Optimal Control Strategies for SiC MOSFET and Si IGBT Based Hybrid Switch

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***Abstract*—The hybrid switch consisting of a high power Si IGBT and a low power SiC MOSFET has been reported to achieve reduction of losses recently. In this paper, a novel integrated gate driver is proposed for the Si/SiC hybrid switch to achieve its optimized performance and cost-effectiveness. A DC/DC boost converter based on the hybrid switch and the integrated gate driver is built and tested to demonstrate the effectiveness of the gate driver and the superior performance of the hybrid switch. Experimental results show that the Si/SiC hybrid switch with the optimal control strategy can achieve excellent thermal performance and greatly improve the power handling capability or switching frequency of the DC/DC converter compared to the Si IGBT solution.**

Keywords—Hybrid switch; SiC MOSFET; thermal balance; efficiency

I. INTRODUCTION

In recent years, the concept of hybrid switch consisting of a Si IGBT and a SiC MOSFET are reported with improved electrical performance [1-6]. A cost-effective Si/SiC hybrid switch consisting of a high power Si IGBT as a main switch and a low power SiC MOSFET as an auxiliary switch was proposed to achieve good tradeoff between its electrical performance and cost [7-8]. In order to achieve loss reduction of the Si/SiC hybrid switch, specific switching patterns for its internal Si IGBT and SiC MOSFET were proposed [5-8], as shown in Fig.1.

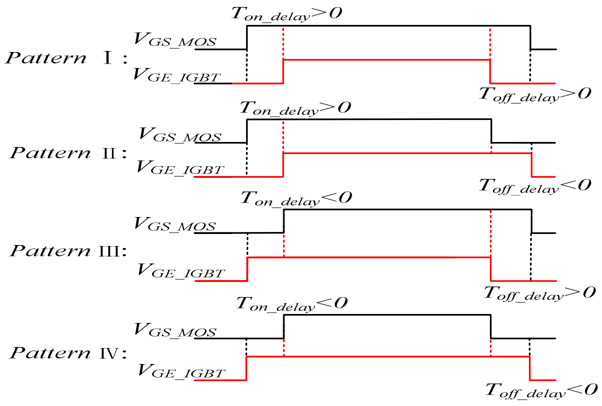

Fig.1: Hybrid switch drive patterns

However, several key issues hinder the wide applications of Si/SiC hybrid switches. First, expensive driver solutions sacrifice the benefit of the cost-effective hybrid switches and increase the complexity of the hybrid switches based power electronics systems since all studies of the Si/SiC hybrid switch make use of two discrete gate drivers with one complicated auxiliary FPGA, CPLD or DSP to achieve the special gate control of the internal SiC MOSFET and Si IGBT in double pulse test circuits or converters. Second, the auxiliary SiC MOSFET has a smaller chip area and larger thermal resistance than the Si IGBT in the hybrid switch. However, few study of the thermal characteristics of the cost-effective Si/SiC hybrid switch have been reported.

In order to overcome these problems, this paper proposes a novel integrated gate driver method for the Si/SiC hybrid switch to achieve its optimized performance and cost-effectiveness. A DC/DC boost converter based on the hybrid switch and the integrated gate driver is built and tested to demonstrate the effectiveness of the gate driver and the superior performance of the hybrid switch. The efficiency and thermal performance of the hybrid switch and the full IGBT solutions are extensively investigated and analyzed.

II. PRINCIPAL OF INTEGRATED HYBRID SWITCH DRIVER

The conventional hybrid switch drive method makes use of two discrete gate drivers with one complicated auxiliary FPGA, CPLD or DSP to achieve the flexible drive patterns. However, these costly solutions sacrifice the benefit of the cost-effectiveness of the hybrid switches and increase the complexity of the hybrid switches based system. Therefore, a novel integrated gate driver is proposed for the hybrid switch to achieve a mutually independent T_{on_delay} and T_{off_delay} for its special drive patterns as shown in Fig.1 with low cost and flexible adjustment.

