Design of Snubber Capacitor for Equalization of Voltage Sharing in Series Connected SiC MOSFETs

Juhwa Min and Yongsug Suh

Chonbuk Nat'l. Univ., Dept. of Elec. Eng., 567 Baekje Road, Deokjin-gu, Jeonju, 561-756, Korea

Abstract

There has been a growing demand for power semiconductor switches equipped with high-voltage blocking capability of kV range and fast-switching characteristics of ns range in various plasma application. This paper investigates the application of SiC MOSFETs in the particular plasma application which requires the blocking voltage of 4.5kV and the switching transient time of less than 100ns. In order to meet the required blocking voltage, the series connection of multiple SiC MOSFETs is adopted in this paper. Also, snubber capacitors are employed to equalize the voltage sharing among the series connected SiC MOSFETs. The simulation and experimental result successfully verifies the application of SiC MOSFETs and snubber capacitors in the plasma application requiring high-voltage and fast-switching load dynamics.

1. Introduction

Recently, plasma application fields are expanding in various industry sectors. More and more plasma application systems require electrical power conversion systems of advanced features. These advanced features usually include high-voltage high-current input/output capability and fast control dynamics. Some types of plasma load require the ac output voltage of kV range and the switching transient time of less than 100ns.

The characteristics of wide-bandgap power semiconductor devices such as SiC and GaN devices have been improving dramatically over the last few years. Some manufacturers offer power semiconductor devices having the blocking voltage of kV range and the switching time of less than 100ns. It is expected that these SiC and GaN power devices will play a significant role in ever-growing plasma application fields. Considering this industrial trend, the practical application of SiC and GaN power devices to advanced plasma systems has received less attention in previous literatures. In particular, switching characteristics of SiC and GaN power devices in the range of kV and 10-100ns necessitate the careful consideration of parasitic components and snubber circuitry.

This paper investigates the application of SiC MOSFET in the particular plasma application system which requires the blocking voltage of 4.5kV and the switching transient time of less than 100ns. In order to meet both the required blocking voltage and switching transient time, the series connection of multiple SiC MOSFETs available in the market is adopted in this paper. In general, the switching of output voltage in the range of kV and 10-100ns range may involve the unwanted switching spike due to various parasitic components. In order to secure the required switching transients without switching spikes and equalization of voltage sharing among the series connected SiC MOSFETs, the snubber capacitor across each SiC MOSFET is employed in this paper. On the basis of the given switching specifications of SiC MOSFET, the design guideline of snubber capacitor is provided. The simulation and experiment are performed to verify the successful application of SiC MOSFET and its snubber capacitors in the plasma application requiring high-voltage and fast-switching load dynamics. The experimental setup consists of eight SiC MOSFETs and its snubber capacitors connected in series. The voltage sharing is investigated using this hardware setup.

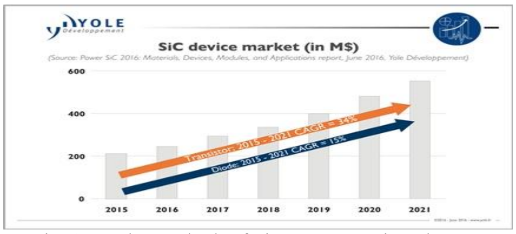


Fig. 1. Market outlook of SiC power semiconductor

2. Design of snubber capacitor

In series connected multiple switches, the voltage sharing among devices during turn-off state becomes important with respect to the safe operation of power semiconductor switch. In particular, the voltage spike during turn-off transient may degrade the reliable operation of power devices. Putting a snubber capacitor and snubber resistor across each switch is regarded as one of cost effective measures to keep even voltage sharing and curb the voltage spike. Depending on the design constraint and parasitic circuit elements, snubber resistor can be omitted. The design of snubber capacitance requires the information of the output capacitance (C_{oss}) and turn-off state resistance (R_{off}) of the power semiconductor device. The equivalent circuit during the turn-off operation of the switch is shown in Fig. 2. The SiC MOSFET (C2M0025120D) considered in this paper has the values of $C_{oss,\,typ}$ = 220pF, R_{off} = 600MΩ (V_{ds} = 1200V, I_d = 2uA). The value of *RC* time constant from the equivalent circuit is 132ms which is much larger than the switching period for the target system considered in this paper. This leads to the fact that the level of voltage sharing among series connected devices during the switching operation of 100kHz is mostly determined by the output capacitance rather than the turn-off state resistance of each switch. Therefore, the snubber capacitance can be added to accurately compensate for the differences among output capacitances of series connected devices.

