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Single PCB current sensor for feedback control in the switch mode power converters

Battuvshin BAYARKHUU† and Ichiro OMURA†

† Department of Life Science and Systems Engineering, Kyushu Institute of Technology, 2-4 Hibikino, Wakamatsu-ku, Kitakyushu, 808-0196 Japan

E-mail: bayarkhuu.battuvshin201@mail.kyutech.jp

Abstract This paper explained the PCB Rogowski coil sensor which have a major advantage over hall-effect sensor and current transformer with its simple structure, cost efficiency and good sensitivity in high frequency range. The sensor could be utilized in a converter with switching element and contribute greatly in terms of total system size and cost. We propose a current feedback control for inverter systems using single PCB sensor. Using a sensor with a complementary analog circuit integrated in an IPM allows for higher power density systems. An op-amp integrator and S/H circuits complete the reproduction process by measuring the rate of current change from the input. We developed a current feedback controller on a full-bridge inverter to demonstrate the method's practicality.

Keywords Current sensor, Rogowski coil, feedback control, full-bridge inverter

PCB 電流センサを用いたインバータフィードバック制御システム

バヤルフー　バトゥフシン† 大村　一郎†

† 九州工業大学 大学院 生命体工学研究科 〒808-0196 福岡県北九州市若松区ひびきの 2-4

あらまし 本稿では、PCB 技術で作製したロゴスキ電流センサをインバータ出力電流センサとして用いフィードバック制御を行った技術について報告する。インバータの出力電流センサにはホール電流センサや電流トランス（CT)が多く用いられるが、外形が大きく高温では使えないという課題がある。我々が開発した PCB ロゴスキ電流センサは従来のセンサに比べて非常に小型でコストが低く、高温でも使えるという特徴を持っている。そこで本論文では、PCB 電流センサを出力センサとして使用したインバータシステムを提案する。

キーワード 電流センサ、ロゴスキーコイル、フィードバック制御、フルブリッジ インバータ

1. Background

As the key devices for electric vehicles, tractions, appliances, and industrial motor drives, power semiconductor devices became a fundamental building block [1]. The emergence of SiC and GaN devices lead to much higher power density system design with their excellence in switching and conduction loss and thermal characteristics[2]. The utilization of fast switching devices as GaN requires advances in active integration technologies such as bonding wire and packaging [3]. IPMs represent this technology trend.

Capacitors and inductors occupy a considerably large amount of space in the system. Research [4,5] suggests the advantages of passive component integration such as size reduction and cost-saving by combining them into a single module and single-core for inductors and transformers.

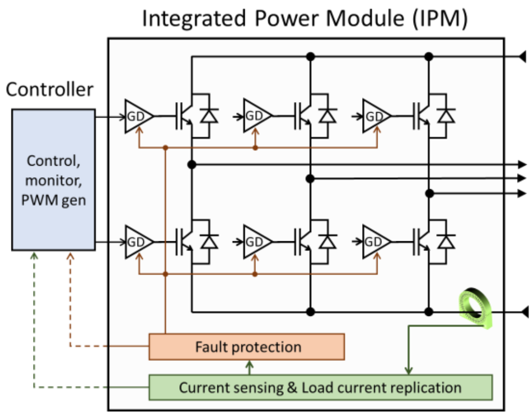

Figure 1. Outlook on power modules, built-in current sensor, protection and gate driver circuits.

As for the current sensor, they remain bulky and costly with the magnetic cores. Paper [6] discussed the coreless current sensor based on magnetic field sensors. A coil with several magnetic sensors and complementary circuits represents a solution to size limitations and better performance in temperature change. Still, the sensor has a complicated structure and practical limitations to integrate into an IPM.

Recently, PCB Rogowski coil sensors have been demonstrated with analog and digital current reproduction approaches. Research [7] proposed FPGAs or digital processors for waveform reproduction. Previously, authors proposed [8-9] a low-cost analog circuit basis demonstration with the “Envelop Tracking” method for the output current measurement using PCB sensors and implemented inverter controller systems.

In this paper, we propose an output current measurement method utilizing only one PCB sensor with an updated op-amp-based analog circuit for the inverter system. A simple feedback controller used a current measurement from the analog circuit outputs to modulate an inverter output.

2. New current measurement method

2.1. The PCB “Rogowski coil” current sensor

The Rogowski coils are commercialized and used extensively, especially in high current applications such as transmission lines. It has several advantages over traditional electromagnetic current sensors such as size, shape, wide frequency band, and better insulation [10]. However, wire-wound coils sensitivity depends on the conducting wire positioning, and external fields inside the power semiconductor module can impair the accuracy [11].

