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Destressing MOSFETs by Series Connection in Low Gain Buck Converters

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Abstract

Low-gain buck converters will enable low voltage loads to access high voltage DC sources by a single stage converter at very low duty cycles. SiC MOSFETs are still limited to 1.7kV commercially and by seriesing them with adequate gate driving strategy, high voltages can be switched. This paper proposes a driving circuit for series SiC MOSFETs to block higher voltages. The driving circuit provides negative off-state voltage and turn on/off transitions in less than 100ns. The low-gain buck converter performance is assessed when using a single IGBT switch and series SiC MOSFETs. A simulation is implemented and shows the superiority of the proposed driven series SiC MOSFETs with distributed voltage and thermal stresses.

1. Introduction

Wide-bandgap semiconductors devices enabled more improvements in the power electronics fields applications [1]. However, Silicon Carbide (SiC) MOSFETs provides high switching speed due to low gate capacitance, high breakdown voltage and low thermal resistance, which makes it strong candidate for medium and high voltage applications. However, Commercially available SiC MOSFETs are limited to 1700 V breakdown voltage devices. Higher voltage MOSFETs are still in the development or costly [2].

According to the work in [3], series-connected SiC MOSFETs features lower ON-resistance, higher current density, and stronger terrestrial cosmic radiation immunity than using a single high-voltage device. Therefore, the series connection of multiple SiC MOSFETs is reasonable to be investigated.

Medium Voltage DC Network (MVDC) have a huge potential in the coming future to be adopted and implemented in DC grids, for example, to couple power from offshore wind turbines to the national grid via power electronics inverters. The access of these voltages by low voltage loads still not enabled.

Fully separated drivers for SiC device equipped with isolated power supply is presented in [4] to drive series connected devices. This provides driving flexibility but challenge the power design and compactness of the design. A floating self-driving circuit is developed in [5] and [6] unitizing the DC capacitors to support switching the high side of two series switches.

Another way of driving series MOSFETs is by using the capacitive coupling [7], where the charge of a capacitor is used

as a buffer to generate a driving signal to the next MOSFETs. This design facilitates using a single driving circuit.

For higher gate immunity, it is recommended to switch off the SiC MOSFET by a negative voltage, i.e. -5V. This provides more margin against false turn-on when the temperature of the MOSFET increases, and the gate voltage threshold decreases [8].

This paper will introduce how the series SiC MOSFET enables the access of very high voltages to obtain low voltages. The proof of concept will be implemented using a buck converter where the switch is exposed to high voltage stress. The paper shows a design of a series SiC MOSFET driving circuit. A three series SiC MOSFETs and a single IGBT switch are used in the buck converter design and compared by investigating the stresses on the series MOSFETs and IGBT and the distributed losses while stepping down 3kV to 48V.

2. The proposed Series SiC Driver

Fig. 1 shows the structure of the driving circuit for series MOSFETs. The circuit here servers for three MOSFETs with a single gate driver. The load is assumed to be inductive as the double pulse testing will be implemented for switching assessment.

Fig. 2 shows the turn on and turn off transition stages as well as the steady off-state of the proposed circuit.

2.1 Turn-on operation

Before turning on the MOSFETs, it is assumed that all MOSFETs were in a complete off-state. Therefore, all capacitors have initial charges. Fig. 2a illustrates how the turn on starts by providing the first MOSFET M1 with a driving signal V_G . This will charge the gate capacitance leading the

MOSFET M1 to decrease the voltage drop between its drain and source as shown as Loop1. At the same time the driving signal from V_G will be coupled through the capacitor C_{M1} to the gate of the second MOSFET M2 as denoted by Loop2. The drain D1 voltage is dropping while the signal delivered to the gate of M2 becoming sufficient to turn on M2. When MOSFET M2 becomes on, Loop3 shows the charge of C_{M2} is delivered to the gate of MOSFET M3 through the on-state resistance of M2. At ON steady state, all MOSFETs are represented by their on-state resistances and the current flows from D3 to S1.

Fig. 1. Driving Series SiC MOSFETs

Fig. 2. (a) Turn-on Switching transition, (b) Turn-off Switching transition, (c) Steady off-state

2.2 Turn-off operation

Fig. 2b depicts the discharging paths of all gate capacitances. The operation is initiated by an off-voltage signal provided by the gate driver V_G . As shown by Loop4, the gate of MOSFET M1 will discharge and turning it off. The source node voltage at S2 of MOSFET M2 will rise leading to pushing the charge of the gate capacitance of M2 back to V_G through the capacitive coupling C_{M1} as shown by Loop5. Similar behaviour to turn off M3 through the coupling capacitors C_{M1} and C_{M2} . The steady off-state is shown in Fig. 2c. The voltage across M1 is dominated by the ratio between $R_{M1}:(R_{M2} + R_{M3})$.

