A TMR-based Integrated Current Sensing Solution for WBG Power Modules

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2024 IEEE Applied Power Electronics Conference and Exposition (APEC) | 979-8-3503-1664-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/APEC48139.2024.10509509

***Abstract*—This paper proposes a contactless and high-precision current measurement solution using Tunneling Magnetoresistance (TMR) sensors to address the challenges of current measurement in wide band gap (WBG) power electronics with high *dv/dt*, *di/dt* and switching frequencies. The solution, referred to as TTS, utilizes two TMR sensors placed on opposite sides of the current-carrying trace or PCB-based terminal. By differentiating the sensor readings, the system achieves enhanced resolution and reduced errors from external magnetic fields and temperature fluctuations. Notably, the Two TMR Sensor (TTS) implementation is compatible with various power module designs, requiring no modification during fabrication, and seamlessly can be integrated into the final stages. Overall, this novel current measurement solution offers significant advantages for improved performance in power modules.**

***Index Terms*—Two TMR Sensor (TTS), Tunneling Magnetoresistance (TMR), wide band gap (WBG), high *dv/dt*, power module, contactless**

I. Introduction

Power modules serve as the backbone of modern electronic systems, facilitating efficient and reliable energy conversion, control, and distribution. These self-contained units house power devices, control circuitry, and thermal management components, making them highly adaptable to a wide array of power electronic applications, including renewable energy systems, electric vehicles, industrial motor drives, and telecommunications equipment. As the demand for increased efficiency and performance in these applications continues to grow, the integration of current sensing capabilities into power modules emerges as a pivotal development.

One crucial aspect of power modules is the accurate sensing of electrical current flowing through the system. Current sensing is indispensable for various functions, including overcurrent protection, closed-loop control, fault detection, and system diagnostics [1]–[3]. Efficient and reliable current sensing is especially vital in high-power applications to prevent catastrophic failures and ensure safe and stable operation.

Various current sensing methods are integrated into power modules to measure current flow accurately. Some of the widely adopted current sensing techniques include shunt resistors, magnetic sensors (such as Hall-effect sensors and current transformers), and sensing based on the voltage drop across the internal resistance of the power semiconductor devices. Each method has its advantages and limitations, and the choice of sensing technique depends on factors like application requirements, accuracy, response time, and cost-effectiveness [4].

Shunt resistors are one of the most straightforward methods for current sensing. They operate by measuring the voltage drop across a small, known resistance in series with the current path. This voltage drop is directly proportional to the current passing through the resistor, allowing for precise current measurement. Shunt resistors are highly accurate and offer a wide dynamic range, making them suitable for many applications. However, they can dissipate some power as heat, and their physical size can limit their use in space-constrained environments.

Magnetic sensors, including Hall-effect sensors and current transformers, are another prevalent choice for current sensing in power modules. Hall-effect sensors use the Hall effect to measure the magnetic field generated by the current-carrying conductor. They are non-intrusive, which means they do not require breaking the circuit to install, and are suitable for applications where isolation between the current-carrying path and the measurement circuit is essential. Current transformers, on the other hand, work on the principle of electromagnetic induction and provide galvanic isolation. Both methods are highly accurate and do not introduce significant power losses, making them valuable for various applications [5], [6]. However, having a limited frequency ban width and large size are the constraints in using hall sensors and current transformers, respectively. Moreover, current sensors based on Magneto Resistors also can be placed in the magnetic sensors category. AMR (Anisotropic Magneto-Resistance), GMR (Giant Magneto-Resistance), TMR (Tunnel Magneto-Resistance) are three types of sensors based on magneto resistors [7], [8].

Sensing based on the voltage drop across the internal resistance of power semiconductor devices is a method specific to power modules that use MOSFETs or IGBTs (Insulated Gate Bipolar Transistors). These devices inherently have a small but predictable resistance when conducting current. By measuring the voltage drop across the device, the current can be deduced. This technique is advantageous in terms of cost, as it doesn't require additional components, but it may have limitations in accuracy and response time compared to dedicated current sensors. Various sensing solutions and their specifications are summarized in Table. I.

Therefore, the choice of current sensing technique in power modules is a critical decision that engineers and designers must make based on the specific requirements of the application. The accuracy, response time, and cost-effectiveness of each method play a crucial role in determining the most suitable approach. As the power electronics industry continues to evolve, innovations in current sensing technologies will further enhance the performance and safety of electronic systems across various domains. It is also important to consider the advancements in communication protocols, such as digital interfaces, that allow for more efficient data transfer and real-time monitoring of current measurements, enabling more sophisticated control and protection strategies. The continuous development of power modules and their integrated sensing capabilities is pivotal to meet the ever-increasing demands of modern technology [9], [10].

