A NON-INVASIVE WIDEBAND ISOLATED CURRENT SENSOR FOR HIGH FREQUENCY POWER ELECTRONICS APPLICATIONS

by

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ABSTRACT

SHAHRIAR JALAL NIBIR. A non-invasive wideband isolated current sensor for high frequency power electronics applications. (Under the direction of DR. BABAK PARKHIDEH)

With the introduction of new generation of wide-bandgap (WBG) power devices, the size and volume of the modern power electronic converters are getting significantly miniaturized. For effective control of power converters maintaining high efficiency and reliability, loss-less and accurate current measurement is a fundamental pre-requisite. Consequently, traditional current sensing techniques are no longer viable for measurement of currents in high frequency converters. Hence, there is a need to investigate alternative approaches to measure the current which should yield to be wideband, fast, accurate, topology-independent and loss-less. In addition, having higher voltage devices (>30V) using wide-bandgap semiconductors that allow high frequency power converters (>1MHz) necessitates having isolated current sensors.

Extraction of the current information is one of the major challenges in high frequency power electronics. Typically, high frequency current passing through a printed circuit board (PCB) trace induces a highly non-uniform magnetic field which varies as a function of frequency and position relative to the current trace. This non-uniform distribution of magnetic fields limits the effective detection bandwidth of most magnetic field transducers used as isolated current sensors such as Hall-effect and Magnetoresistor (MR) sensors. However, the non-uniform magnetic fields can be normalized by means of Magnetic Field Concentrators (MCON) using conductive materials. Smart

implementation of the MCON by selecting the best material having specific thickness and dimensions can result in a much more uniform magnetic distribution through the sensor which consequently improves the effective detection bandwidth of current sensing in power converters.

To meet the demand for high bandwidth loss-less current sensors having fast response time, we have proposed a non-invasive wideband current sensing scheme for high frequency power electronics applications. The proposed current sensor utilizes two different current sensing techniques having complementary characteristics to achieve a very wideband performance - a Magnetoresistor (MR) as the primary sensing element and a Rogowski coil as the secondary sensing element. A magnetic field concentrator (MCON) is also utilized around the sensors to normalize the magnetic field distribution over the wide frequency range as well as to achieve shielding for the sensor from outside interfering fields. The proposed current sensor provides an alternative hybrid current sensing solution having wideband performance while still maintaining desired characteristics such as loss-less and isolated sensing.

DEDICATION

To my beloved wife and parents

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LIST OF ABBREVIATIONS

AMR	Anisotropic Magnetoresistor
CMOS	Complementary Metal–Oxide Semiconductor
CMR	Colossal Magnetoresistor
CT	Current Transformer
EMI	Electromagnetic Interference
FEM	Finite Element Methods
FET	Field Effect Transistor
GaN	Gallium Nitride
GMR	Giant Magnetoresistor
IC	Integrated Circuit
IGBT	Insulated Gate Bipolar Transistor
IPEM	Integrated Power Electronic Modules
MCON	Magnetic Field Concentrator
MOSFET	Metal Oxide Field Effect Transistor
MR	Magnetoresistor
PCB	Printed Circuit Board
Si	Silicon
SiC	Silicon Carbide
TCR	Resistance Temperature Coefficient
TMR	Tunneling Magnetoresistor
WBG	Wide-Bandgap

INTRODUCTION

Motivation

With the introduction of next generation power semiconductor devices based on wide-bandgap (WBG) semiconductor switches such as – SiC and GaN, the switching frequency of the power electronic converters is pushing in the MHz range to achieve higher power density and efficiency. There are several aspects of a power electronics converters that need to be addressed keeping in mind the demand for the smaller and smarter power converters of the future. Recent developments in wide-bandgap semiconductor devices has enabled a new dimension in power electronics design and the demand for higher power density and miniaturization while maintaining a higher efficiency is the most challenging task faced by power electronic circuit designers. In order to keep up with the fast advancements in high frequency power electronics, significant developments are required on the other important aspects of the power converters such as the sensors, controllers, thermal managements etc. The current is an essential parameter in a power electronic converter which is used for control, diagnostics, prognostics and protection of the circuits and systems. Traditional current sensing techniques are no longer viable for measurement of currents in modern power converters demanding high efficiency while maintaining a small footprint. Hence, there is a need to investigate alternative and high bandwidth current sensing methods for measuring the current in power electronic converters.

Review of Current Sensing Techniques

Several current sensing methods for power electronics converters have been investigated by researchers and significant performance improvement have been observed over the years [1]-[6]. The most simple and common non-isolated current sensing method is the sense resistor. However, they are extremely lossy and affects the efficiency and performance of the power electronics converter. Some researchers have discussed a few isolation techniques for sense resistors in [7]-[9] but they add to the cost and complexity in implementation of the techniques. Inductor based DCR current sensing is another popular non-isolated current sensing method which is loss-less and highly applicable for high frequency power converters [10]-[16]. However, there are some major challenges in implementing this technique such as the time constant mismatch issue discussed in [11]-[12]. Different integrated and lossless current sensing methods, such as series MOSFET's on-resistance and parallel current-sensing FET (sense-FET) have been proposed to deduce the switch or inductor current information [17]-[27]. However, most of these approaches applicable to high frequency current sensing in power electronic converters are non-isolated and mostly limited to low voltage (<30V) applications. Isolated current sensors are a mandatory requirement for high frequency (>1MHz) power electronic converters utilizing high voltage wide-bandgap semiconductors having high common mode voltage (>30V).

Among the isolated current sensing techniques, Current Transformers (CT) are one of the most accurate and robust solutions and bandwidth of upto 1MHz has been observed [28]-[29]. However, current transformers are mostly applicable for AC current measurements and limits utility in certain power conversion applications. The DC current transformers have also been developed by researchers [30]-[31]. Current transformers are widely used by several researchers in different power electronic applications [32]-[39] but their issues with coil saturation at higher frequencies limit their applications in mostly lower frequencies.

The Rogowski coil is a simple, lossless and accurate current sensing method for detecting currents and is investigated and implemented in several applications over the years [40]-[49]. Rogowski coils are built with air core with no saturation and inherent wideband response characteristics however their inability to respond to constant DC currents significantly limits their applications in sever power electronics converters. The Rogowski coil can also be implemented on a Printed Circuit Board (PCB). Planar PCB embedded Rogowski coils has also been developed by researchers and they have the advantage of lower size, lower parasitic capacitance, high accuracy, low tolerance and wide bandwidth [50]-[55].

Today, Hall-effect devices make up by far the largest part of all magnetic sensors in the market. Hall-effect sensors can detect both AC and DC fields making then suitable for many power electronic applications. Typical Si-based integrated Hall sensors have their bandwidth is limited to a few tens of kilohertz. Using materials with higher carrier mobility than Si such as GaAs and InAs allows to reduce the thickness of the element while the element becomes more sensitive and can pick up faster transients of the magnetic field [56]-[57]. Several research groups are investigating on the Hall-effect sensors and significant development has been observed over the years [58]-[63]. Conventional planar Hall technology is only sensitive to the flux density applied orthogonally to the IC's surface. Pioneered by Prof. Popovic's research group at EPFL, Switzerland, a contact-less hall sensor was proposed [64]-[65] in which parallel field produced by the current in a wire or a PCB trace is picked up by two carefully designed ferromagnetic plates separated by a defined air gap. Placing the Hall element right underneath the air gap edge allows the element to react to the magnetic field and hence the producing current information can be deduced. The concept has been commercialized by Melexis and the bandwidth goes up to 250 kHz [66].

Magnetoresistors (MR) are another type of magnetic point field detector which respond to the horizontal components of the magnetic field with respect to the current trace. Magnetoresistors (MR) can be fabricated from both semiconductors and metal alloys which allows the sensitivity and performance of the sensing element to be adjusted more precisely based on the application. Magnetoresistor were previously used extensively in magnetometry and compassing applications. However, due to their inherent capability of being able to respond to very high frequency magnetic excitations, recently they are gaining rapid popularity as current sensors in high frequency applications. Anisotropic Magnetoresistors (AMR) and Giant Magnetoresistors (GMR) are two of the most popular magnetoresistive elements having very high inherent bandwidth [67]-[71]. Several researchers have studied and demonstrated the potential of Magnetoresistors to be utilized as current sensors and the hysteresis analysis of the sensors especially the GMR element and the feasibility of integrating them inside power modules have also been studied in detail [72]-[94]. In contrast to Hall-effect sensors, Magnetoresistive sensors have significantly lower temperature drift and are less susceptible to external noise, increasing their utility for current sensing applications in high frequency power electronics.

Hybrid current sensors combine multiple current sensing technologies together to achieve a superior performance and accurate measurement. Usually, two different sensing technologies are selected for two different frequency range of operation to achieve an extreme wideband performance characteristic. The low frequency sensor is responsible for detecting transients from DC to a certain frequency. The high frequency sensor is active after the low frequency sensor limit and extends to a much higher operation frequency. Several post processing circuits are required to condition and combine the output of the low frequency and high frequency sensors to achieve a wideband response. Several researches are investigating in the hybrid current sensors to improve the performance, bandwidth, linearity and accuracy of current sensing [95]-[104].

The concept of hybrid current sensors was first reported in [95]-[96] using a Hall-effect based sensor for detecting low frequency currents and a PCB Rogowski coil for high frequency current sensing. Prof. Kolar's research group based in ETH Zurich, Switzerland has demonstrated a hybrid sensor utilizing Hall-effect sensor and current transformer for current measurements [98]-[100]. Researchers in Delft University of Technology in Netherlands have proposed an integrated wideband hybrid sensor based on Hall-effect sensors and Rogowski coil [101]-[102]. MR based sensors also show good potential to be used as low frequency current detectors in hybrid sensor configurations. A hybrid current sensing scheme utilizing an AMR sensor and the low frequency sensor and a planar Rogowski coil sensor as the high frequency sensor is demonstrated by our research group in [103]-[104]. Other works related to our group's research in the development of wideband current sensing technique has been presented in [105]-[112].

Objective of this Study

In the wake of next generation high frequency wide-bandgap power semiconductor switches and the miniaturization of circuits, alternative means for sensing the current information for power electronic converters need to be considered and evaluated. The objective of this study is to investigate alternative current measurement techniques especially, the Magnetoresitor (MR) based current sensing technique for monitoring of currents for high frequency (>1MHz) power electronic converters. A detailed literature review on the different approaches to current sensing solutions for power converters is performed. The performance and characteristic of the different current sensing approaches is analyzed in detail for their potential applications in wide-band current sensing in power electronics applications.

In this work, a novel wideband current sensing scheme for power electronic converters using the Anisotropic Magnetoresistor (AMR) sensor is proposed taking advantage of the folded trace magnetic concentrator method. Alternative approaches to the magnetic field concentration technique has also been investigated. We have proposed a novel technique for enhanced bandwidth contactless current sensing using Magnetoresistor sensors with planar magnetic concentrators (MCON) utilizing conductive materials. The effect of different magnetic field concentrators (MCON) on the performance of Anisotropic Magnetoresistor (AMR) sensors for high frequency contactless current detection has been investigated and analyzed. Finally, we have proposed a non-intrusive, loss-less and wideband hybrid current sensing technique for high frequency power electronic applications based on two complementary current sensing methods – Anisotropic Magnetoresistor (AMR) and Rogowski coil. The proposed hybrid sensing scheme also takes advantage of the planar magnetic field concentrators (MCON) for normalizing and amplifying the non-uniform magnetic fields generated by the currents over a wide frequency range.

CHAPTER 1: A TECHNIQUE TO ENHANCE THE FREQUENCY BANDWIDTH OF CONTACTLESS MAGNETO-RESISTIVE CURRENT SENSORS

Isolated wideband current measurement is required in many power electronic converters when the switching frequency is above 1MHz. Typically, current passing through a printed circuit board (PCB) trace induces a highly non-uniform magnetic field which varies as a function of frequency and position relative to the trace. This paper proposes a technique to increase the frequency bandwidth of Anisotropic Magneto-Resistive (AMR) current sensors and simultaneously to intensify and normalize the field detected by the sensor in the frequency range of interest, i.e. DC-5MHz. We demonstrate experimentally that the proposed technique yields significant enhancement in detection bandwidth of AMR current sensors.

Introduction

Current information is the most essential parameter for control, diagnostic and prognostic purposes. The miniaturization of high-power electronics generates electromagnetic interference (EMI) between the current traces, the IC, and various components on the circuit board. The introduction of smarter power generation devices, which include current monitoring sensors, brought to light one of the main challenges of high power circuit design, namely, that EMI interferes with the current monitoring circuit and is detrimental to the performance of the electronics if not controlled. The generation of EMI and its interaction with locally placed components are currently not well understood. To advance the understanding of how to mitigate the effects of EMI in high power electronics, there is a need to investigate alternative approaches and techniques to measure current. The aim is to develop current sensors that respond quickly and are accurate and loss-less. Moreover, the increased application of high voltage devices (>30V) using Wide-Bandgap (WBG) semiconductors in high frequency power converters (>1MHz) requires isolated current sensors.

Different integrated and lossless current sensing methods, such as series MOSFET’s on-resistance and parallel current-sensing FET (sense-FET) have been proposed to deduce the switch or inductor current information [1]-[3]. However, these approaches do not provide electric isolation and are limited to low voltage applications. Among many different types of isolated sensors, magnetic field induction-based transducers and Hall-effect sensors are among the most popular technologies, and significant performance improvements have been made over the past years [4]-[6].

Typical Si-based Hall sensors have bandwidth limited to only tens of kilohertz. Using materials with higher carrier mobility than Si, such as GaAs and InAs, allows the element’s thickness reduction while increasing its sensitivity and ability to detect faster transients–up to 1MHz [7]. Due to the emergence of high frequency power converters (>1MHz), there is a need to develop other methods to detect such high frequency currents.

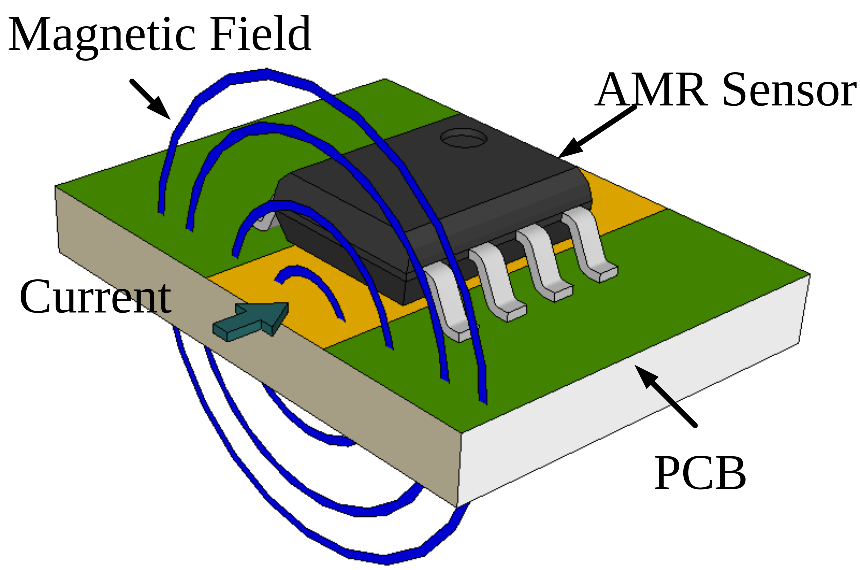

Figure 1.1: General layout, i.e. “standard configuration” of AMR sensor for current measurement.

