Magnetoresistance-based Current Sensor for Wide Bandgap Power Converter Integration Applications

Hossein Niakan
Electrical and Computer Engineering
UNC Charlotte
Charlotte, United States
hniakan@charlotte.edu

Alireza Omidi
Electrical and Computer Engineering
UNC Charlotte
Charlotte, United States
aomidi@charlotte.edu

Babak Parkhideh
Electrical and Computer Engineering
UNC Charlotte
Charlotte, United States
bparkhideh@charlotte.edu

***Abstract*—With the rapid growth of wide bandgap power converters in high power-density applications, current sensors play an increasingly critical role in ensuring precise control and protection. In these compact designs, maintaining low-power signal integrity becomes challenging due to the extremely fast switching speeds, whether hard or soft-switched. This work provides a detailed analysis of the performance of contactless magnetic field detectors for current measurement in such noisy environments. A novel processing technique is proposed to enable the integration of high-performance magnetoresistors (MR) in high-frequency wide bandgap power converters. An early prototype is designed and experimentally evaluated using a tunnel magnetoresistor (TMR) detector. Effectiveness of the proposed solution is demonstrated through the accurate detection of the switch node current of a gallium nitride (GaN) converter operating at a 500 kHz switching frequency.**

***Index Terms*—wide bandgap power converters, contactless current sensor, high $\frac{dv}{dt}$, signal integrity.**

I. Introduction

Devices leveraging materials such as silicon carbide (SiC) and gallium nitride (GaN) are changing the game in power electronics, bringing remarkable advantages in handling high voltages and achieving faster switching speeds [1]. These advanced materials offer superior electrical properties over traditional silicon devices, allowing them to operate more efficiently at higher temperatures and power levels [2]. Such properties make wide bandgap devices ideal for applications that demand high power density and efficiency, including electric transportation [3], [4], distributed energy resources (DERs) [2], mining electrification [5], consumer electronics [6], and more.

The ability of wide bandgap (WBG) and ultra-wide bandgap (UWBG) devices to achieve high switching speeds significantly reduces the need for bulky passive components, such as inductors and capacitors, which have traditionally constrained the size and design of power converters. This reduction in component size directly translates to more compact and lighter power converters, thereby enhancing power density and overall system efficiency [1].

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This is while, as switching frequencies increase, switching losses become a critical factor that can limit efficiency gains. To mitigate these losses, soft switching techniques have become popular in recent developments [7], [8], [9]. Soft switching reduces the voltage and current overlap during switching transitions, minimizing energy dissipation and allowing devices to operate efficiently at high frequencies [10], [11]. By incorporating soft switching techniques, WBG and UWBG devices can maintain their advantages in speed and efficiency without being hindered by excessive switching losses, thus unlocking their full potential in advanced power conversion systems [12], [13], [14].

Although soft switching reduces switching losses and boosts efficiency at high frequencies, precise control over these transitions requires accurate current measurement [15], [16]. In advanced soft-switched converters, directly measuring the current through switching devices is essential for real-time feedback and fine-tuning control strategies, ensuring optimal operation. For isolated converters, high-frequency current measurement is also needed at key points like the primary current of transformers or resonant tanks to enable dynamic control and early fault detection. Reliable current sensing is thus crucial for fully leveraging the advantages of WBG and UWBG devices in advanced power conversion systems [17], [18].

Accurately measuring current in high-frequency environments poses several challenges, particularly with the extremely fast switching speeds of WBG power devices, which operate in the nanosecond range [17]. These speeds produce current waveforms with components that far exceed the fundamental switching frequency. Linear magnetic field detectors, such as Hall effect sensors and magnetoresistors, have some key advantages such as being non-intrusive, low-cost, low-power, and well-researched over the years. Several studies have enabled the development of various enhancement techniques, such as temperature drift compensation [19], [20] [21], and active offset compensation [22], [23], to improve magnetic sense detectors precision. These advantages make the aforementioned sensors promising to be implemented as current detectors in modern power electronics.