Loop7 shows that the turn-off voltage for MOSFETs M2 and M3 are set by the voltage drop created by the Zener diodes D_T and D_B . The leakage currents of C_{M1} , C_{M2} and C_{M3} are used to bias these Zener diodes and maintain a negative voltage between the gate and source while in off-state.

$$I_{leakage} > I_{Z(min)} \\ = \frac{V_s - (n-1) \times (V_{DT} + V_{DB}) - V_{drive-off}}{(n-1) \times R_G} \quad (1)$$

where n is the number of MOSFETs and here is 3, $V_{drive-off}$ is the off-state voltage of the gate driver, V_{DT}, V_{DB} are the voltage drop across the Zener diodes in operation and R_G is the gate resistance.

The steady state for all MOSFETs are as follows, assuming that the voltage across the resistor R_G is neglected,

$$V_{off-M1} = V_s \times \frac{R_{M1}}{R_{M1} + R_{M2} + R_{M3}} - (V_{DT} + V_{DB}) \quad (2)$$

The voltage across C_{M2} and C_{M3} are determined by

$$V_{(R_{M2}+R_{M3})} = V_s \times \frac{R_{M2} + R_{M3}}{R_{M1} + R_{M2} + R_{M3}} \\ = V_{CM3} + (V_{DT3} + V_{DB3}) + V_{CM2} + (V_{DT3} + V_{DB3}) \quad (3)$$

Here it is assumed that $V_{CM2} = V_{CM3}$ due to similarity. Therefore,

$$V_{off-M2} = V_{CM2} + (V_{DT} + V_{DB}) \quad (4)$$

$$V_{off-M3} = V_{CM3} \quad (5)$$

Fig. 3. Double pulse testing and its zoomed view for the turn-on and turn-off transitions.

Table 1 Parameter for the DPT simulation

Component	Value	Component	Value
V_s	3000V	D_B	6.8V
L	1000μH	D_T	22V
R_M	100k Ω	R_G	6Ω
C_M	200pF	$V_{drive-on}$	20V
MOSFETs	C2M1000170D	$V_{drive-off}$	-5V

3. Double Pulse Testing Simulation

LTspice was used to simulate switching three MOSFETs in series as in Fig. 1 with a clamped inductor load. The modelled SiC MOSFET is C2M1000170D. Wolfsped provides the spice model, the simulation values are shown in Table 1. The DPT waveforms are shown in Fig. 3 including the gate-source voltages and the drain-source voltages. The results depict a semi-balanced voltage sharing at off- steady state due to the existence of Zener voltages. In addition, it shows consistent dynamics of voltage and currents among all MOSFETs.

Fig. 4. Low gain buck converter

Fig. 5. (a) Output voltage and current and voltage stresses on the three MOSFETs (b) Total losses of each MOSFET (c) Output voltage and current and voltage stresses on the IGBT (b) Total losses of the IGBT

4. Simulation of Low Gain Buck Converter

The design of buck converter components is well-established in the literature and here the focus is on the performance of the power switch in the buck converter which is supplied by a high voltage as 3000V as shown in Fig. 4. The desired output voltage is 48V and load current is 3A. Therefore, the calculated steady state duty cycle is 1.6%. PLECS has been used to conduct the simulation where each power switch is equipped with similar heatsink. The inductor is 2mH and

capacitor is 200μF. The diode is capable to handle the voltage stress. The PLECS models of the used power switches are provided by the manufacturers. The simulated results are shown in Fig. 5 for the output voltage, current/voltage stresses in the power switches and total losses including the switching and conduction loss. The switching frequency is selected as 10kHz. A three series SiC MOSFETs with braking voltage of 1.2kV, C2M1000170D, are used where their voltage stresses are shown in Fig. 5a, as 1kV per MOSFET, and losses in Fig. 5b as 0.64W per MOSFET. The output voltage is stable at 48V. Similarly, the three MOSFETs are replaced with a 3.3kV IGBT, FZ1200R33HE3, and the simulation results are shown in Fig. 5c where the voltage stress is 3kV and losses are calculated as 168.5W in Fig. 5d. It is surprisingly shown that the series MOSFETs outperform the IGBT switch.

5. Conclusion

In this paper, a low gain buck converter is used to assess the performance of series SiC MOSFET against a high breaking voltage IGBT to step down 3000V to 48V. Each MOSFET is able to block 1200V. A driving circuit is proposed with a single gate driver to be able to switch on/off the three MOSFETs. The double pulse testing validated the operation of the driving circuit. The buck converter shown high performance when it used the three MOSFETs compared with a single IGBT. In addition, the electrical and thermal stresses have been distributed leading to longer lifetime and less colling requirement.

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