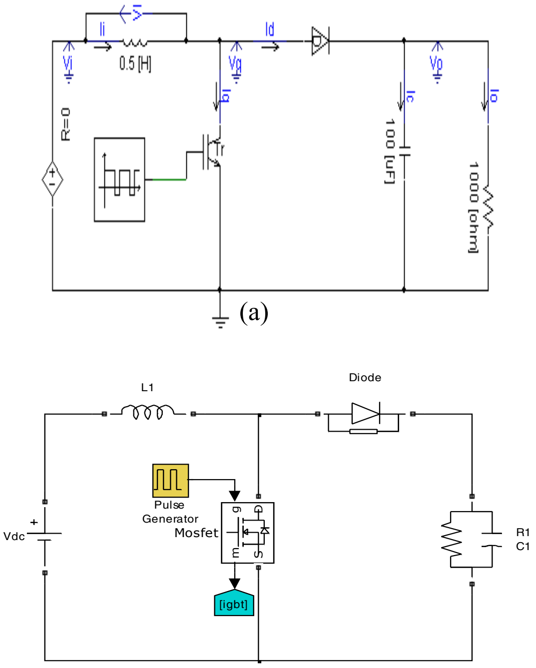

Figure 5. (a) PSCAD model of Boost converter (b) Matlab/Simulink model of Boost converter

The transistor simulation results, specifically the gate current and gate voltage of the SiC module operating with a 20 kHz switching frequency and 50% duty cycle into a 1kΩ resistive load bank are shown in Fig. 6. Other measurements such as the inductor voltage and current, diode current, output voltage and current were also analyzed by both simulation programs. Both simulation platforms present the same results, except for the capacitor current which is caused by the charging or discharging of the capacitor.

By comparing the power losses of the transistors in the two systems, the SiC MOSFET circuit showed superior performance with its lower power loss, higher efficiency and smaller sized technology achieved with this material. The results demonstrate the potential applications of SiC technology in HVDC applications.

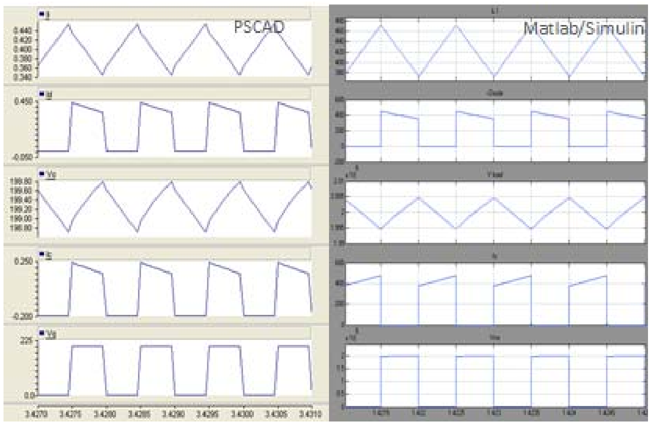

Figure 6. Boost converter characteristic simulation results

III. POWER LOSS CALCULATION BY MATLAB SIMULATION

Fig. 7 provides the SiC MOSFET voltage and currents by simulating the circuit in Fig 2. The drain-to-source voltage (green line) and drain current (red line) of the power MOSFET are plotted.

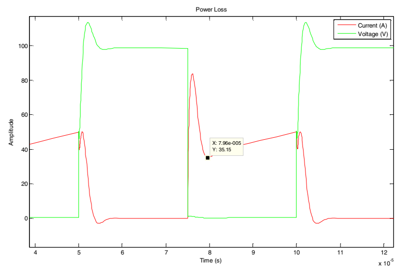

Figure 7. Power loss simulation result for calculating the switching losses

The average power loss dissipated by the semiconductor over one switching period was calculated by Eq. (1). [14]

$$P_{sw} = \frac{1}{T_s} \int_{sw/transitions} I_D V_{Tr} dt \qquad (1)$$

Note that P_{SW} is switching power loss of the transistor, T_s is the time period of the switching signal, I_D is the semiconductor drain current, V_{Tr} is the drain-to-source voltage across the power MOSFET, and t is time.

The conduction losses were calculated using Eq. (3).The power loss in the circuit is a combination of the switching loss, conduction loss, and other losses like block voltage loss (leakage loss) [13, 14]. Since the other losses are much smaller compared to conduction and switching loss, the other losses can be neglected. Therefore, the total power losses can be demonstrated by Eq. (2).

$$P_{total} \cong P_{sw} + P_{cond} \tag{2}$$

$$P_{cond} = I_{out}{}^{2} x R_{DS(ON)} x \frac{V_{out}}{V_{in}} \tag{3}$$

The power dissipated through both transistors is tabulated in Table 1. The intrinsic resistance of different materials varies [15, 16]. The on-resistance of the silicon carbide material is much smaller than that of silicon. The conduction loss is caused by the power dissipated through the intrinsic resistance of the transistor. This experiment was to study the switching loss between these two transistors, so we assume both on-resistances to be the same. However, the results show that the switching losses are approximately about the same for both transistors. The conduction losses had the biggest difference between both devices. In order to reduce the conduction loss, on-resistance must be minimized [17], which requires more silicon resulting in cost increase. Therefore, there is a trade-off between the conduction loss and silicon cost. Besides, the result also presents that the switching turn-on and turn-off time of the SiC MOSFET devices are both smaller than the Si IGBT devices. SiC is a better material for fast switching performance than Si.

