Letters

A New Output Current Measurement Method With Tiny PCB Sensors Capable of Being Embedded in an IGBT Module

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***Abstract*—This paper proposes a new output current measuring method using tiny printed-circuit-board (PCB) current sensors. The method will make it possible to install the PCB current sensors in an insulated-gate bipolar transistor (IGBT) module. The PCB sensor picks up a switching current flowing through an IGBT chip, and then a combination of a digital circuit based on field-programmable gate array and an integrator circuit reproduces the output current of an inverter from the switching current. A proof-of-concept experimental verification is carried out using a buck converter, which verifies that the proposed method detects a dc component of the output current as well as a ripple component although the PCB sensor is based on the so-called Rogowski coil.**

***Index Terms*—Insulated-gate bipolar transistor (IGBT) modules, integration, inverters, printed-circuit-board (PCB) current sensors.**

I. Introduction

INTEGRATION technology in power electronics is more and more attractive because it contributes to cost reduction, system miniaturization, and reliability improvement [1]–[7]. As for power semiconductor devices, the so-called intelligent power module is a representative integrated module, which combines multiple insulate-gate bipolar transistors (IGBTs), and gate-driving and protection functions. Attention has been also paid to gate-drive circuits having additional functions to be integrated [1], [2], [5]–[7]. For example, Chen *et al.* [6] has proposed a gate-drive circuit with a self-diagnosis function for IGBTs and metal-oxide-semiconductor field-effect transistors (MOSFETs) based on monitoring the gate charge and discharge current. Hasegawa *et al.* [7] have proposed a short-circuit protection method for an IGBT with detecting the gate voltage and gate charge with a real-time monitoring system using a field-programmable gate array (FPGA).

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The inverter often employs a current sensor at the output terminal because it has to control the output current in motor-drive and grid-connected applications. The Hall current sensor and the current transformer (CT) are representative ones. However, these current sensors are a constraint to reduce the volume and cost of the inverter. The so-called Rogowski coil is a candidate for the low-cost and small current sensor [8]–[10] but has a poor characteristic in a low-frequency region like a line frequency of 50 or 60 Hz.

Chakrabarti *et al.* [11] have proposed a technique for measuring output currents of a three-phase inverter using pilot current sensors that are also referred as sense emitters. This technique can reproduce the output current from the switching currents flowing through the lower-side switches. Although existing power modules employ sense emitters for overcurrent protection, they would not have enough precision for inverter control. This is because current distribution among multiple IGBT chips including the sense emitter tends to be imbalanced due to imbalanced thermal distribution in a module.

This paper proposes a new output current measuring method using a tiny current sensor that is based on the Rogowski coil and is constructed of a printed-circuit board (PCB) [10], namely, the PCB current sensor. The PCB current sensor picks up a switching current flowing through an IGBT chip, and can be embedded in an IGBT module. A digital circuit based on an FPGA is used for converting the output signal of the sensor into the waveform following the output current. The method can detect not only ripple component but also a dc component of the output current, although the sensor is based on the Rogowski coil.

II. New Current Measurement Method

A. Basic Concept

Fig. 1 shows a concept of the new current measurement method in an IGBT module, in which (a) illustrates the installation of the PCB current sensor in the power module. The sensor is put on the main electrode of the emitter terminal. Fig. 1(b) shows a three-phase inverter as an example of the method. The inverter equips three PCB sensors at emitter terminals of the low-side switches instead of the output terminals because of the following reasons:

