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Letters

New Current Measurement Procedure Using a Conventional Rogowski Transducer for the Analysis of Switching Transients in Transistors

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***Abstract*—Developing new power converters often requires the measurement of current transients in transistors once they are positioned on its definitive location at the final printed circuit board (PCB) layout. Non-invasive conventional measuring methods such as active current probes or current transformers require a minimum space around the path of the current under measurement, but that space is not always available on definitive PCBs. The Rogowski current transducer is built by a flexible and thin coil, offers low insertion losses and a high bandwidth, so it is commonly used when space restrictions are important. New semiconductors such as SiC MOSFETs allow faster switching transients and therefore higher *dv/dt* occurs, leading to important perturbations on the Rogowski coil. This letter presents a two-step measurement procedure that allows the rejection of this perturbation. After a first conventional measurement, a second measurement, not encircling the current under study, is performed. During the second measurement the Rogowski coil is located close to the initial position, thus the second measurement records only the *dv/dt* perturbation. This perturbation can be easily subtracted to the first measurement, and therefore a perturbation-free current evolution is obtained.**

***Index Terms*—*dv/dt* immunity, Rogowski current transducer, silicon carbide (SiC) MOSFET, switched current measurement.**

I. INTRODUCTION

ONE of the main concerns of engineers working in the field of power electronics is the maximization of the conversion efficiency [1]. Switching losses at semiconductors can contribute significantly to overall conversion losses, penalizing the input-to-output efficiency. As the switching losses depend on the switching time, manufacturers are offering significantly faster power semiconductors. In a large number of applications operating at industrial voltage levels, the IGBT has been common place, but recently silicon carbide (SiC) MOSFETs are being commercialized, offering a much faster switching behavior [2], [3]. Therefore, new products and systems are being developed using the new SiC MOSFETs and, accordingly, it is necessary to improve some laboratory test procedures [4], [5].

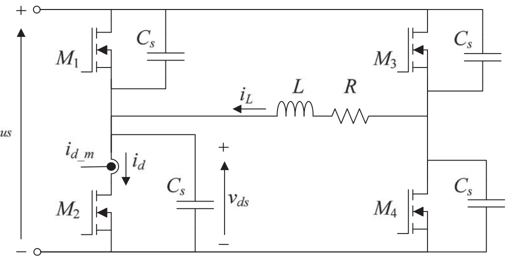

Fig. 1. Full bridge DC/AC converter containing the device under study M_2, being i_d the actual current through the drain of M_2, i_{d_m} the measured id current, $v_{\rm ds}$ the drain to source voltage at M_2, and i_L the inductor current.

Fig. 1 shows a DC/AC converter where the turn-off behavior of the semiconductor M_2 must be characterized. Using a square-wave modulation pattern, a triangular-shape current i_L is obtained. Setting the adequate $V_{\rm bus}$ voltage and switching frequency it is possible to test the turn off behavior under almost any voltage–current scenario. In this example, the turn off behavior of the SiC MOSFET CMF20120D by CREE is being tested at $V_{\rm bus} = 600\,{\rm V}$ and $i_d = 8\,{\rm A}$ ($f_{\rm sw} = 57.2\,{\rm kHz}$).

To compute power losses at M_2, the drain current i_d must be measured, obtaining the measured variable i_{d_m}. Fig. 2 shows a lateral view of the location of the MOSFET on the printed circuit board (PCB), the heat sink, and the path, where the current under measurement flows. The Rogowski current transducer, composed of a Rogowski coil and an electronic integrator, offers a high bandwidth and low insertion losses so it is a good candidate for measuring high-frequency currents [6], [7]. Fig. 2 depicts a typical location of the Rogowski coil with the near field induced distributed parasitic capacitances. Fig. 3(a) shows a picture of the coil in that location.

The coil of the Rogowski current transducer is flexible and thin so it is the best choice when measuring switched currents in narrow spaces. But, unfortunately, Rogowski current transducer suffers of electrostatic interference through capacitive coupling, and this drawback becomes the key issue when measuring currents close to devices with high *dv/dt* [8].