As a solution for these drawbacks, a group [12] developed a PCB “Rogowski coil” current sensor. The PCB sensor has a new coil pattern and a shield layer for better accuracy and elimination of the effects of the electromagnetic field in an IPM. It is highly cost-effective and compatible with the high-frequency region. Conveniently, the sensor can be placed inside the power module and on the bonding wires and catch switching currents.

Characteristics of the PCB sensor were tested up to 110MHz. Coil’s self-inductance and output voltage with amplifier are constant over the wide range of input frequency. It is worth mentioning that the high-frequency region was not fully discovered due to equipment limitations indicating that the sensor could perform well over the 100MHz range. Also, the group tested the accuracy of the PCB sensor in various shapes and sizes, and the results were comparable to a commercially available current transformer.

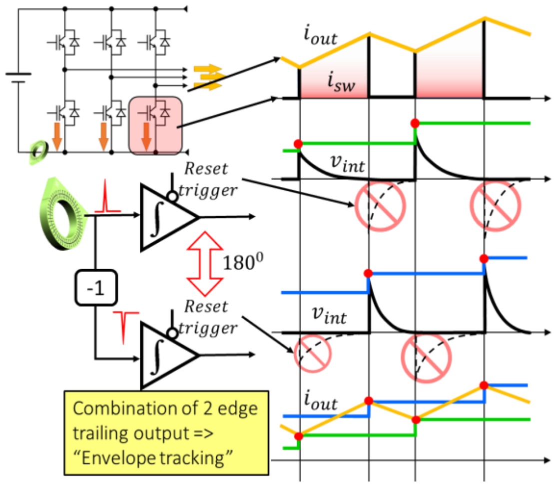

Figure 2. Analog circuit based current measurement, “Envelop tracking” method.

2.2. Envelop tracking current measurement method

As mentioned before, the so-called “envelope tracking” method proposed a practical solution to integrate PCB sensors with complementary integrator and S/H circuits. The current reproduction process used two sensors for a single-phase current, suggesting six PCB sensors can effectively measure the three-phase currents.

An updated “envelop tracking” method uses one PCB sensor compared to two sensors for each phase current in previous work. The method detects and tracks the maximum point value of the PCB sensor signal at each switching (turn-on/turn-off) time of the power semiconductor device. Op-amp integrator circuit has a function to integrate and amplify the PCB sensor output that has a few millivolts of amplitude and microseconds of width. The S/H circuit is catching the peak value from the integrator output signal. Captured peak values are proportional to the current value.

The single sensor captures all the switching information, but current reproduction circuits are used separately. We used an inverting buffer to track opposing edges. So, the first set of integrator and S/H circuit tracks only one side of the output current and, the second set captures the other edge as shown in figure 2.

Mean current and ripple components are the essential parameters for controller and monitoring systems in inverter applications. The mean output current is an average value of the outputs from two analog circuits. The difference between the two outputs indicates the ripple amplitude that must be monitored to track motor torque ripple and circuit parameter changes. The current reproduction process takes up to five microseconds, thus the method with the PCB sensor will be sufficient for the switch-mode applications utilizing up to 200 kHz, such as monitoring and control of motor drive, tractions and home appliances.

2.3. Sampling and reset trigger signal generation

It is crucial to generate a trigger signal with proper timing for the S/H circuit to capture the current value. For this purpose, we used simple edge detecting and delay circuits with Schmitt triggers and optocouplers. Complementary analog circuit is needed either upper or lower side tracking of the measured current.

Edge detection happens on the inverter output, then the trigger signal for the S/H and reset signal for the integrator circuits are generated with proper delay time, as shown in figure 3. Timing of the trigger and reset signals will depend on a time constant of RC on inputs of the Schmitt trigger. It is worth mentioning that the delay in the trigger signal is necessary to mitigate the superimposed overshooting effect from the reverse recovery current of the freewheeling diode.

Previous research mentioned a tracking error due to the control signal being narrower than the integrator time constant, thus resulting in a shift in the tracking outputs. This error will limit the accuracy of the current reproduction in unity modulation index operation. Resetting the feedback capacitor in the integrator circuit reduces the error margin with switching elements just after the sampling step or during the other edge tracking process. Generated reset trigger affects the second set integrator circuit to eliminate a signal which is already measured in the first set of integrator and S/H.

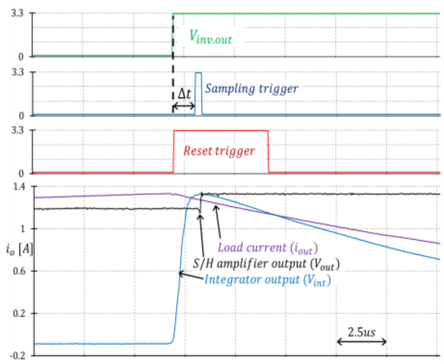

Figure 3. Measurement waveforms of analog circuit.