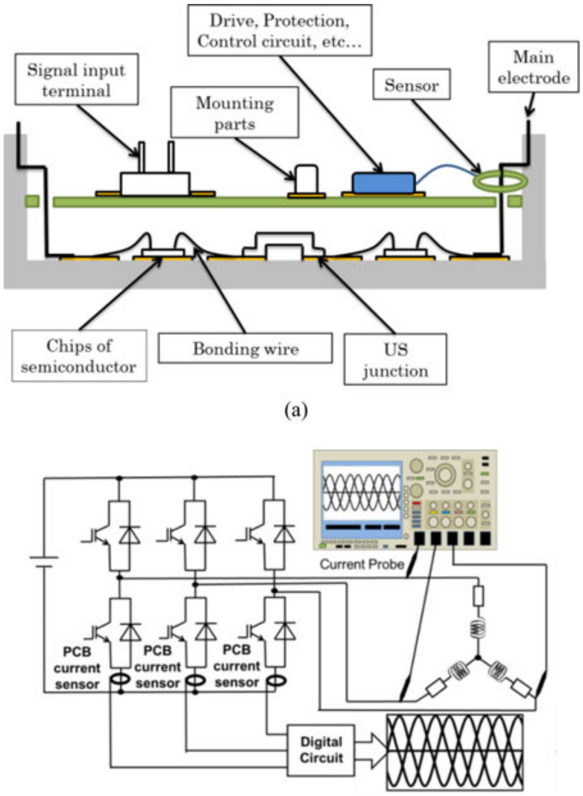


Fig. 1. Basic idea of the new method. (a) Installation in an IGBT module. (b) Application to a three-phase inverter.

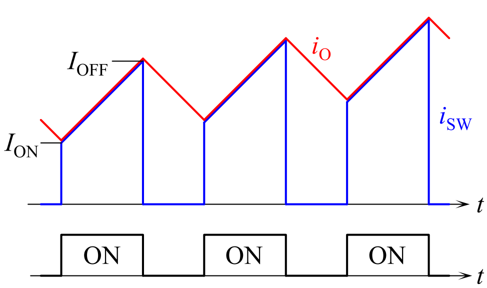


Fig. 2. Relation between the output current i_O and switching current flowing through an IGBT, i_{SW}.

1) each sensor does not suffer from a displacement current caused by a high dv/dt;
2) each sensor has only to pick up a high-frequency switching current that does not contain low-frequency component like the output frequency.

B. Relation Between the Switching and Output Current

Fig. 2 shows the relation between the switching current of the IGBT chip, i_{SW} and output current of the inverter, i_O, along with the switching sequence. The turn-ON current I_{ON} and turn-OFF current I_{OFF} of the IGBT correspond to the minimum and maximum values of the output current over a switching period, respectively. Hence, one can reproduce the output current waveform from the turn-ON and -OFF currents. Note that inverter control utilize an average value over a switching period in practice [12], [13]. Therefore, it does not have to continuously sense the output current.

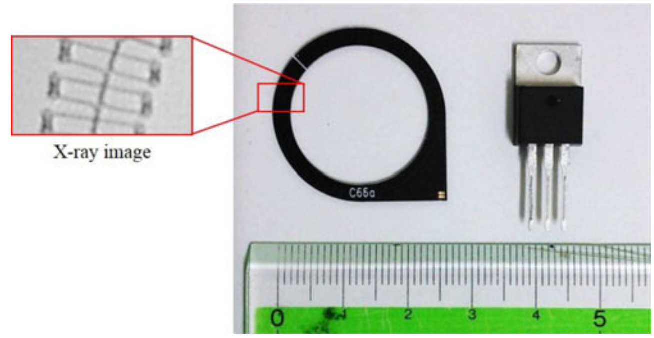


Fig. 3. Photo of the PCB current sensor [10] and its X-ray image, along with a TO-220 package.

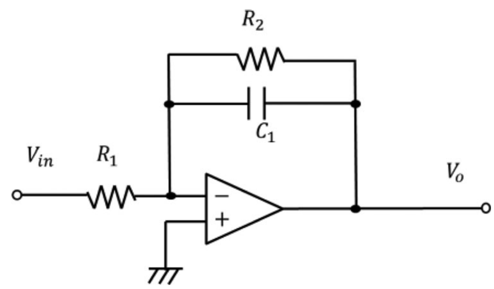


Fig. 4. Integrator circuit for the PCB current sensor.

C. PCB Current Sensor

The authors of this paper have developed the PCB current sensor based on the Rogowski coil [10]. Fig. 3 shows a photo of the PCB current sensor and its X-ray image that exhibits the internal coil. The thickness of the sensor is only 0.6 mm. The sensor can be installed on an IGBT chip in a power module, so that it is useful for monitoring the current distribution of multiple IGBT chips connected in parallel. Moreover, the sensor has a wide frequency bandwidth more than 100 MHz. Note that it is possible to employ a more compact sensor [10].

