Output-Current Measurement of a PWM Inverter with a Tiny PCB Rogowski Sensor Integrated into an IGBT Module

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***Abstract*—Inverters used in motor-drive and grid-connected applications usually employ current sensors at the output terminal because they have to control the output current. Existing current sensors like the Hall sensor and the current transformer are a constraint to reduce the volume and cost of the inverter. This paper proposes an output-current measurement method of a PWM inverter using a tiny PCB sensor that is based on the so-called Rogowski coil and can be integrated into an IGBT module. The method utilizes the switching current of the low-side switch for reproducing the output current, which allows using the PCB sensor because the switching current consists of high-frequency components. The method uses a single PCB sensor per leg and takes the polarity of the output current into account. Experimental results using a half-bridge sinusoidal PWM inverter verify that the proposed method measures the output current including its fundamental frequency component, switching ripple one, and polarity.**

***Index Terms*—PWM inverters, current measurement, PCB Rogowski sensors, IGBT modules**

I. Introduction

Integrated technology in power electronics is more and more attractive because it contributes to cost reduction, system miniaturization, and reliability improvement [1]–[4]. The so-called intelligent power module (IPM) is a representative integrated power semiconductor device, which combines multiple insulated-gate bipolar transistors (IGBTs), and gate-driving and protection functions like short circuit and overcurrent. Attention has been also paid to gate-drive circuits having additional integrated functions such as self-diagnosis [5] and short-circuit protection for IGBTs [6].

Most power electronic converters equips current sensors to control power flow and/or to protect themselves [7]–[9]. Inverters used in motor-drive and grid-connected applications usually employ current sensors at the output terminal because motor-drive inverters have to control the motor torque and grid-connected ones have to regurate the output power. The Hall current sensor and the current transformer (CT) are representative ones but are a constraint to reduce the volume and cost of inverters. The so-called Rogowski coil is a candidate for the low-cost and small current sensor [7], [8], [12] but has a poor characteristic in a low-frequency region like a line frequency of 50 or 60 Hz.

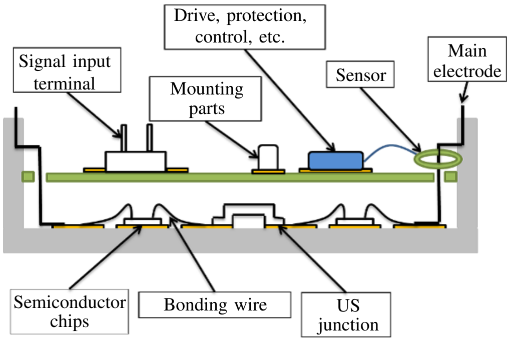
The authors of this paper have proposed an output current measurement method of a buck converter with a tiny printed-circuit board (PCB) Rogowski current sensor that can be embedded in an IGBT module [10], [11]. This method, however, is not directly applicable to pulse-width modulated (PWM) inverters because it cannot distinguish the polarity of the output current unless two sensors are introduced into both the high- and low-side switches [12]–[14].

This paper proposes an output-current measurement method suitable for a sinusoidal PWM inverter with a single tiny PCB sensor that is installed at the low-side switch per leg. The method reproduces the output current including its fundamental-frequency component, switching ripple one, and polarity.

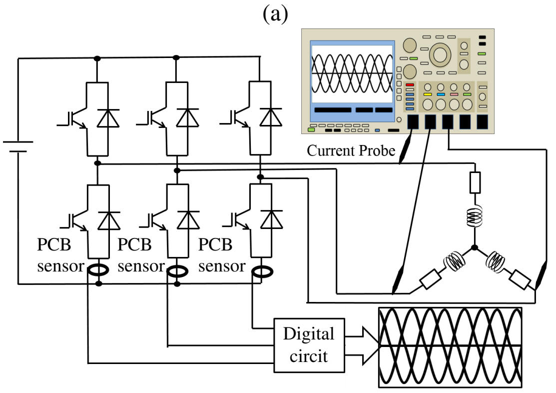
II. PCB Rogowski Sensor for Output Current Measurement

A. Basic Concept

Fig. 1 shows a basic concept of the current measurement method in an IGBT module [11], in which (a) illustrates the installation of the PCB sensor in the power module. The sensor is placed on the main electrode of the emitter or source terminal. Fig. 1(b) shows an application to a three-phase inverter that equips three PCB sensors at emitter terminals of the low-side switches instead of the output terminals. This brings the following benefits: (a) Each sensor does not suffer from a displacement current caused by a high dv/dt, (b) Each sensor has only to pick up a high-frequency switching current



(a)



(b)

