Online and Offline Isolated Current Monitoring of Parallel Switched High-Voltage Multi-Chip IGBT Modules

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***Abstract* - This paper presents the application and the implementation of planar PCB air-coil based current sensors for online current monitoring and offline switching losses characterization of high-voltage, multi-chip IGBT modules. Two types of sensors are presented: a planar PCB Rogowski coil, for measuring alternating currents, and a prototype of a HOKA current sensor, capable of broadband current measurement from DC to 50 MHz without derating. These sensors present superior advantages with respect to the shunt technology since they are more compact, isolated, lighter and integratable. They are advantageous also with respect to conventional magnetic wound current sensors, since the performance characteristics of the planar PCB sensors are more reproducible. The issues related to the measurement of the current sharing of parallel connected modules are analyzed as well as the problems related to the thermal optimization and current sharing within a multi-chip IGBT power module. The advantages of the current measurement in order to perform the monitoring and fault detection of the modules are discussed. In addition, the techniques used to measure the current within a power module are reviewed. Experimental results of current measurements and dynamic performance are included.**

***IndexTerms* - Current measurement, current sensors, high-voltage multi-chip IGBT, switching losses, current control, planar PCB Rogowski coil, current shunt, HOKA probe, current transformer.**

I. Introduction

The feedback current control [1]–[3] and the switching losses characterization [4]–[6] of semiconductor devices are fundamental procedures for the safe and reliable operation of power converters and for assessing the efficiency and reliability of modules. In high power applications, these procedures, operated online and offline respectively, are usually performed by using shunts or conventional cored and coreless current transformers as the current sensing devices. Modern IGBTs present numerous advantages and have replaced old semiconductors technologies in many high-power applications. IGBT chips and freewheeling diodes can be assembled in a compact way and in a variety of configurations, including single switching elements, single inverter legs, or complete three-phase power stages [7]. The relative low voltage blocking capability of IGBTs (usually $\leq$ 6.5 kV compared, for instance, to tens of kV provided by the thyratrons) is such that higher currents have to be switched to achieve high-power levels. Thus, to achieve the required current rating, many switching elements (IGBT chips) are connected in parallel to form a module (see Fig. 1); diodes are placed in anti-parallel to serve as freewheeling elements for inductive load currents. Two main issues have to be carefully considered for the safe operation of the module. The first one, which can result into an excessive power dissipation in one or more devices, is related to the on-state and dynamic loss unbalances that mainly depend on the statistical spread of the device parameters (e.g. V_{CEsat}, V_{th}, switching time), differences in wiring inductance, and on the uneven temperature distribution, all factors, which cannot be avoided in complex modules.

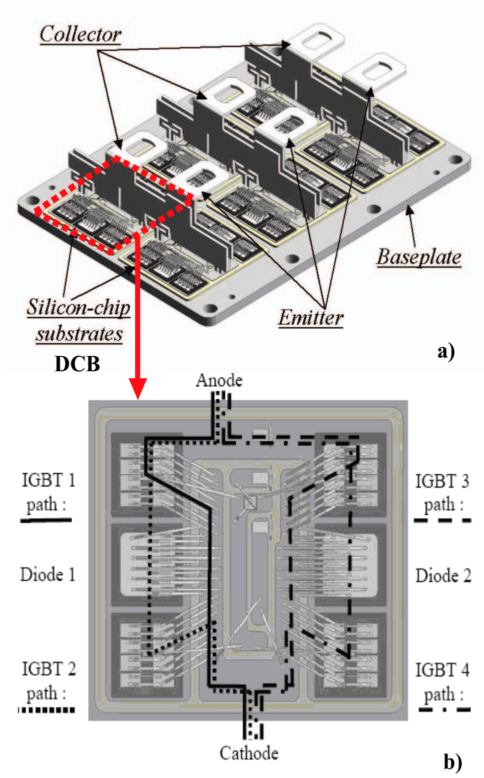

Fig. 1. a) Three-dimensional CAD model of an IGBT module, made out of twenty-four discrete IGBTs and twelve freewheeling diodes, allocated onto six ceramic substrates; b) image of a single ceramic substrate (DCB) showing the asymmetry of the current paths.

The second one is the thermal stability of the device, i.e.