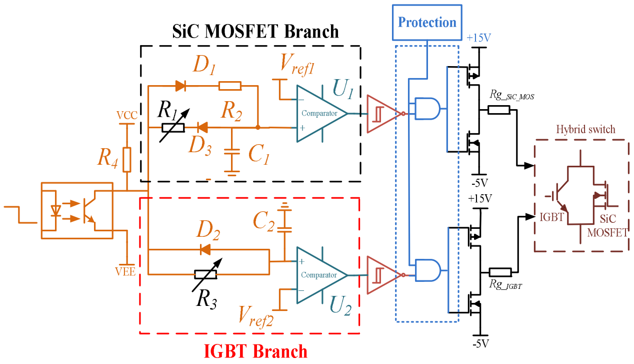

Fig.2 Schematic of integrated hybrid switch driver

Fig. 2 shows the schematic of the integrated gate driver for the hybrid switch. It consists of the SiC MOSFET drive branch, the IGBT drive branch and the protection unit. The protection unit monitors the hybrid switch's saturation voltage, detects desaturation of the IGBT or SiC MOSFET，and immediately turns off the hybrid switch without affecting by the T_{on_delay} and T_{off_delay} in the case of the short-circuit condition. The SiC MOSFET drive branch and the IGBT drive branch are used to achieve the special control patterns for the hybrid switch with a mutual independence T_{on_delay} and T_{off_delay} by means of a simple and convenient method.

A. Hybrid driver turn-on process

The turn-on process of the hybrid switch is shown in Fig.3.

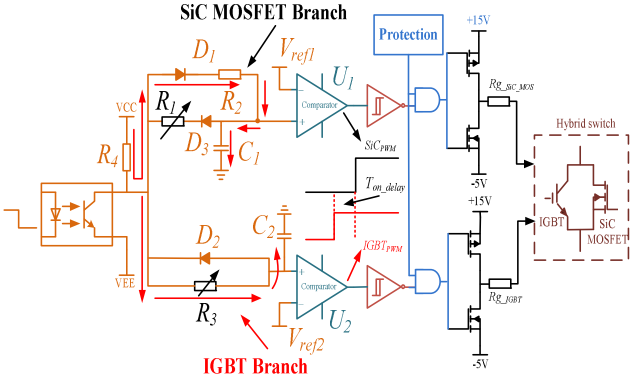

Fig.3: Hybrid switch driver turn-on

When the output of the optical coupler is high level, the current flows through the resistor R_4, diode D_1 and R_2 to charge the capacitor $C1$ in the SiC MOSFET driver branch. The equation of the charging current is expressed as

$$C_1\frac{dV_{C1}}{dt}=\frac{V_{CC}-V_{C1}}{R_4+R_2+R_{D1}} \tag{1}$$

where V_{cc} is the positive power source voltage, V_{C1} is the voltage of the capacitor C_1, R_{D1} is the diode conduction equivalent resistance of D_1. Due to the R_{D1} is very small compared with the R_4 and R_2 which can be ignored. The equation (1) can be simplified as equation (2).

$$C_1\frac{dV_{C1}}{dt}=\frac{V_{CC}-V_{C1}}{R_4+R_2} \tag{2}$$

The initial voltage of capacitor C_1 V_{c1}= $-V_{ee}$, the solution of the equation (2) is depicted as follows.

$$V_{C1}(t)=V_{CC}-(V_{CC}+V_{EE})\cdot e^{-\frac{1}{(R_4+R_2)C_1}t} \tag{3}$$

When V_{c1} is larger than the reference voltage V_{ref1}, the comparator U_1 outputs high voltage. V_{c1} reaches the reference voltage V_{ref1} at time:

$$t_{on1}=-(R_4+R_2)C_1\ln(\frac{V_{CC}-V_{ref1}}{V_{CC}+V_{EE}}) \tag{4}$$

In the IGBT branch, the current flows through the resistor R_4, R_3 to charge the capacitor C_2 according to

$$C_2\frac{dV_{C2}}{dt}=\frac{V_{CC}-V_{C2}}{R_4+R_3} \tag{5}$$

Where the initial voltage of capacitor C_2 is V_{c2}= $-V_{ee}$, the solution of the equation (5) is given as

$$V_{C2}(t)=V_{CC}-(V_{CC}+V_{EE})\cdot e^{-\frac{1}{(R_4+R_3)C_2}t} \tag{6}$$

When V_{c2} is larger than V_{ref2}, the comparator U_2 will output high voltage. V_{c2} reaches the reference voltage V_{ref2} at time:

$$t_{on2}=-(R_4+R_3)C_2\ln(\frac{V_{CC}-V_{ref2}}{V_{CC}+V_{EE}}) \tag{7}$$

The time duration between t_{on2} and t_{on1} is the T_{on_delay} as given by

$$T_{on\_delay}=(R_4+R_2)C_1\ln(\frac{V_{CC}-V_{ref1}}{V_{CC}+V_{EE}})-(R_4+R_3)C_2\ln(\frac{V_{CC}-V_{ref2}}{V_{CC}+V_{EE}}) \tag{8}$$

The key parameter of for the equation (8) is the variable resistance R_3, which could regulate the polarity and length of the T_{on_delay}.