Despite the advancements in current sensing methods integrated into power modules, several challenges persist in the present approaches. Accuracy and linearity of current sensors are critical for precise measurements, but factors like temperature variations, electromagnetic interference, and offset voltage errors can introduce inaccuracies.

To accurately measure current in small-sized and fast-switching power modules, a suitable solution must be accurate, noise-immune, and high-bandwidth. Ideally, the solution should require minimal changes to the power module design. Among various options, magnetoresistors-based current sensors like Giant Magnetoresistance (GMR) and Tunneling Magnetoresistance (TMR) are well-suited due to their small size and high bandwidth [13], [14]. Moreover, A notable advantage of these sensors is their capacity to precisely measure direct current (DC) while also offering the benefit of a compact design.

Magneto-resistive sensors rely on alterations in a material's resistance properties when subjected to a magnetic field, generating a signal output proportionate to the current flowing through a conductor [1]. These sensors allow contactless current measurement, making it sufficient to place them on the current-carrying trace without electrical connection. However, challenges remain, as these sensors are not immune to noise and may encounter capacitive coupling issues caused by high *dv/dt* current flow.

In this paper, a current measurement solution integrable into the power modules with different configurations without changing their design is presented. This innovative solution seeks to address the challenges associated with existing current sensing methods. The key features of this proposed solution are as follows:

1. Enhanced Resolution: By using a specific two sensor configuration, a higher resolution in current measurements is achieved. This will enable more precise monitoring and control of power modules, particularly in applications where small current fluctuations are of great significance.

2. Noise Immunity: The proposed solution incorporates noise-reduction mechanisms to mitigate the impact of electromagnetic interference and temperature variations, which confirms that current measurements remain accurate even in electrically noisy environments.

3. High Bandwidth: To meet the demands of fast-switching power modules, the high bandwidth TMR sensors used in the solution application guarantee the high bandwidth current measurement.

4. Minimal Design Changes: For the implementation of the proposed solution, there is no need to change the layout of the power module. Moreover, it is compatible with any module configuration.

5. Improved Coupling Resilience: The proposed solution has been applied in three steps to relieve the capacitive coupling to ensure an accurate current measurement.

This paper aims to provide a comprehensive overview of the proposed current measurement solution, including its working principles, design considerations, and experimental results. This innovative approach holds the potential to significantly enhance the accuracy and reliability of current measurements in power modules, ultimately leading to improved performance and safety in a wide range of electronic applications. Although some literature has proposed using two Magneto-Resistor sensors for achieving improved current measurement, they have limits, such as needing an extensive area for solution implementation and capacitive coupling concerns. The solution proposed in this paper has addressed concerns with precise current measurement.

II. TTS METHOD

The proposed TTS method addresses the limitations found in the literature by adopting a configuration in which two sensors are placed in parallel with the conductor sandwiched between them. As illustrated in Fig. 1 (a). In this setup, the central copper trace positioned between the sensors generates a magnetic field, which is perceptively detected by two identical current sensors strategically oriented in opposing directions. These sensors produce output signals designated as V_{S1} and V_{S2}, respectively. Due to the precisely orchestrated arrangement of the sensors, it is noteworthy that V_{S1} is equivalent

TABLE I
COMPARISON OF EXISTING CURRENT SENSING TECHNOLOGIES [8], [11], [12]

Sensing Solution	Bandwidth	System Integration	Limits
Shunt	MHz	Low	Bulky
Current Transformer	MHz	High	Unable to measure DC current
Hall effect sensor	kHz	High	Low bandwidth
Rogowski coil	MHz	Medium	Unable to measure DC current
MR sensor	MHz	Low	Noise immunity and temperature drift

in magnitude but opposite in polarity to V_{S2}. Moreover, given their proximity, both sensors are subjected to the same ambient temperature and external field interference. Consequently, V_{S1} and V_{S2} can be aptly characterized as:

$$V_{S1} = S_1 \cdot B_1 + \Delta V_1 + K_1 \cdot \Delta T_1 \tag{1}$$

$$V_{S2} = S_2 \cdot B_2 + \Delta V_2 + K_2 \cdot \Delta T_2 \tag{2}$$

In the given equation, S_1 and S_2 represent the sensitivities of the TMR sensors in units of V/mT. ΔV_1 and ΔV_2 denote the errors in the output voltage attributed to external fields, while B_1 and B_2 represent the magnetic fields to which the sensors are exposed. Furthermore, K_1 and K_2 stand for the sensitivities of the sensors with regard to temperature variations, signifying the errors in the output voltage resulting from temperature fluctuations. The disparity between V_{S1} and V_{S2}, denoted as ΔV_S, can be expressed as:

$$\Delta V_S = (S_1 B_1) - (S_2 B_2) + (K_1 \Delta T_1) - (K_2 \Delta T_2) \tag{3}$$