Nevertheless, even with soft switching techniques used in modern power converters, high $\frac{di}{dt}$ or $\frac{dv}{dt}$ transients still occur,

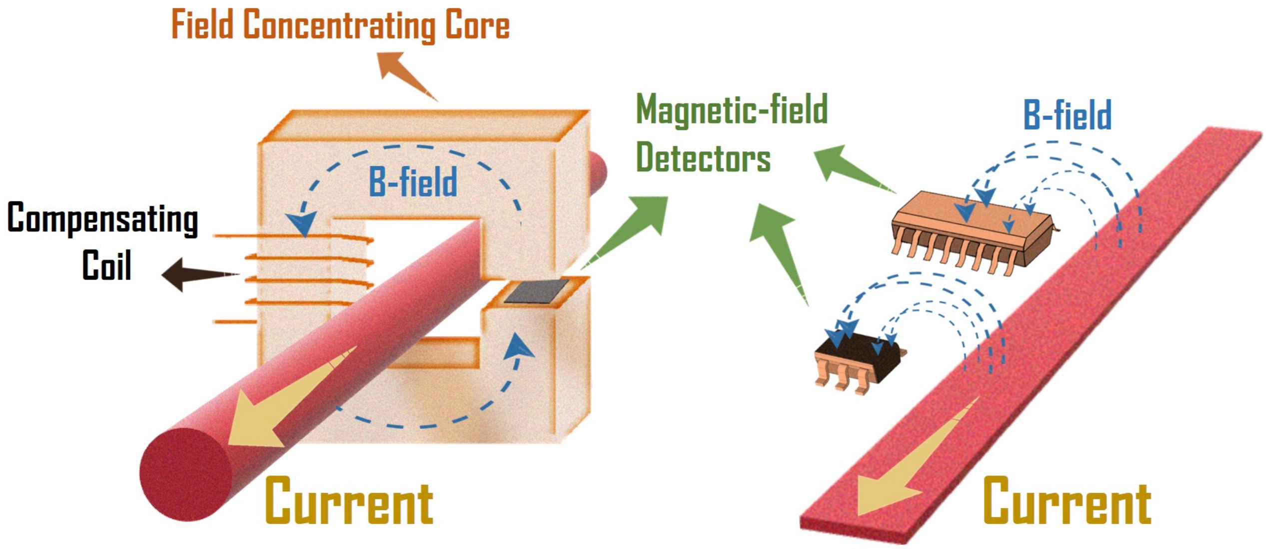

Fig. 1. A holistic depiction of magnetic field sensors working principle.

meaning sensors must also be resilient to electromagnetic interference (EMI) and other disturbances common in these systems. Previous studies have shown that such magnetic field detectors can be excessively vulnerable to high $\frac{dv}{dt}$ effects [24]. This paper investigates the impact of high $\frac{dv}{dt}$ transients on state-of-the-art magnetic field sensors and proposes a novel solution to improve their integrability in WBG power converters. Section II delves into a brief on magnetic element sensors for power electronics applications, while Section III presents the proposed solution, supported by experimental verification and analysis.

II. Magnetic Field Detectors for WBG Power Electronics

Wide bandgap power converters are expected to deliver much higher power density at the cost of the abundance of care and creativeness needed in their design to achieve optimum performance. As the nominal operating switching frequency of such converters increases, any extra converter layout parasitic will become a burden to converter stability and efficiency. Hence, highly reliable circuit intrusive detectors such as shunt resistors could not be an option when it comes to current sensor alternatives for high-frequency converters.

Inductive sensors such as current transformers (CTs) and Rogowski coils are often considered alternatives due to their non-intrusive nature and ability to handle high-frequency measurements [25]. However, these sensors do not measure DC magnetic field components, which limits their use in applications where DC measurement is essential or adds complexity by requiring sophisticated signal processing techniques to reconstruct the DC component accurately [26], [27], [28].