The internal coil is characterized by a new fishbone pattern, which has excellent noise immunity to external magnetic field caused by other wirings (see Appendix).

D. Integrator Circuit for PCB Sensor

The output signal of the PCB sensor, v_S is in proportion to the time differential of the current flowing through the sensor, *i*, as the following:

$$v_s = -M\frac{di}{dt} \tag{1}$$

where *M* is the mutual inductance between the sensor and the wiring of the current. Fig. 4 shows an integrator circuit consisting of an operational amplifier, which reproducing the current waveform from the output signal. In practice, however, the integrator circuit equips a resistor connected in parallel with the

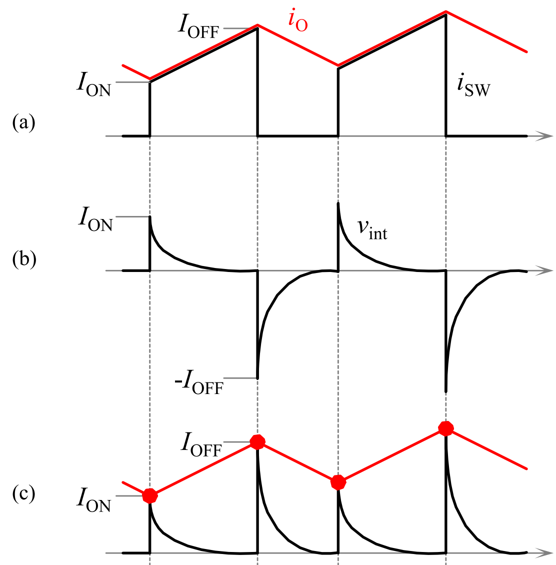


Fig. 5. How to reproduce the output current.

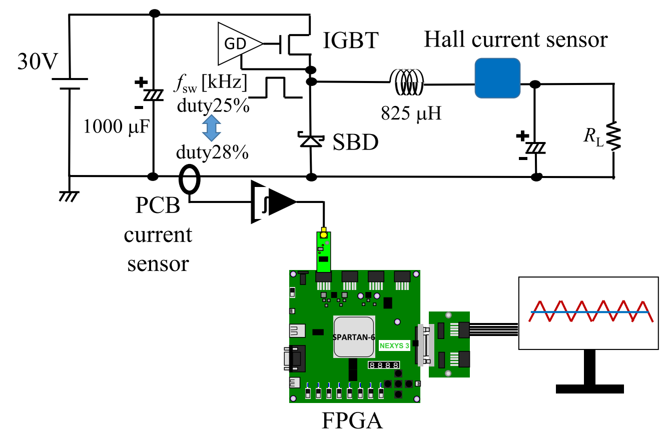


Fig. 6. Experimental setup using a buck converter.

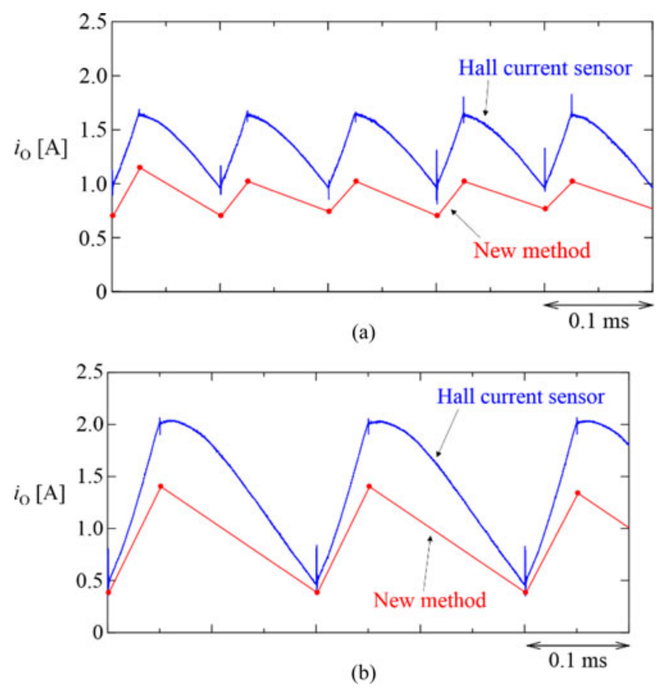


Fig. 7. Steady-state current waveform of the output current i_O. (a) f_{sw} = 10 kHz. (b) f_{sw} = 5 kHz.