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

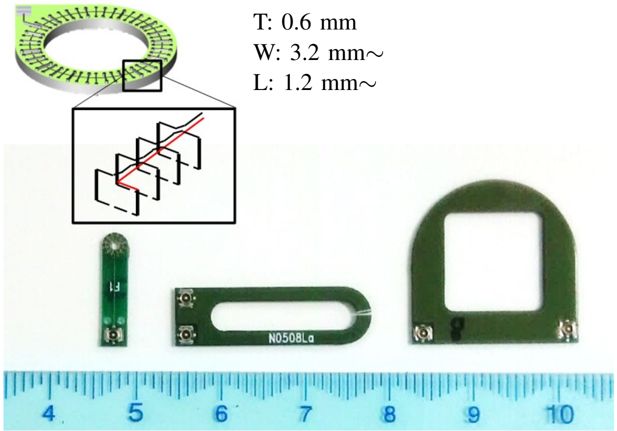


Fig. 2: Exteria of the PCB sensor

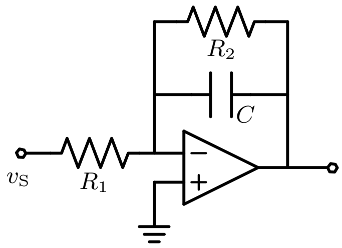


Fig. 3: Integrator circuit for the PCB current sensor

that does not contain a low-frequency component, i.e., the output frequency.

B. PCB Rogowski Sensor

Fig. 2 shows a photo of the PCB current sensor [8], [15]. Its internal coil winding consists of via holes and copper patterns in a printed circuit board. The coil winding is characterized by a new fishbone pattern that has excellent noise immunity to the external magnetic field caused by other wirings [8]. Since the sensor consists of the printed-circuit board, it can be fabricated at low cost. Moreover, the sensor has a wide frequency bandwidth of more than 100 MHz [8].

The sensor is also applicable to current monitoring and protection of an IGBT module because it can be installed on bonding wires [8], [15], [16].

C. 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:

$$v_\mathrm{S} = -M\frac{di}{dt} \tag{1}$$

where M is the mutual inductance between the sensor and the wiring of the current. Fig. 3 shows an integrator circuit consisting of an operational amplifier, which reproduces the current waveform from the output signal v_S. In practice, however, the integrator circuit equips a resistor R_2 connected in parallel with the feedback capacitor C to limit its dc gain because an input offset voltage and an input bias current give a saturated output voltage of the operational amplifier. Hence, the circuit acts as an incomplete integrator. The transfer function of the circuit, $G_\mathrm{int}(s)$ is given by

$$G_\mathrm{int}(s) = \frac{V_\mathrm{Int}(s)}{V_\mathrm{S}(s)} = -\frac{1}{CR_1}\cdot\frac{1}{s+1/CR_2} \tag{2}$$

Equation (2) suggests that a time constant of CR_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 [11], [12].

III. New Output Current Measurement Method for a PWM Inverter

A. Relation between the output current and switching current

Fig. 4 shows the relation between the output current of the PWM inverter and the switching current flowing into the low-side switch. The output current comprises the fundamental frequency component and the switching ripple one. The turn-on current I_ON and the turn-off current I_OFF correspond to the bottom and peak points of the output current over a switching period, respectively. Thus, measuring the turn-on and -off currents completely shows the output current waveform [17]. The PCB current sensor can measure the turn-on and -off currents because they contain only high-frequency components The sensor, therefore, can be used for measuring

