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Clamp type built-in current sensor using PCB in high-voltage power modules

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Abstract

High reliability is required for power modules because they are increasingly demanded as key devices in an energy-saving society. However, commercially available current sensors like current transformers and Rogowski coils are still of large size. Therefore, it is impossible to measure the current in small parts. In addition, long wiring with large sensors reduces the performance of power modules. In previous studies, we proposed a current sensor of PCB Rogowski coil with a fishbone pattern. The sensor is sufficiently small and thin with high accuracy for power module application. The PCB current sensor can be used as a built-in current sensor in power modules from the viewpoint of size. However, the sensor requires further improvement to be attached to bonding wire from a usability perspective.

We propose a new pattern for the clamp-type PCB sensor and fabricate the PCB sensor as a built-in sensor in a power module. With the new pattern, it is possible to move and widen the gap for clamping. The signal error is small even though the sensor is inclinedly attached to the bonding wire. The accuracy is confirmed by a comparison between the clamp-type PCB sensor in the module and a commercially available current sensor outside the module. The clamp-type PCB sensor can be applied for intelligent power modules as well as current measurement for power electronic converters.

1. Problems of current sensors for power modules

High reliability is required for power modules because they are increasingly demanded as key devices in an energy-saving society. To realize highly reliable power modules with control, the collector current, collector voltage, and gate voltage of power semiconductor devices must be monitored accurately. At the same time, miniaturization of current sensors is strongly required because large sensors induce large waveform noise like surge voltage by increased stray inductance. However, commercially available current sensors like current transformers (CTs) and Rogowski coils are still large in size because they need a magnetic core or coil of many turns [1-4]. Other current sensor technologies have not been substantially discussed regarding compatibility between accuracy and miniaturization up till now [5-12].

In our previous studies, we proposed a current sensor of a printed circuit board (PCB) Rogowski coil with a fishbone pattern (see Fig. 1) [13-15]. The sensor is sufficiently small and thin with high accuracy for power module application (see Fig. 2).

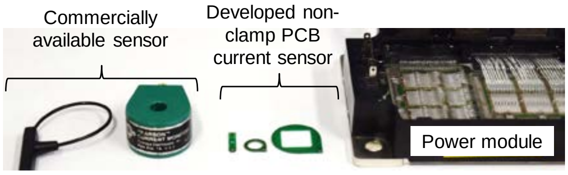
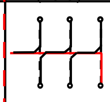
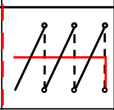
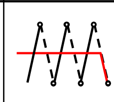
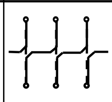
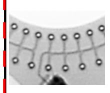
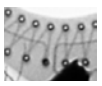
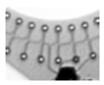


Fig. 1. Developed non-clamp-type PCB sensor in our previous study.

Pattern name	Fishbone (Novel)	Saw blade	Triangle	Fishbone w/o return line
Picture				
X ray photo				
Max. variation with outside conductor	±7%	±10%	±26%	±218%

- Solid black, red and doted black lines are 2nd, 3rd and 5th layers respectively
- PCB sensors are no shield and soldering connection type

Fig. 2. Fishbone pattern for a high-accuracy PCB sensor.

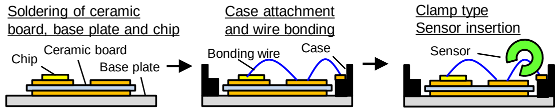


Fig. 3. Assumed procedure to attach the PCB sensor in power modules.

The PCB current sensor can be used as a built-in current sensor in a power module from the perspective of size. However, the sensor needs further improvement to be attached to bonding wire from the viewpoint of usability. Bonding wires must be inserted to the sensing area through the sensor board after wire bonding (see Fig. 3). In this paper, we propose a clamp-type PCB current sensor in a high-voltage power module.