B. Hybrid driver turn-off process

The turn-off process of the hybrid switch is shown in Fig.4.

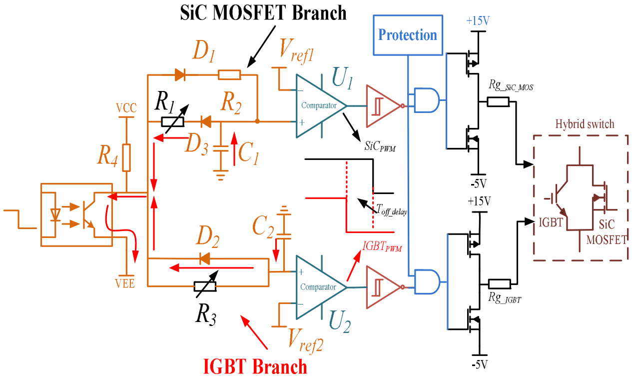

Fig.4: Hybrid switch driver turn-off

When the output of optical coupler is low level, the current only flows through the resistor R_1 to discharge the capacitor C_1 in the SiC MOSFET driver branch according to

$$\frac{-V_{EE}-V_{C1}}{R_1}=C_1\frac{dV_{C1}}{dt} \tag{9}$$

Where the initial voltage of capacitor C_1 V_{c1}= V_{CC}, the solution of the equation (9) is depicted as follows.

$$V_{C1}(t) = (V_{CC} + V_{EE})e^{-\frac{1}{R_1 C_1}t} - V_{EE} \tag{10}$$

When the V_{c1} is lower than the V_{ref1}, the comparator U_1 outputs low voltage. V_{c1} reaches the reference voltage V_{ref1} at time:

$$t_{off1} = -R_1 C_1 \ln\left(\frac{V_{ref1} + V_{EE}}{V_{CC} + V_{EE}}\right) \tag{11}$$

In the IGBT branch, the current flows through the diode D_2 to discharge the capacitor C_2 according to

$$C_2 \frac{dV_{C2}}{dt} = \frac{-V_{C2} - V_{EE}}{R_{D2}} \tag{12}$$

Where R_{D2} is the diode conduction equivalent resistance of D_2. The initial voltage of capacitor C_1 V_{c2}= V_{CC}, the solution of the equation (12) is given as

$$V_{C1}(t) = (V_{CC} + V_{EE})e^{-\frac{1}{R_{D2} C_2}t} - V_{EE} \tag{13}$$

When the V_{c2} is lower than the V_{ref2}, the comparator U_2 outputs low voltage. V_{c2} reaches the reference voltage V_{ref2} at time:

$$t_{off2} = -R_{D2} C_2 \ln\left(\frac{V_{EE} + V_{ref2}}{V_{CC} + V_{EE}}\right) \tag{14}$$

Due to the R_{D3} is very small, the t_{off2} is very close to zero. It means that the comparator U_2 outputs low voltage almost immediately when the optical coupler is low level in the IGBT driver branch. So the T_{off_delay} is mainly determined by the t_{off1}.

$$T_{off\_delay} \approx t_{off1} = -R_1 C_1 \ln\left(\frac{V_{ref1} + V_{EE}}{V_{CC} + V_{EE}}\right) \tag{15}$$

The key parameter of for the equation the equation (15) is the variable resistance R_1, which could regulate the length of the T_{off_delay}.

C. Prototype of the integrated hybrid driver

The prototype of the integrated hybrid switch driver is shown in Fig.5.

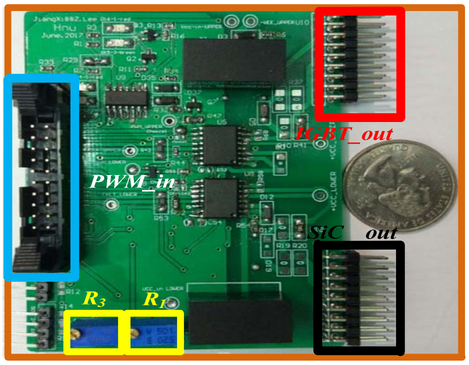

Fig.5: Hybrid switch driver board

The value of the other constant parameters of the hybrid switch driver in equation(8) and (15) are shown in Table 1.