feedback capacitor C_1 to limit a dc gain because an input offset voltage and input bias current result in a saturated output voltage of the operational amplifier. Hence, the circuit act as an incomplete integrator. The transfer function of the circuit, $G_{\rm int}(s)$, is given by

$$G_{\rm int}\,(\mathrm{s}) = \frac{V_o\,(s)}{V_{\rm in}\,(s)} = -\frac{1}{C_1 R_1}\cdot\frac{1}{s+1/C_1 R_2}. \qquad (2)$$

Equation (2) suggests that a time constant of $C_1 R_2$ determines the lowest frequency that the circuit acts as a complete integrator. The time constant should be larger than rise and fall times of the switching device so as to reproduce turn-ON and -OFF current.

E. How to Reproduce the Output Current Waveform

Fig. 5 illustrates reproduction procedure of the output current, indicating the relation among the output current i_O, switching current $i_{\rm sw}$, and the output signal of the integrator, $v_{\rm int}$. The incomplete integrator can detect rise and fall of the input voltage because they contain only high-frequency components. If a time constant of $C_1 R_2$ is much smaller than a switching period, $v_{\rm int}$ falls or rises to 0 V before the next turn-OFF or -ON event. Fig. 5(c) is the rectified waveform of (b), which still contains the turn-ON current $I_{\rm ON}$ and turn-OFF current $I_{\rm OFF}$. Hence, it is possible to reproduce the output current waveform by means of sampling and holding the turn-ON and turn-OFF current from the rectified waveform.

It should be point out that this procedure can obtain the dc component as well as ripple component of the output current although the PCB current sensor picks up only high-frequency components.

III. Experiment

This paper confirms the effectiveness of the new method using a buck converter as a proof-of-concept experimental verification.

A. Circuit Configuration

Fig. 6 shows circuit configuration of the experimental system, where an FPGA is used for reproducing the current waveform and for generating a gate signal for the buck converter. The FPGA equips an analog-to-digital (A/D) converter to obtain the output voltage of the integrator circuit. The integrator circuit has the time constant of $C_1 R_2 = 1\,\mu$s. The PCB sensor measures the switching current flowing through the IGBT. Although the sensor is placed on the ground pass of the converter, the same current as the switching one flows through the ground pass.

A Hall current sensor, LTSR6-NP, LEM co., ltd., is equipped for comparison with the new method. The sensor has a linearity error less than 0.1%.

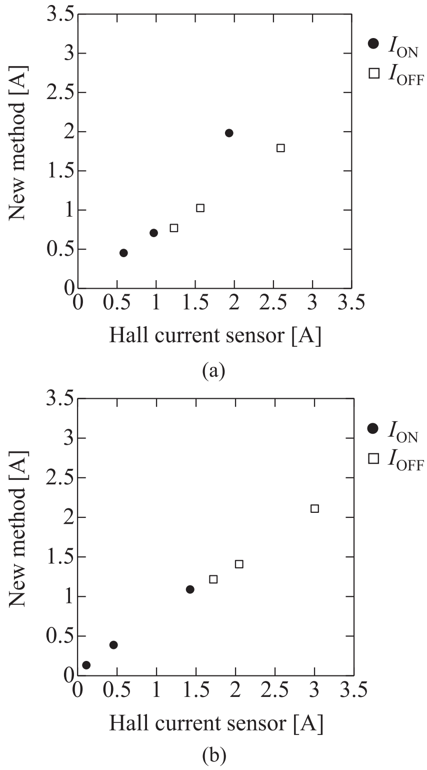


Fig. 8. Relation between measured currents by the new method and by the Hall current sensor, indicating linearity of the new method. (a) $f_{sw} = 10\,\text{kHz}$. (b) $f_{sw} = 5\,\text{kHz}$.