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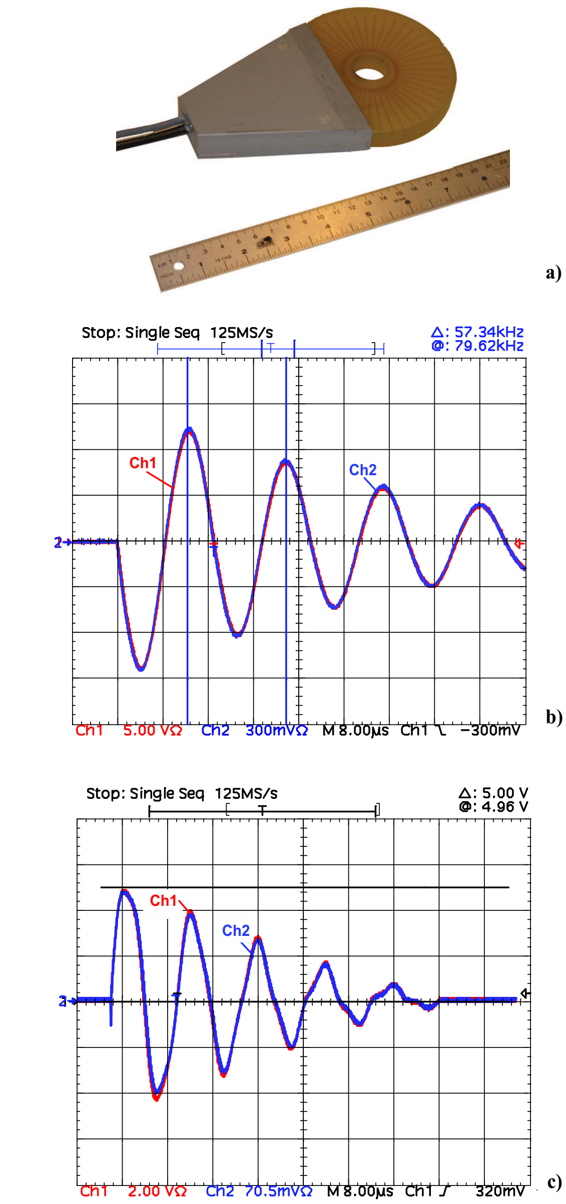

Fig. 2. a) PCB Rogowski coil, bandwidth: 10 MHz, current rating: 50 kA, length: 15 cm. Measurements of a short circuit discharge current of an 40 μF capacitor charged at 2 kV: b) Ch1: Pearson 4418, Ch2: PCB Rogowski coil, 10 kA/div, current-peak 28 kA, time base: 8 μs/div; c) Ch1: Pearson 4418, Ch2: PCB Rogowski coil, 4 kA/div, current-peak 10 kA, time base: 8 μs/div.