Table 1 Parameters of hybrid driver circuit

Parameter	Value
$+V_{CC}$	+5V
V_{EE}	0V
V_{ref1}	1V
V_{ref2}	1V
R_2	15Ω
R_4	1kΩ
C_1	22nF
C_2	22nF

Since the length and the polarity of the T_{on_delay} and T_{off_delay} is mutual independence, it is very convenient to achieve the different drive patterns for hybrid switch. The measured turn-on delay time of integrated hybrid switch driver at varies R_3 is shown in Fig.6.

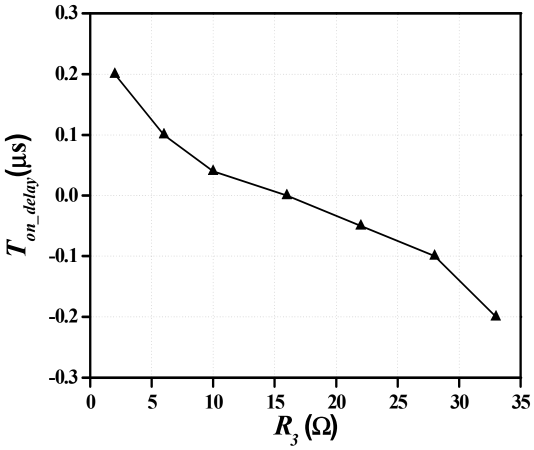

Fig.6: Dependency of T_{on_delay} on R_3

The linear relationship between the turn-on delay time and the R_3 is observed from the Fig.6. When the value of R_3 is lower than 15Ω, the polarity of the turn-on gate signal's delay time is negative, which means the IGBT is turned on prior to the auxiliary SiC MOSFET. When the value of R_3 is larger than 15Ω, the polarity of the turn-on gate signal's delay time is positive and the auxiliary SiC MOSFET is turn-on prior than the IGBT. The measured turn-off delay time of integrated hybrid switch driver at varies R_1 is shown in Fig.7.

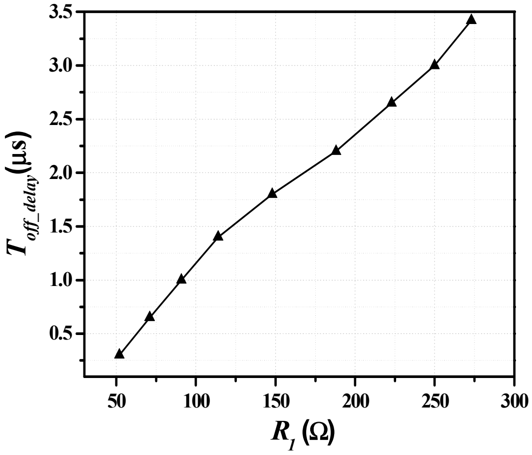

Fig.7: Dependency of T_{off_delay} on R_1

The linear relationship between the turn-off delay time and the R1 is observed from the Fig.7. To eliminate the large tail current loss of the IGBT in the hybrid switch, the turn-off delay time is always positive, which means the auxiliary SiC MOSFET is always turn-off prior than the IGBT.

III. EXPERIMENT

To demonstrate the superior performance of the hybrid switch to full IGBT solutions, a 10kw cost-effective hybrid switch: 1200V 40A Si IGBT (IKW40T120)[9] paralleling with 1200V 11A SiC MOSFET (C2M0160120D)[10] based boost converter prototype is built and tested. The switching frequency is 20kHz, the input voltage is 300V, the output voltage is 600V, the boost inductor is 1mH and the output capacitor is 2200µF. The 40A full IGBT solutions are tested with the same switching frequency and hardware conditions.