Hall-effect and magnetoresistive devices can detect both DC and AC fields. Whereas Hall-effect sensors are made of semiconductors, magnetoresistive sensors can be fabricated from both semiconductors and metal alloys. This permits the conductivity and the sensitivity to be tailored precisely to the application. In contrast to Hall-effect sensors, magnetoresistive sensors do not suffer from drift and are less susceptible to external noise, increasing their utility for application in high frequency power electronics. Several research groups are investigating techniques to improve the sensitivity and accuracy of current sensing by hall-effect as well as MR and GMR based devices for power electronics applications [8]-[13]. While MRs are based on low bandgap semiconductors, such as InSb and InAs, AMRs are based on metal alloys. The most widely used AMR device developed and integrated into a chip is composed of four Permalloy ($Ni_{0.81}Fe_{0.19}$) AMRs in a full sensitivity Wheatstone bridge configuration [14]-[15].

In a general power electronic application, the MR-based current sensor is placed on top or underneath a printed circuit board trace carrying the current without any conductive contact to the trace. Figure 1.1 shows the “standard configuration” and necessary layout for an AMR sensor IC to measure the current. The sensor detects the magnetic field generated by the current carrying power PCB trace. At low frequencies, the magnetic field around the trace is uniformly distributed and intersects the sensor along the default axis generating a response. However, at higher frequencies, especially above 1 MHz, due to the skin effect, the current tends to flow mostly on the edges of the PCB trace. As a result, the generated magnetic field distribution is not uniform and is mostly concentrated around the edges. Unfortunately, the AMR current sensor detects the weaker part of field distribution over the frequency of operation, giving the false impression that it loses its sensitivity at higher frequencies. Consequently, its application is limited to much less than 1 MHz [16]. Normalizing the magnetic field over the frequency range of interest with magnetic concentrators, results in an increase in the detected bandwidth and sensitivity of the sensor. These magnetic concentrators maximize the magnetoresistive sensor’s bandwidth. The concept of using magnetic concentrators as a method of increasing the sensitivity of devices has already been established for Hall-effect based devices using ferromagnetic materials [17]-[18].

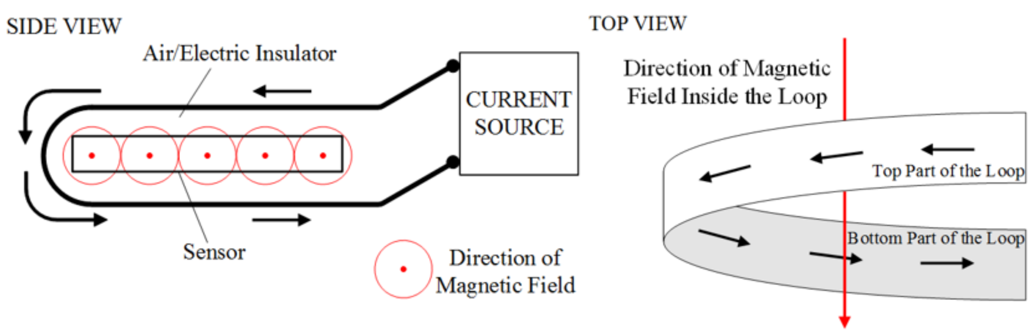

Figure 1.2: Proposed folded trace technique to normalize and intensify the field.

In this letter, we propose a method to increase the sensitivity and frequency bandwidth of MR sensors, specifically, AMR sensors, enabling the detection of current with very fast transients. The approach presented in this paper concentrates and normalizes the magnetic field induced by the wideband current in PCB traces commonly seen in power electronics applications. Section II details the proposed method to increase the detected bandwidth of the AMR sensor. It is followed by the experimental verification of the proposed method. Section III summarizes the findings and conclusions.

Proposed Method for Wideband Current Measurements Using AMR Sensor

A. Proposed folded power trace to normalize the magnetic field vs. frequency

The magnetic field distribution around the current trace is significantly non-uniform at high frequencies due to the skin effect. This means that point-field detectors such as AMR sensors need to be placed accurately where the respective radiated magnetic field can be measured uniformly over the bandwidth of interest i.e. DC-5MHz. In other words, the general scheme shown in Figure 1.1 may not be used for wideband current measurements, and proper magnetic field concentration technique is required for sensing the high frequency current.

The proposed method addresses these challenges by modifying the layout of the current trace carrying the current to be detected and combining it with a sensitive AMR sensor. By wrapping the current trace around the top and the bottom of the AMR sensor, the magnetic field detected by the sensor becomes uniform in the frequency range of interest. The proposed method generates a much more uniform magnetic field, whose magnitude depends on the current, along the sensitive axis of the sensor. The proposed method is visualized in Figure 1.2.

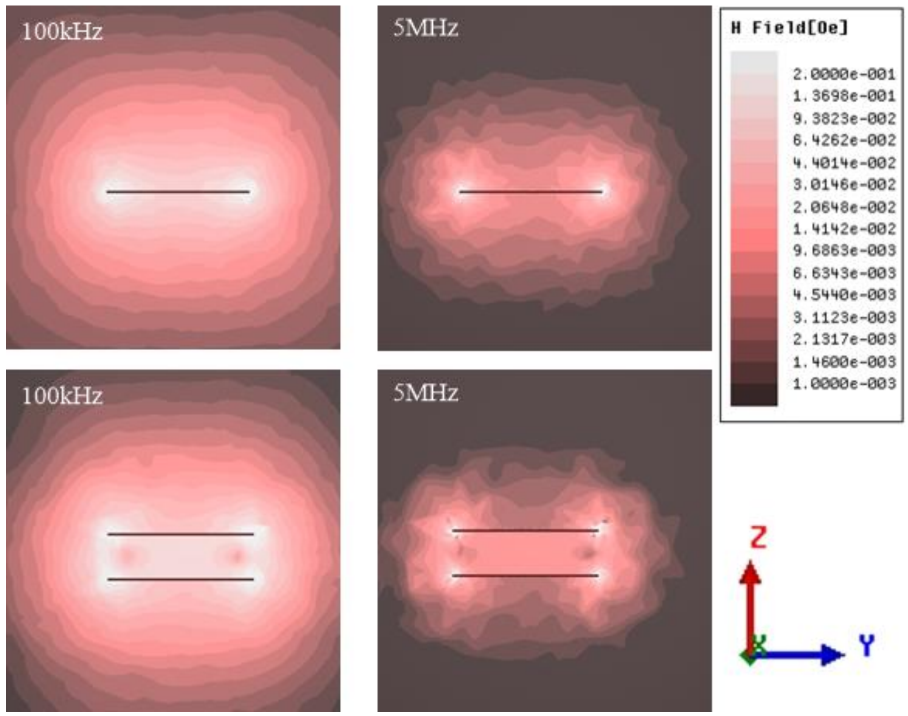

Figure 1.3: Simulation results: magnetic field distribution of bare trace (top) and folded trace (bottom) at two different frequencies.

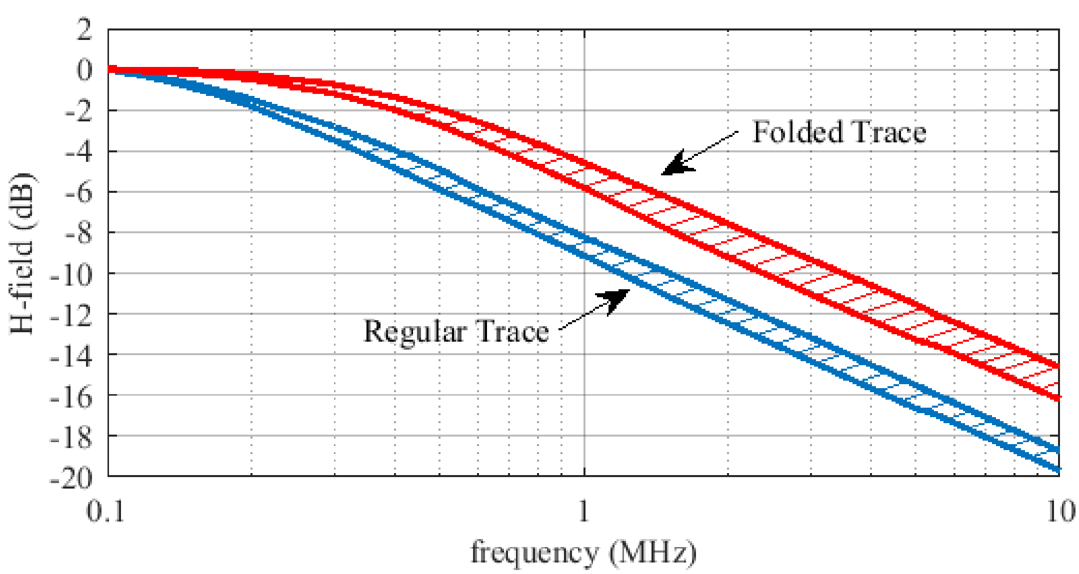

Figure 1.4: Normalized magnetic field distribution with respect to frequency for the simulations results in Figure 1.3 for different positions of the sensor element on the current carrying trace in regular and folded trace configuration.

To better understand the distribution of magnetic field around the bare trace and the proposed folded trace, a set of simulations are provided using a full-wave commercial electromagnetic solver, Ansys HFSS. The simulations include copper traces with dimensions of 10mm and 5mm along the X and Y axes, respectively, and with a thickness of 35μm (equivalent to 1Oz copper) along the Z-axis. The folded trace technique has been implemented with 1.5mm gap between the two traces. Figure 1.3 presents the FEM simulation results for the bare and folded trace cases. By increasing the current's frequency from 100 kHz to 5 MHz, a much more uniform magnetic field distribution is obtained around the trace with the folded trace technique compared to the bare trace case. The difference in magnetic field distribution for 5 MHz frequency is visible in the top-right and bottom-right figures in Figure 1.3. The field distribution in between the two traces for the bottom-right figure is much more uniform compared to the one with only a single bare trace.

The simulation study is further carried out considering the relative position of the sensing element on top of the current trace. In this study, measurements have been taken for different positions around the trace going from the middle of the trace toward the edges where the magnetic field has the highest intensity, but is scattered and non-uniform. Consequently, the area from the middle of the trace to around 2/3 of the distance toward the edge is the area that has a positive effect on the sensitivity of the sensor. The simulated results for the change in magnetic field distribution within this area with respect to different frequencies for both bare trace and folded trace configurations are presented in Figure 1.4. The captured H-field data from the simulations with respect to the change in frequency varying from 100 kHz to 10 MHz is normalized for each case shown in Figure 1.4. The proposed folded trace method has an overall improved magnetic flux distribution in terms of uniformity and intensity.

It is also worth mentioning that the proposed method concentrates the magnetic field onto the current sensor without altering the current on the trace and simultaneously shields the sensor from any other stray magnetic fields, which are very common in switching power converters.

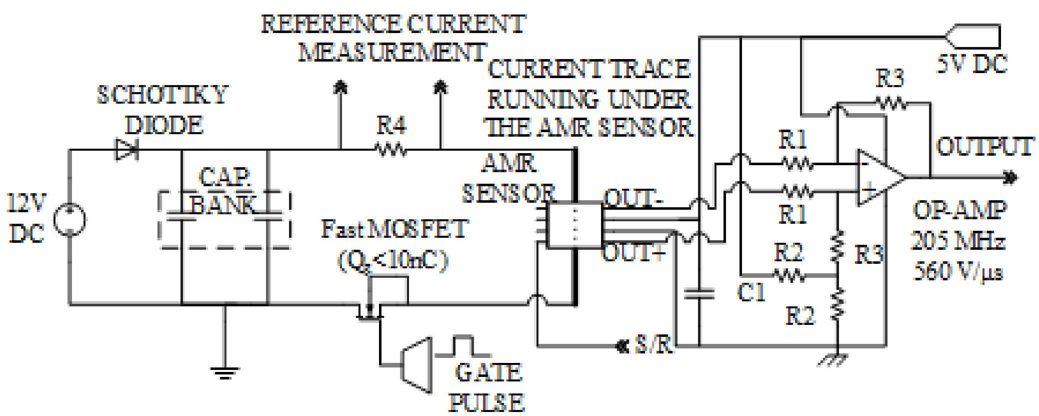

Figure 1.5: Circuit diagram of the set-up for testing the AMR sensing scheme.

B. Experimental verification of the proposed method

To examine the performance of the AMR-based current sensor, several circuits were designed and implemented. Figure 1.5 presents the circuit diagram of the hardware setup designed to evaluate the performance of the proposed method. To evaluate the bandwidth of the current sensor in a timely manner, a fast high-rise current step function generator was used. The step current was obtained by charging a capacitor bank and then discharging it through a small power resistor. The voltage across the resistor was taken as the reference current measurement, as shown in the left side circuit in Figure 1.5.

Subsequently, a current sensing scheme using a commercially available AMR sensor was designed and developed [16]. The sensor output was amplified by a differential amplifier with a gain of 50. The right side circuit of Figure 1.5 shows the sensor and signal conditioning circuit.

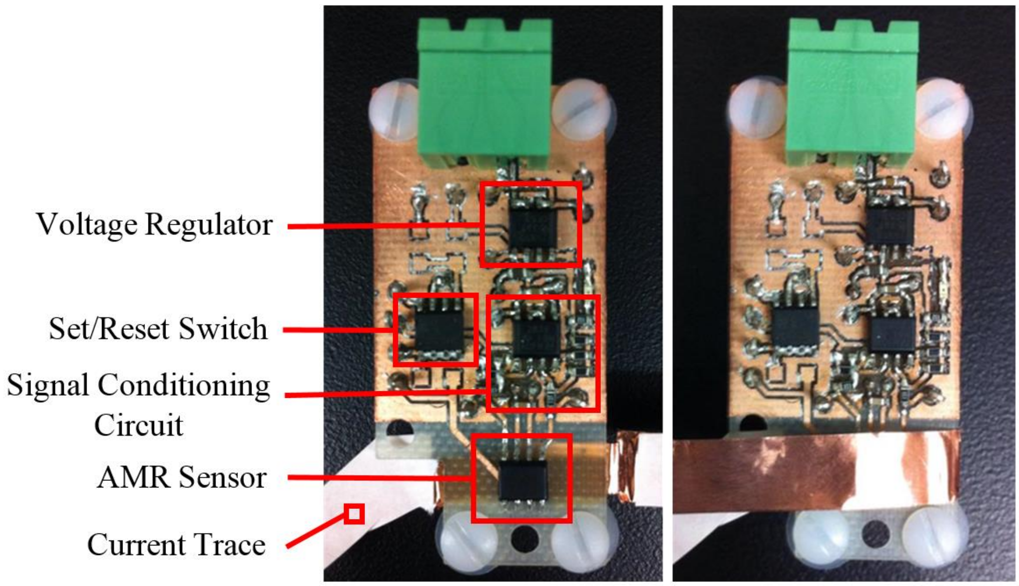

Figure 1.6: Hardware setup for evaluation of the AMR current sensor. Left: standard scheme, Right: sensing scheme with the folded trace technique.