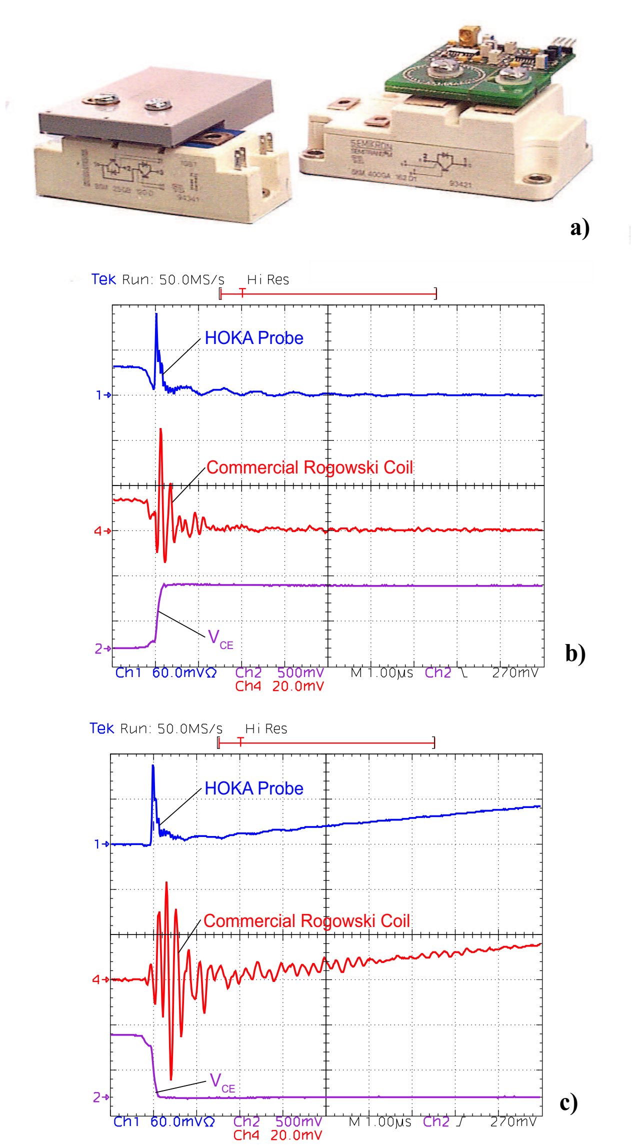

Fig. 3. HOKA current probe: bandwidth from DC to 10 MHz, current rating: 500 A. a) The sensors are directly mounted on an IGBT module. Measurements b) and c) show a comparison with a commercial Rogowski coil having a lower frequency bandwidth, hence showing a pronounced ringing. Current scale: 10 A/div, voltage V_{CE} scale: 200 V/div, voltage-peak 300 V, time base: 1 μs/div.

the susceptibility of the device to thermal runaway phenomena. Therefore, the parallel connection of more IGBTs can result into an uneven distribution of the load and hence of the losses. Online feedback control strategies have been proposed to enhance the performance of parallel switched modules and to compensate by proper modulation the asymmetries and the unbalances [1], [7], [8]. One active gate control method to balance the current share among parallel switched IGBTs without derating or preselection of any IGBT is presented in [3]. To implement these control strategies, first the current has to be measured with a broadband current probe. The importance of measuring the current of the modules as well as the current distribution among the chips within the same module has been widely recognized [3]–[11].

This paper presents the application and the implementation of planar PCB air-coil based sensors for online current monitoring as well as offline switching losses characterization of high-voltage, multi-chip IGBT modules. Two types of sensors are presented: a planar PCB Rogowski coil, for measuring alternating currents, and a prototype of a HOKA current sensor (cf. Section II), capable of broadband current measurement from DC to 50 MHz without derating [11] . These sensors present superior advantages with respect to the shunt technology since they are more compact, galvanically isolated, lighter and integratable. They present as well advantages with respect to conventional magnetic wound sensors, since the performance characteristics of the planar PCB sensors are more reproducible. The issues related to the measurement of the current of parallel connected modules are analyzed as well as the problems related to the thermal optimization

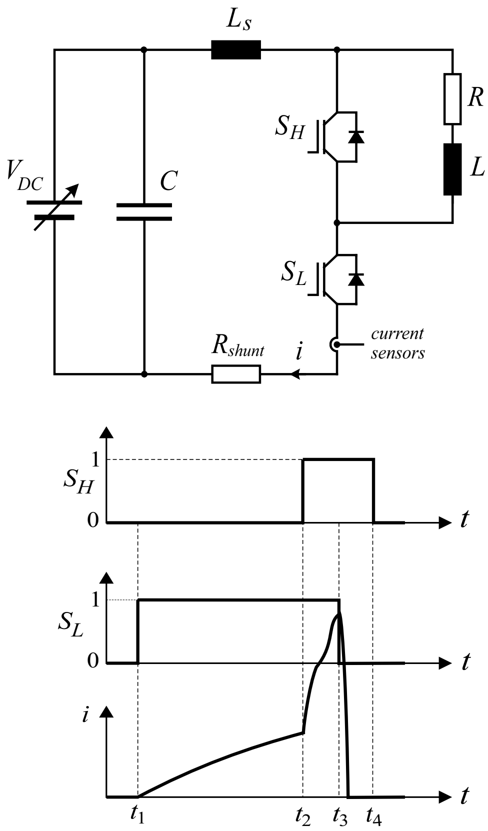

Fig. 4. Short circuit current test bench for IGBT and gate signals and current waveform for a bridge leg short-circuit.

and current within a multi-chip IGBT power module. The advantages of the current measurement in order to perform the monitoring and fault detection of the modules are discussed. In addition, the techniques used to measure the current within a power module are reviewed. Experimental results of current measurements and dynamic performance are included.

II. PCB Rogowski Coil Based Current Sensors

The output signal of a Rogowski coil is proportional to the magnetomotive force (mmf) given by the Ampere's Law:

$$\begin{aligned} mmf &= \oint_C \mathbf{H}d\mathbf{l} = \int_S \mathbf{J}d\mathbf{S} + \frac{d}{dt}\int_S \mathbf{D}d\mathbf{S} \\ &= I_c + I_d \end{aligned} \qquad (1)$$

where I_c is the conduction current and I_d is the displacement current. If the conduction current only contributes to the output signal and the total displacement current I_d, is negligible, then shielding the coil or the device is not necessary. This is allowable in low dv/dt environments.