$$\tau = R \times C = 600 \times 10^{6} \times 220 \times 10^{-12} = 1.32 \times 10^{-1} \qquad (1)$$

3. Simulation Results

Two switches are assumed to have different output capacitances. Simulation is performed under two different conditions; without snubber capacitor and with snubber capacitor. The voltage waveforms of each device under these two different conditions are given in Fig. 3 and 4, respectively. Simulation results show that the output capacitance value plays a critical role in voltage sharing problem and the snubber capacitor can effectively compensate for the voltage sharing under the given switching frequency condition.

TABLE I

SIMULATION PARAMETERS

Parameter	Value
Input step voltage	1200V
Output capacitance of switch 1 ($C_{oss,sw1}$)	220pF
Output capacitance of switch 2 ($C_{oss,sw2}$)	440pF
Off state resistance of switch 1 ($R_{off,sw1}$)	600MΩ
Off state resistance of switch 2 ($R_{off,sw2}$)	600MΩ
Snubber capacitance of switch 1 ($C_{s\,1}$)	470pF
Snubber capacitance of switch 1 ($C_{s,2}$)	470pF

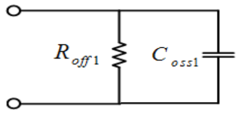
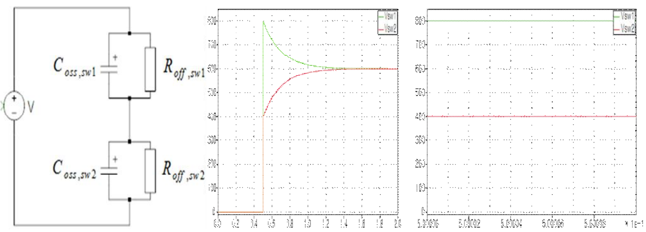
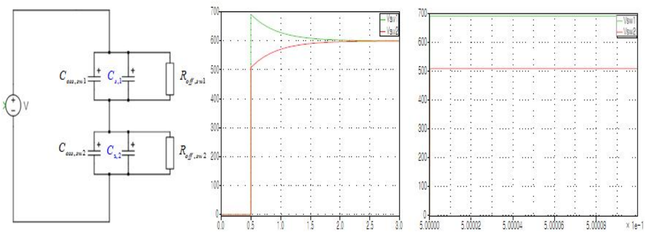


Fig. 2. Equivalent circuit of switch during turn-off state



(a) (b) (c)

Fig. 3. Simulation result during turn-off operation without capacitive snubber (a) simulation circuit (b) voltage waveform of long time range (c) voltage waveform of one period



(a) (b) (c)

Fig. 4. Simulation result during turn-off operation with capacitive snubber (a) simulation circuit (b) voltage waveform of long time range (c) voltage waveform of one period

4. Experimental Results

The corresponding hardware setup is shown in Fig. 5. A total of eight SiC MOSFETs are connected in series in the hardware setup. Each switch is equipped with a snubber capacitor of 470pF. The voltage waveform of every switch is measured during the given switching operation. In Fig. 6, the voltage waveforms of three switches (6^{th}, 7^{th}, and 8^{th}) are illustrated. It is noted in Fig. 6 that the peak spike voltage of each switch during turn-off transient is not equalized. This uneven voltage sharing is attributed to either parasitic components or different values of output capacitances. In order to compensate for this uneven voltage sharing problem, the different value of snubber capacitor is added to the device whose peak spike voltage is at maximum, that is, the 8^{th} device in the test setup. The test result with 940pF and 740pF are presented in Fig. 7 and 8, respectively. The waveforms in Fig. 7 suggest that the snubber capacitance for the 8^{th} device has been over compensated resulting in the voltage drop below the average value of the 6^{th} and 7^{th} device. The snubber capacitance of 740pF for the 8^{th} device is regarded to be nicely tuned as shown by the balanced voltage sharing in Fig. 8. It is confirmed that, with the accurate compensation of snubber capacitor, the voltage sharing becomes very even among series connected SiC MOSFETs.

