Analog Basis, Low-Cost Inverter Output Current Sensing with Tiny PCB Coil Implemented inside IPM

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***Abstract*— This paper proposes a practical current sensor integration in the intelligent power modules (IPMs) using simple PCB Rogowski coil sensors. The PCB sensors produce signals that proportional to the high frequency switching current from high and low side IGBTs. Then with only general-purpose Op-Amps and photo-couplers based integrator and sample and hold (S/H) circuits reproduce output current of the inverter. Specifically, the "envelop tracking" method has successfully proved on an experimental inverter setup. A significant accomplishment of an improved new analog circuit is the measurement during narrow pulse width around unity modulation index that leads to higher inverter output power.**

Keywords—IPMs, PCB current sensor, Rogowski coil, integration.

I. Introduction

As an integral part of electric vehicle and energy system, the power semiconductor devices are becoming a trend [1]. It is getting high power density, faster and cheaper. As a result, devices such as SiC and GaN have been actively researched for higher power density and power loss reduction with high switching characteristics [2]. Overall volume and passive components of the system are getting smaller because of properties of those new power semiconductor devices. The properties are including higher voltage withstand, thermal conductivity, operating temperature and current density [3].

The study [4] estimated the power densities of Si and SiC DC-DC converters. It predicted that operating at two times higher temperature, SiC devices based DC-DC converter would have relatively higher efficiency than the Si based counterparts and improve the power density by 50%. [5] also predicted that converters fully utilizing SiC devices will be able to reach power ratings of 1MW that will be 1/50 of their former size by 2025.

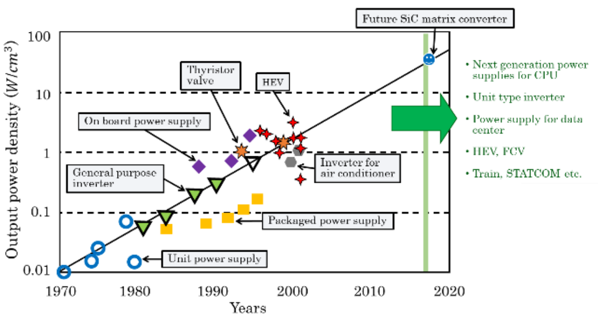
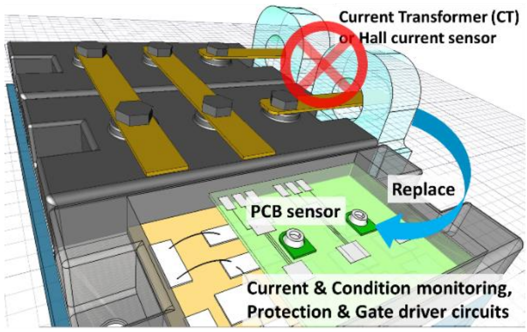


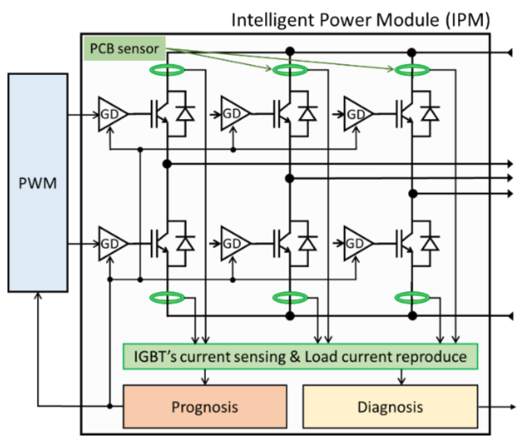
Fig. 1 Power density change in power semiconductor devices [2].

IPMs are another representative of the development of the power semiconductor device. IPM is designed to integrate dedicated drive and protection circuitry along with power switching elements (IGBTs and diodes) in an optimized module structure [6]. They provide easy usage in applications and reliability improvement of applied power electronics systems.

Despite the development in both main power semiconductor devices and auxiliary components, magnetic parts of the inverter system remain bulky and costly. The current sensors are a core component in terms of a control system, monitoring, and reliability of the system. Hall-effect-based current sensors and current transformers (CT) are mainly adopted for output current monitoring. However, these current sensors have become a constraint to reduce the volume and overall power density of the systems due to their limited operating range of magnetic core.



(a) Illustration of the PCB current sensor integration inside IPMs.



(b) Circuit diagram of the basic concept.