Figure 1.6 shows the hardware prototype developed for the experiment with the standard configuration (left) and the proposed folded trace configuration (right). The current carrying trace with 1Oz copper is implemented on the bottom layer of the PCB with 1.5mm thickness as shown in Figure 1.6-left picture. Copper foil with 35μm (1Oz) thickness is used to implement the proposed folded trace covering the AMR sensor. The main signal conditioning circuit is designed with high speed components (205MHz, 506V/μs) such that it does not limit the frequency range of interest. Figure 1.6-right presents the picture of the hardware prototype that was fabricated to study the AMR sensor with the proposed method.

Figure 1.7 presents the experimental results captured from our prototype testing with the bare/regular trace and the proposed folded trace. Data collected from the prototype revealed that the detected voltage signal in the “folded trace” configuration is amplified compared to the “standard configuration”, in which the sensor is positioned over the current trace. In other words, it can be concluded that the sensor with the proposed method has an improved sensitivity compared to the standard configuration.

It is also clear from Figure 1.7 that the AMR sensor in the folded trace configuration follows the reference current significantly better than in the standard configuration. During the characterization of the AMR sensor in the vicinity of a current carrying PCB trace with standard configuration, initially the sensor output behaves completely out of phase at very high frequencies. Based on that result, one might not expect the AMR sensor to be capable of following a very high frequency magnetic field. The sensor output is expected to behave like a first-order system. The reason for such behavior of the sensor can be explained by the simulation results of Figure 1.3 with bare trace having non-uniform magnetic field distribution around the current trace. The scattered magnetic field causes the AMR elements to align in different directions generating out-of-phase response from the sensor. This behavior is unique to AMRs and needs further study by modeling the AMR element in terms of frequency over the range of detection. Nonetheless, the results obtained from the experiment using the proposed method show that by amplification and normalization of the field at the sensor’s sensitive axis (easy axis), it is possible to achieve higher sensitivity over the linear region of the point-field detector, in this case, AMR. This amplification can also be observed by comparing the steady-state response (low frequency) of the AMR in the "folded trace" with the "standard" configurations (Figure 1.7).

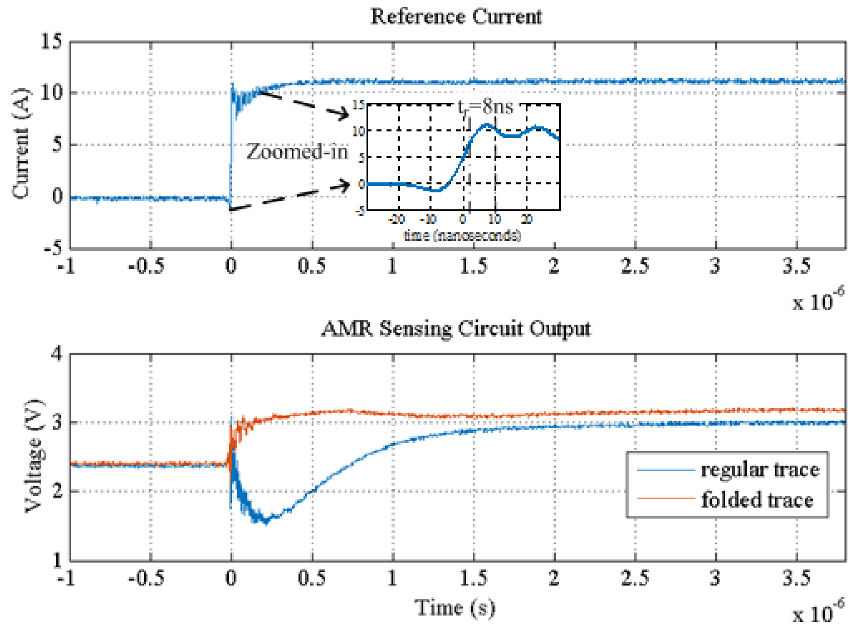

Figure 1.7: Experimental Results: step response comparison of the AMR sensing circuit for regular trace and the proposed folded trace implementation.

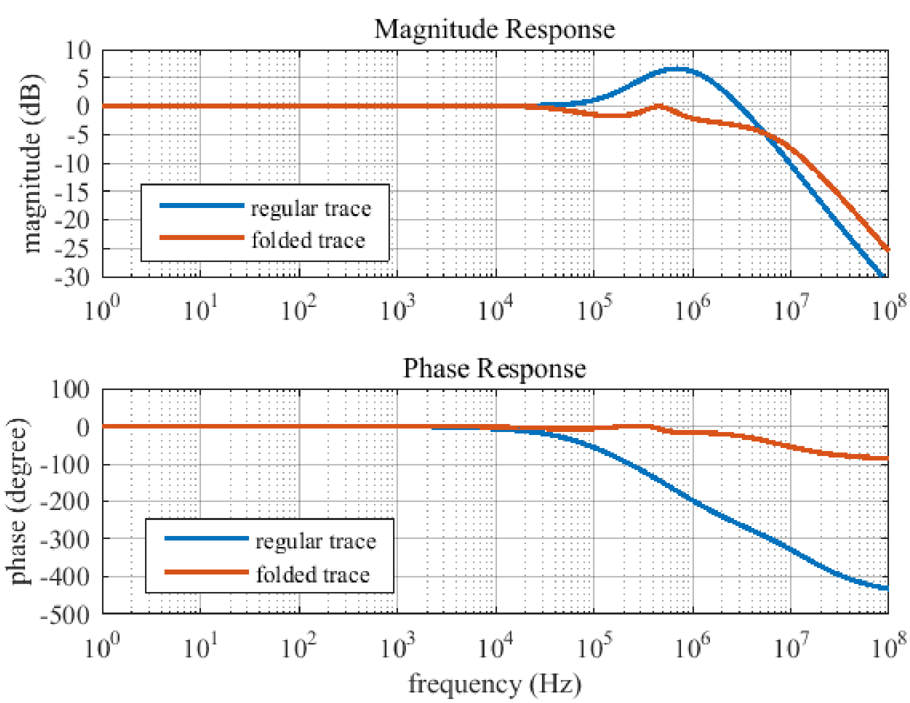

Figure 1.8: Frequency Analysis (normalized) of AMR sensor with Regular (Bare) Trace and Folded Trace based on the experimental results shown in Figure 1.7.

Figure 1.8 presents the frequency response analysis of the normalized experimental data shown in Figure 1.7. The difference in detection bandwidth for the sensor is clearly visible in the magnitude response plot. The gain magnitude for the proposed folded trace method remains more stable for a much higher frequency range compared to the bare trace configuration. More importantly, if we look at the phase response, in case of the standard bare trace configuration, the phase begins to deviate at about 20 kHz. As we approach 1 MHz frequency, the phase becomes completely out of phase, which is in accordance with the out-of-phase response we have observed in Figure 1.7. The proposed folded trace method remains fairly constant until 5 MHz. For high frequency applications in the megahertz range, the AMR sensor exposed to a bare current trace has a slightly higher gain, but the out-of-phase behavior of the sensor response means that the sensor is not able to react to high frequency magnetic fields properly. The proposed method to amplify and make the magnetic field more uniform results in the AMR elements responding in phase and accurately to currents at higher frequencies.

These results lead us to conclude that 1) if the magnetic field is large enough and uniform over frequency, the AMR sensor can detect MHz changes, unlike Hall elements, and 2) isolated magnetic concentrators, such as the proposed folded trace, improve the performance and response time of the AMR elements when they are used as contactless current sensors.

Conclusions

This paper proposed a technique for an AMR-based sensing circuit that allows current measurements over a wide frequency range. This is accomplished by folding the current carrying trace around the AMR sensor to amplify and normalize the magnetic field generated by the current over a wide frequency range. The experimental results show that the sensor, when implemented with the proposed method, has an improved bandwidth of up to 5 MHz and enhanced sensitivity to high frequency currents evinced by the sensor output at DC. It is believed that the proposed method is applicable in high frequency power converters where the inductor current is used to control the ripple and transient response.

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CHAPTER 2: MAGNETORESISTOR WITH PLANAR MAGNETIC CONCENTRATOR AS WIDEBAND CONTACTLESS CURRENT SENSOR FOR POWER ELECTRONICS APPLICATIONS

High frequency power electronic converters require lossless, accurate and isolated current measurement. High frequency currents through a Printed Circuit Board (PCB) trace generate non-uniform magnetic field around the trace. The non-uniform magnetic fields can be normalized by means of Magnetic Field Concentrators (MCON) using conductive materials. In this work, a novel technique for high frequency contactless current sensing using Magnetoresistor sensors with planar magnetic concentrators (MCON) utilizing conductive materials has been proposed. The effect of different magnetic field concentrators (MCONs) on the performance of Anisotropic Magnetoresistor (AMR) sensors for high frequency contactless current detection has been investigated. The performance of the AMR sensor equipped with different MCONs is demonstrated experimentally with respect to a fast rise step current. A detailed frequency analysis is performed on the sensor response with different MCONs to determine the effect on the detection bandwidth of the current sensors.

Introduction

Extraction of the current information in high frequency converters is one of the major challenges in high frequency power electronics. With recent advancement in high frequency power electronics and with the introduction of new generation of wide-bandgap power devices, the passive components, as well as the circuit volume is getting significantly miniaturized. For fast, effective and efficient control of power converters, lossless and accurate current measurement is a fundamental pre-requisite. Traditional current sensing techniques are no longer viable for measurement of currents in high frequency converters. Hence, there is a need to investigate alternative approaches and techniques to measure the current. These approaches should yield to have current sensors that are fast, accurate, topology-independent and loss-less. In addition, having higher voltage devices (>30V) using Wide-Bandgap (WBG) semiconductors that allow high frequency power converters (>1MHz) necessitates having isolated current sensors.

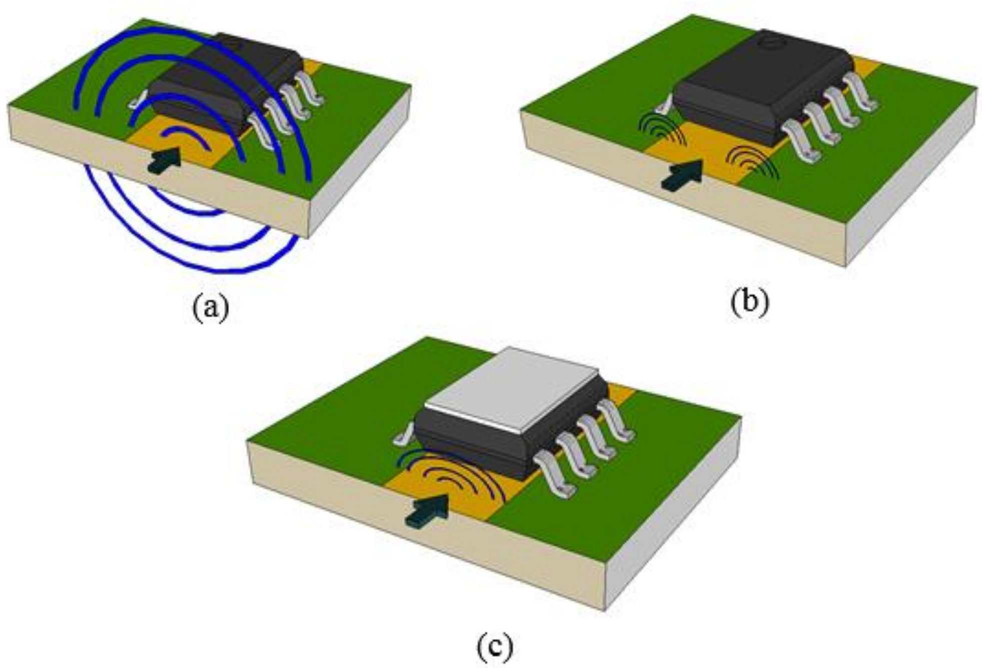

Figure 2.1: The concept visualization: (a) Magnetic field distribution at low frequencies, (b) Magnetic field distribution at high frequencies due to skin effect, (c) Magnetic field distribution with the proposed magnetic concentrator (MCON)

Hall-effect based sensors and Magnetoresistor (MR) based sensors are some of the most popular solutions for isolated and contactless current sensing. Hall-effect sensors are widely used in different applications and significant performance improvement has been observed over the years [1]-[5]. The fabrication of hall elements using materials with high carrier mobility such as GaAs and InAs has led to a significant improvement in sensitivity and detection bandwidth of 1 MHz [6]. However, this technique requires the main current path to be interrupted and pass through the sensing device.

The introduction of contactless current sensors based on Hall elements was enabled by application of planar magnetic field concentrators [7]-[8]. Hall elements respond to magnetic fields which are normal to the trace orientation. As a result, unlike conventional methods, the Hall element is placed underneath the magnetic concentrator which provides a normal field to the sensor. These magnetic concentrators utilize ferromagnetic materials to concentrate the field through the hall sensing element. The most advanced contactless hall-effect based current sensor has a bandwidth limited to 250 kHz [7]-[8] hence, making them unsuitable for high frequency (>1 MHz) contactless current measurements.

Magnetoresistor (MR) sensors can be developed based on both metal alloys and semiconductors which enable increased design flexibility. MR sensors have excellent sensitivity and measurement accuracy as they suffer from less drift compared to hall-effect based sensors. They can respond to both AC and DC fields and have a very high detection bandwidth which makes them an attractive choice for high frequency current sensing in power electronic converters. Unlike Hall-effect based sensors, the MR sensors respond to horizontal magnetic fields which enable utilization of conductive materials such as copper or aluminum as planar magnetic field concentrators. Several research groups are investigating techniques to improve the sensitivity and accuracy of current sensing by hall-effect as well as MR and GMR based devices for power electronics applications [9]-[17].