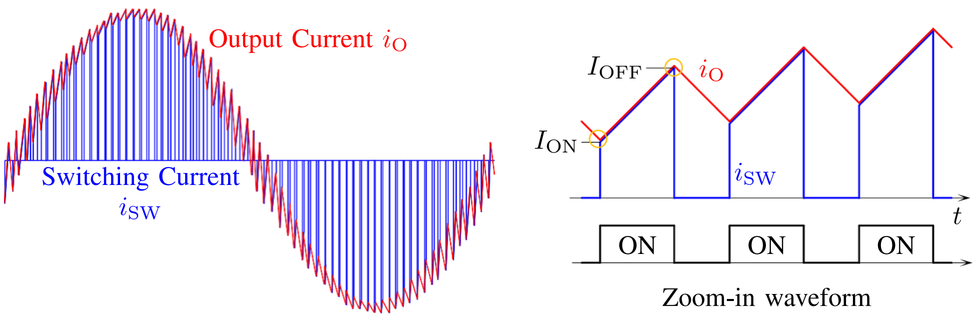


Fig. 4: Relation between the output current and switching current

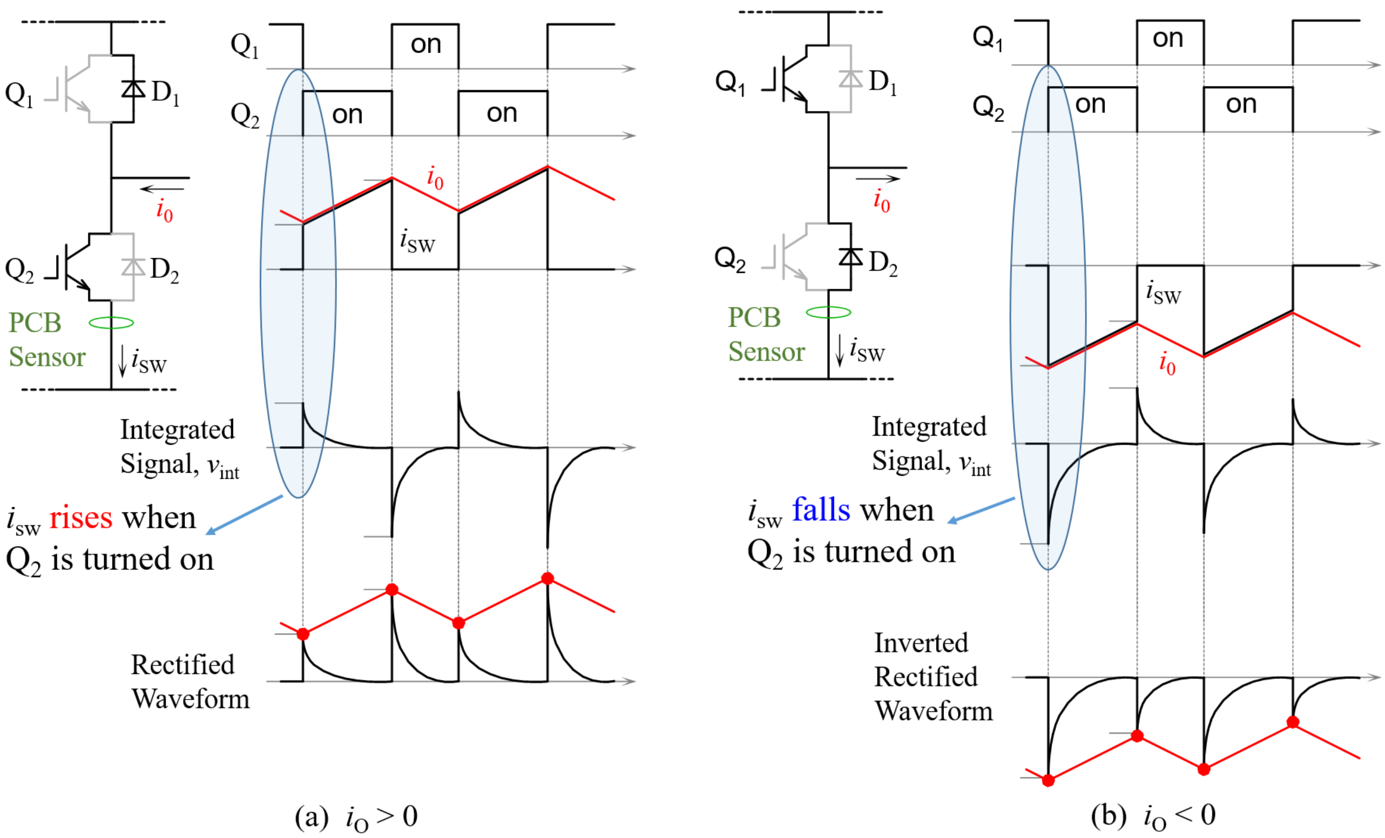


Fig. 5: Proposed reproducing method of the output current with judging its polarity.

the output current even though it contains a low-frequency or dc component.

B. How to judge current polarity

Since the PWM inverter generates a sinusoidal output current, the polarity of the output current alternately changes, unlike the buck converter. The output current flows either into the IGBT or out of the anti-parallel connected freewheeling diode (FWD) in the low-side switch according to the polarity. It is necessary to confirm whether the output current flows into the IGBT or out of the FWD.