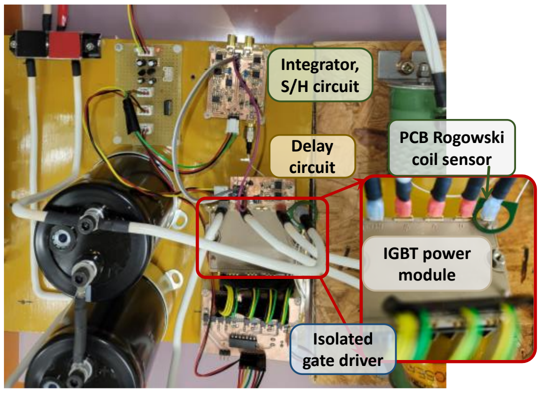

Figure 4. Full-bridge voltage source inverter setup with PCB "Rogowski coil" sensor placement.

3. Results

3.1. Experimental setup

We constructed a single-phase voltage source inverter to test the viability of the current measurement method, as shown in figure 4. The inverter circuit is attached to an inductive and resistive load. We used an FPGA board to implement simple current feedback control to maintain output current levels in various input voltage sources (Vsource). The controller operates at 10kHz carrier and 50Hz modulation frequency using an onboard analog-digital converter (ADC).

3.2. Envelop tracking result

The tracking result in figure 5 shows the tracking of the upper and lower edges of the output current. The mean electrical current used for feedback control is the average of upper and lower edges tracking results. Also, it is possible to calculate the ripple amplitude of the measured current from the results. In the figure 5, the purple curve indicates the current transformer output to validate our newly developed current measurement method.

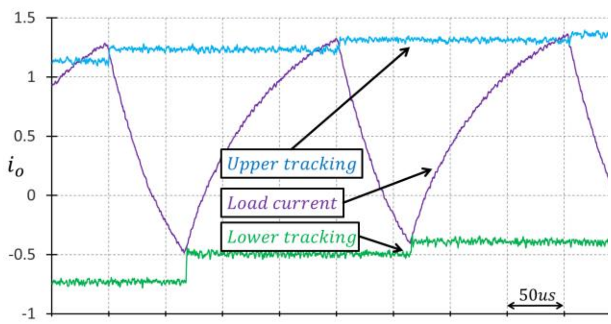

Figure 5. Output current measurement with "envelop tracking" upper and lower edges.

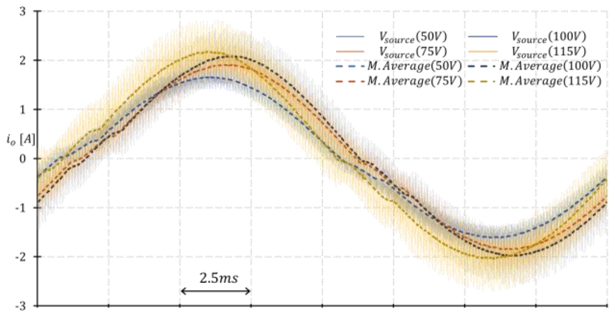

Figure 6. Current controlled closed loop inverter output with PCB sensor.

S/H circuit consistently follows the upper and lower edges of the output current through the whole period. In some regions, the shift of tracking signals is noticeable even with the integrator circuit with an optocoupler to discharge feedback capacitor. The result can improve with faster switching elements and better timing of reset signals.

3.3. Single loop current feedback controller result

We tested the new measurement method in a simple, single loop, current feedback control on a full-bridge inverter, as shown in Figure 6. The experiment was successful at controlling the current by maintaining the current level in various input voltage changes as well as following the reference value change from the controller.

There is a slight variation in the maintained current levels due to the immature control algorithm and current ripple amplitude as it gets considerably high as the input voltage increase. There has been a factor that limited the measurement range. Photocoupler used to detect edge from output voltage have effective input current range. A voltage limiter circuit can extend this input current range to the desired level.

4. Conclusion

The paper describing a method for integrating current sensing into an inverter system using PCB coils (also known as Rogowski coils) embedded in the inverter power module (IPM) package. These coils can be used to accurately measure the output current of the inverter, and this method is both cost-effective and allows for high power density. The current reproduction process use only low-cost analog circuits (such as op-amps and photo-couplers) in combination with Schmitt triggers to reproduce the output current, and it is possible to implement a current feedback control system based on the "envelop tracking" method.

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