Fig. 2 Basic concept of the current sensor integration inside IPMs.

On the other hand, the PCB "Rogowski coil" current sensor has been developed to reduce the volume and cost of the systems. The PCB sensor has a simple structure with reduced cost. Moreover, the sensor catches up high frequency switching current from the switching device which well suited for the PCB sensor characteristics [7].

Recently, PCB Rogowski -coil approach for current sensing has been demonstrated [8-12]. In those papers, however, FPGAs or digital processors are needed for waveform reproduction which requires a too high cost to integrate into IPMs. The authors' group has proposed a low-cost, analog basis demonstration of "envelop tracking" method [13]. However, the narrow pulse width control signals cause an accuracy problem when the output signal of the integrator circuit does not fall or rise to zero before the next turn-on or turn-off event of the switching device. The method also limited to a low amplitude modulation index.

In this paper, for the first time, tiny PCB coils are embedded inside the IGBT power module package to demonstrate noise immunity of the system and applied new circuit to solve the accuracy problem. Only general-purpose OP-amps and photo-couplers are used in the proposed demonstration circuit to show a practical possibility of integration of current sensing in IPMs.

II. New Output Current Measurement Method

As mentioned before, a simple structured PCB current sensor which based on Rogowski coil shown in Fig.3, measures high frequency switching current of the IGBTs. The sensor fabricated within printed circuit board by a new fishbone pattern and supported by shield layer to eliminate the effect of electromagnetic field inside a power module. Characteristics of the PCB sensor are highly compatible with the high-frequency region such as controller switching signal [7].

The analog approach, named "envelop tracking" method uses two sets of PCB sensors, integrator amplifiers, and S/H circuits. The method detects and tracks the maximum point value of PCB sensor signal at each switching (turn-on or turn-off) time of power semiconductors device Op-amp integrator and S/H circuits are amplifying and sampling the peak points from sensor signals. Separately sampling the current of upper and lower arms of inverter system, two sensors and proposed analog circuits reproduce a envelop measurement signals. Those signals are following an upper edge and a lower edge of the output current, as shown in Fig.4.

In applications of an inverter, mean current and ripple component are the main parameters for controller and monitoring systems. With the method, a calculated average value of the outputs from two analog circuits represents the mean output current. The difference of the two outputs show the ripple amplitude that necessary to monitor motor torque ripple and circuit parameter change.

$$Error[\%] = 100\, x\, e^{-\frac{t_{on}}{RC}} \qquad (1)$$

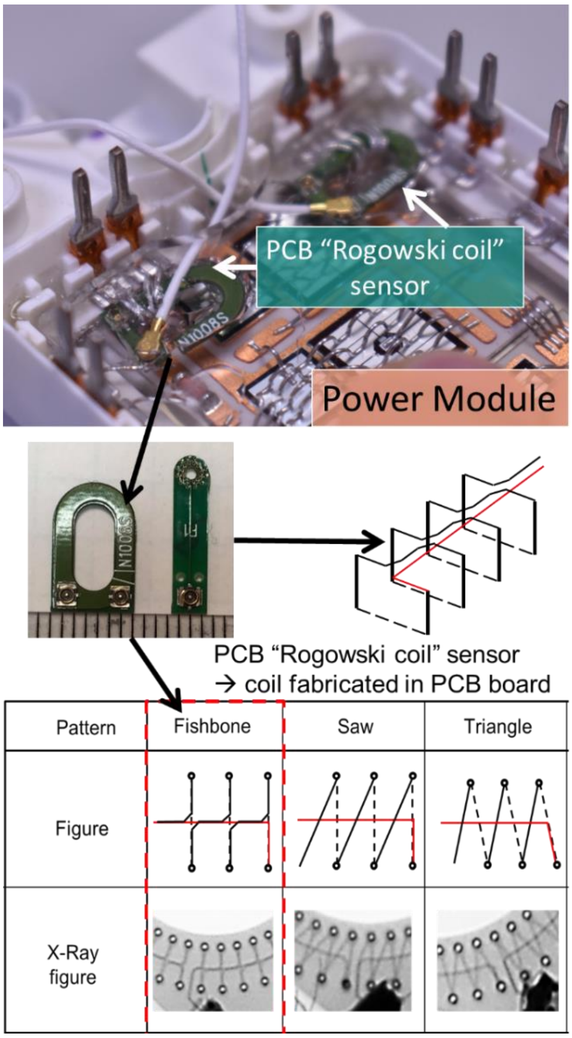


Fig. 3 PCB "Rogowski coil" sensor, placement and structure. [2]

The accuracy error occurs when switching signal pulse (t_{on}) becomes narrower than the integrator time constant (RC), as described in Eq. (1). A photo-coupler has employed as a reset trigger in the integrator circuit which eliminates an unnecessary part of the integrator output signal as shown in Fig.4.