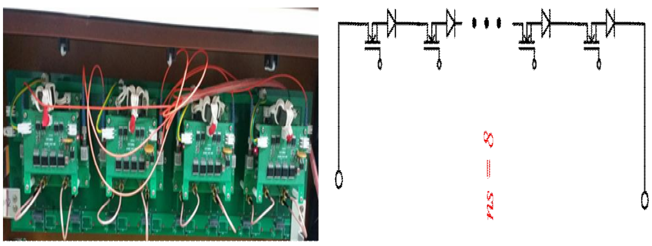


Fig. 5. System hardware configuration

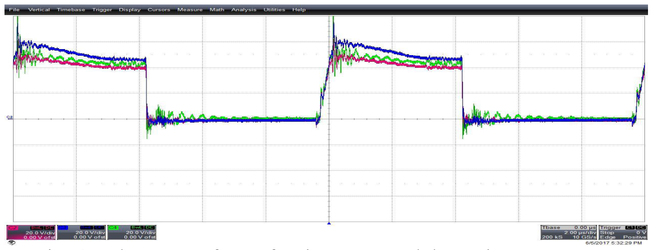


Fig. 6. Voltage waveform of series connected three SiC MOSFETs ($C_{s,6}$, $C_{s,7}$, $C_{s,8}$ = 470pF)

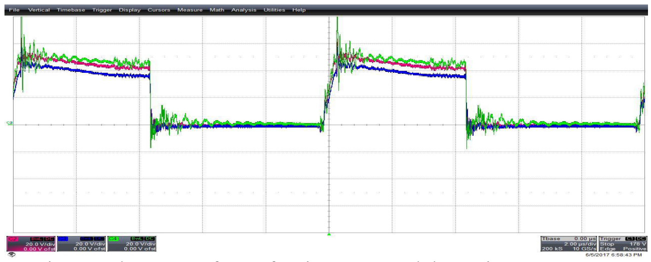


Fig. 7. Voltage waveform of series connected three SiC MOSFETs ($C_{s,6}$ = 470pF, $C_{s,7}$ = 470pF, $C_{s,8}$ = 940pF)

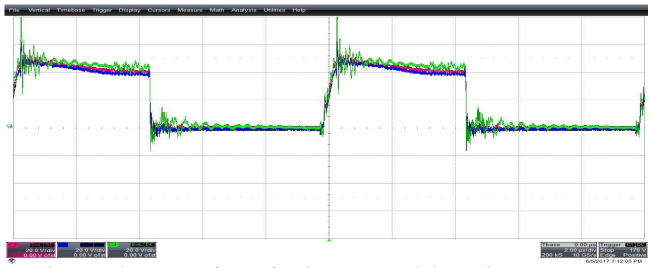


Fig. 8. Voltage waveform of series connected three SiC MOSFETs ($C_{s,6}$ = 470pF, $C_{s,7}$ = 470pF, $C_{s,8}$ = 740pF)

5. Conclusion

In this paper the design guideline of snubber capacitor for a series connection of multiple SiC MOSFETs is provided. It is found that the design guideline of snubber capacitor heavily depends on the accurate information of output capacitance of SiC MOSFET (C_{oss}) in order to secure successful voltage sharing. Simulation and experiment have been performed to prove the proposed design guideline of snubber capacitor. By applying the proposed design guideline of snubber capacitor, the voltage sharing in the case of series connection of eight devices, i.e. n_s=8, has been achieved successfully in the target plasma system requiring the output voltage of 4.5kV and the switching transient time of less than 100ns.

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