B. Experimental Results

Fig. 7 shows current waveforms in a steady state with a load resistance R_L of 5 Ω, where the switching frequency f_{sw} was 10 and 5 kHz, and the duty ratio of the IGBT was 25%. Each waveform of the new method reproduced the dc component as well as ripple one, and has a greatly short delay time against that of the Hall current sensor because the delay time resulted only from the A/D converter and the FPGA. Fig. 8 shows the relation between measured turn-ON/OFF currents by the new method and by the Hall current sensor, where the load resistance R_L was adjusted to be 2.5, 5, or 7.5 W in order to show the relation in a wide output current range. The relation indicates that the new method has a good linearity. Although amplitudes of the turn-ON/OFF current in the new method were smaller than those in the Hall current sensor by 30%, the difference could be calibrated.

Fig. 9 shows transient current waveforms when the duty ratio was changed from 25% to 28%. The waveform of the new method well followed a transient change of the dc component.

Fig. 10 shows current waveforms when the switching was changed from 10 to 5 kHz, which confirmed that the new method detected a ripple-amplitude change.

IV. Application to Pulse-Width-Modulated (PWM) Inverters

The new method has the following concerns in practical use when it is applied to PWM inverters.

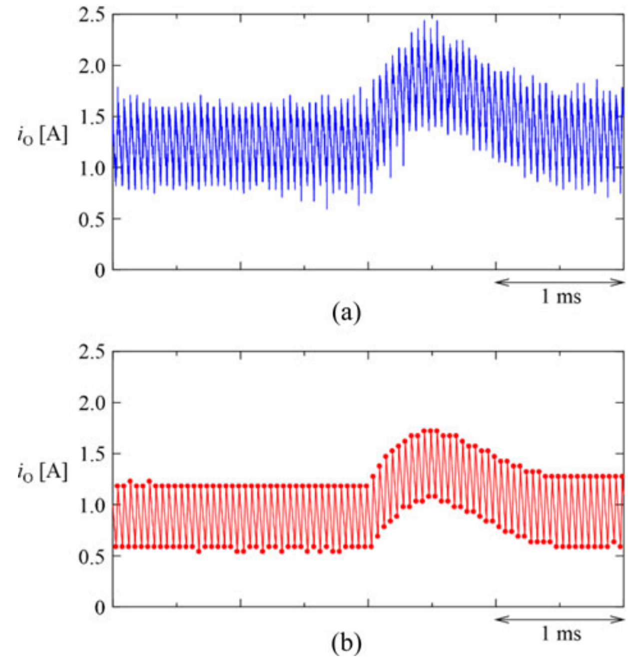


Fig. 9. Transient current waveform of the output current i_O when the duty ratio was changed from 25% to 28%. (a) Hall current sensor. (b) New method.

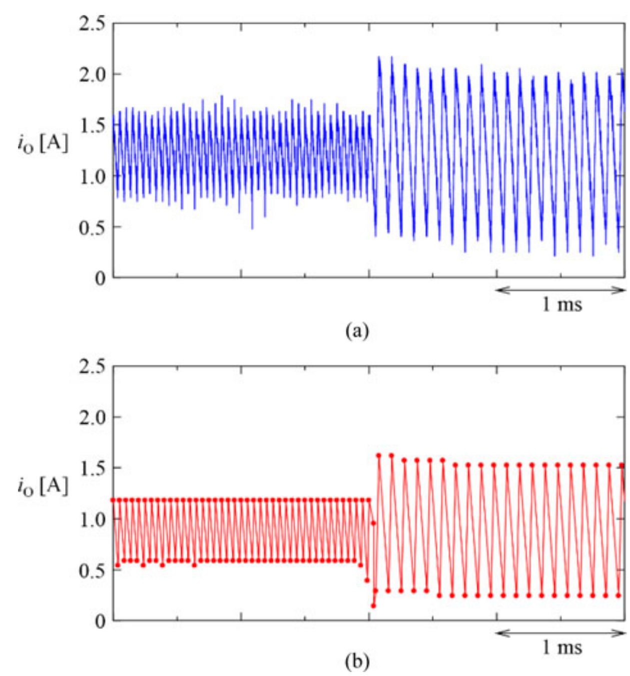


Fig. 10. Transient current waveform of the output current i_O when the switching frequency was changed from 10 to 5 kHz. (a) Hall current sensor. (b) New method.