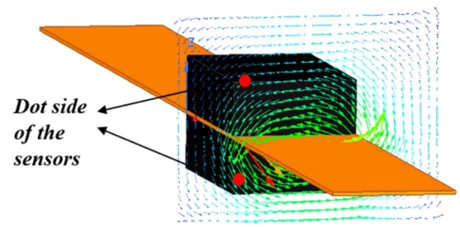
Given the particular arrangement of the sensors, which results in $V_{S1} = -V_{S2}$ and $B_1 = -B_2$, coupled with the placement of sensors on opposite sides of the terminal ensuring exposure to identical temperatures, where $\Delta T_1 = \Delta T_2$, (3) can be rendered in a simplified form as:

$$\Delta V_S = 2S_1 \cdot B_1 \tag{4}$$

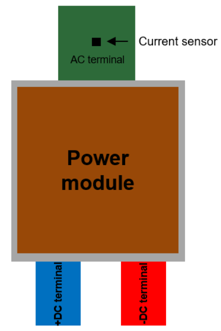
Consequently, the optimal noise cancellation effect is achieved through the strategic placement of the sensors in symmetrical positions, ensuring that they encounter equivalent magnetic fields and noise levels. Furthermore, in contrast to a strategy of merely enhancing the resolution or sensitivity of the current measurement system, the TTS method excels in diminishing the influence of temperature fluctuations on sensor performance, which is due to the mitigation of errors stemming from temperature sensitivity, which ultimately contributes to a more stable and reliable output in the current measurement system. Fig. 1 (b) presents a conceptual drawing of implementing the TTS method on a power module AC terminal.

For the purpose of validation of this solution, Fig.2 (a) depicts the TTS prototype board, featuring two CT100 current sensors from Crocus. Furthermore, in order to maintain consistency and uniformity in the experimental setup, the width of the current-carrying PCB trace has been held at the same dimensions as that of the AC output terminal of the designed power module.

In Fig. 2 (b), the output of a single sensor utilizing the TTS method is presented alongside the output from a conventional current probe, both subjected to 40 A peak-to-peak 70 kHz current pulses. The primary objective of this test is to assess the performance of each sensor individually and to evaluate their collective impact on the overall TTS system.



(a)



(b)

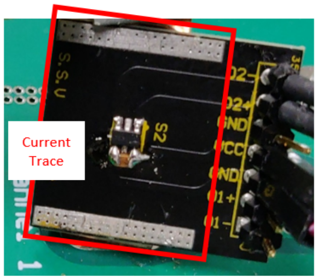
Fig. 1. TTS method implementation for a (a) Current carrying trace, (b) Conceptual power module

Upon examining the results, it becomes evident that the current measured by the current probe exhibits minor deviations from the ideal square-wave shape. These deviations are primarily attributed to parasitic inductance within the system. In contrast, the output of the current sensor also follows a similar waveform pattern, but with noticeable spikes occurring during transitions.

The emergence of these spikes can be attributed to the capacitive coupling effects between the main current-carrying trace and the sensor output trace. To comprehensively analyze and evaluate the coupling phenomenon, a strategic modification has been implemented. This modification involves the design of a PCB terminal with a thinned current trace that intentionally passes underneath the sensor. This innovative approach and its testing are depicted in Fig. 3 (a) and (b). This modification is specifically intended to reduce the unwanted coupling effects between the primary current-carrying trace and the sensor output trace.

Fig. 4 presents the test results aimed at evaluating the impact of varying the thickness of the current trace on the capacitive coupling effect. This test involves altering the thickness of the central copper trace while keeping other parameters constant. The corresponding test results, shown in Fig. 4, provide a clear visualization of the relationship between trace thickness and the coupling effect. As observed, thinning the current-carrying trace reduces the capacitive coupling noticeably.