HOKA probes are constituted by the combination of a Rogowski coil and active components or devices able to sense a DC to low frequency current signal [11], hence the HOKA probe has the advantage over the Rogowski coil of having a frequency bandwidth which extends to DC. The HOKA probe is able to achieve a very wide bandwidth with no current derating at high-frequency and it is easily custom designable. The Rogowski coil is most often realized by winding a wire around a toroidal coil former. This winding process can be automated but will never guarantee identical impedance

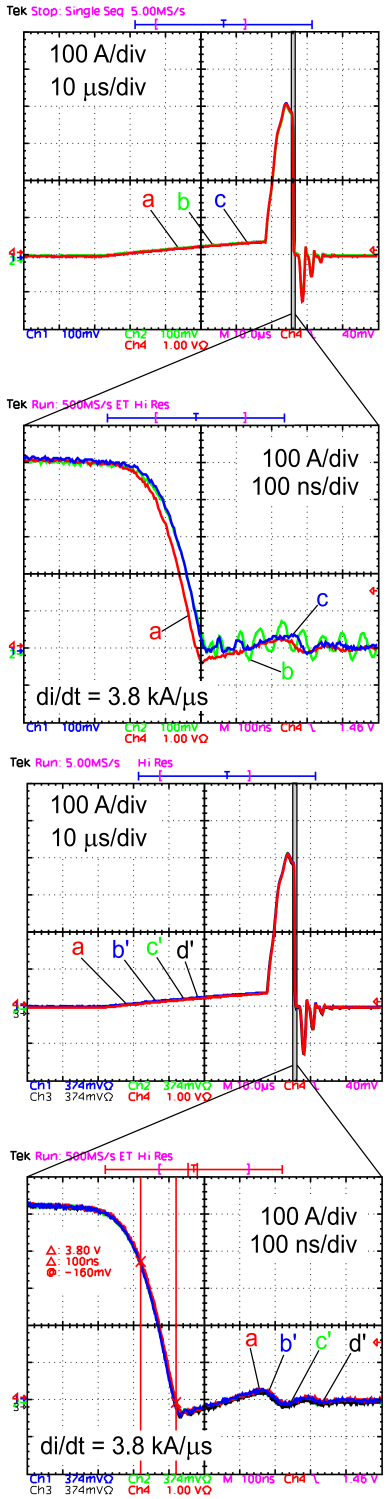

Fig. 5. Reproducibility of Rogowski current sensors demonstrated by measuring the short circuit current of a bridge leg (cf. Fig. 4). Shunt (trace a) and two identical conventional wound Rogowski coils (traces b, c) having a lower corner frequency with respect to the shunt and ringing. The coils show different ringing frequencies although the sensor model is the same. Planar PCB Rogowski coils (traces b', c', d') show excellent agreement with the shunt trace a. The three coils show same ringing frequencies because PCB coils can be reproduced with high accuracy.

behavior of two coils since there is little control over stray inductances and capacitances.

This leads to coils with slightly different resonance frequency. When measuring surge currents, the resonance fre-

TABLE I

PCB-BASED ROGOWSKI CURRENT SENSORS FEATURES

Frequency Bandwidth	up to 100 MHz
Current Rating	mA ... 100 kA
dv/dt immunity	50 kV/μs
di/dt	30 kA/μs
Voltage insulation	5 kV
Layout	low profile, light weight closed or clip-around coil

TABLE II

ADVANTAGES OF THE PCB-BASED ROGOWSKI SENSOR TECHNOLOGY WITH RESPECT TO OTHER COMMERCIAL CURRENT SENSORS

	DC	AC	Frequency Bandwidth	Current Rating	Type
Shunt	yes	yes	up to GHz	up to 100 kA	passive
CT	no	yes	up to 500 MHz	up to 100 kA	passive
Closed loop	yes	yes	50 MHz	up to kA	active
Traditional Rogowski	no	yes	up to MHz	up to kA	active
PCB Rogowski	no	yes	up to 100 MHz	up to kA	active
HOKA Probe	yes	yes	up to 100 MHz	up to kA	active

quency of the coil can be excited thus causing ringing in the output signal. To damp the ringing a damping resistor can be introduced. If a small damping resistor is used, the ringing will be smaller and the output signal will be smaller as well; in addition, the bandwidth will be larger but the power dissipated in the resistor will increase. The Rogowski coil is in this case used as a current transformer.

