New Power Module Integrating Output Current Measurement Function

S.Tabata[1], K.Hasegawa[2], M.Tsukuda[1,3], I.Omura[1]

[1] Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata-ku, Kitakyushu, 804-8550 Japan

[2] Kyushu Institute of Technology, 2-4 Hibikino, Wakamatsu-ku, Kitakyushu, 808-0196 Japan

[3]Green Electronics Research Institute, Kitakyushu, 1-8 Hibikino, Wakamatsu-ku, Kitakyushu 808-0135 Japan

q349515s@mail.kyutech.jp

***Abstract*—This paper proposes a new power module concept that integrates output current measurement function to make inverters compact. The current measurement function is realized by tiny printed-circuit-board (PCB) Rogowski coils. The PCB Rogowski coil picks up a switching current flowing through an IGBT chip, and then a combination of a digital circuit based on a field-programmable-gate-array (FPGA) and an integrator circuit reproduces the output current of the inverter from the switching current. A major concern of the new power module is the effect of reverse recovery current of free-wheeling diodes because the reverse recovery current is superimposed on the switching current. This paper proposes a mitigating method of the reverse recovery current.**

Keywords—Insulated-gate bipolar transistor (IGBT), Rogowski-coil, Printed-Circuit-Board(PCB), Hall current sensor

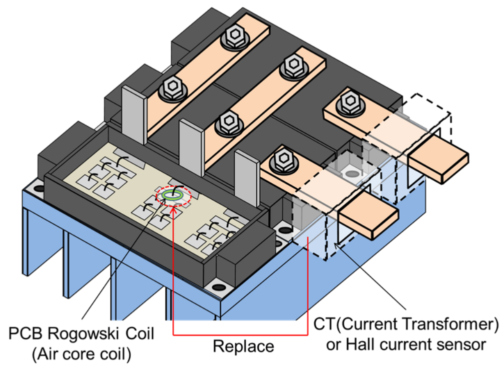
I. Introduction

Integration technology in power electronics is more and more attractive because it contributes to cost reduction and system miniaturization [1-5]. 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-drive circuits. Attention has been also paid to power modules having additional functions or components to be integrated, e.g., short-circuit protection [6], and self-diagnosis function [7], and inductors [5].

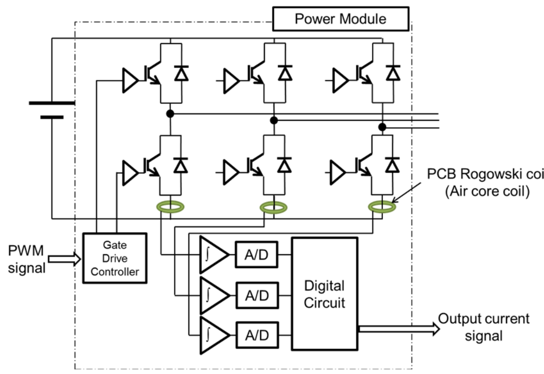
The inverter often employs a current sensor at the output terminal because it has to control the output current in motor-drive and grid-connected applications. The Hall current sensor and the current transformer (CT) are representative ones. However, these current sensors are a constraint to reduce the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

The authors of this paper have confirmed that the output current can be measured by the Rogowski coil from the switching current flowing through an IGBT [9]. However, the effect of reverse recovery current of diodes has not been fully discussed.

This paper proposes a new power module concept that integrates output current measurement function, which does not suffer from the recovery current of free-wheeling diodes.



(a) Impact of the output current function integration into power modules



(b) Circuit diagram for the new power module concept

Fig. 1 Basic consept of the new power module with output current measurement function.

A mitigating method of the recovery current is developed and tested by a buck converter.

II. Output Current Measuring Method

Fig. 1 (a) shows the basic concept of the new power module, in which PCB Rogowski coils are installed. The module does not need current sensors like Hall sensors and CTs at output terminals. Fig. 1 (b) shows the implementation of the current measurement function. The PCB Rogowski coils are put on either the emitter pass of the low-side devices or the collector pass of the high-side ones, i.e., close to the negative or positive bus of the module. This allows the PCB Rogowski

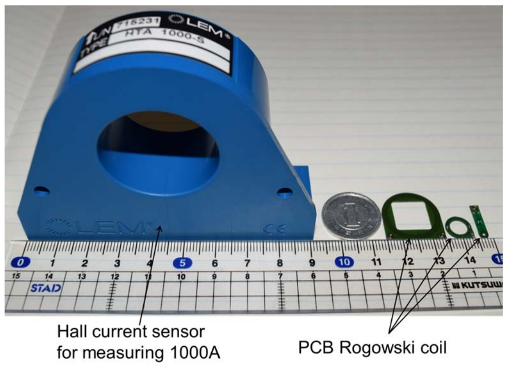


Fig. 2 Hall current sensor and developped PCB Rogowski coil [10].