In this work, we have proposed a novel technique for enhanced bandwidth contactless current sensing using Magnetoresistor sensors with planar magnetic concentrators (MCON) utilizing conductive materials. The effect of different magnetic field concentrators (MCON) on the performance of Anisotropic Magnetoresistor (AMR) sensors for high frequency contactless current detection has been investigated and analyzed. A commercially available AMR sensor Honeywell HMC1021S [18] is utilized as a contactless current monitoring device. The AMR sensor is evaluated for detecting currents with a very fast transient current generated by a custom designed step current generator. Six different Magnetic Concentrators (MCONs) of different material and thickness are designed for analyzing the effect on the sensor performance in detecting the fast transient currents up to 20A. The sensor response equipped with different MCONs is recorded and detailed analysis is performed to analyze the effect of MCONs. A frequency analysis of the sensor response with different MCONs is performed to analyze the effect of MCONs on the sensing performance and the detection bandwidth of the AMR sensor.

Magnetic Concentrator (MCON) for Magnetoresistor (MR) Sensors

In a typical power electronic application, the MR sensor is placed on the top or underneath (bottom layer) the current carrying trace on a Printed Circuit Board (PCB) as shown in Figure 2.1. The sensor has no physical contact with the current trace and the magnetic field generated by the current passing through the trace is detected by the AMR sensing elements inside the sensor chip.

When a low frequency current is passed through the PCB trace, the magnetic field generated by the current is uniform and evenly distributed surrounding the current trace. Figure 2.1(a) and Figure 2.1(b) visualizes the magnetic field distribution at low and high frequency currents. The magnetic flux lines intersecting the AMR sensor's default axis of detection creates a response in the sensor output which is proportional to the current magnitude in the trace. However, at high frequencies, due to skin effect, most of the current flow through the trace is concentrated near the edges of the trace. The magnetic flux lines generated by the high frequency currents are no longer uniform around the trace and most flux lines are concentrated near the edge of the current trace. The field distribution near the sensing element is very weak and the relatively weaker field is detected by the sensor. As a result, the sensor gives a false impression of losing its sensitivity at high frequency current sensing. However, normalizing the magnetic field with magnetic field concentrators (MCONs) results in uniform field distribution in the sensing region and enhanced detection bandwidth from the sensor.

One method to amplify and normalize the magnetic fields generated by high frequency currents is folding the current carrying trace around the sensor [9]. This approach has also been demonstrated for planar Rogowski coil in which the coil is sandwiched between the trace [19]-[22]. If the application allows such layout modification, this method can be well adopted for point-field detectors such as magnetoresistive sensors. However, it is possible to implement magnetic field concentrators that can shape and amplify the field above a PCB trace carrying high frequency current with no or minimal PCB layout modifications.

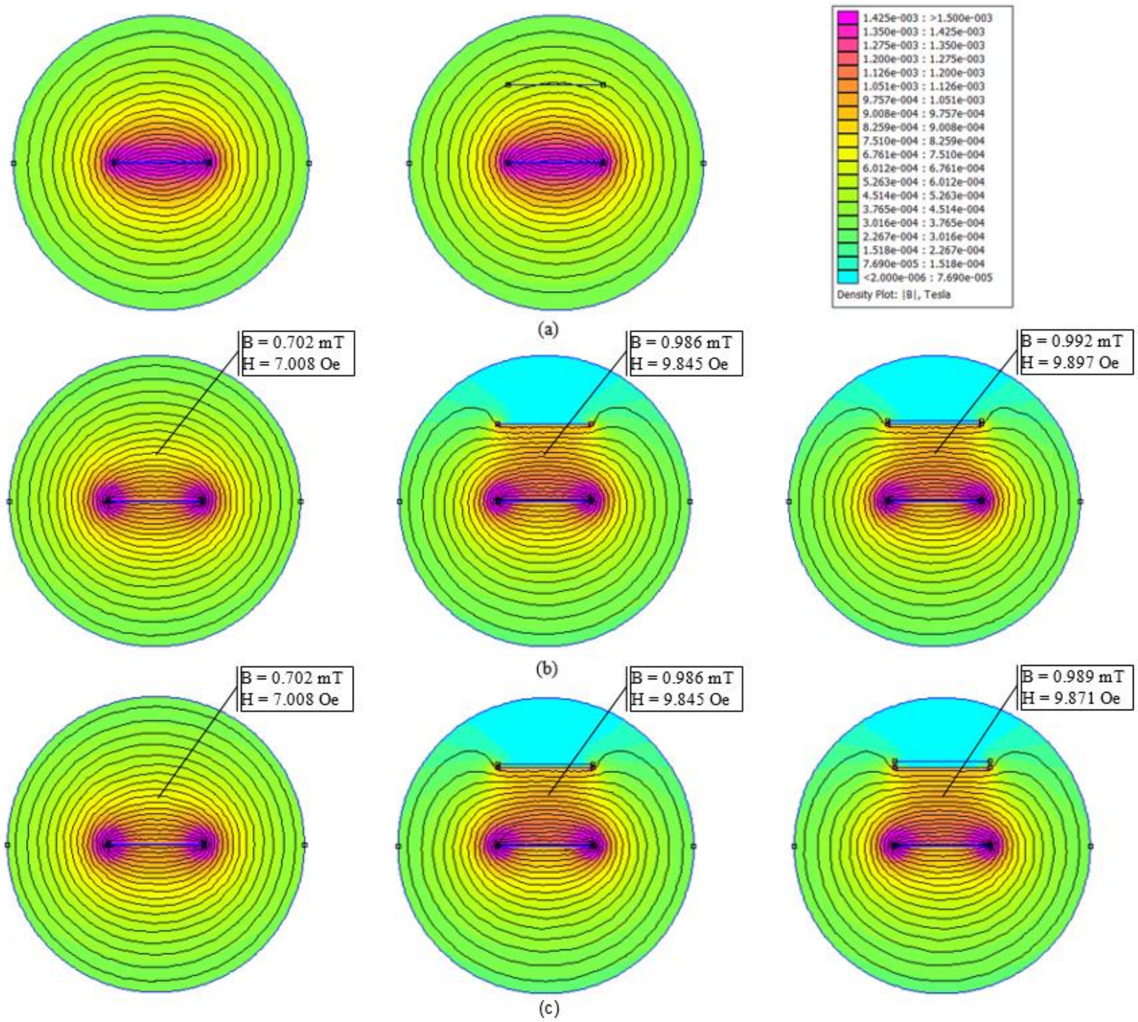

Figure 2.2: Simulation results for the effect of MCON on magnetic field distribution for 10A current at (a) DC, (b) 5MHz with No MCON (left), 1mil Cu MCON (middle) and 5mil Cu MCON (right), (c) 5MHz with No MCON (left), 5mil Al MCON (middle) and 10mil Al MCON (right)

Magnetoresistor (MR) elements respond to horizontal components of the magnetic field contrary to the Hall-effect elements which respond to the vertical components of the magnetic fields for accurate sensing. This unique property associated with the MR sensors can be utilized to a great extent when designing the proposed MCONs for magnetic field normalization purposes. In principle, the electromagnetic field reflection property is utilized when is exposed to a conductive surface to normalize and intensify the magnetic field through the sensor. Ideally, a superconductive surface with zero field absorption is desired for maximum performance. However, using materials having excellent electrical conductivity such as Copper (Cu) or Aluminum (Al) having specific dimensions and thickness, magnetic field normalization can be achieved to a great extent. The material, dimensions and thickness of the MCON play a big role in the field normalization and the performance of the MR sensor.

To get a clear understanding of the effect of MCON on the magnetic field distribution around a current trace, a detailed simulation study is performed using Finite Element Method Magnetics (FEMM) electromagnetic solver. Figure 2.2 and Figure 2.3 presents the simulation results for 10A and 20A currents respectively showing the change in magnetic field distribution for MCON technique compared to the regular current trace. The simulation is carried out on a 1oz PCB copper trace having a width of 150mils. Current is passed through the PCB trace in the direction going away from the observer. The frequency of the current is varied from DC to 5MHz to understand the effect on the magnetic field distribution. The MCONs having length and width of 0.19” and 0.15” respectively are placed at a distance of 3.07mm from the PCB trace which is the distance from the PCB trace to the top of the chip placed on the PCB.

For DC currents, the magnetic field generated by the current is uniform and evenly distributed around the trace. The DC fields are not affected by MCON and are unchanged as shown in Figure 2.2(a) and Figure 2.3(a). The magnitude of the magnetic field generated by the 20A current is higher than field generated by the 10A current and in both cases and the field is unaffected by MCONs. However, when a 5MHz current is passed through the trace, most of the magnetic fields generated by the trace is concentrated near the edge of the trace due to skin effect. As a result, the field near the middle section of the trace, which is the effective sensing region, is non-uniform.

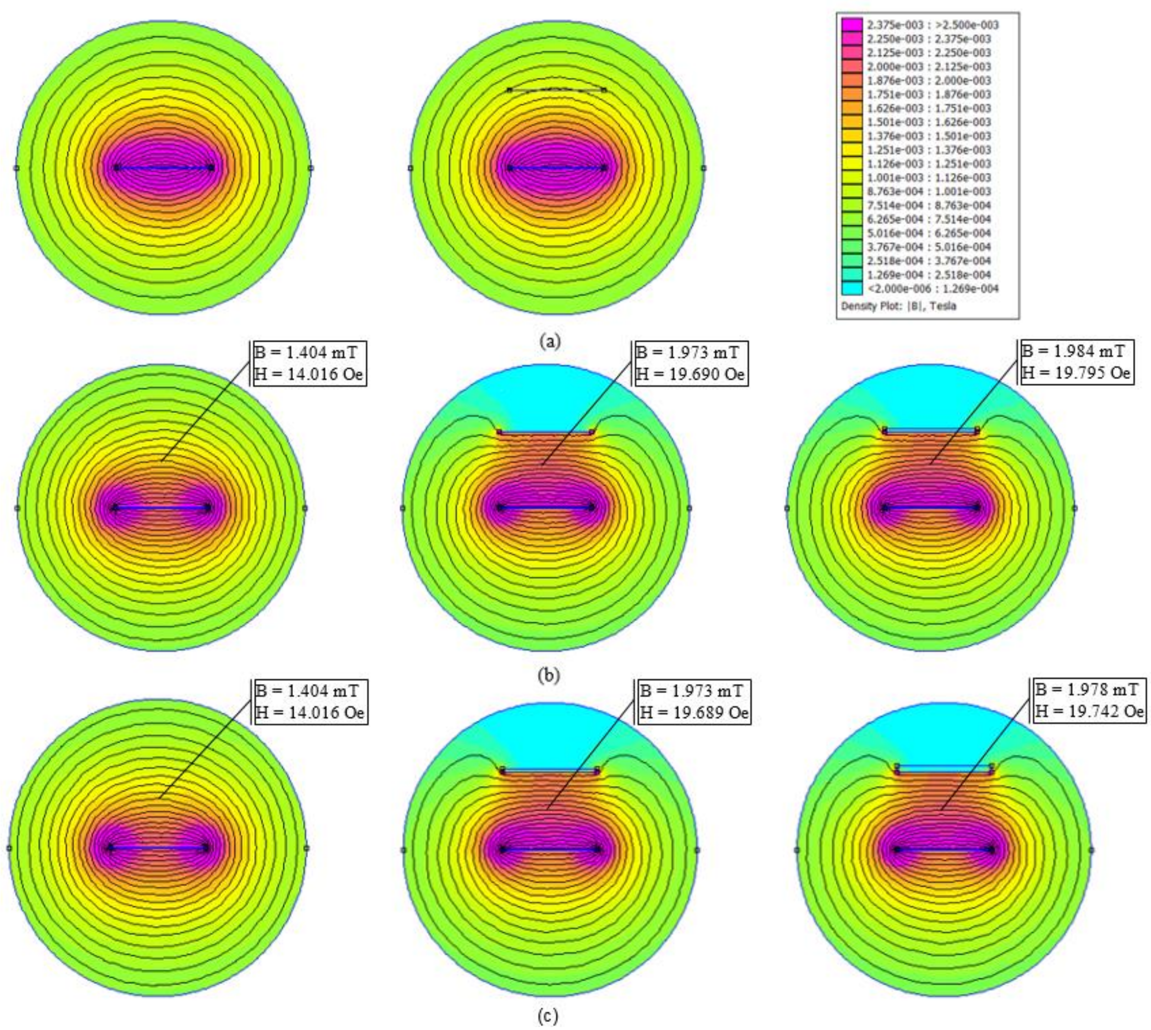

Figure 2.3: Simulation results for the effect of MCON on magnetic field distribution for 20A current at (a) DC, (b) 5MHz with No MCON (left), 1mil Cu MCON (middle) and 5mil Cu MCON (right), (c) 5MHz with No MCON (left), 5mil Al MCON (middle) and 10mil Al MCON (right)

Figure 2.2(b) shows the results of the simulation at 5MHz with no MCON (left) and copper MCONs having thickness of 1mil (middle) and 5mil (right) respectively for 10A current. It can be clearly seen that the non-uniform magnetic field distribution of high frequency currents is concentrated, normalized and made uniform using the MCONs. The magnetic flux density (B) and the magnetic field intensity (H) measured at the sensing point of 2.1mm from the current trace shows that the B and H values are increased with the use of MCONs. Similar results can be observed in the case of aluminum MCONs having 5mil (left) and 10mil (right) thickness for 10A current as shown in Figure 2.2(c).

The 5 mil copper MCON shows the most significant improvement in terms of field density with the B value increasing from 0.702mT to 0.992mT. The change in magnetic flux density is, $\Delta B = (0.992 - 0.702)$ mT = 0.29 mT = 2.9 gauss.

The sensitivity of the MR sensor in consideration from the manufacturer datasheet [18] is S_m = 1 mV/V/gauss. Assuming a bridge voltage of 5V and a gain of 20 in the post processing circuits (explained in later sections) the corresponding voltage gain in the output with 5 mil copper MCON is, $\Delta V = \Delta B * S_m * 5 * 20 = 290$ mV.

By implementing 5 mil copper MCON, the sensor output for 5 MHz current of 10A magnitude can be theoretically increased by 290mV which corresponds to 11.6% improvement in the sensor response. The simulation results for 20A current shows similar results in concentrating and normalizing the magnetic field in the sensing region as shown in Figure 2.3(b) and Figure 2.3(c). Hence, varying the material and the thickness of the MCON, different level of magnetic field normalization can be achieved.

Experimental Verification of the Magnetic Concentrator (MCON) Performance

A. Experimental Setup

To evaluate the effect of MCON on the performance of the magnetoresistive (MR) sensor [18] as a current measuring device, several test circuits were developed. Figure 2.4 shows the circuit diagram of the hardware setup designed to evaluate the performance of the AMR sensor when equipped with different MCONs. A custom designed fast high-rise step current generator was used to generate a current pulse which is used as the reference current for the AMR sensor. The step current generator can generate a current pulse of up to 20A with a transition time of around 5ns which enabled us to analyze the bandwidth of the sensing up to 50MHz.