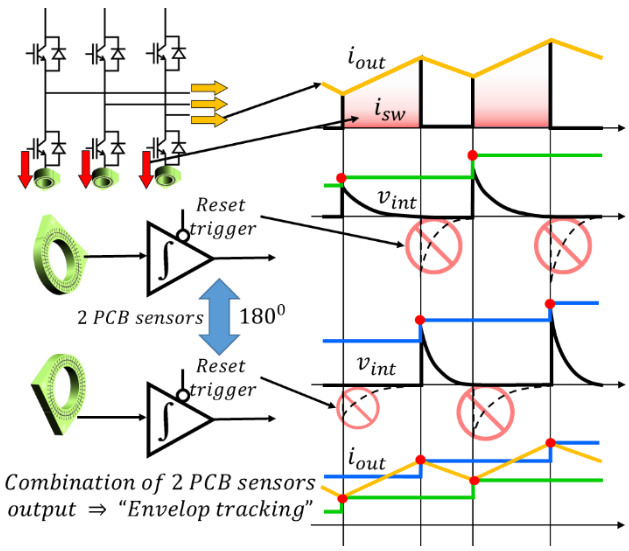


Fig. 4 Analog circuit based current measurement, "Envelop tracking" method. Improvement of the integrator circuit.

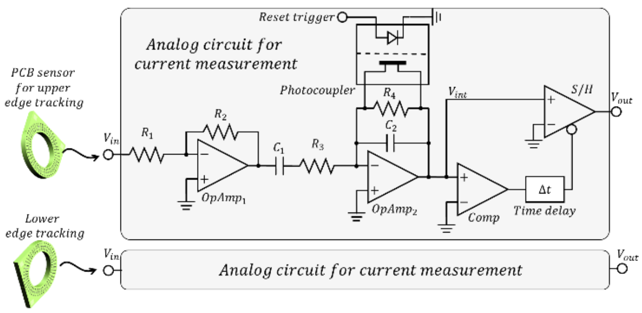
III. CURRENT MEASUREMENT

Fig.4 illustrates the main reproduction procedure of the output current that defines the relations between output current i_{out}, switching current i_{SW}, the output signal of the integrator v_{int} and effect of the reset trigger. The output signal generated in the PCB sensor is proportional to the rate of change of current in the IGBT, the output is connected to an integrator circuit to provide an output signal that is proportional to the current.

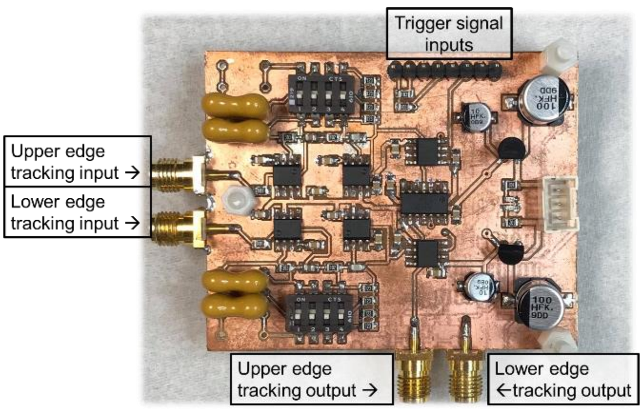
The integrator can detect rising and falling of the PCB sensor output signals. Since the current reproduction process is using multiple sensors and analog circuits, a photo-coupler cancels out each half of the output signals of the integrator. As described in Eq. (1), the time constant of the integrator circuit is determined by C_2R_4 from Fig 5 (a).

A combination of two PCB sensor outputs still contains the turn-on and turn-off current. Therefore, it is possible to reproduce the output current waveform by means of sampling the turn-on and turn-off current from integrator outputs. Fig.6 shows the measured waveforms of the analog circuit, which the S/H amplifier updates output value just after a rise of the integrator output.