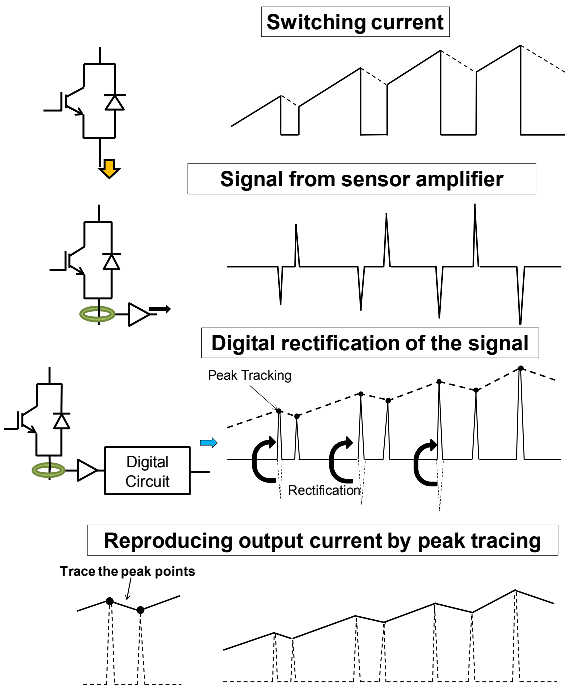


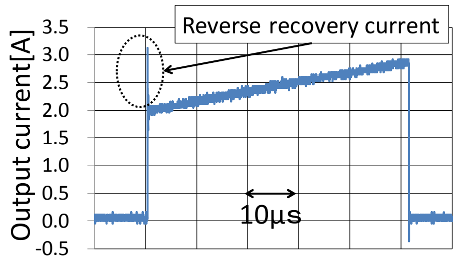
Fig. 3 Reproduction procedure of the output current

coils not to suffer from a displacement current caused by a high *dv/dt*. In addition, the module integrates integrator circuits and a digital circuit based on FPGA.

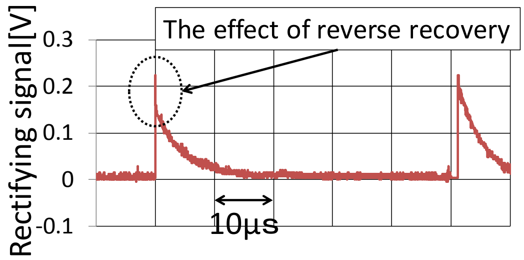
Fig. 2 is a photo of the PCB sensor along with a Hall current sensor [10]. The PCB Rogowski coil can be fabricated at low cost with a significantly small size because it does not have a magnetic core.

The PCB Rogowski coil cannot directly measure the output current of inverters because it has a poor characteristic in a low-frequency region like 50 and 60 Hz. Therefore, the new module employs the reproduction method of the output current of inverter [9].

Fig. 3 illustrates the reproduction procedure of the output current. Since the output signal of the PCB Rogowski coil is in proportion to the time differential of the current, an integrator



(a) Spike due to reverse recovery of diode



(b) Spike in the measured signal

Fig. 4 Effect of diode reverse recovery to output current measurement.

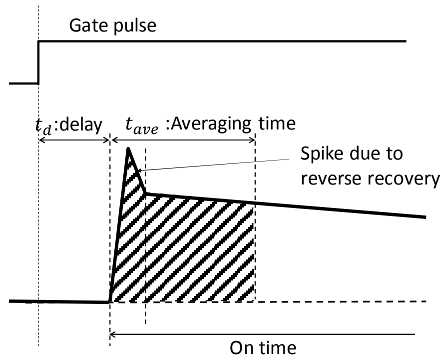
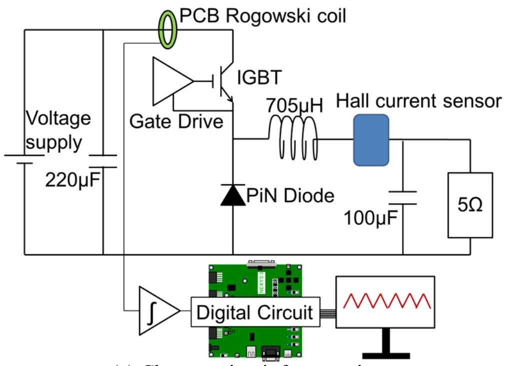


Fig. 5 Mitigating method of the error caused by reverse recovery

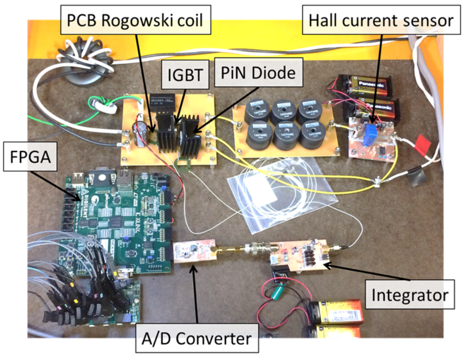
circuit is introduced to reproduce the switching current. The integrator circuit has only to operate in a high-frequency region, so that an incomplete integrator is acceptable. The digital circuit based on the FPGA reproduces the output current waveform by means of rectifying the peak points of the output signal of the integrator circuit, where the peak points correspond to turn-on and –off current.