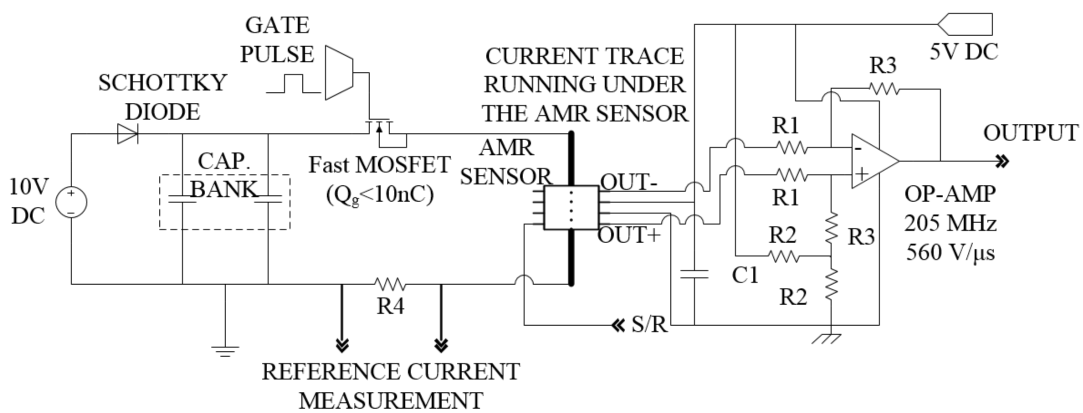

Figure 2.4: Circuit diagram of the hardware setup for evaluation of the performance of the AMR sensor equipped with different MCONs.

The current carrying PCB trace and the MR sensor is placed on opposite sides of the PCB having a thickness of 1.57mm. The carrying current trace with 1Oz Copper is implemented on the bottom layer of the PCB while the MR sensor is placed on the top layer making the distance between the current trace and the sensing element to be 2.1mm.

The output from the AMR sensor is further amplified by a differential gain of 20 which is implemented using high speed components (205 MHz, 506 V/us) such that it does not limit the frequency range of interest. Figure 2.5 shows the hardware prototypes developed for the experiment.

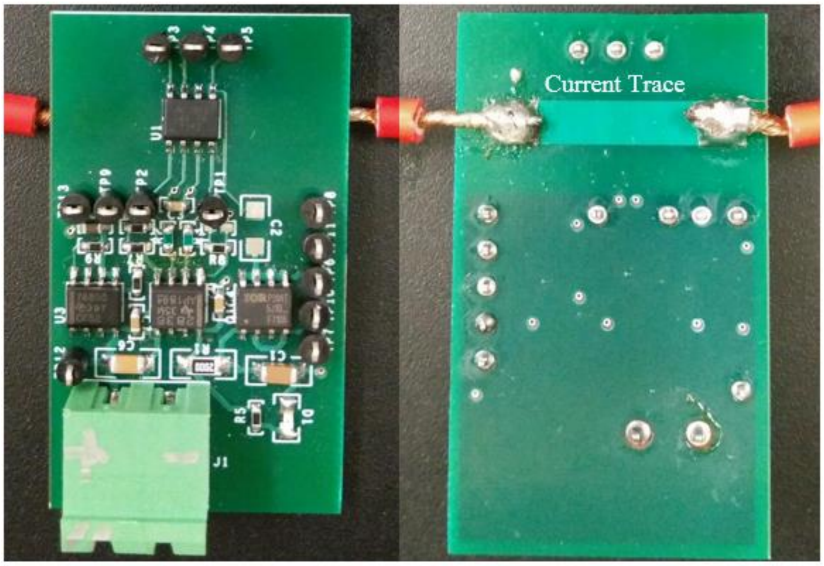

Figure 2.5: Prototype board for AMR sensor evaluation with the sensor and the current trace on opposite sides of the PCB

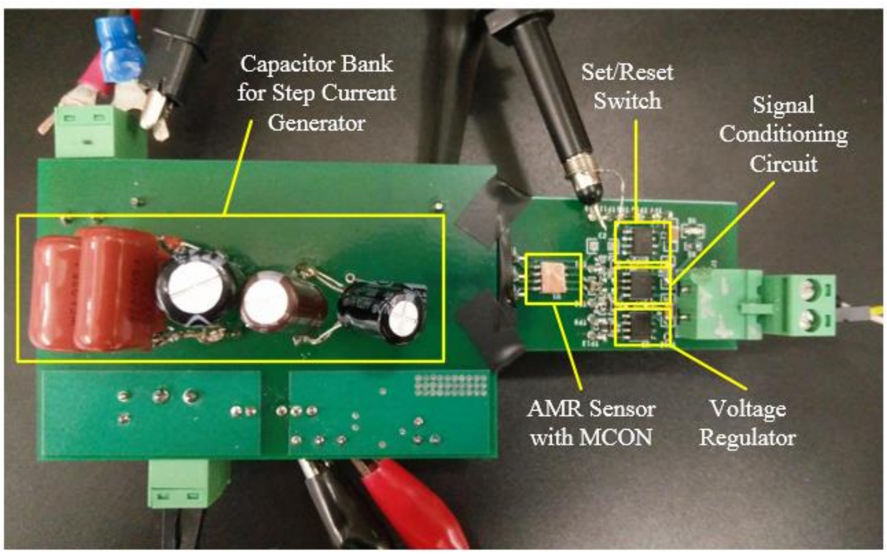

Figure 2.6: Experimental setup with step current generator and AMR sensor equipped with 1 mil copper MCON

In this work, the AMR sensor is evaluated with 6 different configurations of MCONs. The MCONs are configured using materials having excellent conductivity such as Copper (Cu) and Aluminum (Al). The length and width of the MCONs are 0.19” and 0.15” respectively matching the top dimensions of the SOIC8 chip of the AMR sensor. The thicknesses of the different MCONs are varied to observe the effect on the sensor output. The Copper (Cu) MCONs are used with 3 different thicknesses of 1 mil, 5 mil and 10 mil whereas the Aluminum (Al) MCONs are used with 5 mil, 10 mil and 22 mil thickness. The MCONs are placed on top of the AMR sensor one at a time, and the response of the sensor with respect to a fast rise step currents having magnitudes up to 20A is observed. Figure 2.6 shows the experimental setup of the step current generator and AMR sensor equipped with 1 mil copper MCON.

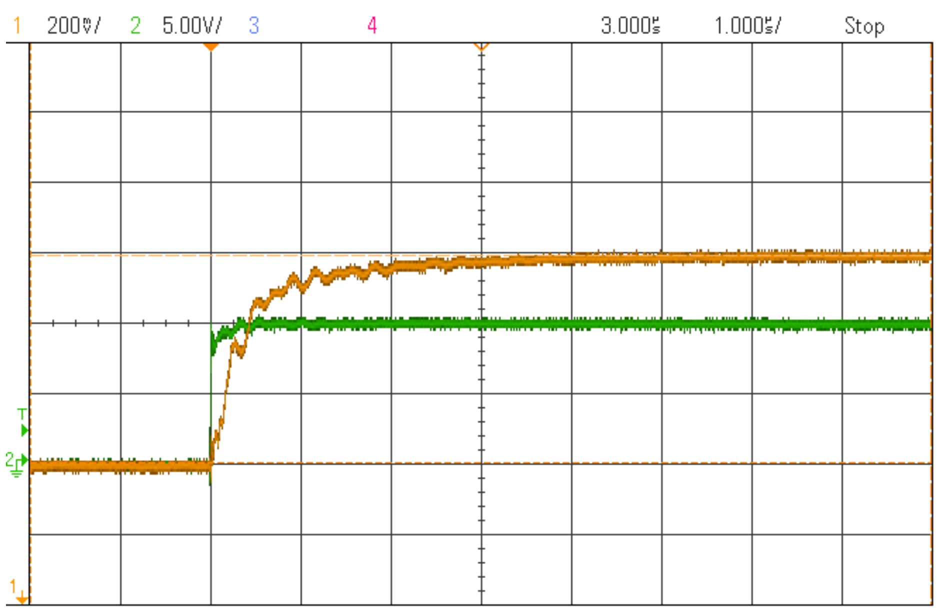

Figure 2.7: Response of the AMR sensor with respect to 10A step current with no MCON. Scales - X-axis: 1us/div, Y-axis: 5v/div (green), 200mv/div (yellow)

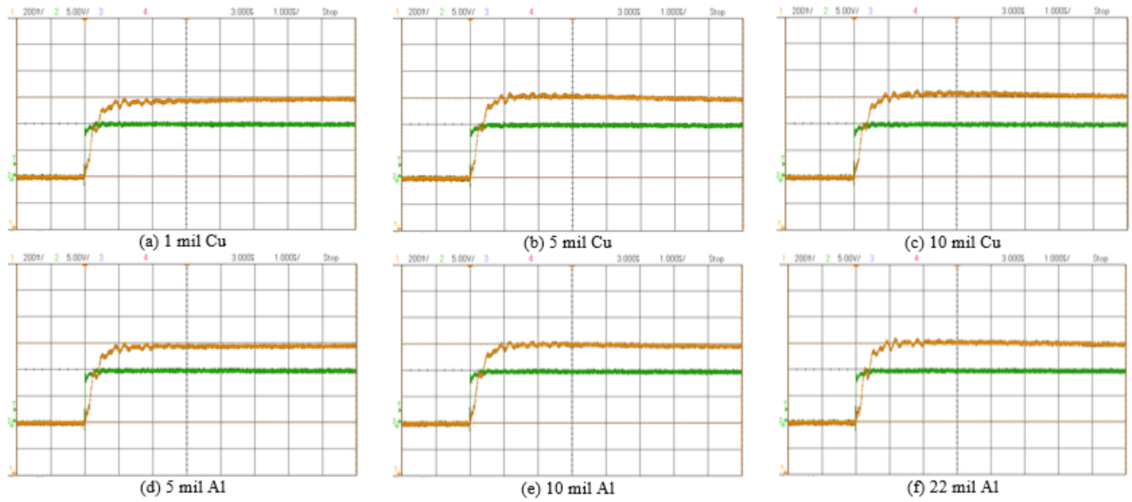

Figure 2.8: Improvement in the response of the AMR sensor with respect to 10A step current with 6 different MCONs. Scales - X-axis: 1us/div, Y-axis: 5v/div (green), 200mv/div (yellow)

B. Experimental Results

The AMR sensor response to the fast high rise step current of 10A magnitude is presented in Figure 2.7. The green waveform corresponds to the reference current measurement using a small power resistor in the step current generator board. The yellow waveform corresponds to the response of the AMR sensor without any MCON. The sensor output is biased at 2.5V when no current is present in the trace. With the 10A step current in the trace, the steady state sensor response of 3.08V is reached at 3.1us. The sensor is then evaluated under the same operating conditions and using the 6 different configurations of MCON described above. The response of the AMR sensor equipped with MCONs with different materials and thickness is shown in Figure 2.8. It is clearly evident that the sensor when equipped with MCON shows much better response irrespective of the type of MCON used. In all cases, the steady state is reached much faster than the case with no MCON. This is due to the fact that, implementation of MCON by means of using a sheet of conductive materials such as copper and aluminum, has normalized the magnetic field in the sensing elements region. The results presented in Figure 2.8 shows that, the AMR sensor response when equipped with the 1 mil, 5 mil and 10 mil copper MCONs reaches the steady state of 3.08V in 1.16us, 0.83us and 0.86us respectively. Similarly, for aluminum MCONs the steady state of 3.08V is reached in 0.91us, 0.87us and 0.86us for MCON thickness of 5 mil, 10 mil and 22 mil respectively.

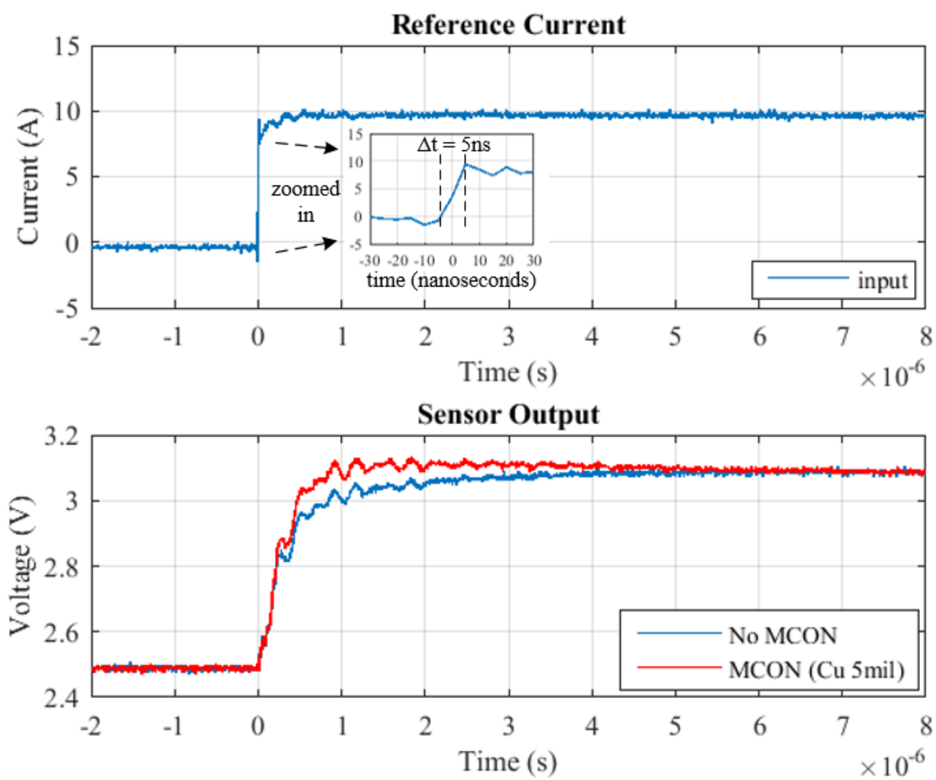

Figure 2.9: Comparison of AMR sensor response for 10A step current with no MCON and 5 mil copper MCON

For better understating of the improvement in the transient response of the sensor when equipped with MCON, the rise time to 80% of the steady state value is determined. For the case with no MCON, the rise time to 80% of the steady state is determined to be 0.51us while for cupper MCONs having 1 mil, 5 mil and 10 mil thickness, the rise time to

80% of the steady state is 0.46us, 0.44us and 0.44us respectively. Similarly, for the 5 mil, 10 mil and 22 mil thick aluminum MCONs, the rise time to 80% of the steady state value is 0.46us, 0.45us and 0.45us respectively.