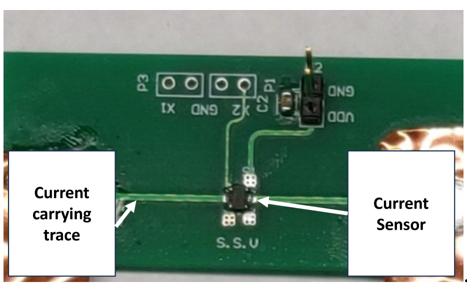
Although thinning the trace can help reduce the capacitive coupling, this solution brings concerns about heating the trace and limits the current rating of the main trace. To address this concern, a slitted current trace has been designed and depicted



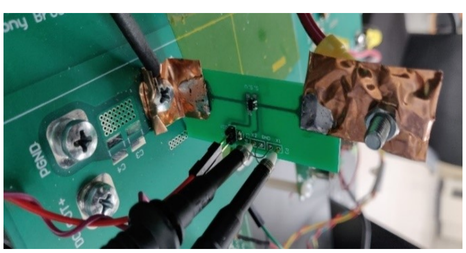
(a)

(b)

Fig. 2. (a) Prototype for TTS method implementation for a PCB based current trace. (b) Test Result



(a)



(b)

Fig. 3. (a) TTS method implementation for PCB based terminal, (b) Test setup

in Fig. 5 (a) and (b), top and bottom view, respectively. In this design, the thin trace carries a portion of the primary current sensed by the sensors above the trace on the two sides of the board, and the other two sections of the board carry the more significant portion of the current. Therefore, with this solution,

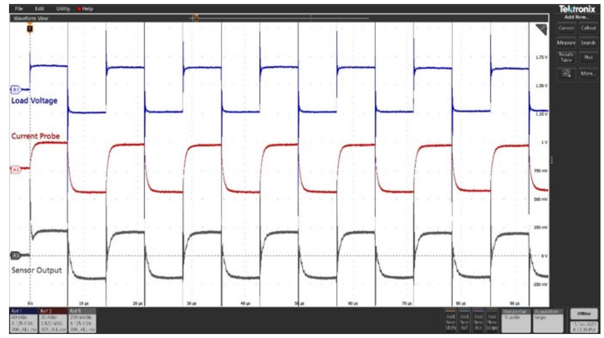
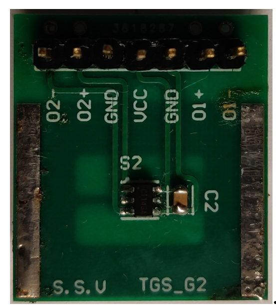


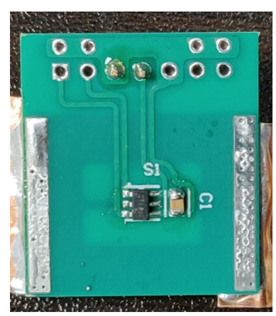
Fig. 4. Test result for validating effect of thinning the current carrying trace on capacitive coupling effect

concerns of capacitive coupling and limiting the current rate of the trace simultaneously with increasing the measurement resolution and decreasing the errors generated from noise are addressed. Fig. 6 shows the test result for the slitted trace design.

As it can be observed from the test results, slitting the trace helps with reduction of the capacitive coupling which leads to controlling the spikes in riding and falling flanks due to the high *dV/dt*.



(a)



(b)

Fig. 5. TTS method implementation for slitted trace (a) Top view, (b) Bottom view

III. Conclusion

In this paper, a small size, low cost, and precise power module integrated current measurement solution capable of accurately measuring high switching current is presented. The proposed solution is contactless with no power loss and

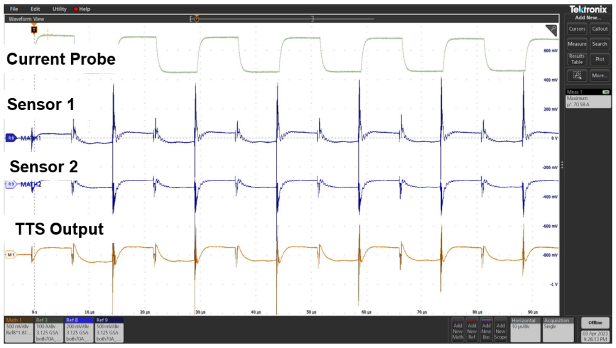


Fig. 6. Test result for validating TTS solution on the slitted trace

independent of the structure of the power module. To alleviate the coupling issue of the current measurement while keeping the capability of the terminal for passing high current, the current trace slitting solution is proposed and tested. Rather than enabling noise immune current measurement, the TTS method can alleviate the errors in the current measurement due to the temperature fluctuations by canceling the errors of two sensors together.

Acknowledgments

The authors would like to acknowledge the National Science Foundation (NSF Award No. 1846917) for lending financial support for this work.

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