To solve this issue, this paper proposes two types of planar air coil: a PCB Rogowski coil (see Fig. 2) and a HOKA probe (see Fig. 3). PCB coils can be reproduced with high accuracy and show therefore all the same stray inductance and capacitance. Two identical PCB Rogowski coils will ring with quite the same frequency; this is not always the case with traditional wound Rogowski coils. PCB Rogowski coils have in general a higher resonance frequency in the range from 10 MHz to 150 MHz. Drawbacks of these PCB coils is that they can not be opened with the same ease as traditional ones and they have lower output signal strength. An advantage of PCB Rogowski coils compared to current transformer or traditional Rogowski coil is their thickness of few millimeters for equal or higher bandwidth. The insertion inductance of a PCB Rogowski coil is negligible [9].

III. ON-LINE CURRENT MEASUREMENT

Since the shape and the rate-of-change of the switching currents to be measured is not known in advance, as typical for a power converter prototype setup, a current probe with a large bandwidth is desired in order to record reliable and accurate current waveforms. This is important since the current signal is often used to calculate the switching losses, to detect current ringing (with its actual magnitude!) and to perform direct and indirect current control strategies. The proposed current sensor have high-bandwidth performance up to 100 MHz and HOKA probes extend the lower bandwidth limit to DC. A setup with a shielded HOKA probe is shown in Fig 3a. The probe is directly mounted on the IGBT module. Comparative measurements with a commercial Rogowski sensor are shown in Fig. 3b and Fig. 3c. The commercial Rogowski coil shows a prominent ringing.

When measuring the current sharing in parallel branches by using in each branch the same type of current sensor, in order to perform an accurate control and monitoring, the sensors should have the same characteristics. To check the ability of different prototypes of the same current sensor to reproduce the same current waveform, the setup shown in Fig. 4 has been built. The measurement results, where different sensors have been compared, are shown in Fig. 5. The PCB planar Rogowski coils demonstrate a better performance rather than the conventional wound Rogowski coils, which show different ringing frequencies although the sensor model is the same.

IV. OFF-LINE DEVICE CHARACTERIZATION AND CHIP CURRENT MEASUREMENT

Two examples are shown hereafter, where direct measurement of the current sharing and redistribution among different substrates connected to the same busbar, and among IGBT chips assembled onto the same substrate would be a substantial support in the design of robust modules. In both cases, the local current has been derived by compact simulation, where the Non-Punch-Through type IGBTs have been modeled by a mixed behavioral and physical description, presented in [12], [13]. A schematic cross-sectional view of an NPT-IGBT is shown in Fig. 6a, where the principal current components are indicated.

A. Current Sharing and Redistribution among Substrates

The first example deals with the characterization of repetitive failure modes observed during overload transient operation of IGBT modules and the associated failure mechanism [14]. Fig. 6b shows the typical result of an over current turn-off transition failure, for which a repetitive pattern can be detected; in this module it is always caused by the burnout of the same four IGBT chips (out of twenty-four) arranged in the lower left Direct Copper Bond (DCB) of the module. Under these circumstances, typical concerns are current tails, associated with the removal of the charge stored in the base of the IGBT, and the overshoot of the collector emitter voltage due to parasitic inductances. Fig. 6c shows the turn-off current sharing unbalance between two IGBT on different DCBs of the same leg (the numbering refers to Fig. 2b; the subscripts (a) and (b) identify the upper and lower DCB, respectively). In particular, the intrinsic p-n-p BJT current components are shown; the device interested by higher current experiences a stronger activation of the parasitic n-p-n transistor. This can cause the device to enter a thermal runaway condition with a subsequent failure of the transistor.

B. Current Sharing and Redistribution within the DCB

A different current sharing can be due to the resistive and inductive unbalances among the different IGBT chips within the same DCB [13]. Taking into consideration the substrate of Fig. 1b, it can be shown that differences in the values of parasitic resistance and inductance among IGBTs, in both driving and power paths, can result in a macroscopic current unbalance. Fig. 7 shows the simulated current sharing between IGBT1 and IGBT4 during a short-circuit event. Current unbalances are already present both in the initial current peak,