The experimental results from the step current test depicted that, the 5 mil copper shows the most significant improvement on the AMR sensor response with respect to the 10A step current. The captured data from the experiment is exported to MATLAB for further comparison and analysis. Figure 2.9 shows the time domain results of the AMR sensor response without any MCON implementation and when equipped with the 5 mil copper MCON. It is clearly visible from the figure that the, sensor response with respect to a 20A step current gets significantly improved when used with the 5 mil copper MCON.

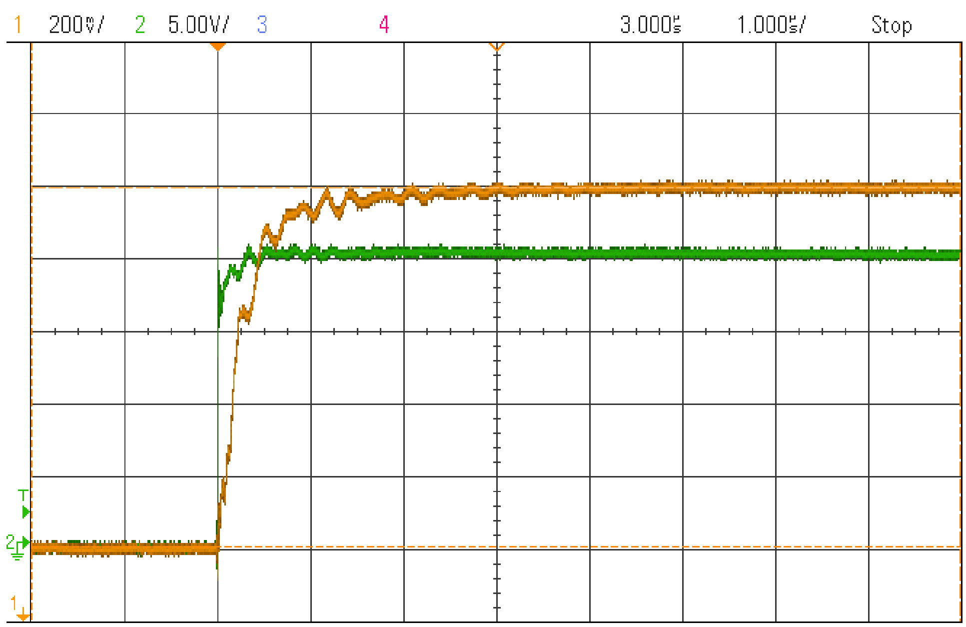

Figure 2.10: Response of the AMR sensor with respect to 20A step current with no MCON. Scales - X-axis: 1us/div, Y-axis: 5v/div (green), 200mv/div (yellow)

For verification of the consistency of the effect of MCON on the AMR sensor response, the step current generator is reconfigured to generate a 20A step current and the sensor response is observed without using any MCON and then with the 6 different MCONs used in the previous experiment. Figure 2.10 shows the oscilloscope capture of the sensor response with no MCON used and Figure 2.11 presents the AMR sensor response with 6 different MCONs for 20A step current. The green waveform corresponds to the reference step current and the yellow waveform corresponds to the sensor response. The steady state sensor output for 20A step current is 3.5V. When no MCON is used, the sensor output reaches the 3.5V steady state at 3us. When equipped with the copper MCONs having 1mil, 5 mil and 10 mil thickness, the response gets faster and the steady state is reached at 2.4us, 0.8us and 0.8us respectively. In the case of the aluminum MCONs, similar trend is observed with the steady state of 3.5V achieved at 0.9us, 0.87us and 0.86us for MCONs having thickness of 5 mil, 10 mil and 22 mil respectively.

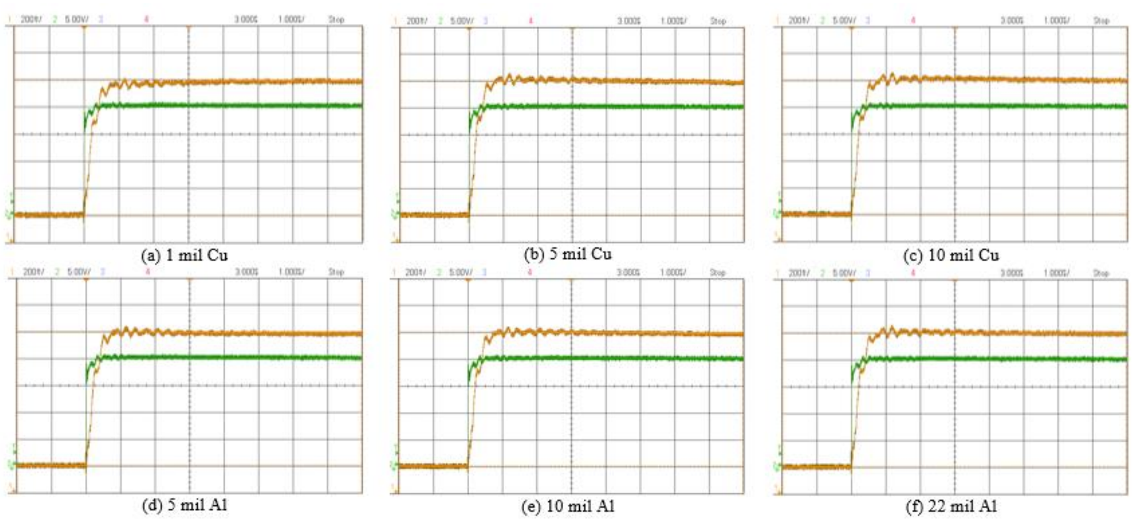

Figure 2.11: Improvement in the response of the AMR sensor with respect to 20A step current with 6 different MCONs. Scales - X-axis: 1us/div, Y-axis: 5v/div (green), 200mv/div (yellow)

When analyzing the rise time to 80% of the steady state sensor output for the 20A experiment, the case with no MCON shows 0.45us while for the 1 mil, 5 mil and 10 mil thick copper MCONs the rise time to reach 80% steady state is 0.425us, 0.41us and 0.415us respectively. Also, for the aluminum MCONs having thickness of 5 mil, 10 mil and 20 mils, the rise time to reach 80% of the steady state value is found to be 0.42us, 0.41us and 0.415us respectively.

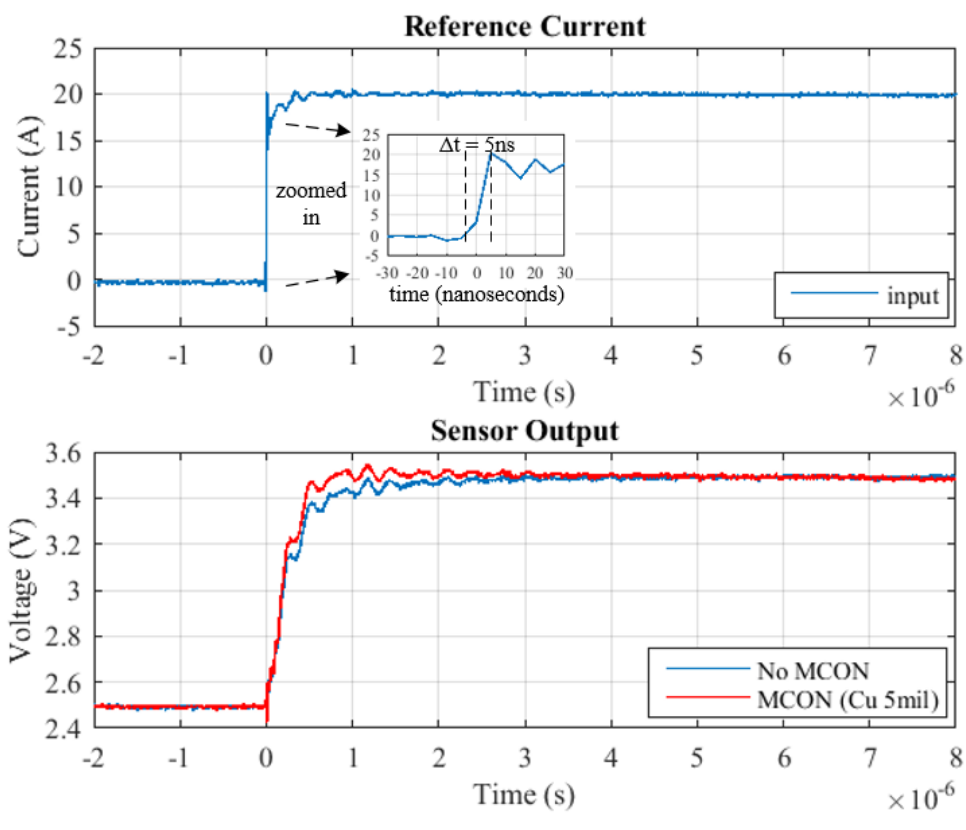

Figure 2.12: Comparison of AMR sensor response for 20A step current with no MCON and 5 mil copper MCON

This observation confirms the performance improvement gained by normalizing the magnetic fields using MCONs based on conductive materials for 20A step current.

The 5 mil copper MCON shows the best results in the 20A step current response as well. Figure 2.12 shows the time domain comparison of the AMR sensor response for 20A step current transient with no MCON and the 5 mil copper MCON.

TABLE 2.1
SUMMARY OF RESULTS AND ANALYSIS FROM THE STEP CURRENT TEST

MCON Material	Reference Current (A)	Steady State Sensor Output (V)	MCON Thickness (mils)	Rise Time to Steady State (us)	Rise Time to 80% of Steady State (us)
No MCON	10	3.08	-	3.1	0.51
Cu			1	1.16	0.46
			5	0.83	0.44
			10	0.86	0.44
Al			5	0.91	0.46
			10	0.87	0.45
			22	0.86	0.45
No MCON	20	3.5	-	3	0.45
Cu			1	2.4	0.425
			5	0.8	0.41
			10	0.8	0.415
Al			5	0.9	0.42
			10	0.87	0.41
			22	0.86	0.415

C. Discussions

The results and analysis from the experiments 10A and 20A step current discussed in the previous section are summarized in Table 2.1. It is clearly evident from the data presented in Table 2.1 that, the rise times for the sensor response with the implementation of MCONs are significantly improved when compared with the ones without any MCON. Implementation of the 5 mil copper MCON results in the most improved response from the AMR sensor for both 10A and 20A step current transients.

One of the important findings from the experiments is that, increasing the thickness of the MCON with same material increases the magnetic field normalization and hence, generates better sensor response. The observation is reflected on the sensor response getting faster in the case of 5 mil copper MCON when compared with the 1 mil copper MCON with the response time to reach the steady state of 3.5V getting reduced from 2.4us to 0.8us for 20A step current and also from 1.16us to 0.83us for 10A step current.

However, once the maximum field normalization possible using the MCONs in consideration is achieved, increasing the thickness further does not result in a better response from the sensor. Hence, the time required for the sensor to reach the steady state is no longer reduced further. For both the 10A and 20A step current transients, increasing the thickness of the copper MCON from 5 mil to 10 mil resulted in similar response from the AMR sensor. A similar trend is also noticed for Al where increasing the thickness of the aluminum MCON from 10 mil to 22 mil did not result in any improvement the sensor response with respect to the step current.

Another important observation from the experiment is that, the magnetic field normalization achieved by the 5 mil copper and 10 mil aluminum MCON are almost similar although 5 mil copper MCON generates slightly better response in spite of having less thickness than aluminum. This observation leads us to the conclusion that, as a conductive material used as MCON for magnetic field normalization, copper offers lighter and thinner solution in terms of size when compared with aluminum.

To observe the consistency of the MCON performance on the transient response time of the AMR sensor, the sensor performance is evaluated with step currents having magnitudes of 2A, 5A, 10A, 15A and 20A, respectively. In each case, the AMR sensor responses are analyzed without MCON and with 5 mil copper MCON equipped. Figure 2.13 presents the steady-state sensor outputs from the experiments for currents varying from 2A to 20A. It can be seen from the figure that, the sensor output has a linearity error of 16.67% at 20A. It is important to note that this linearity error is inherent in the sensor characteristics and not affected by the implementation of MCONs. The effects of the MCONs are primarily on the transient performance of the sensor output and the steady-state is not affected. Figure 2.14 presents the variation in the sensor output rise time to reach the steady state for different current magnitudes. It can be observed that, the response time is significantly improved using MCONs. The rise time to steady state is fairly constant with the variation of current magnitude both in case of no MCON and with MCON for the sensor output. This validates the performance improvement achieved by the implementation of MCONs to improve the transient performance of the AMR sensor is consistent with different currents.

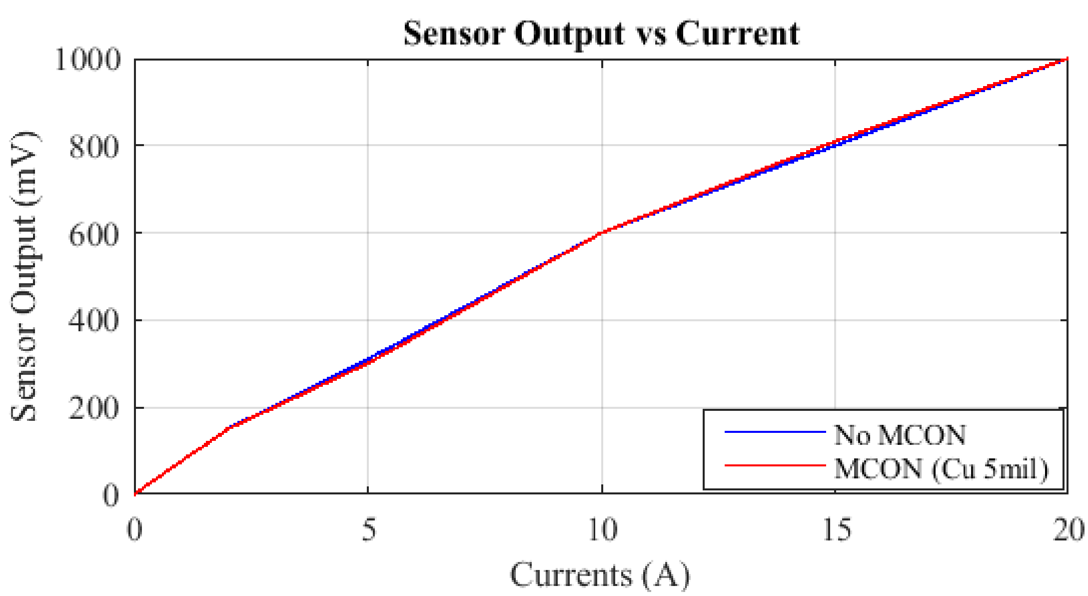

Figure 2.13: Change (offset 2.5V) in steady state sensor output with step currents of different magnitude for no MCON and 5 mil copper MCON