III. Mitigating Method of Error Caused by Reverse Recovery Current Spike

A major concern of the output current reproduction method is a measurement error caused by the reverse recovery current spike due to the high-side diode. Fig. 4 shows the effect of the reverse recovery current in a switching period, where (a) is the switching current obtained by a Hall current sensor and (b) shows the rectified waveform that indicates the turn-on and –off current. The rectified waveform contained a spike because the reverse recovery current is superimposed on the switching current. Thus, the reverse recovery brings an overestimate



(a) Chopper circuit for experiment



(b) Photograph of the setup

Fig. 6 Setup for experimental verification. The supply voltage was 30V for the verification.

reproduced output current unless the mitigating method introduced.

Fig. 5 shows a mitigating method of the error caused by the reverse recovery. Since the period during which the reverse recovery occurs is much shorter than the switching period, the average over a larger period than the reverse recovery time mitigates the effect of the reverse recovery. Note that there is a delay time t_d from the time that gate pulse rises to that the switching current rises. This delay time results from a delay time of a gate-drive circuit and turn-on delay time of the switching device due to the miller effect. The averaging time t_{ave} must exclude the delay time t_d. In practice, an offline measurement can estimate the delay time.

IV. Experimental Verification

A. Experimental setup

Fig. 6 shows the setup for experimental verification, where a chopper circuit is used for demonstration of the new module concept. The PCB Rogowski coil (0.6mm thick) is placed on the collector pass of the circuit and picks up the switching current of the IGBT. The circuit was configured with discrete IGBT and PiN diode. The combination of an integrator circuit and a digital circuit consisting of an FPGA reproduces the output current of the chopper circuit (8-bit 50MHz A/D converter and 100MHz FPGA). A Hall current sensor is equipped, and measures

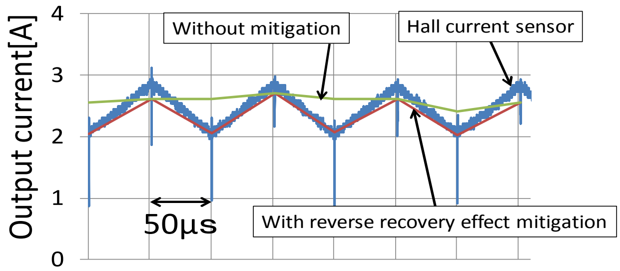


Fig. 7 Reduction of measurement error

the output current for comparison with the reproduction method.

B. Effect of mitigating method

Fig. 7 shows experimental waveforms of the output current with three different ways: (1) the reproduction method without the mitigating method, (2) that with the mitigating method and (3) the Hall current sensor. The averaging time t_{ave} of the mitigating method was 400 ns. The waveform without the mitigating method did not agree with that of the Hall sensor, whereas the waveform with the mitigation method almost agreed with that of the Hall sensor. This confirmed that the mitigating method is indispensable for the new power module with the output current measurement.

C. Demonstration with a power module

Fig. 8 is a photo of a demonstration using a power module of , where the PCB coil is installed on the collector terminal of the high side. Fig. 9 shows transient current waveforms when the duty ratio was changed from 40% to 50%. Good agreement was found between the proposed method and the output of the Hall current sensor.