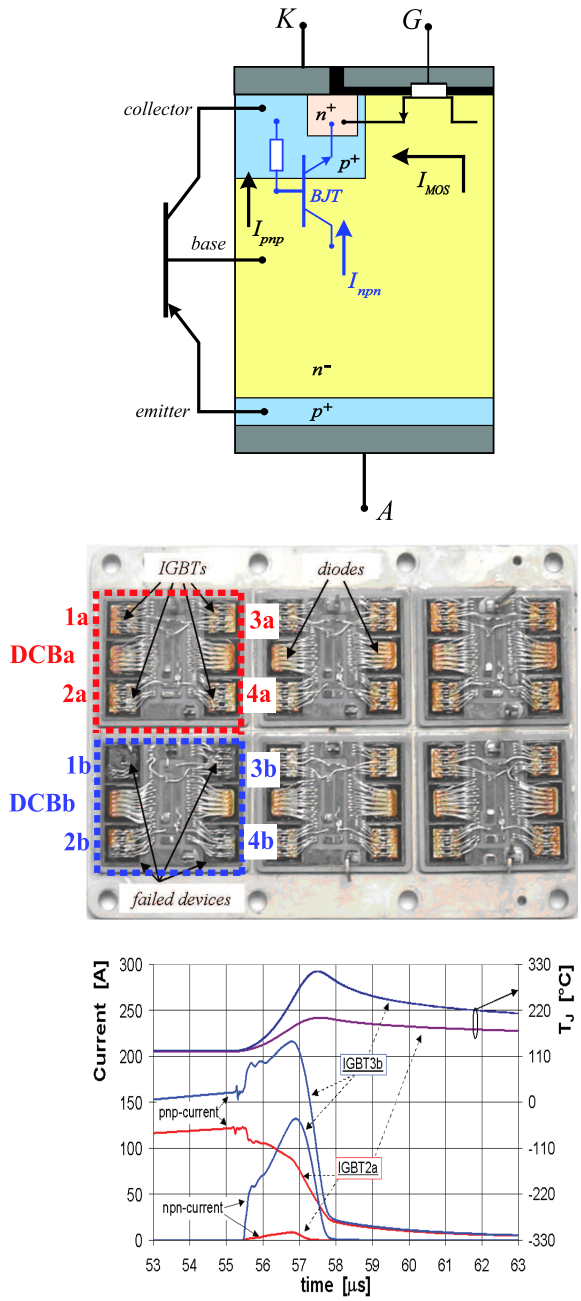

Fig. 6. a) Schematic cross-sectional view of an NPT-IGBT with indication of the principal current components. b) Image of a module failed for an overcurrent turn-off transition. c) Simulated current and temperature increase of two IGBT chips assembled in a critical (IGBT3b) and in an uncritical (IGBT2a) DCB.

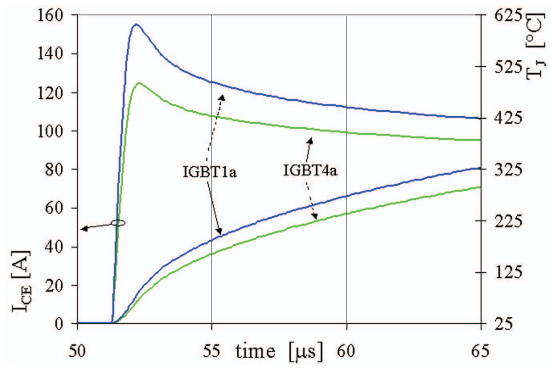

Fig. 7. Simulated current and temperature waveforms of two IGBT chips assembled on the same DCB during a short-circuit.

as well in the subsequent time phase. The first one can be related both to the resistive and inductive mismatch of the different driving paths, while the latter is related mainly to the resistive mismatch of the power path and to the different thermal evolution of the chips. Thus, the simulation clearly demonstrates that relevant current unbalances are often due to the unsymmetrical patterning of the interconnects and to the topology of the substrate. Fig. 7 also shows that this current unbalance immediately impacts the junction temperature of the related IGBTs, reaching values of several degrees and the significance of this effect for the reliability of the system is evident.

C. Current Measurement within the Module

Multiple requirements are imposed to the non-invasive current measurement techniques. The module may not be modified mechanically to avoid additional inductance, and the volume of the probe should not exceed 125 mm^3 to fit into a commercial package. The probe should have a reduced number of terminals and be preferably galvanically isolated. Further, the probe shall be immune to stray signals from nearby busbars, wiring, or DCBs. The insertion impedance of the probe should be negligible in comparison to the overall module resistance (some few mΩ). Due to the high dv/dt observed during the switching, the probe shall have sufficient current dynamics, since the current switched by a chip under normal conditions is 50 A, while it can increase up to an order of magnitude under switching or short circuit conditions. The probe needs sufficient high-frequency bandwidth, since the oscillation occurring between paralleled devices may reach several teens of MHz. Finally, the probe and the processing electronics have to survive the hostile environment in form of high temperature, temperature cycles, as encountered in traction applications. Several attempts have been made in the past to use existing techniques. Commercially available current transformers have been shown to be too bulky (few centimeters) for integration into the modules. Nevertheless, Pearson current monitors have been used successfully to measure the overall module current by providing low insertion impedance (better than 200 mΩ), a bandwidth starting from a few Hz up to 20 MHz, and a rise time in the range of 20 ns. Commercial measurement systems combining a current transformer and a Hall sensor for DC measurements have still a size, which is not compatible with the intended use. Probes based on flux compensation and in combination with a Hall sensors show an insufficient bandwidth around 100 kHz. The inductance of coaxial resistive shunts is sufficiently low to provide with a sufficiently high bandwidth, such that they are often used to measure the total module current with a low insertion resistance (hundreds of $\mu\Omega$). However, resistive shunts are still too bulky to be integrated in modules, very invasive (since they require the package to be opened for insertion), do not provide galvanic isolation, and exhibit a limited signal dynamics.