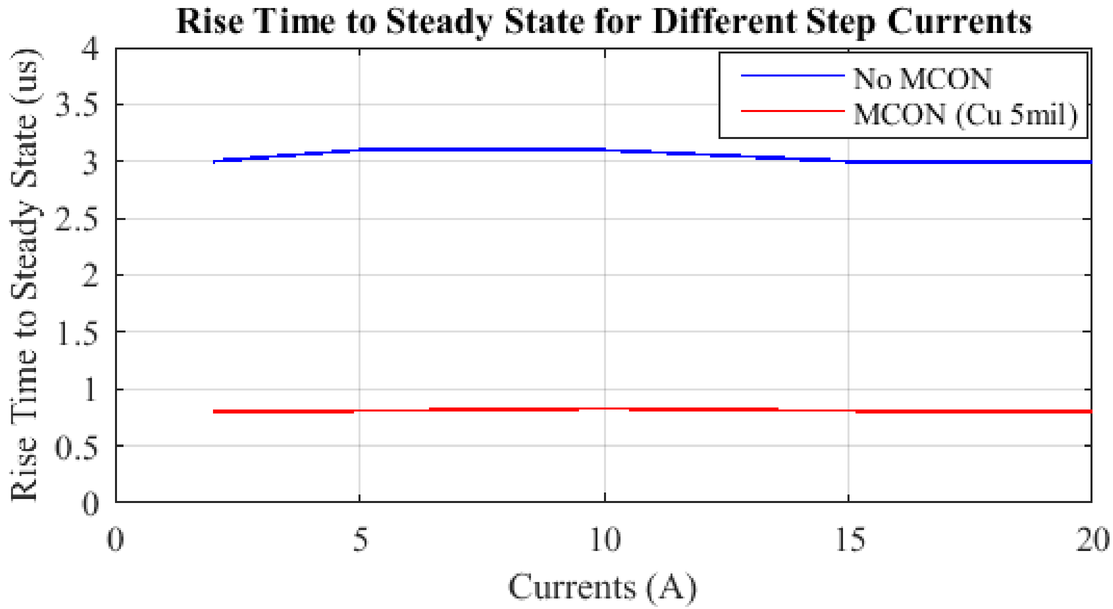

Figure 2.14: Change in rise time to steady state for sensor output with step current of different magnitudes for no MCON and 5 mil copper MCON

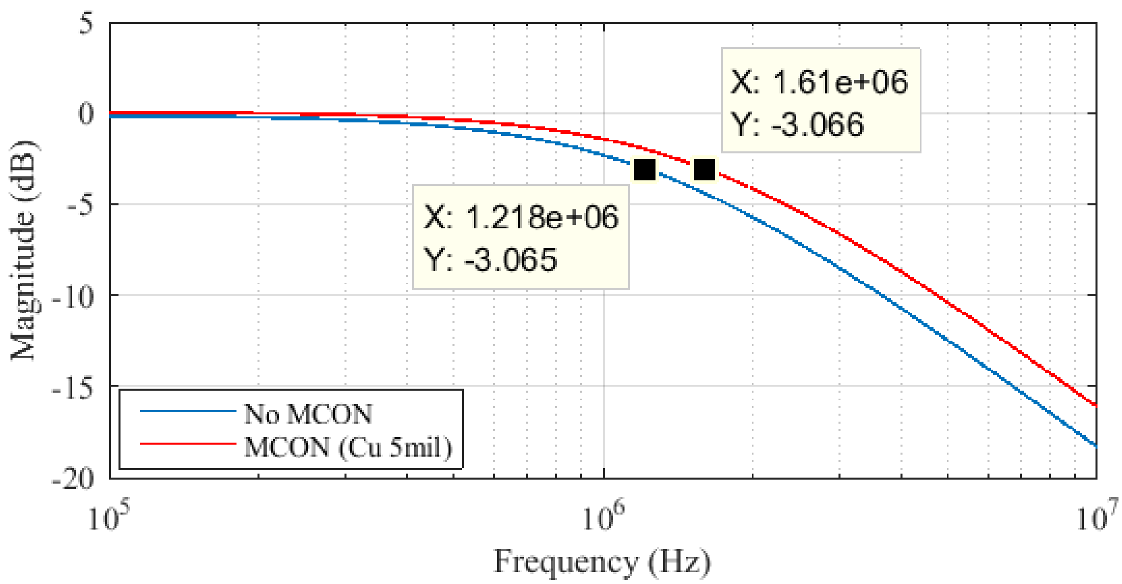

Figure 2.15: Frequency response showing the bandwidth improvement for the step current response presented in Figure 2.12 for no MCON and 5 mil copper MCON

For further analysis of the experimental data, a frequency analysis of the captured data from the 20A step current test as shown in Figure 2.12 is performed using MATLAB. Figure 2.15 shows the frequency analysis of the time domain response of the sensors shown in Figure 2.12. It can be observed from the results shown in Figure 2.15 that, the bandwidth of the sensor response of the cases with MCON has improved compared to the case with no MCON. Detailed analysis shows that, the sensing bandwidth (-3dB response) of the AMR sensor without use of any MCON is 1.21 MHz. The 5 mil copper MCON translates to the best response from the AMR sensor and the sensing bandwidth is improved from 1.21 MHz to 1.61 MHz as shown in Figure 2.15 which translates to a 33.06% improvement in the overall sensing bandwidth. Increasing the thickness of the copper MCON provides no further improvement in response and the bandwidth is limited to 1.55 MHz. The results from the frequency analysis with respect to the 20A step current response showing the bandwidth improvement with the implementation of different conductive MCONs are presented in Table 2.2.

TABLE 2.2
SUMMARY OF FREQUENCY ANALYSIS FROM THE 20A STEP CURRENT TEST

MCON Material	Reference Current (A)	MCON Thickness (mils)	Bandwidth (MHz)	Bandwidth Improvement (%)
No MCON	20	-	1.21	-
Cu		1	1.42	17.36 %
		5	1.61	33.06 %
		10	1.55	28.10 %
Al		5	1.54	27.27 %
		10	1.56	28.93 %
		22	1.54	27.27 %

Conclusion

In this paper, a technique for enhanced bandwidth contactless current sensing using Magnetoresistive sensors with planar magnetic concentrators (MCON) utilizing conductive materials has been proposed. We have investigated and analyzed the effect of different magnetic concentrators (MCONs) on the performance of AMR current sensors for contactless current monitoring. A detailed simulation study is performed to clearly understand the magnetic field distribution for high frequency currents. The observations are experimentally verified and detailed analysis is performed. A fast rise step current generator is designed and utilized to generate a fast current step. To analyze the performance of the AMR sensor in detecting fast transient step current, four different MCONs made with copper and aluminum having different thicknesses are implemented. The sensor response equipped with different MCONs are recorded and presented accordingly. A frequency response of the sensor response with different MCONs is performed to analyze the effect of MCONs on the detection bandwidth of the AMR sensor. The use of MCONs normalized the magnetic field through the sensing element and improved the bandwidth of current sensing. Implementation of the 5 mil copper MCON results in a significant improvement in the sensing bandwidth of around 400 kHz which translates into a 33.06% increase in detection bandwidth of the AMR sensor. It is believed that the proposed method is applicable for current sensing in high frequency power converters where the current information is used to control the ripple and transient response.

Acknowledgments

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CHAPTER 3: A NON-INVASIVE DC-10MHZ WIDEBAND CURRENT SENSOR USING HYBRID MAGNETORESISTOR-ROGOWSKI SENSOR FOR ULTRA-FAST CURRENT SENSING IN HIGH FREQUENCY POWER ELECTRONIC CONVERTERS

The goals of modern power electronic converters are high efficiency, high power density and higher switching frequency. High frequency power electronic converters having high common mode voltage and switching frequencies in the megahertz domain require fast, wideband, isolated and loss-less current measurements for effective controls, diagnostics and prognostics. In this work, we propose a non-invasive wideband current sensing method for isolated and loss-less current measurement in high frequency power electronic converters. The proposed hybrid current sensing scheme combines two different isolated sensing technologies - a Magnetoresistor sensor and a differential Rogowski coil sensor, which have complementary characteristics to achieve a wide sensing bandwidth. The proposed hybrid current sensor also utilizes planar magnetic field concentrators (MCON) using conductive materials to normalize the non-uniform magnetic field distributions generated by the current over a wide frequency range. We demonstrate through hardware prototypes and experiments that the proposed hybrid sensor yields to a very high sensing bandwidth of DC to 10MHz. The performance of the proposed hybrid sensor is also evaluated in a 1MHz DC-DC converter as well as a high frequency H-bridge inverter module.

Introduction

With the introduction of next generation power semiconductor devices based on wide-bandgap semiconductor switches such as – SiC and GaN, the switching frequency of the power electronic converters is pushing in the MHz range to achieve higher power density and efficiency. In order to keep up with the fast advancements in high frequency power electronics, significant developments are required on the other important aspects of the power converters such as the sensors, controllers, thermal managements etc. The current is an essential parameter in a power electronic converter which is used for control, diagnostics, prognostics and protection of the circuits and systems. Traditional current sensing techniques are no longer viable for measurement of currents in modern power converters demanding high efficiency while maintaining a small footprint. Hence, there is a need to investigate alternative and high bandwidth current sensing methods for measuring the current in power electronic converters. Different integrated and lossless current sensing methods, such as series MOSFET's on-resistance and parallel current-sensing FET (sense-FET) have been proposed by researchers to measure the inductor current and switch current information [1]-[4]. However, most of these approaches are non-isolated and mostly limited to low voltage (<30V) power converter applications. Isolated current sensors are a mandatory requirement for high frequency (>1MHz) power electronic converters utilizing high voltage wide-bandgap semiconductors having high common mode voltage (>30V).

Magnetic field induction-based transducers and Rogowski coils are among the most popular technologies to be used for isolated current sensing in power converters. A Rogowski coil is a magnetic coupling transducer that utilizes Faraday's law of induction to detect the current in a conductor in as isolated manner. The Rogowski coil delivers an output voltage proportional to the time derivative of the input current which is integrated using either active or passive circuits to deduce the actual current information. Rogowski coils are built with air core with no saturation and inherent wideband response characteristics. Rogowski coils are widely used in wideband current monitoring probes and such measurement applications. However, one significant drawback is their inability to respond to constant and DC fields which makes them unsuitable for many applications.

One of the most common magnetic sensors used as isolated current sensors is the Hall-effect sensor. Hall-effect based current sensors are widely used in different power electronics applications and significant improvements have been observed over the years in the performance and development of the Hall sensors [5]-[6]. Despite its popularity, most Hall-effect sensors are manufactured based on Silicon (Si) and they have a limited bandwidth of only a few kilohertz. Recently some new Hall-effect sensors are introduced having much improved sensitivity and sensing bandwidth that take advantage of utilizing materials having higher career mobility and lower bandgap such as InAs and GaAs [7]. However, these sensors require the current path to be interrupted and pass through the sensor IC resulting in layout considerations and parasitic inductance in the path which often limit the volume and performance of the power electronic converters. The introduction of contactless current sensors based on Hall elements was enabled by application of magnetic field concentrators [8]-[9]. These magnetic concentrators utilize ferromagnetic materials to concentrate the field through the hall elements in orthogonal orientation. The most advanced contactless hall-effect based current sensor has a bandwidth limited to 250 kHz [8]-[9] hence, making them unsuitable for high frequency (>1 MHz) contactless current measurements.

Magnetoresistors (MR) are another type of magnetic point field detector which respond to the horizontal components of the magnetic field with respect to the current trace. Magnetoresistors (MR) can be fabricated from both semiconductors and metal alloys. This unique feature of the Magnetoresistive element allows the sensitivity and performance of the sensing element to be adjusted more precisely based on the application. Magnetoresistor were previously used extensively in magnetometry and compassing applications. However, due to their inherent capability of being able to respond to very high frequency magnetic excitations, recently they are gaining rapid popularity as current sensors in high frequency applications. Several researchers have studied and demonstrated the potential of Magnetoresistors to be utilized as current sensors [10]-[15]. In contrast to Hall-effect sensors, Magnetoresistive sensors have significantly lower temperature drift and are less susceptible to external noise, increasing their utility for current sensing applications in high frequency power electronics.

In a typical power electronic application, the Magnetoresistor (MR) sensor is placed on the top or underneath (bottom layer) the current carrying trace on a Printed Circuit Board (PCB) as shown in Figure 3.1. The magnetic field generated by the current passing through the trace is detected by the MR sensing elements inside the sensor chip without any physical contact with the current trace. When a low frequency current passes through the current trace, the resulting magnetic field is uniform and evenly distributed around the current trace as visualized in Figure 3.1(a). But at high frequencies, due to the skin effect, the charge carriers are pushed towards the edge which consequently results in most of the current flow being concentrated near the edges of the trace. The resulting magnetic field distributions around the current trace are non-uniform and concentrated near the edge of the trace as visualized in Figure 3.1(b). Hence, the weaker fields are picked up by the sensing element and the effective detection bandwidth is compromised.

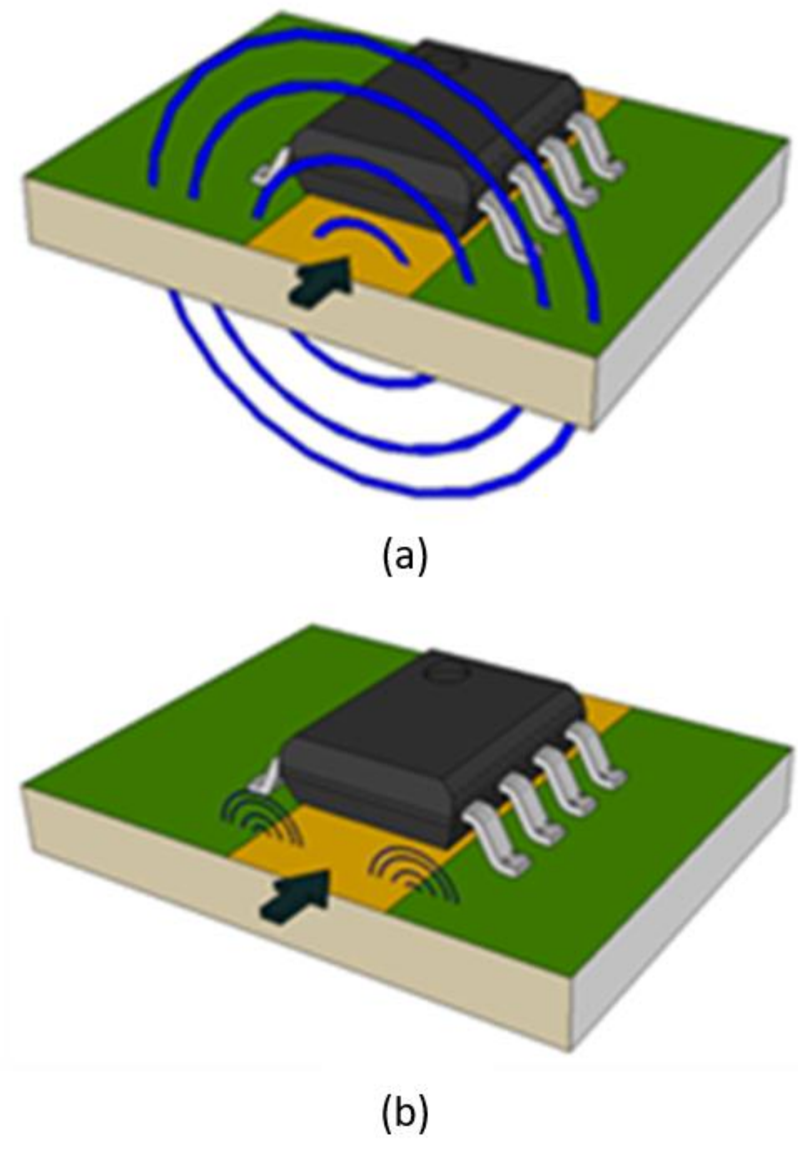


Figure 3.1: Magnetic field distribution generated by current in a PCB trace at: (a) low frequencies and (b) high frequencies

One method to amplify and normalize the magnetic fields generated by high frequency currents is folding the current carrying trace around the sensor [15]. This approach has also been demonstrated for planar Rogowski coil in which the coil is sandwiched between the trace [16]-[19]. However, the property of Magnetoresistor (MR) sensors to respond to horizontal magnetic fields can be utilized to design the proposed planar magnetic field concentrators (MCONs) using conductive materials. Using materials having excellent electrical conductivity such as Copper (Cu) or Aluminum (Al) along with specific dimensions and thickness, the non-uniform magnetic fields due to high frequency currents can be normalized to a great extent [20]-[21]. The material, dimensions and thickness of the MCONs have significant impact on the field normalization and performance improvement of the Magnetoresistor (MR) sensor.