On the other hand, magnetic element sensors, such as Hall effect, anisotropic magnetoresistance (AMR), giant magnetoresistance (GMR), tunneling magnetoresistance (TMR), and micro fluxgate (MFG), offer a compelling alternative for current sensing. A holistic depiction of their working principle is shown in Fig. 1. Although they operate based on different principles, these sensors all provide electrical isolation, and are capable of precise measurements from DC to a few megahertz, depending on the specific technology [23], [31], [32]. Their versatility and ability to handle a wide frequency range make them particularly suited for high-performance WBG power converters, where both DC and high-frequency measurements are crucial for effective control and protection [17].

Hall effect sensors are well-established in the field of current sensing and have been widely adopted for their simplicity and effectiveness. They provide a reliable, contactless method for measuring both AC and DC magnetic fields [23]. Due to being well established and relatively low cost, Hall effect sensors have found use in various applications where moderate bandwidth is acceptable. However, they often fall short in more demanding environments, particularly those involving high-frequency operations, due to their limited sensitivity and bandwidth [29]. Despite these limitations, their ease of use and integration keep them as a solid base design choice for advanced sensing solutions.

Magnetoresistive sensors (AMR/GMR/TMR) on the other hand offer much higher sensitivity compared to the hall effect and are better suited for precision applications [30], [31] [32]. TMR sensors, among the MR-based options, stand out as the superior choice due to their remarkable performance in terms of linearity, response bandwidth, and sensitivity. TMR technology, is based on electron tunneling through a thin insulating barrier affected by an external magnetic field [31]. High sensitivity, combined with low power consumption and high bandwidth, allows TMR sensors to excel in applications that require fast response times and high accuracy. Fig. 2 shows the basic half and full MR bridge configurations commonly used in magnetoresistance-based detection. Full-bridge MR sensors are often preferred for linear magnetic detectors, as they provide a fully differential output, keeping the signal integrity preserved before any single-ended processing.

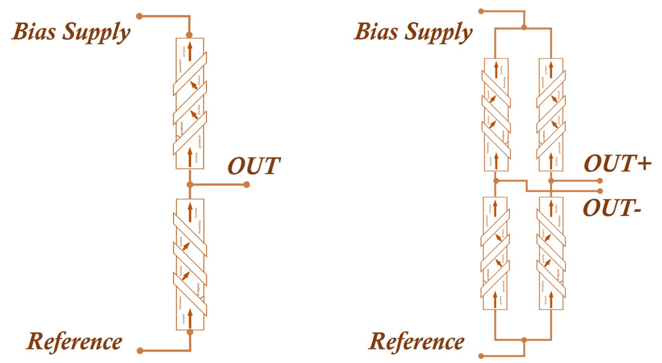

Fig. 2. Demonstration of simple half and full magnetoresistive bridges.

A common issue with conventional linear TMR sensors is their susceptibility to cross-field effects, leading to errors and degraded sensor performance. To overcome this limitation, Infineon developed its TMR Vortex technology, which utilizes a unique vortex magnetization design [31]. This innovative approach minimizes the impact of cross-fields, enhancing the precision and reliability of TMR sensors in applications that require high accuracy. Major manufacturers similar to Infineon [31] and Allegro [32], tackle the specific challenges of modern magnetic field sensing, making these technologies a top competitor for high-frequency power electronics.

It is important to note that MR sensors, including TMR, have their external supply bias and output pins closely tied through a pair of magnetoresistors (shown in Fig. 2), making them more susceptible to external disturbances compared to the hall effect sensors. Any fluctuations or noise on the bias supply can directly affect the sensor output, potentially compromising measurement accuracy and reliability. This sensitivity to external factors necessitates careful design and filtering to ensure robust operation, especially in environments prone to magnetic interference and other noise sources.

In the following section, a novel solution is presented to address the susceptibility of magnetic field sensors to high $\frac{dv}{dt}$ environments in wide bandgap power electronics applications. This approach is versatile and can be applied to various magnetic field-detecting elements. To validate the concept, a state-of-the-art TMR-based detector is developed to demonstrate the effectiveness of the proposed solution.

III. Proposed Solution and Experimental Results

The luxury of power filtering component size reduction becomes a nightmare when it comes to non-intrusive contactless current sensor design and integration. The nanoseconds range of switching transients in wide bandgap power converters translates to the formation of extremely high $\frac{dv}{dt}$ occurrences on the power planes of such converters. Given the size reduction in power filtering components, such transient occurrences will further propagate through components such as transformers and inductors. Hence, reliable measurement of current waveforms with much smaller slew rates, such as those in inductive components, becomes significantly more challenging compared to traditional silicon converters.