Recently, near field probes have been integrated in the backside of ceramic substrate of elementary IGBT modules to measure di/dt directly underneath every chip. A maximum bandwidth of 3.5 MHz and a rise time of 100 ns are claimed

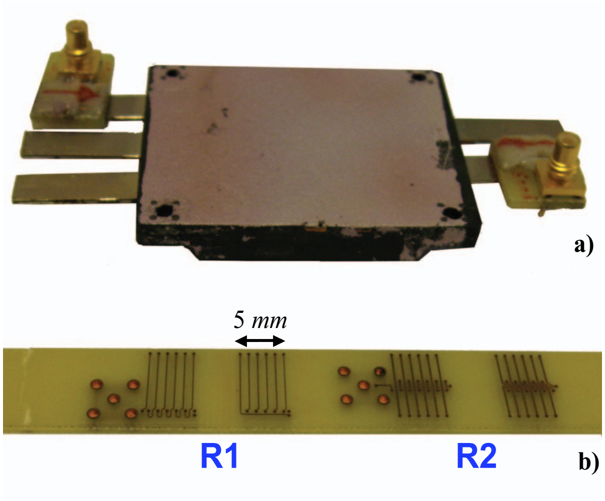

Fig. 8. Mini PCB Rogowski coils for the measurement of the current in environments with limited probe insertion room. a) Insertion of two mini PCB Rogowski coils for measuring the current flowing through bus bars of small size, and b) particular of two mini PCB coil-layouts. The frequency bandwidth is 160 MHz (layout R1) and 130 MHz (layout R2), respectively.

[15]. These probes have shown a large sensitivity to cross talking, such that quantitative measurements can be only obtained, if the magnetic coupling coefficients of the different conductors are accurately known. Furthermore, patterning of the ceramic substrate backside is not a suitable solution for the traditional module design, where the backside metallization is soldered on the top of the base plate.

Rogowski coils are frequently used both for the measurement of the total module current, or in their miniaturized form, to measure the current sharing among the busbars in the module [6], [8], [10]. Recent operational amplifiers are fast enough to produce both a differential and integral signal with sufficient bandwidth for the main applications. In particular, ideal Rogowski coils are intrinsically immune to cross-talking phenomena, such that they are very suited for the use inside a module, where multiple conductors are present. Due to the fact that Rogowski coils are wound around the busbars to be monitored, the lateral spacing between adjacent conductors (often at different voltages) is reduced, such that the risk of partial discharge within the module is highly increased, leading to the destruction of the probes.

D. Mini PCB Rogowski Current Sensor

Two mini PCB Rogowski sensors suited for current measurements in environments with limited probe insertion room have been realized (cf. Fig. 8). The coils are constituted by two layers of turns which are placed on the upper and lower surface of the primary bus conductor. The two coil layouts are shown in Fig. 8b, and they have frequency bandwidth of 160 MHz (layout R1) and 130 MHz (layout R2), respectively. Fig. 8b shows the sensors installed around the bus bars; the output terminals, realized through SMC connectors, is then interfaced to the process electronic stage. Since the planar PCB Rogowski sensor can be miniaturized and also integrated on a substrate, it can therefore used to measure the current within a IGBT module.

V. Conclusion

This paper has presented the application and the implementation of planar PCB air-coil based sensors for online current monitoring and offline switching losses characterization of high-voltage, multi-chip IGBT modules. Two novel types of sensors were presented: a planar PCB Rogowski coil, for measuring alternating currents, and a prototype of a HOKA current sensor, capable of broadband current measurement from DC to 100 MHz without derating. Two examples have been illustrated, where direct measurement of the current sharing and redistribution among different substrates connected to the same busbar, and among IGBT chips assembled onto the same substrate would be a substantial support in the design of robust modules. A review of the techniques used to measure the current within a power module has shown that the Rogowski coils are very suited for the use inside a module, where multiple conductors are present. Two prototypes of mini PCB Rogowski sensors have been realized, for the measurement of currents in environments with limited probe insertion room.