Fig. 5 shows the proposed method to judge the polarity of the output current along with gate signals, current waveforms, and the integrated signal v_{Int} (output of the integrator circuit), where the positive polarity is defined as the direction of the current flowing into the inverter. The PCB sensor is equipped with the low-side switch, so that attention is paid to the current flowing into the low-side IGBT Q_2 or out of the FWD D_2. The output current flows into the IGBT Q_2 when the polarity is positive as shown in Fig. 5(a). The integrated signal rises and gets a positive value when Q_2 is turned on. On the other hand, the output current flows out of the FWD when the polarity is negative as shown in Fig. 5(b). The integrated signal falls and becomes a negative value when D_2 turns on, where a turn-on gate signal is applied to the IGBT but the current does not

Gate signal		Integrated signal	Current polarity
Turn on		Rise	Positive
		Fall	Negative
Turn off		Rise	Negative
		Fall	Positive

Fig. 6: Summary of the polarity judgment of the proposed method.

flow into the IGBT. Hence, the relation between the gate and integrated signals indicates the polarity. Fig. 6 summarizes this relation. Finally, rectifying the integrated signal v_{Int} shows the output current waveform when the polarity is positive, whereas inversely rectifying v_{Int} results in the waveform when the polarity is negative. Note that inverter control utilizes an average value over a switching period in practice [18], which is the same as the average of the turn-on and off currents. Hence, this method can provide the average value over a switching period, which the inverter control requires.

IV. Experiment

A. Circuit configuration

Fig. 7 shows the experimental circuit configuration using a half-bridge sinusoidal PWM inverter, where the PCB sensor was installed on the low-side switch. The dc voltage V_{dc} is 100 V and the current rating is 50 A. A Hall sensor was introduced to sense the output current i_{O} for comparison with the proposed method. An FPGA provided gate signals of Q_1 and Q_2 and implements the proposed method based on based on the summary shown in Fig. 6. Fig. 8 is a photo of the installation of the PCB sensor in the IGBT module used for the experiment. The sensor was inserted between a bus bar and the emitter terminal of the low-side IGBT Q_2.

B. Results

Fig. 9 shows experimental waveform of the output current obtained from the Hall sensor, i_{O}, and that done from the proposed method, $i_{\mathrm{O}}{}'$ that is the rectified waveform, where the fundamental frequency was 50 Hz and the switching frequency was 1.5 kHz. Fig. 10 shows a zoom-in waveform of the output current i_{O} along with peak points of $i_{\mathrm{O}}{}'$ with the proposed method. The peak points well agreed with the output current obtained from the Hall sensor even though the polarity changed.

V. Conclusion

This paper has proposed an output-current measurement method of a PWM inverter using a tiny PCB Rogowski sensor. The method is characterized by reproducing the output current including its polarity using a single PCB sensor at the low-side switch per leg. Experimental results using a half-bridge sinusoidal PWM inverter have verified that the proposed method measures the output current including its fundamental frequency component, switching ripple component, and polarity.

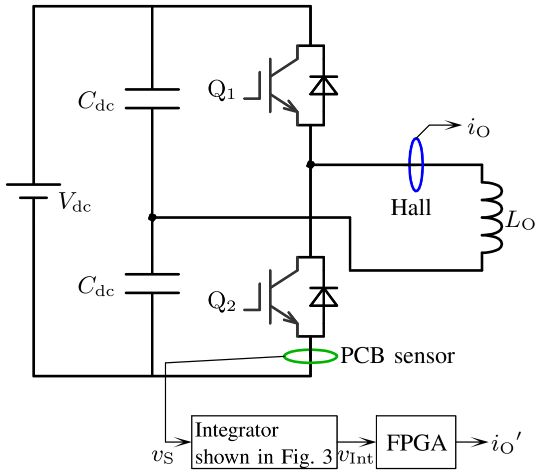


Fig. 7: Experimantal circuit configuration using a half-bridge PWM inverter.

Fig. 8: Installation of PCB sensor

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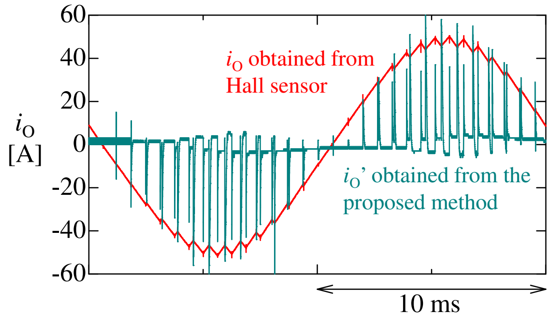

Fig. 9: Experimantal waveforms of the output current.

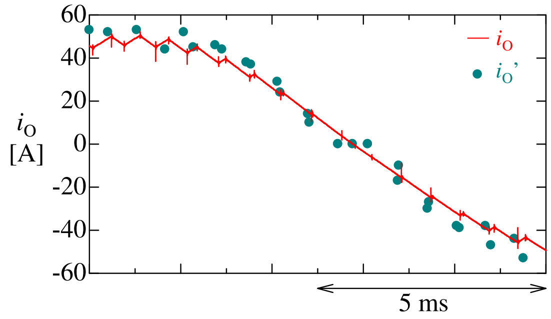

Fig. 10: Zoom-in waveforms of the output current around a zero-crossing point.

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