Visualization of noise current distribution in an SiC power module using near-field magnetic scanning

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Abstract: This report investigates noise current distribution in the switching operation of a silicon carbide (SiC) power module for optimization of the layout and packaging design. The noise current distribution is measured via the intensity of the near-field magnetic field, and the measurement methodology visualizes the noise current distribution on a wiring plane in the power module. The effect of a direct-current-link (DC-link) snubber capacitor on suppressing the voltage overshoot and ringing oscillation is evaluated using the proposed noise current identification method.

Keywords: SiC power module, parasitic inductance, near-field magnetic scanning, DC-link snubber capacitor

Classification: Electromagnetic Compatibility (EMC)

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1 Introduction

High-voltage silicon carbide (SiC) power semiconductor devices offer faster switching operations and lower switching losses compared with conventional silicon power devices [1]. However, the fast changes in the current during hard-switching transients induce voltage overshoots and high-frequency parasitic ringing oscillations. The SiC power module design should be able to minimize the parasitic inductance of the wiring plane to achieve both low switching losses and low electromagnetic interference (EMI). Previous studies have analyzed the parasitic components using three-dimensional electromagnetic analysis and have evaluated their influence on the switching characteristics [2, 3]. This report focuses on the noise current distribution, measured using the magnetic near-field intensity, in the switching operation of a module. This noise current distribution can then be used for optimizing the layout and packaging design of the SiC half-bridge power module. This report also investigates the effect of a direct-current-link (DC-link) snubber capacitor on suppressing the voltage overshoot and ringing oscillation in an SiC power module.

2 Wiring plane design of the studied SiC power module

The fast switching operation of an SiC metal-oxide-semiconductor field-effect transistor (MOSFET) causes voltage overshoots and parasitic ringing oscillations. These issues result from a resonance in the circuit that comprises the output capacitance in the power device and the stray inductance in the wiring of the module and the smoothing capacitors. The DC-link snubber capacitor is connected across the power bus lines as close as possible to the module to suppress the voltage overshoots and ringing oscillations. The configuration of a prototype SiC half-bridge power module is depicted in Fig. 1(a). There are three SiC MOSFETs (1200 V, 80 mΩ) on the upper side and three on the lower side. Two samples were prepared to evaluate the device characteristics with and without the DC-link snubber capacitor ($C_{sn}$).

Fig. 1(b) depicts the frequency characteristics of the impedance across ports P and N $|Z_{pn}|$ with a 20 µF smoothing capacitor ($C_{smooth}$) as measured by an impedance analyzer (Agilent 4294A). SiC MOSFETs were not implemented to identify the parasitic inductance on a wiring conductor. The frequency characteristics of $|Z_{pn}|$ without $C_{sn}$ are nearly equal to the impedance with $C_{smooth}$. The loop inductance can be identified as 50.4 nH, which includes the parasitic inductance of the wiring in the power module and the input-smoothing capacitor. $|Z_{pn}|$ with $C_{sn}$ shows series-resonance at 100 kHz and 2 MHz and parallel-resonance at approximately 1 MHz. The value of $|Z_{pn}|$ with $C_{sn}$ for frequencies above 2 MHz is lower than the value with the smoothing capacitor. The parasitic inductance, which
comprises the module wiring and the equivalent series inductance of the DC-link snubber capacitor, is extracted as 10.4 nH.

The magnetic field near the conductor current is proportional to the magnitude of the current. Therefore, the magnitude of the current and its distribution on a wiring plane can be estimated by measuring the near-field magnetic field [4]. A magnetic probe (NEC Engineering, MP-10L) connected to a spectrum analyzer (Tektronix, RSA3308B) was used to measure the near-field magnetic field around the device under test (DUT) in this study. The magnetic field was measured by two-dimensional scanning, and the field was reported in two orthogonal directions \( (H_x, H_y) \) at each measurement point. The total magnetic field \( H_{xy} \) was calculated after the measurements were recorded.

### 3 Identification of noise current distribution on the wiring plane in the tested SiC power module

The magnetic field near the conductor current is proportional to the magnitude of the current. Therefore, the magnitude of the current and its distribution on a wiring plane can be estimated by measuring the near-field magnetic field [4]. A magnetic probe (NEC Engineering, MP-10L) connected to a spectrum analyzer (Tektronix, RSA3308B) was used to measure the near-field magnetic field around the device under test (DUT) in this study. The magnetic field was measured by two-dimensional scanning, and the field was reported in two orthogonal directions \( (H_x, H_y) \) at each measurement point. The total magnetic field \( H_{xy} \) was calculated after the measurements were recorded.