2. Proposed pattern for the clamp-type PCB sensor

The PCB sensor is composed of six layers (see Fig. 4). In the non-clamp-type pattern, the first and sixth layers are used as a noise shield, the second layer is the forward line, and third layer is the return line. And the second and fifth layers with via holes compose coils. The pattern lines to the signal connector pass through between the via holes on the second and third layer. The point for low signal error

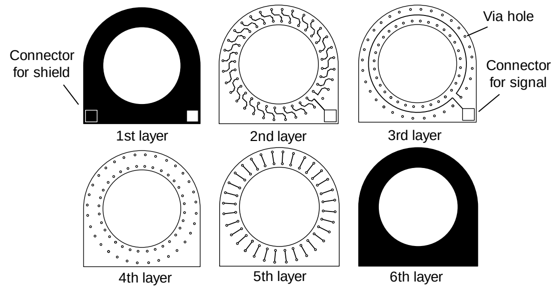


Fig. 4. Non-clamp-type fishbone pattern for each layer.

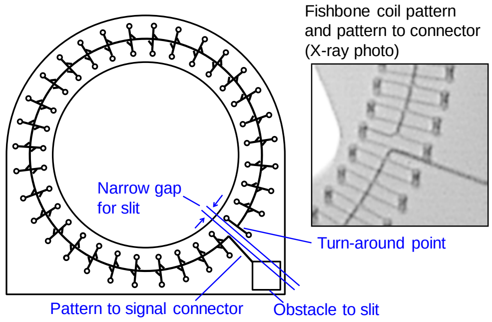


Fig. 5. Overlapped pattern of non-clamp-type fishbone from the second to fifth layers.

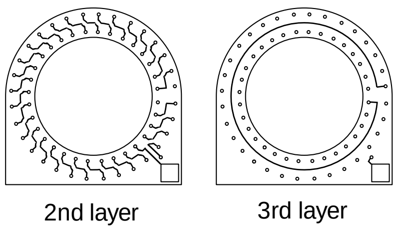


Fig. 6. Clamp-type fishbone pattern for the second and third layers.

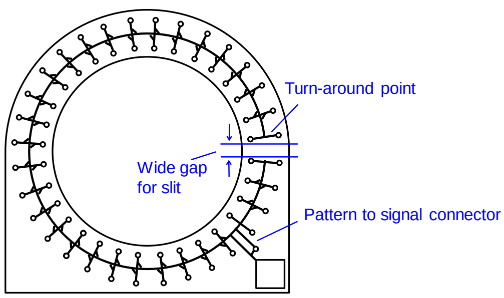


Fig. 7. Overlapped pattern of clamp-type fishbone from the second to fifth layers.

is the pattern overlap of the forward pattern between coils and the return pattern as viewed from above (see Fig. 2). A quasi overlap from the side view is easy because the second and third layers are automatically closed on both sides of the thin insulating layer. In this structure, it is difficult to make a clamp-type sensor because the signal connector is placed on a straight line of a narrow gap of the sensor pattern for clamp slit cutting (see Fig. 5). The connector position should be as close to the coil pattern as possible in order not to increase signal error.

We propose a new pattern for the clamp-type sensor. The proposed pattern is also composed of six layers and the function of each layer is same as the pattern in the non-clamp-type pattern. The different patterns are only the second and third layer (see Fig. 6). With the proposed pattern, it is possible to make a pattern gap in the required position by free setup of a turn-around pattern point. Therefore, the pattern lines to the signal connector passing through between the via holes are modified to two lines on the second layer. This is also better for making the slit because the pattern gap is wider than in previous studies (see Fig. 7).