Because of the dead time in switching signal, timing of the sampling trigger must be adjusted properly. So, comparator in the analog circuit determines the correct timing of the sampling. With the small delay time Δt shown in fig. 6, the comparator or switching signal becomes a reference for sampling trigger signals for the S/H. Delay time adjusted to eliminate reverse recovery current effect superimposed in the integrator output signal.



(a) Circuit schematics of the analog circuit for output current reproduction.



(b) Photo of the proposed analog circuit.

Fig. 5 The proposed analog circuit for current measurement.

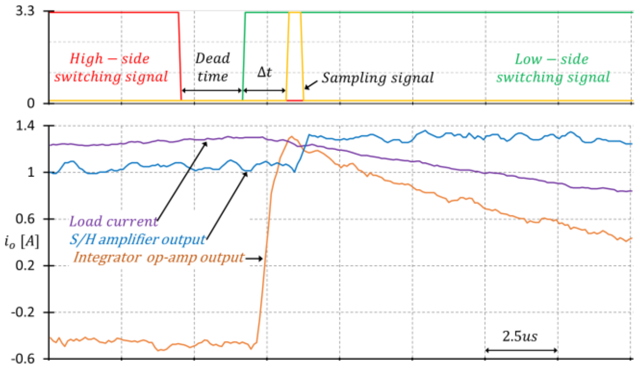
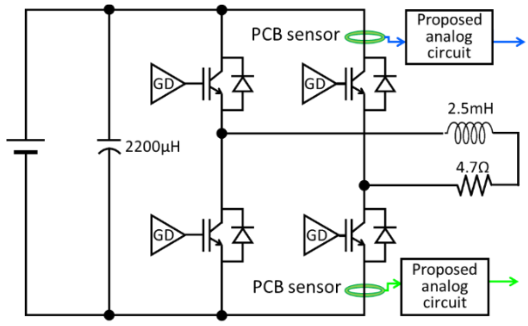


Fig. 6 Measurement waveforms of analog circuit.

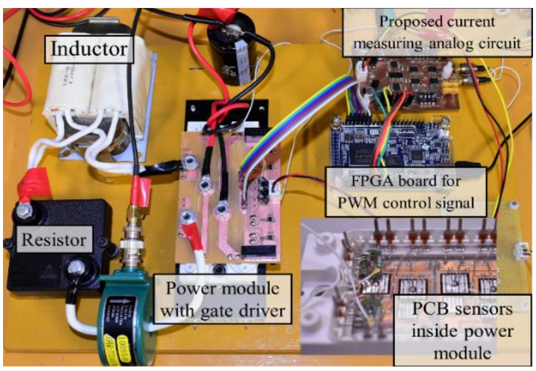
IV. EXPERIMENTAL VERIFICATION

An experiment is carried on investigating the effectiveness of the proposed method in practice. The proposed method is implemented on a full bridge inverter setup using an FPGA with sinusoidal PWM control of 50Hz reference and 5kHz carrier signals. The proposed analog circuits reproduce the output current from switching currents of the full-bridge inverter. Output signals of the analog circuit are directly connected to the oscilloscope for monitoring. Fig.7 is the photo of experimental inverter setup where the PCB sensors placed inside the IGBT power module in the bottom right corner of fig.7 (b).

Fig.8 shows the output current measurement without the integrator circuit reset trigger. As discussed before, measurement accuracy error appears when SPWM signal gets narrower around positive or negative peaks. According to Eq. (1), accuracy error value displacement must be around 20% from the actual current value. Furthermore, the measurement value has displaced 19% from the real current value in this experiment.



(a) Full-bridge inverter circuit diagram.



(b) Photo of experimental setup.

Fig. 7 Full-bridge inverter experimental setup.

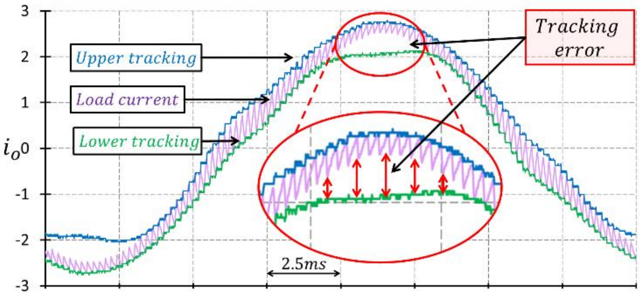


Fig. 8 Output current measurement result without integrator reset. The tracking error appears during narrow pulse width signal.