#### 3.1 Current distribution

This section evaluates the noise current distribution on a wiring plane in the SiC power module using near-field magnetic scanning. It also discusses the effect of the DC-link snubber capacitor on the reduction and confinement of noise current. The height of the probe was kept constant while scanning in the \( x-y \) horizontal plane. A magnetic probe scanned the copper foil above 6 mm. The measurement pitch was set to 1 mm. Fig. 2(a) depicts the setup for the near-field magnetic measurements to validate the effect of the DC-link snubber capacitor on the reduction of the high-frequency noise components within the power module. A single-frequency sinusoidal voltage \( (V_{pp} = 10 \text{ V}, \text{Freq.} = 150 \text{ kHz}, 1 \text{ MHz}, \text{ and } 10 \text{ MHz}) \) was applied as the source of the noise current component in the SiC power module. A 20 \( \mu \text{F} \) film capacitor was connected in parallel with a 0.5 \( \mu \text{F} \) DC-link snubber capacitor \( C_{sn} \) across the P and N terminals. The measured magnetic field at each frequency is depicted in Figs. 2(b) and 2(c).

The current distribution and its intensity for 150 kHz and 1 MHz are almost the same regardless of whether the DC-link snubber capacitor is added to the device. The highest measured magnetic field intensity for 10 MHz with \( C_{sn} \) in Fig. 2(c) is
109.9 dBµA/m, which is 7.5 dB smaller than the 117.4 dBµA/m value corresponding to the device without $C_{sn}$ as shown in Fig. 2(b). Thus, the high-frequency noise
current caused by the fast switching operation of the SiC MOSFETs is expected to shunt through the snubber capacitor instead of flowing through the DC-bus line.

3.2 Dynamic characteristics of SiC power module

Fig. 3(a) depicts the circuit diagram of a double-pulse test [5] to investigate the switching noise in the studied SiC power module. The DC voltage $E$ was 600 V, and the current flowing through the DUT was set to 40 A by adjusting the first pulse width of the gate drive voltage. The same input-smoothing capacitor $C_{\text{smooth}}$ and the DC-link snubber capacitor from section 2 were applied in the experimental circuit. The SiC MOSFETs were driven by $20/−5$ V gate voltages through a $2\Omega$ gate resistor.

Figs. 3(b)–(d) show the switching characteristics of the studied transistors. There is little difference in the rate of the voltage rise-up for the devices with and without the DC-link snubber capacitor $C_{\text{sn}}$ when they are in turn-off operation. The turn-off operation of the SiC MOSFETs without $C_{\text{sn}}$ in Fig. 3(c) show both
overshoot (706 V) and ringing oscillation characteristics. The ringing oscillation is caused by resonance with the output capacitance of the turned-off transistor and commutation loop inductance. The ringing frequency in the Q2 turn-off voltage is 42.9 MHz. The output capacitance of Q2 at 600 V measured by a curve tracer (Agilent B1505A) is 270 pF. Therefore, the loop inductance is identified as 51.0 nH, which is almost identical to the identified loop inductance (50.4 nH) from Fig. 1(c). The surge voltage of the SiC MOSFET with the DC-link snubber capacitor in the turn-off operation is reduced by 73.5% (628 V). The ringing frequency of the Q2 turn-off voltage is 92.6 MHz. The measured current flowing through the N-terminal of the SiC power module in turn-off operation is depicted in Fig. 3(d). The switching noise current flowing from the DC-bus line is observed for the module without $C_{sn}$. However, the module with $C_{sn}$ does not show the high-frequency noise current component. The lower parasitic inductance will cause higher ringing oscillation frequencies, but high-frequency noise current shunts through the DC-link snubber capacitor, and is confined within the SiC power module. However, the device also displays relatively long-period (approximately 500–600 ns) current oscillations, as shown in Fig. 3(d). The noise component near 2 MHz would flow from the studied SiC power module. This oscillation does not appear in the voltage in the input DC power supply; it is the resonance current flowing through the DC-link snubber capacitor, the input-smoothing capacitor, and the wirings parasitic inductance. Further study is needed to optimize the design of the $C_{sn}$ and $C_{smooth}$ values to reduce and fast damping of this long-period current oscillation.

4 Conclusion

This report studies the current distribution in an SiC power module using a near-field magnetic scanning technique. The measurement methodology visualizes the noise current distribution on a wiring plane in a power module and evaluates the effect of a snubber capacitor in a half-bridge DC link to suppress the voltage overshoots and to confine the high-frequency switching noise to within the power module. Near-field magnetic scanning is an effective tool to evaluate the wiring layout and packaging design for novel SiC power modules because of its compact size, low losses, and low EMI characteristics.

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