A. Polarity of the Output Current

Although the operating mode in inverters helps to know the polarity of the output current, the polarity is also a function of the power factor of the load. Thus, the new method cannot specify the current polarity only from the operating mode. It is possible to exactly specify the polarity by installing PCB

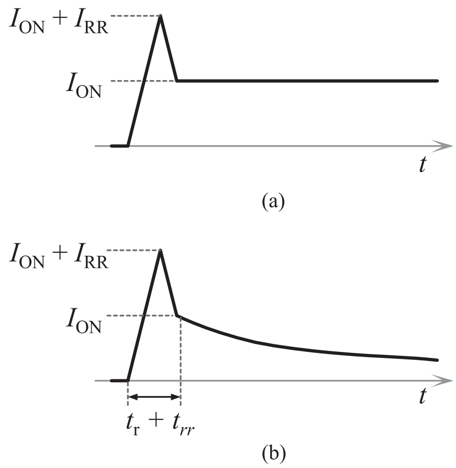


Fig. 11. Turn-on current including reverse recovery current. (a) Actual switching current. (b) Output signal of the incomplete integrator circuit.

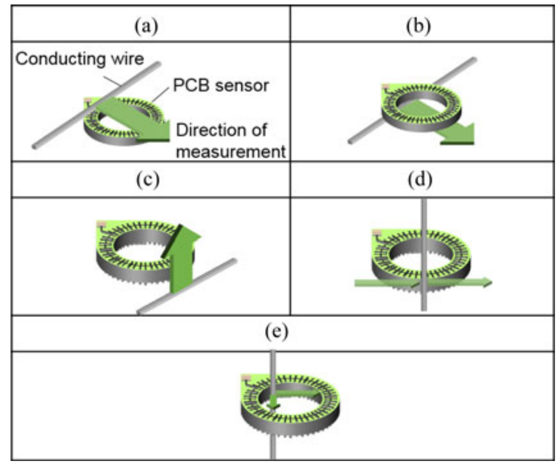


Fig. 12. Testing procedure for S/N ratio of each coil pattern.

sensors both to the IGBT and to its antiparallel diode. Note that the PCB sensor is intended for measuring either the total current of parallel-connected IGBT and antiparallel diode chips or individual currents of the chips to monitor current distribution by installing the PCB sensors on all the IGBT chips and all the diode chips. As a result, one can distinguish the total IGBT current and total diode one even if a power module consists of multiple parallel chips. If the PCB sensors are just used for monitoring the total arm current in the inverter, installation of the PCB sensors into both the high-side and low-side arms also makes possible to specify the current polarity. The increase in the number of PCB sensors will not result in a cost increase of the inverter because the PCB sensor can be fabricated at low cost.

B. Narrow Pulse Width Around Unity Modulation Index

The narrow pulse width causes an offset voltage in the rectified waveform shown in Fig. 5(c) when the output signal of the integrator circuit does not fall or rise to zero before the next turn-ON or -OFF event. However, the offset voltage can be canceled out by means of sampling and holding the output signal shortly before the switching event.

C. Effect of Reverse Recovery Current

Most inverters suffer from a turn-ON spike current resulting from a reverse recovery current. Fig. 11 shows turn-ON current waveform focusing on the current spike caused by a reverse recovery current. The output signal of the integrator circuit completely reproduces the current waveform during the rise time t_r and reverse recovery time $t_{\rm rr}$ if the time constant of the integrator circuit is larger than the sum of t_r and $t_{\rm rr}$. The turn-ON current $I_{\rm ON}$ without recovery current can be obtained by means of sampling the output signal shortly after the reverse recovery ends. In practice, the new method can utilize typical values of t_r and $t_{\rm rr}$ available on the datasheet of the corresponding IGBT module or diode.