In the middle point of a typical half-bridge circuit, the current connection is kept as short as possible to minimize parasitic inductances, and therefore the Rogowski coil is to be located close to the SiC MOSFET and the heatsink (including the clip),

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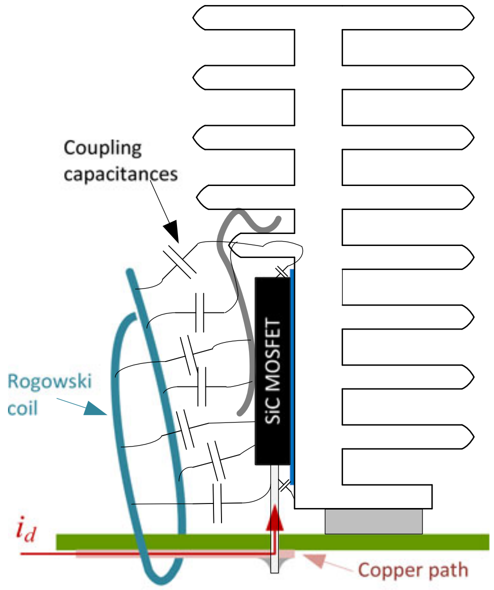


Fig. 2. Lateral view of the SiC MOSFET and Rogowski coil location.

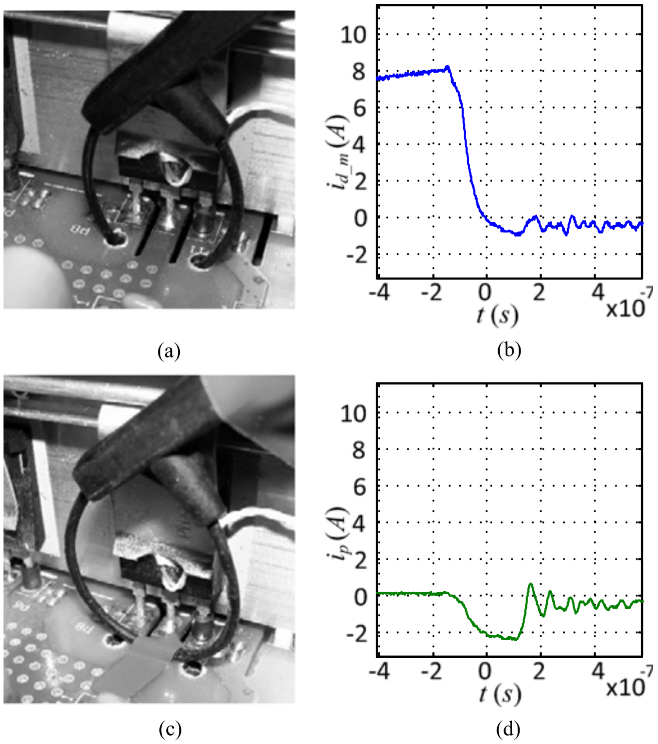
so the parasitic coupling capacitances are more relevant, see Fig. 2. Additionally, during the turn-off switching $v_{\rm ds}$ evolves at a rate of 5 kV/μs, so a high interference voltage is generated at the Rogowski coil. A typical method intended to reduce this interference is based on the insertion of an electrostatic screen fitted to the Rogowski coil. The problem of this solution is that the bandwidth of the Rogowski current transducer is reduced [8], [9] so some work has been carried out trying to overcome this problem by optimizing the geometry of the coil and the electrostatic screen [10].

The procedure presented in this letter enables rejecting perturbations originated by high *dv*/*dt* using any ordinary Rogowski current transducer and avoiding the complexity and drawbacks of an electrostatic shield.

II. DOUBLE MEASUREMENT PROCEDURE

The measurement procedure is performed in two steps. First, a conventional measurement (the so called "first measurement") is performed as seen in Fig. 3(a), obtaining the signal evolution of Fig. 3(b), denoted as i_{d_m}. This signal is the result of the superposition of the actual current i_d, the important perturbation originated by the *dv*/*dt*, and other less important noises. Next, the Rogowski coil is located almost at the same position but without encircling the current to be measured, see Fig. 3(c). This is the "second measurement." The measured signal, shown in Fig. 3(d) and denoted as i_p, contains the perturbation originated by the *dv*/*dt* (and other negligible noise again). Finally, the perturbation current i_p is subtracted to the overall current i_{d_m} and the compensated (or unperturbed) current i_{d_c} is obtained. Using this de-embedding technique leads to a much more precise measurement of the switching process at no additional cost.

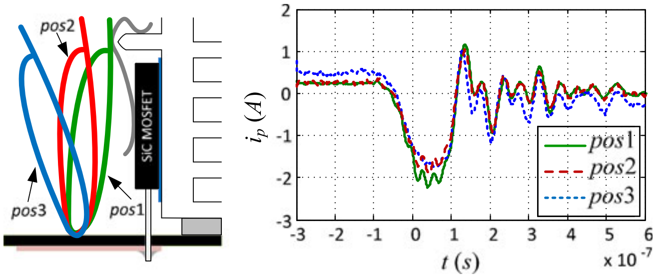
During the second measurement, it could be difficult to position the coil exactly at the same location as in the first measurement so some doubts about the validity of the measurement could remain. In order to overcome this issue, a position-sensitivity test has been carried out by performing a series of three measurements at different positions as shown in Fig. 4(a). Resulting *dv*/*dt* perturbations are summarized at Fig. 4(b).