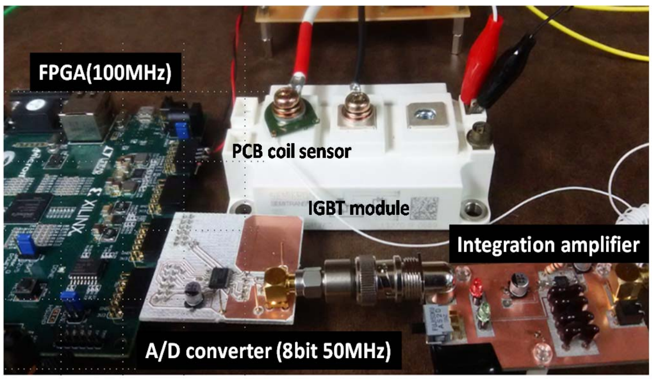
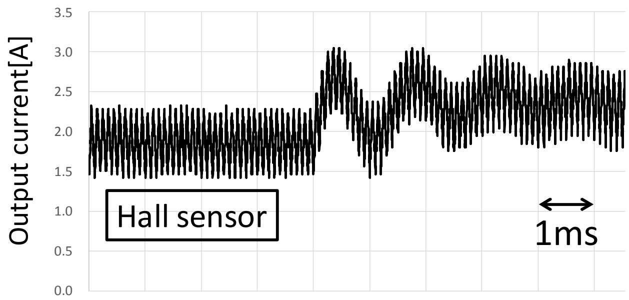
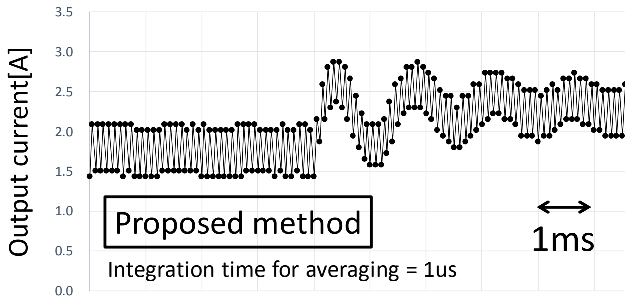


Fig. 8 Demonstration with an IGBT power module. The PCB Rogowski coil sensor of 96 turn, 0.6 mm thick, 20mm diameter is used in the experiment.



(a) Measured output current by Hall current sensor



(b) By the proposed method

Fig. 9 Comparison of measured output current of IGBT power module chopper shown in Fig. 8 by Hall current sensor (a) and the proposed method with PCB coil sensor (b).

V. Conclusions

This paper has present a new power module concept that integrates output current measurement function with tiny PCB Rogowski coils to make inverters compact. The output current of the module can be obtained although the PCB coils measure switching current flowing into IGBT chips. This paper has proposed a mitigating method or the measurement error caused by the reverse recovery of a free-wheeling diode. Experimental results obtained by a chopper circuit have verified the effectiveness of the mitigating method.

Acknowledgments

The authors express our thank to members in the laboratory, specially Mr. M. Ichiki for preparing high speed 8 bit A/D converter board specially designed for the experiment.

References

[1] R. Herzer, "Integrated gate drive circuit solutions," *in Proc. Intl. Conf. on Integrated Power Electron. Sys. (CIPS)*, no. 1.2, Mar. 2010.

[2] B. Vogler, M. Rossberg, R. Herzer, and L. Reusser, "Integration of 1200V SOI gate driver ICs into a medium power IGBT module package." *in Proc. Intl. Sympo. on Power Semiconductor Devices and ICs (ISPSD),* pp. 97-100, 2010.

[3] M. März, A. Schletz, B. Eckardt, S. Egelkraut, and H. Rauh, "Power Electronics System Integration for Electric and Hybrid Vehicles," *in Proc. Intl. Conf. on Integrated Power Electron. Sys. (CIPS)*, no. 6.1, Mar. 2010.

[4] G. Majumdar, T. Oi, T. Terashima, S. Idaka, D. Nakajima, and Y. Goto, "Review of Integration Trends in Power Electronics Systems and Devices," *in Proc. Intl. Conf. on Integrated Power Electron. Sys. (CIPS)*, Mar. 2016.

[5] D. Cooper, "Power Module Integration: A new approach," *IEEE Power Electron Mag.*, vol. 3, no. 3, pp. 31-36, Sep. 2016.

[6] K. Hasegawa, K. Yamamoto, H. Yoshida, K. Hamada, M. Tsukuda, and I. Omura, "Short-circuit protection for an IGBT with detecting the gate voltage and gate charge," *Microelectron. Rel.*, vol. 54, no. 9-10, pp. 1897-1900, Sept./Oct. 2014.

[7] D. Gerber, T. Guillod, and J. Biela, "IGBT gate-drive with PCB Rogowski coil for improved short circuit detection and current turn-off capability," *in Proc. IEEE Pulsed Power Conf.*, pp. 1359-1364, Jun. 2011.

[8] L. Dalesandro, N. Karrer, M. Ciappa, A. Castellazzi, W. Fichtner, "Online and Offline Isolated Current Monitoring of Parallel Switch High-Voltage Multi-Chip IGBT Modules", *IEEE Power Electronics Specialists Conference (PESC)*, pp. 2600-2606, 2008.

[9] K. Hasegawa, S. Takahara, S. Tabata, M. Tsukuda and I. Omura, "A New Output Current Measurement Method with Tiny PCB Sensors Capable of Being Embedded in an IGBT Module," *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 1707-1712, Mar. 2017.

[10] M. Koga, M. Tsukuda, K. Nakashima, and I. Omura,"Application-specific micro Rogowski coil for power modules─Design tool.novel coil pattern and demonstration," *in Proc. Intl. Conf. on Integrated Power Electron. Sys. (CIPS)*, Mar. 2016.