D. Current Protection Function

Since the PCB sensor is based on the Rogowski coil, it does not suffer from magnetic saturation even though it is subject to a large amount of fault current. In addition, the sensor has a greatly short delay time less than 50 ns [10]. The measuring method samples the current at switching events in order to reproduce the output current waveform, while the FPGA always monitors the output signal of the integrator circuit. The FPGA can find a large amount of current with a high di/dt rate resulting from a short circuit, even though the short circuit happens between switching events. Hence, the current measurement method can combine a current protection function.

V. Conclusion

This paper proposes a new output current measuring method using tiny PCB current sensors. The PCB sensor is used for measuring a switching current flowing through an IGBT chip. An FPGA and an incomplete integrator reproduce the output current waveform using the switching current. Experimental results obtained from a buck converter have confirmed that the new method can measure a dc component of the output current as well as a ripple component, although the PCB sensor is based on the so-called Rogowski coil.

The method will make it possible to combine current-sensing function into IGBT modules, instead of using existing current sensors like Hall sensors and CTs.

Appendix

Koga *et al.* [10] have proposed a new fishbone pattern for the internal coil structure of the PCB sensor, and has confirmed its signal to noise (*S/N*) ratio, where the noise corresponds to the external magnetic field.

Fig. 12 shows the testing procedure for the $S/N\,\mathrm{ratio}$ of each coil pattern, in which a conducting wire was scanned on the PCB sensor in every direction as a source of the external magnetic field. A step current with an amplitude of 100 A was

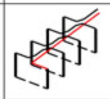
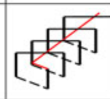
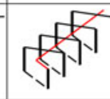
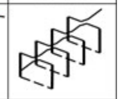
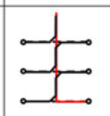
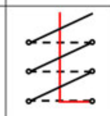
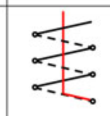
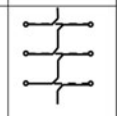
Pattern name	**Fishbone**	Saw	Triangle	Fishbone without return line
Pattern (3D)				
Pattern (2D-above)				
S/N Ratio	23 dB	20 dB	12 dB	-7 dB

Fig. 13. Structures of the new fishbone pattern and three typical coil patterns, along with their S/N ratios.

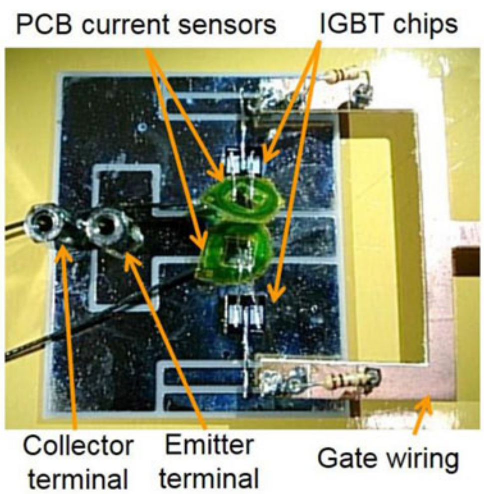


Fig. 14. Real installation of the PCB sensors in a DBC substrate.

injected into the conducting wire. The S/N ratio is given by

$$S/N \text{ ratio} = 20\log\frac{A_S}{A_{N\ \max}}\ \ [\text{dB}] \tag{3}$$

where A_S is the output signal amplitude of the PCB sensor for a current flowing into the inside of the sensor, whereas $A_{N\ \max}$ stands for the maximum output signal amplitude for the external magnetic field. Fig. 13 shows structures of the new fishbone pattern and three typical coil patterns, and summarizes their S/N ratios. The fishbone pattern has the highest S/N ratio of 23 dB.

Fig. 14 is a photo of a real installation of the PCB sensors in a direct bonded copper (DBC) substrate on which two IGBT chips are put. The installation has confirmed that the sensor is available for a dozen of amperes or more without the influence of the external magnetic field, and has a greatly short delay time less than 50 ns compared to the CT [10].

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