(a) (b)

(c) (d)

Fig. 3. Double measurement procedure and preliminary results: (a) Rogowski coil location for drain current measurement; (b) measured current i_{d_m} obtained by the transducer at the location (a); (c) Rogowski coil layout for measurement of *dv/dt* perturbations; and (d) measured *dv/dt* perturbations by transducer using the layout of (c).



(a) (b)

Fig. 4. Impact of different Rogowski coil positions on the measurement of perturbations: (a) three positions at which the *dv/dt* perturbation has been measured; and (b) measured dv/dt perturbations at positions of Fig. 4(a).

Observed perturbations show almost the same transient evolution so it can be concluded that, in the particular case of the PCB layout of the converter prototype of this paper, the sensitivity is low and therefore a good perturbation measurement can be achieved. Each particular layout can exhibit different coupling phenomena so the position-sensitivity analysis will always be required.

In order to carry out the compensation of i_{d_m} by subtracting i_p both recorded waveforms must be synchronized. This

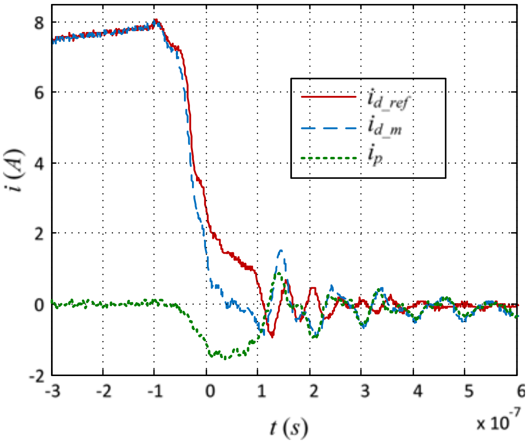


Fig. 5. Measured currents.

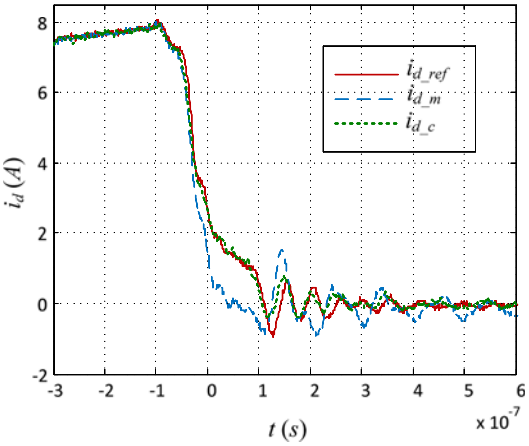


Fig. 6. Evolution of the compensated and noncompensated currents compared to the reference current.

synchronization is achieved by two means: first, the trigger mode is set as the rise edge of v_{ds} (trigger level at 200 V). This may be enough. Nevertheless, the remaining misalignment (if any, e.g., a maximum of 2 ns has been measured for this case) is compensated until both v_{ds} transients match each other perfectly. A perfect matching of both v_{ds} waveforms also indicates that exactly the same transient is being measured (the same dv/dt, resulting ringing and so on).

Fig. 5 shows in detail measured currents during the double measurement procedure. For verification purposes of the proposed method, a reference current waveform i_{d_ref} has been obtained using a Keysight N2783A current probe, which exhibits a bandwidth of 100 MHz and an insertion loss of only 60 mΩ at 10 MHz. During the transient, the measured current i_{d_m} shows a faster evolution toward zero than the reference current i_{d_ref}, leading to an important error of 1.5 A, i.e., up to 19% of the switched current (8A). As it can be observed, the measured perturbation i_p, which is embedded in i_{d_m}, falls down to -1.5 A during the same transient, so it can be the responsible of the abnormal evolution of i_{d_m}.

Fig. 6 shows the results of the compensation. The compensated current i_{d_c} shows now the expected evolution pattern and remains close to the reference current i_{d_ref} during almost all the transient. The new measuring error is around 8%, a clear improvement when compared with the first measurement error.

III. CONCLUSION

A novel but very simple current measurement procedure has been presented. The proposed method allows the accurate and noninvasive measurement of switched currents at SiC MOSFETs directly in their actual location in the final production PCB. Low-cost conventional Rogowski current transducers can be used on a double-measurement basis, allowing the rejection of measurement perturbations originated by large *dv/dt* coupling. This way, using standard laboratory material, it has been possible to accurately measure the turn-off current of SiC MOSFETs and compute precisely the related switching losses.

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