From the measurements and the analysis presented, the following features of the sensors can be highlighted. For the conventional Rogowski sensors:

- the highest achievable self-resonance frequency of wound coil is about 1 MHz;
- they can measure only for AC signals and
- can be opened easily.

An improvement of this technology are the planar PCB Rogowski sensors, which:

- possess an highest achievable self-resonance frequency of 150 MHz;
- their manufacturing technique is well established and accurate;
- they are integratable on a substrate;
- they are made out of solid material, which is ideal for permanent mounting;
- they can be made openable, but with technical effort.

The performance of the PCB Rogowski sensor is further improved by the HOKA probe, which:

- combines the advantages of a planar PCB Rogowski coil with the ability to measure also DC signals.
- has an extremely wide bandwidth, from DC up to 150 MHz (with a high-frequency evaluation circuit), with no current derating at higher frequency.

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References

[1] M. P. Kazmierkowski, R. Krishnan, and F. Blaabjerg, “Control in power electronics,” *Academic Press*, 2002.

[2] M. P. Kazmierkowski and L. Malesani, “Current control techniques for three-phase voltage-source PWM converters,” *IEEE Trans. Ind. Electronics*, vol. 45, no. 5, pp. 691–703, 1998.

[3] P. Hofer-Noser and N. Karrer, “Monitoring of parallel IGBT/Diode modules,” *IEEE Trans. Power Electronics*, vol. 14, no. 3, pp. 438–444, 1999.

[4] E. U. Krafft and A. Steimel, “Measurement of the radial cathode current distribution during the turnoff-process of a 4-kA-IGCT under different driving conditions,” *European Power Electronics Conf.*, pp. 1–10, 2001.

[5] M. Bland, J. Clare, Wheeler, and L. Empringham, “Measurement and simulation of commutation phenomena in direct AC-AC converters,” *European Power Electronics Conf.*, pp. 1–9, 2001.

[6] B. Bock, E. U. Krafft, and A. Steimel, “Measurement of multiple chip currents in a Press-Pack IGBT using Rogowski coils,” *European Power Electronics Conf.*, pp. 1–10, 2003.

[7] D. Schröder, “Power electronics devices,” *Springer, Second Edition (in German)*, 2006.

[8] P. R. Palmer, B. H. Stark, and J. C. Joyce, “Non-invasive measurement of chip currents in IGBT modules,” *Proc. Power Electronics Specialists Conf.*, 1997.

[9] M. Bland, J. Clare, P. Wheeler, and L. Empringham, “Measurements and simulation of commutation phenomena in direct AC-AC converters,” *Proc. European Power Electronics Conf.*, 2001.

[10] B. Bock, E. U. Krafft, and A. Steimel, “Measurement of multipole chip currents in a press-pack IGBT using Rogowski coils and simulation of commutation phenomena in direct AC-AC converters,” *Proc. European Power Electronics Conf.*, 2003.

[11] N. Karrer and P. Hofer-Noser, “PCB Rogowski coils for high di/dt current measurements,” *Proc. Power Electronics Specialists Conf.*, vol. 3, pp. 1296–1301, 2000.

[12] E. Batista, A. Castellazzi, J. M. Dienot, M. Ciappa, W. Fichtner, and M. Mermet-Guyennet, “Accurate mixed electrical and electromagnetic model of a 6,5 kV IGBT module,” *Proc. Int. Conf. on Power Electronics*, 2007.

[13] A. Castellazzi, M. Ciappa, M. Mermet-Guyennet, G. Lourdel, and W. Fichtner, “Compact modelling and analysis of power-sharing unbalances in IGBT-modules used in traction applications,” *Microelectronics Reliability*, vol. 46, pp. 1754–1759, 2006.

[14] J. Urresti-Ibanez, A. Castellazzi, M. Piton, J. Rebollo, M. Mermet-Guyennet, and M. Ciappa, “Robustness test and failure analysis of IGBT-modules during turn-off,” *Microelectronics Reliability*, vol. 47, pp. 1735–1799, 2007.

[15] G. Lourdel, “Méthodologie et outils de calcul numérique pour la prise en compte de la compatibilité électromagné tique des nouveaux prototypes de circuits intégrés de puissance,” *PhD thesis, Université Toulouse*, vol. 47, pp. 1735–1799, 2005.