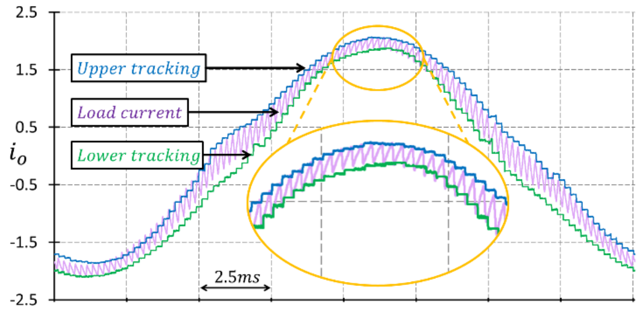


Fig. 9 Output current measurement result of envelop tracking method after integrator reset.

Our final result Fig.9 shows an excellent correspondence between the conventional sensor output and proposed method output. An effect of the photo-coupler in the integrator signal significantly improved the accuracy of "envelop tracking" method for output current measurement.

V. Conclusion

In this paper, for the first time, tiny PCB coils are embedded inside the IGBT power module package to demonstrate noise immunity of the system and applied new circuit to solve the accuracy problem. Only general-purpose op-amps and photo-couplers are used in the proposed demonstration circuit to show a practical possibility of integration of current sensing in IPMs. Most importantly, we proved an accurate current measurement with high power output inverter using embedded PCB "Rogowski coil" sensors and low-cost analog circuits.

Acknowledgements

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References

[1] 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.

[2] Yusuke Hayashi, Kazuto Takao, Toshihisa Shimizu, Hiromichi Ohashi, "An Effective Design Method for High Power Density Converters," 13th International Power Electronics and Motion Control Conference, 2008.

[3] Ian Laird, Xibo Yuan, James Scoltock, Andrew J. Forsyth, "Design Optimisation Tool for Maximising the Power Density of 3-Phase DC-AC Converters Using Silicon Carbide (SiC) Devices," in IEEE Trans.Power electronics, Vol. 33, No. 4, pp. 2313-2932, 2018.

[4] K. Shenai, "Silicon carbide power converters for next generation aerospace electronics applications," in National Aerospace and Electronics Conference, 2000. NAECON 2000. Proceedings of the IEEE, pp. 516–523, 2000.

[5] I. Takahashi, "SiC Power Converter Technology in Future," in Electric Machines and Drives Conference, 2003. IEMDC'03. IEEE International, vol. 3, Jun., pp. 1903–1908, 2003.

[6] Gourab Majumdar, Masanori Fukunaga, Toshifumi Ise, "Trends of Intelligent Power Module," Transactions on Electricaland Electronic Engineering IEEJ, pp. 143–153, 2007.

[7] 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. IEEE Appl.Power Electron. Conf. (APEC), 2016, pp. 700-703.

[8] N. Langmaack, G. Tareilus, and M. Henke, "Novel Highly Integrated Current Measurement Method for Drive Inverters," in IEEE 1997 Applied Power Electronics Conference, 1997, pp. 455-452.

[9] S. Takahara, K. Hasegawa, M. Tsukuda and I. Omura, "Built in Load Current Measuring Method for IGBT Power Module," in Power technology / Power system technology / Semiconductor power conversion joint research group conference, Mar. 2016, pp. PE-16-039.

[10] S. Tabata, K. Hasegawa, M. Tsukuda, I. Omura, "New Power Module Integrating Output Current Measurement Function," in 29th International Symposium on Power Semiconductor Devices and IC's (ISPSD), Jun. 2017, pp. 267-270.

[11] 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," in IEEE Trans.Power electronics, vol. 32, no. 3, pp. 1707-1712, Mar. 2017.

[12] Jun Wang, Slavko Mocevic, Yue Xu, Christina DiMarino, Rolando Burgos, Dushan Boroyevich, "A High-Speed Gate Driver with PCB-Embedded Rogowski Switch-Current Sensor for a 10 kV, 240 A, SiC MOSFET Module" in IEEE 3rd Workshop on Wide Bandgap Power Devices and Applications (WiPDA), pp. 5489–5494 Nov. 2015

[13] B. Bat-Ochir, B. Bayarkhuu, K. Hasegawa, M. Tsukuda, B. Dugarjav, I. Omura, "Envelop Tracking Based Embedded Current Measurement for Monitoring of IGBT and Power Converter System," in Microelectronics Rel., Vol. 88–90, p.p 500-504, Sep. 2018