Table 1. Power losses measurement via Matlab Simulink

	Turn-on Time	Turn-off Time	Switching Loss	Conduction Loss	Total Loss
SiC MOSFET	0.18µs	2.228 µs	1.787mW	1.1239W	1.125W
Si IGBT	0.27 µs	2.693µs	2.13mW	2.0518W	2.0539W

IV. Simple Prototype with Measurements

The prototype was set up based on the circuit shown Fig. 1 circuit with a 50 V-DC power supply at room temperature.

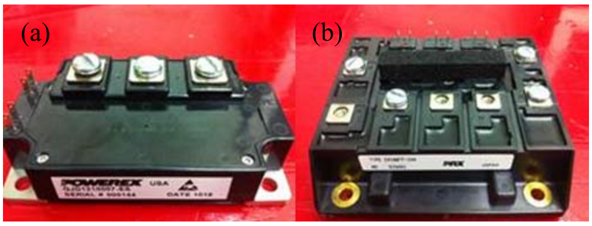

Figure 8. External view of the transistor (a) SiC MOSFET QJD1210007 (b) Si IGBT CM100TF-24H

A high speed op-amp logic inverter was set up to turn the MOSFET (Fig.8(a)) and IGBT (Fig.8(b)) on and off; one driven by the function generator and another driven by the inverter generator signal. The gate driver provides $5V_{div}$ pulse width modulation in the switching operation with 10 kHz switching frequency and 50% duty cycle to both transistor modules as shown in Fig 9. The time-scale is 20µsecond division. Fig 10 shows the gate voltage and drain current of the SiC MOSFET module taken from the oscilloscope, and Fig. 11 shows the behavior of the Si IGBT module.

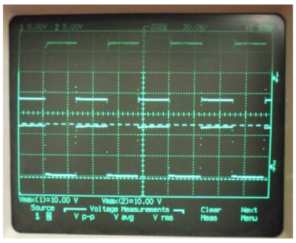

Figure 9. Gate drive signal Oscilloscope capture

The SiC MOSFET turns off faster than the Si IGBT module as shown in Fig 10 and 11, due to charging of the MOSFET's intrinsic capacitance, as well as the switching behavior of the SiC Schottky diode. Therefore, the forward voltage drops increase the breakdown voltage of the devices. [8] During the transistor turn off, there was a tail current in the Si IGBT because the current is proportional to the stored minority charge concentration. In contrast, since the current through SiC MOSFET module did not interrupt, the MOSFET module did not have a tail current [14]. The Si IGBT also showed more oscillation than the SiC MOSFET which means Si IGBT had less damping and would have less switching loses than SiC MOSFET. The oscillation ringing indicated the switching losses that decayed before the end of the switching period. The ringing oscillation stems from the mutual interaction between the parasitic inductance in the circuit and terminal capacitance in the power module.

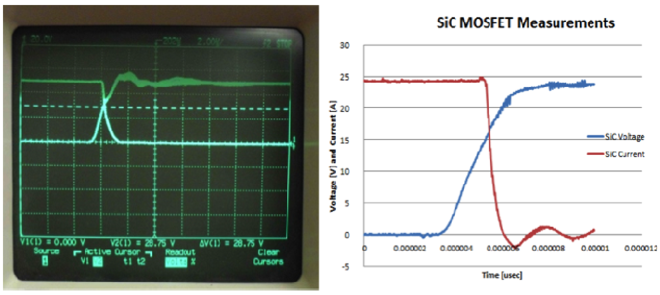

Figure 10. SiC MOSFET Oscilloscope captures

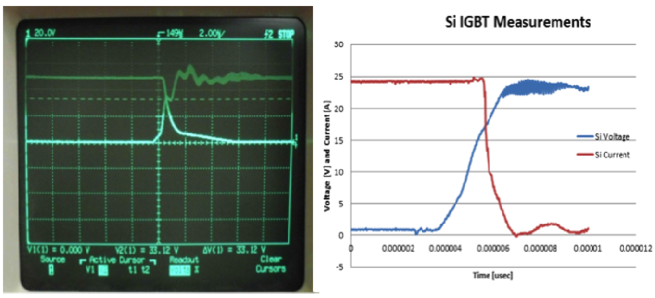

Figure 11. Si IGBT Oscilloscope capture

V. Conclusion

A circuit has been successful designed to measure the power loss of the SiC MOSFET. With the characterization data from the manufacturer, the SiC MOSFET model can be simulated with Matlab/Simulink, a modeling tool which takes into consideration all of the important static and dynamic characteristics of the device. The obtained MOSFET model has been verified by comparing the simulation results with the experimental switching waveforms, and great accuracy has been achieved. Matlab/Simulink shows higher accuracy of the losses analysis compared to PSCAD. In addition, Matlab/Simulink has the ability to directly interface to Matlab and calculate the switching and conduction losses. Compared to the switching power losses, the SiC MOSFET devices losses are 19.19% less than the Si IGBT device. The prototype loss analysis results demonstrate that the SiC MOSFET is a better material than Si IGBT for high power applications.

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