In this study, a commercial linear single-axis TMR magnetic field detector was chosen for evaluation. The experimental setup, as depicted in Fig.3, was designed to assess the sensor's performance and the effectiveness of the proposed solution. This setup features a GaN half-bridge module from Infineon, configured as a buck converter to enable high-frequency switching. The designed sensor evaluation board is strategically placed to measure the output inductor current, directly above the power plane at the switching node. To minimize radiated interference, the components in the converter setup are intentionally spaced further apart.

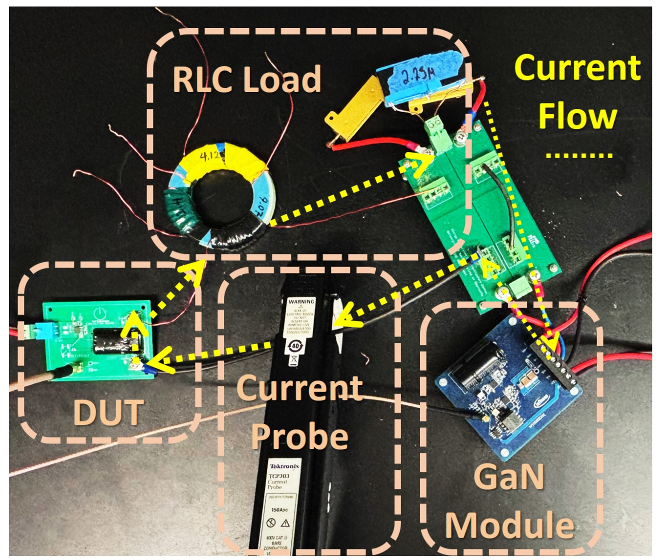

Fig. 3. GaN buck converter testbed used for the TMR sensor evaluation.

For the specific TMR under study, uneven propagation of noise through the differential outputs of its Wheatstone bridge creates significant unwanted common mode noise on final processed signal. Fig. 4(a) and Fig. 4(b) depict the single-ended measurements of TMR differential outputs before any signal conditioning, showing how $\frac{dv}{dt}$ transients propagate differently in terms of frequency and amplitude across these outputs. This uneven propagation is amplified and distorts the output when processed through an active amplification stage, as shown in Fig. 5.

Fig. 5 depicts the impact of high $\frac{dv}{dt}$ on processed TMR single ended output during transients. To overcome this measurement error, a dual-path active processing circuit is designed, utilizing noise suppression blocks and a high-frequency detection portion to compensate for any bandwidth reduction in the final sensor output. Fig. 6 presents the block diagram of this proposed processing circuit, while Fig. 7 demonstrates the enhanced noise suppression achieved by this approach