3. Signal error simulation and measurement of the fabricated PCB sensor

Before sensor fabrication, the signal error of the clamp-type PCB sensor is confirmed with simulation based on mutual inductance between the via holes and the sensing position (see Fig. 8). The PCB outside diameter, the PCB thickness, and the PCB width of the designed current sensor are 21 mm, 0.8 mm, and 3 mm, respectively. The maximum signal error in the current sensing area is only 0.2% (see Eq. 1).

$$Signal\ error = \left|\frac{Each\ signal - Benchmark\ signal(Center, 0°)}{Benchmark\ signal(Center, 0°)}\right| \quad (1)$$

The signal simulation tool using MATLAB was developed to calculate the mutual inductance between the total Rogowski coils and hundreds of thousands of current sensing positions by Neumann's formula. The calculation speed is at least one hundred times faster than the speed of commercially available tools. To improve the calculation speed, the design tool incorporates two approaches. The first approach is where mutual inductance is calculated by using a simplified fishbone-like model of the Rogowski coil. The second approach is where the mutual inductance is calculated in advance and tabulated as a function of

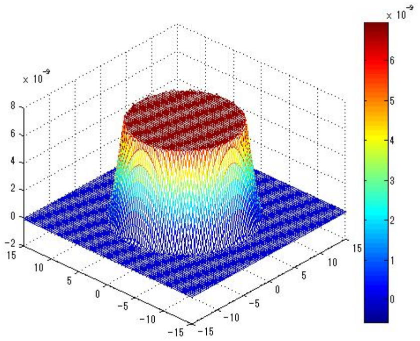


Fig. 8. Signal error simulation in the sensing area.

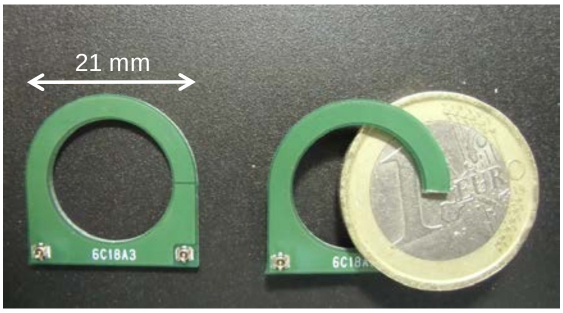


Fig. 9. Fabricated clamp-type PCB current sensor (Thickness: 0.8 mm).

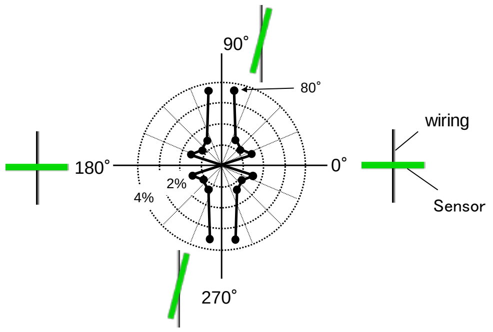


Fig. 10. Angle dependency of signal error in experiment.

the distance to eliminate the integral calculation time. With this tool, signal sensitivity and signal error can be estimated and designed to a practical level despite the arbitrary geometry.

The pattern gap of the fabricated PCB current sensor was cut by a diamond wire saw to make the clamp-type sensor (see Fig. 9). PCB has flexibility, so wiring like bonding wires can be passed through the PCB slit without breaking.

The angle dependency of the PCB sensor with respect to objective current wiring was evaluated by measurement (see Fig. 10). The signal error was less than 2% from an angle of 0° to 60° (see Eq. 1). The error was less than 4% even though the angle reached was 80°.

4. Demonstration of current measurement in a high-voltage power module

The clamp-type PCB sensor was demonstrated by switching current measurement of a two-in-one IGBT module in comparison with a commercially available current sensor (CT) that was installed outside the IGBT module. The switching condition was 50 A and 600 V single-pulse test with an inductive load. The gate voltage is set to 0 V and 15 V. The sensor is clamped on bonding wires between the ceramic board and the module case flowing emitter current of IGBT (see Fig. 11). The current signal by the PCB sensor corresponds to the current by CT. The IGBT current is successfully measured by the clamp-type PCB current sensor in the power module (see Fig. 12). Incidentally, a little time delay of the op-amp can be compensated for by a corrected value, and the ringing after turn-off is a subject of future study.