The turn-on gate signal's delay time of the hybrid switch is selected as 0µs, which means the IGBT and the auxiliary SiC MOSFET are turned on at the same time. Due to the forward voltage drop of the IGBT during its switch-on transient is substantially larger than its on state voltage drop under steady-state conduction because of the time taken to modulate the conductivity of its N-drift region, most of the forward conduction current will flow through the auxiliary SiC MOSFET because of its low on-state resistance. It creates the zero current switching-on condition for the IGBT to reduce the turn-on loss of the hybrid switch

The turn-off gate signal's delay time of the hybrid switch is selected as 1.8µs, which means the IGBT is turned off prior than the auxiliary SiC MOSFET 1.8µs. It will create the zero voltage switching-off condition for the IGBT to eliminate the large turn-off and tail current loss of the hybrid switch.

When the variable resistance R_1=150Ω and R_3=15Ω, the integrated hybrid switch driver could produce the mutual independence T_{on_delay} =0µs, T_{off_delay} =1.8µs, as shown in Fig.6 and Fig.7. The efficiency of the hybrid switch boost converters and the 40A single IGBT based boost converters is shown in Fig.8.

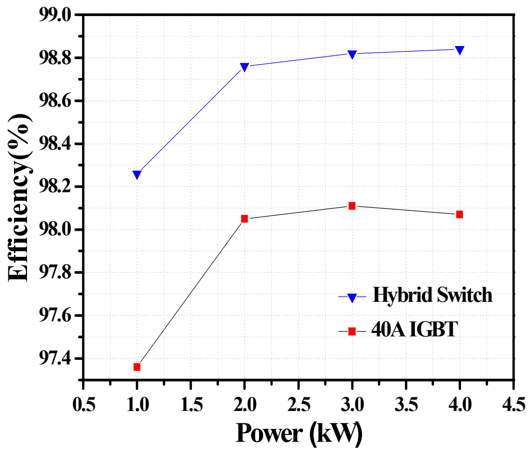

Fig.8: Efficiency of hybrid switch and 40A IGBT

The overall efficiency of the hybrid solution is approximately 0.8% higher than the full IGBT solution at the same power rating. The infrared images of the hybrid switch solution and 40A full IGBT solution are shown in Fig.9 and Fig.10 respectively.

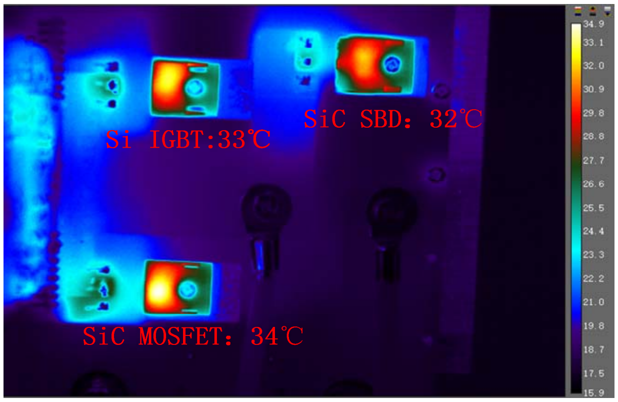

Fig.9: Hybrid switch 4kw

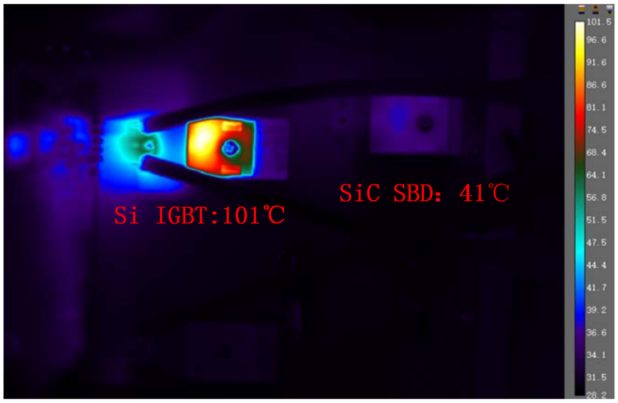

Fig.10: 40A full IGBT 4kw

The case temperature of 40A full IGBT solution is about 101℃ at 4kw, while the case temperature of IGBT and auxiliary SiC MOSFET in the hybrid switch are 33℃ and 34℃ respectively at 4kw, which is about 67℃ lower than the 40A full IGBT solutions.

IV. CONCLUSIONS

A novel integrated hybrid switch driver is proposed for hybrid switch to achieve its optimized performance and cost-effectiveness. With the optimum gate control pattern, the Si/SiC hybrid switch shows excellent thermal performance and significant improvement in the efficiency compared to the single IGBT solutions.

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