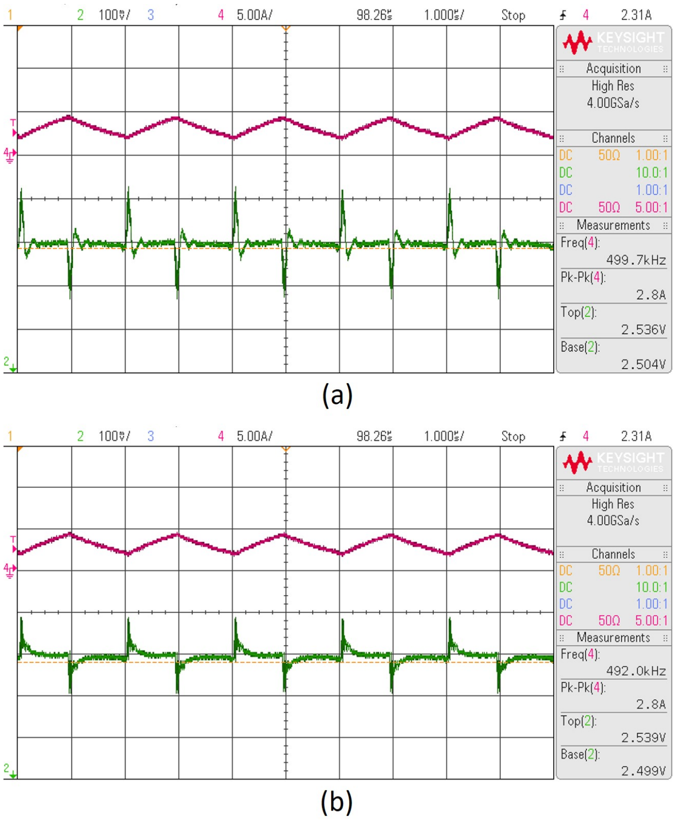

Fig. 4. Experimental results showing the uneven noise propagation through differential outputs of the TMR under study: (a) TMR positive differential output, (b) TMR negative differential output. In these captures, green is the measured TMR output (500 MHz passive probe), and magenta is the reference current probe measurement (DC-30 MHz)

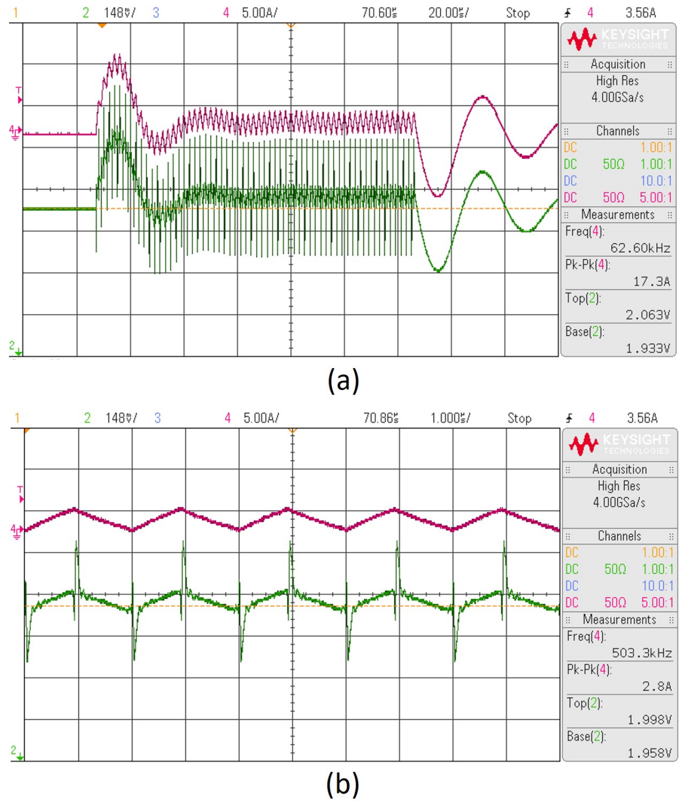

Fig. 5. Scope captures illustrating the impact of excessive $\frac{dv}{dt}$ disturbances on the TMR sensor output: (a) start-up capture and (b) zoomed-in view of the converter's steady-state. Green trace shows the sensor signal measured through a 50-ohm SMA connector, while the magenta trace represents the reference current probe measurement (DC-30 MHz).

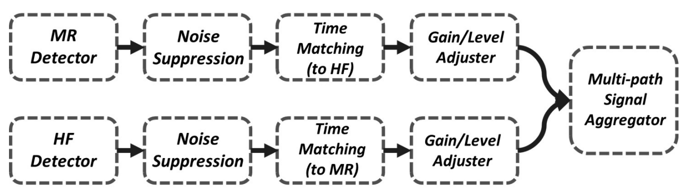

Fig. 6. Block diagram of the proposed processing solution.

compared to existing solutions.