5. Conclusion

We proposed and fabricated a new clamp-type PCB sensor with a new pattern. The PCB sensor is installed in power modules as a built-in sensor. With the new pattern, it is possible to move and widen the pattern gap for the slit. The signal error is small even though the sensor is inclinedly attached to the bonding wire. The accuracy is confirmed by a comparison between the clamp-type PCB sensor in the module and a commercially available current sensor outside the module. The clamp-type PCB sensor with the new pattern is applied for intelligent power modules (IPMs) as well as power electronic converters to

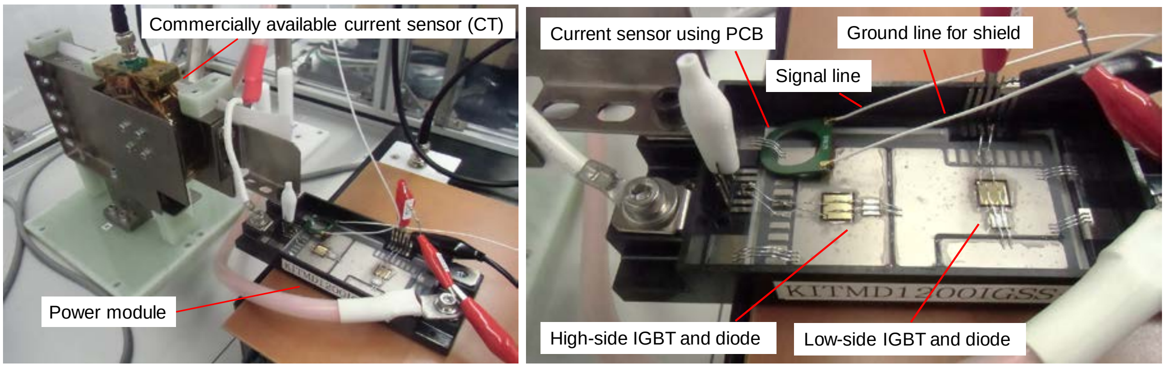


Fig. 11. Inductive load single pulse test system and power module for demonstration of the clamp-type PCB current sensor.

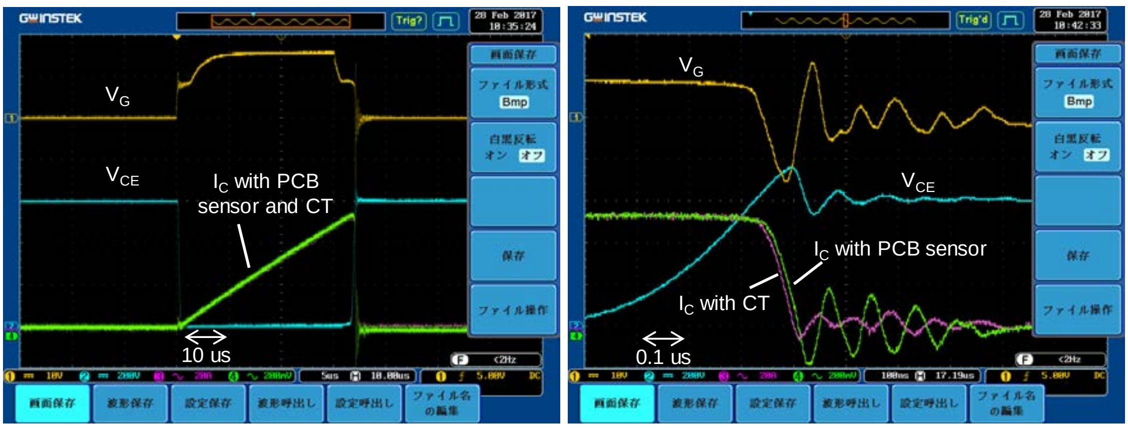


Fig. 12. Waveforms of 50 A - 600 V single-pulse test for confirmation of the clamp-type PCB current sensor and CT.

monitor current and current distribution.

Acknowledgements

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