The core of the proposed solution involves applying a robust differential early stage filter to the TMR sensor outputs, effectively eliminating the high $\frac{dv}{dt}$ impact that typically distorts the measurements. This early filtering stage is crucial for ensuring that transient-induced oscillations do not degrade the sensor's performance, thereby preserving the integrity of the differential signal. However, while this filtering process mitigates high $\frac{dv}{dt}$ disturbances, it also heavily impacts the bandwidth of the TMR sensor. To overcome this limitation and also further enhance the overall detection bandwidth, a high-frequency noise-immune pickup coil is integrated within the processing circuit. The low profile embedded coil captures high-frequency components lost during filtering and blends them back into the original TMR signal path. This dual-path approach not only ensures that the sensor remains accurate and reliable in harsh electrical environments typical of WBG power converters but also provides a comprehensive current sensing solution that enables field detectors integration within such applications.

Fig. 7 shows performance of the proposed solution measuring the switch-node inductor current of a WBG DC-DC converter operating at 500 kHz switching frequency. Sensor output (in green) was measured using a 50-ohm SMA connector through a 4.0 GSa/s Keysight oscilloscope. The reference (in magenta) is measured using a DC-30 MHz commercial current probe. Comparing against the results shown in Fig. 5, it is evident that the high $\frac{dv}{dt}$ impacts are well suppressed, confirming the effectiveness of the proposed solution for modern power electronics sensing applications.

IV. Conclusions and Future Works

The integration of high-performance magnetoresistance-based current sensors in wide bandgap power converters presents a practical solution for achieving precise current measurements in high-frequency power electronics. This study highlights the significant challenge of transient noise propagation, especially in compact, high-density designs where maintaining low-power signal integrity is critical due to fast switch-

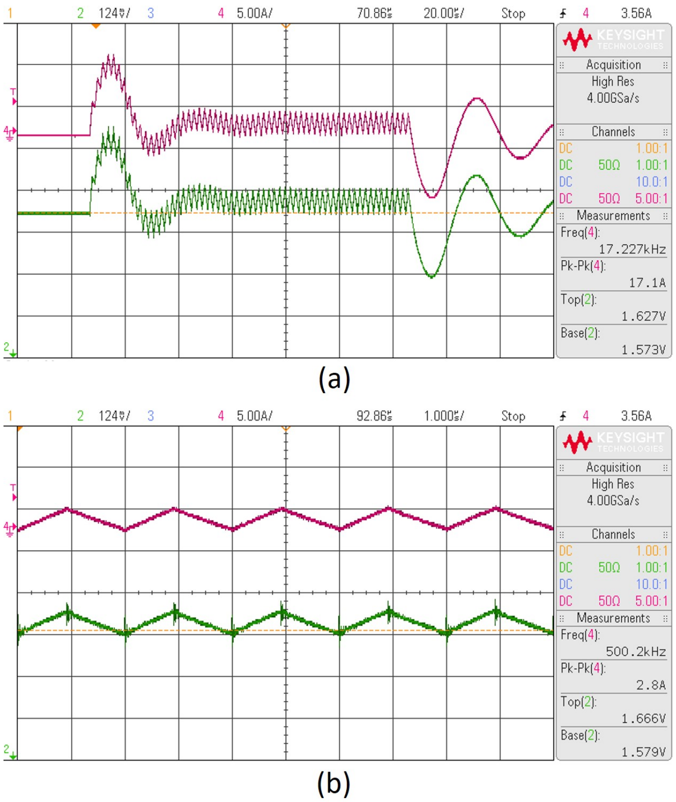

Fig. 7. Experimental results showing performance of the proposed TMR-based sensing solution: (a) start-up capture, (b) converter's steady-state zoom-in. In these captures, green is the measured sensor signal (50-ohm SMA connector), and magenta is the reference current probe measurement (DC-30 MHz)

ing speeds. To address these challenges, a novel dual-path processing circuit is proposed, incorporating advanced noise suppression and high-frequency compensation techniques to preserve the differential signal characteristics of a state-of-the-art TMR sensor. Experimental results from the prototype, tested in a GaN buck converter operating at a 500 kHz switching frequency, validate the robustness of this approach in effectively suppressing unwanted noise while maintaining the necessary bandwidth for accurate current detection across a broad frequency range. As wide bandgap technology continues to advance power electronics, the proposed methods and findings in this work provide essential insights and practical strategies for enhancing sensor performance in next-generation power conversion systems.

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