In this paper, we propose a loss-less and wideband hybrid current sensing technique for high frequency power electronic applications based on two complementary current sensing methods – Anisotropic Magnetoresistor (AMR) and Rogowski coil. The low frequency current is sensed using a commercially available high bandwidth AMR sensor and the high frequency currents are measured using a differential Rogowski coil designed on a Printed Circuit Board (PCB). Comparable works on merging two different sensing methods to achieve a wideband current measurement have been reported in [16]-[18], [22]-[25]. The proposed hybrid sensing scheme also takes advantage of the planar magnetic field concentrators (MCON) for normalizing and amplifying the non-uniform magnetic fields generated by the currents over a wide frequency range. In section II, the proposed AMR-Rogowski hybrid current sensing scheme has been theoretically analyzed in detail. In section III, the design of the proposed wideband current sensor utilizing the magnetic field concentrators is explained. In section IV, the implementation of the proposed hybrid current sensor on a working prototype as well as the test circuits developed for the evaluation of the proposed sensor are discussed. The sensor performance is evaluated with a fast-rise step current as well as a high frequency converter. Section V presents the experimental verification of the proposed wideband current sensing scheme and comparative analysis with a commercially available high bandwidth Hall-effect sensor are discussed. Finally, in section VI, the findings from the experiments are summarized and a conclusion is drawn.

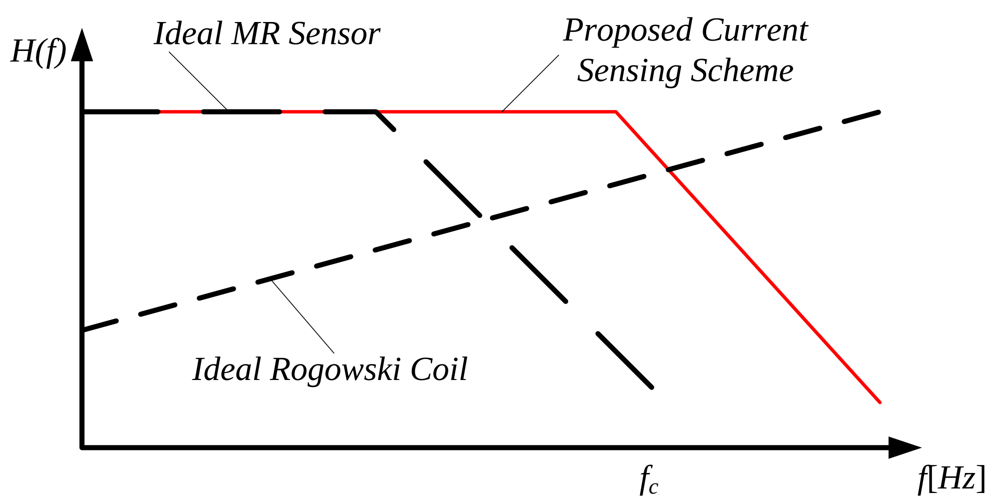


Figure 3.2: The proposed AMR-Rogowski hybrid current measurement scheme.

Proposed Magnetoresistor-Rogowski Current Sensing Scheme

The proposed hybrid current sensing scheme utilizes two different sensing elements operating at different frequencies to obtain a wideband characteristic. One sensing element is utilized for sensing current from DC up to a certain frequency and the other sensing element is responsible for picking up the higher frequency transients. The main concept of the proposed hybrid current sensing scheme is presented in Figure 3.2. For the proposed hybrid sensing scheme, we have selected Anisotropic Magnetoresistor (AMR) as the low frequency sensing element and a PCB embedded differential Rogowski coil as the high frequency sensing element. The Magnetoresistor sensor detects the current from DC to a few megahertz. As the frequency increases, The MR sensor response starts to fall but the Rogowski coil response starts to increase. Theoretically, the Rogowski coil does not have a frequency limit of operation but often limited to the resonance frequency of the coil which is much higher than the frequency range of interest for current sensing. The responses from these two sensing elements are conditioned, filtered and aggregated to obtain a final sensor output corresponding to current measurements from DC to very high frequency.

The AMR sensor has an output which is proportional to the input current to be measured. The transfer function model of an AMR sensor can be approximated by means of a low pass term as shown in (1).

$$H_A(s) = \frac{V_{out(amr)}}{I_{in(amr)}} = \frac{K_A}{sT_A + 1} \qquad (1)$$

where, K_A is the sensitivity and TA is the cutoff frequency of the AMR sensor.

The Rogowski coil has an air core and does not suffer from saturation at high frequencies. The output of an ideal Rogowski coil is proportional to the time derivative of the current. The output of the Rogowski coil depends on the magnetic coupling between the field generated by the current and the coil. The transfer function model of an ideal Rogowski coil can be approximated as shown in (2).

$$H_R(s) = \frac{V_{out(rog)}}{I_{in(rog)}} = sM \qquad (2)$$

where, M is the mutual inductance of the coil.

The Rogowski coil output needs to be integrated to deduce the actual current information. Hence, the output of the Rogowski coil is passed through a low pass filter matching the cut-off frequency for the AMR sensor which acts as the integrator for the Rogowski coil at higher frequencies. The responses from both sensors are gain adjusted and aggregated to obtain a final output which is proportional to the sensing current. The transfer function model of the ideal hybrid sensor characteristics can be deduced as shown in (3).

$$H_{HB}(s) = \frac{V_{out}}{I_{in}} = \left[\frac{K_A}{sT_A + 1} * \frac{K_S}{K_A}\right] + \left[sM * \frac{1}{sT_A + 1} * \frac{K_S T_A}{M}\right] = K_S \qquad (3)$$

Figure 3.3 shows the simple block diagram of the proposed Magnetoresistor-Rogowski hybrid current sensing scheme for ideal characteristics of the sensing elements. In an ideal case, the wideband current sensing scheme can be realized with the conditioning transfer functions and aggregation of the output of the sensing elements as shown in (3). However, the frequency dependent behavior of the actual sensing elements as well as the parasitic and no-ideal characteristics of the Rogowski coil need to be taken into consideration while designing the sensor and implementing the theoretical concept in a real prototype. Using a high bandwidth primary sensing element such as the AMR sensor in our case, allows the Rogowski coil to be designed for very high frequency current pickups. This unique advantage provided by the high bandwidth AMR sensor enables design and implementation of PCB embedded Rogowski coils which is significantly smaller in size and footprint compared to traditional Rogowski coil designs. The Rogowski coil is also designed to have a very high resonant frequency so that any effect of the coil resonance is avoided in the frequency range of interest for the proposed wideband sensing scheme.

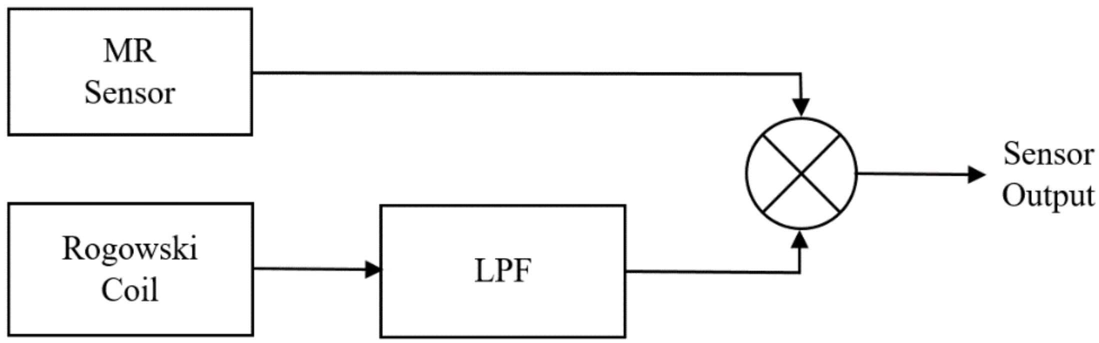


Figure 3.3: Simplified block diagram of the proposed wideband Magnetoresistor-Rogowski hybrid current sensing scheme.

Design of The Proposed Wideband Current Sensing Scheme

A. Anisotropic Magnetoresistor (AMR) Sensor

The proposed non-intrusive wideband current measurement scheme is developed in combination of two different current sensing techniques having complementary characteristics. The low frequency sensor is responsible for picking up transients from DC to a certain frequency while the high frequency sensor is effective for very high frequency transients. In the proposed non-intrusive wideband hybrid current sensor, we have used a commercially available Anisotropic Magnetoresistor (AMR) sensor as the low frequency sensor.

Magnetoresistor (MR) sensors are generally capable of responding to very high frequency fields due to the inherent property of the Magnetoresistive elements.

Magnetoresistor sensors, like Hall-effect sensors, can detect both AC and DC fields which makes them very useful in current sensing for power electronic converters. In contrast to Hall-effect sensors, the Magnetoresistor sensors respond to the horizontal components of the magnetic field. The Anisotropic Magnetoresistor (AMR) and Giant Magnetoresistor (GMR) are two of the most popular Magnetoresistor technologies used in current sensing applications. While the GMR sensor has much higher sensitivity compared to the AMR sensor for a fixed magnetic excitation, it also suffers from higher hysteresis error. Moreover, the GMR sensor has a unipolar response meaning the output of the sensor with respect to an alternating magnetic field is rectified. A detailed study characterizing these two major Magnetoresistor sensors in current sensing applications has been reported in the authors' previous works [26]. We have selected a commercially available AMR sensor as the low frequency sensors for the proposed wideband current sensing scheme due to its capability of detecting bi-directional fields, lower hysteresis loss, lower temperature drift, considerable sensitivity, non-invasive field detection characteristics and much higher sensing bandwidth compared to the Hall-effect based sensors.

The AMR sensor used in the development of the proposed wideband sensor is also used in conjunction with the planar magnetic field concentrators (MCON) utilizing conductive materials. This is required because of the non-uniform magnetic field distribution around the PCB trace associated with high frequency currents. As explained in the previsou section, the magnetic flux lines around a current carrying PCB trace is concentrated near the edges of the trace when a high frequency current flows through the trace. MCONs are designed using as simple as a single sheet of material with high electrical conductivity such as Copper (Cu) or Aluminum (Al) having specific dimensions and thickness. The magnetic reflection principal of a conductive surface is utilized in the design of the MCON which results in a simple implementation yet considerable improvement in the normalization of the magnetic field distribution at high frequency transients. Figure 3.4 visualizes the concept of the MCON for normalizing the high frequency non-uniform magnetic field distribution around the PCB trace.

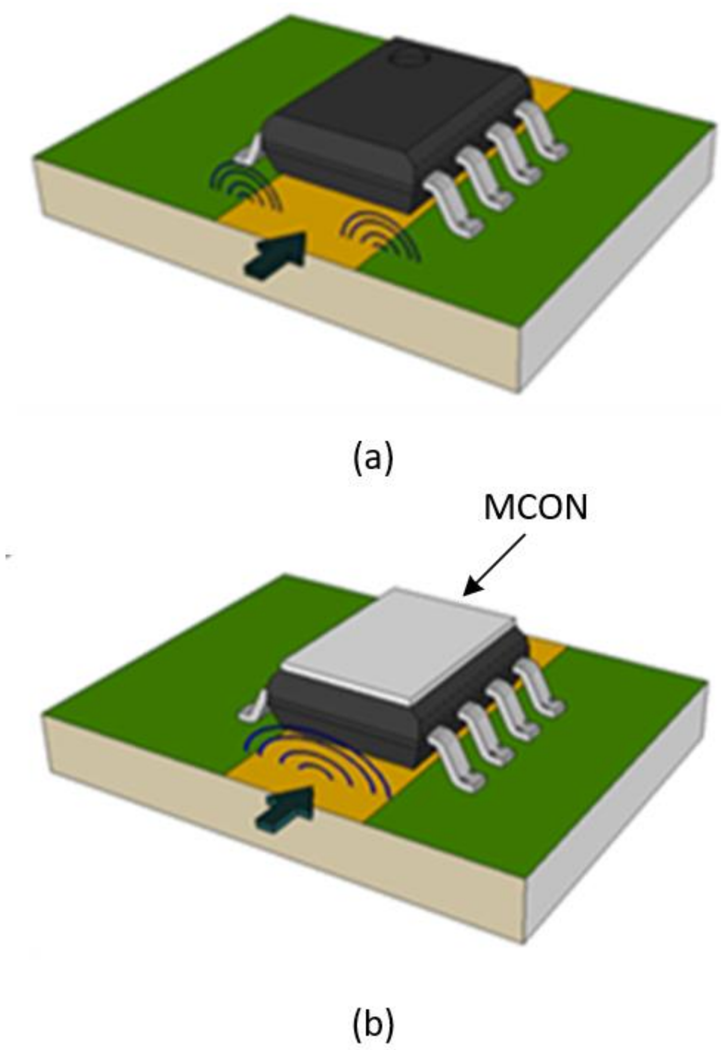


Figure 3.4: Planar Magnetic Concentrator (MCON) concept: (a) Magnetic field distribution at high frequencies due to skin effect and (b) Magnetic field distribution with MCON

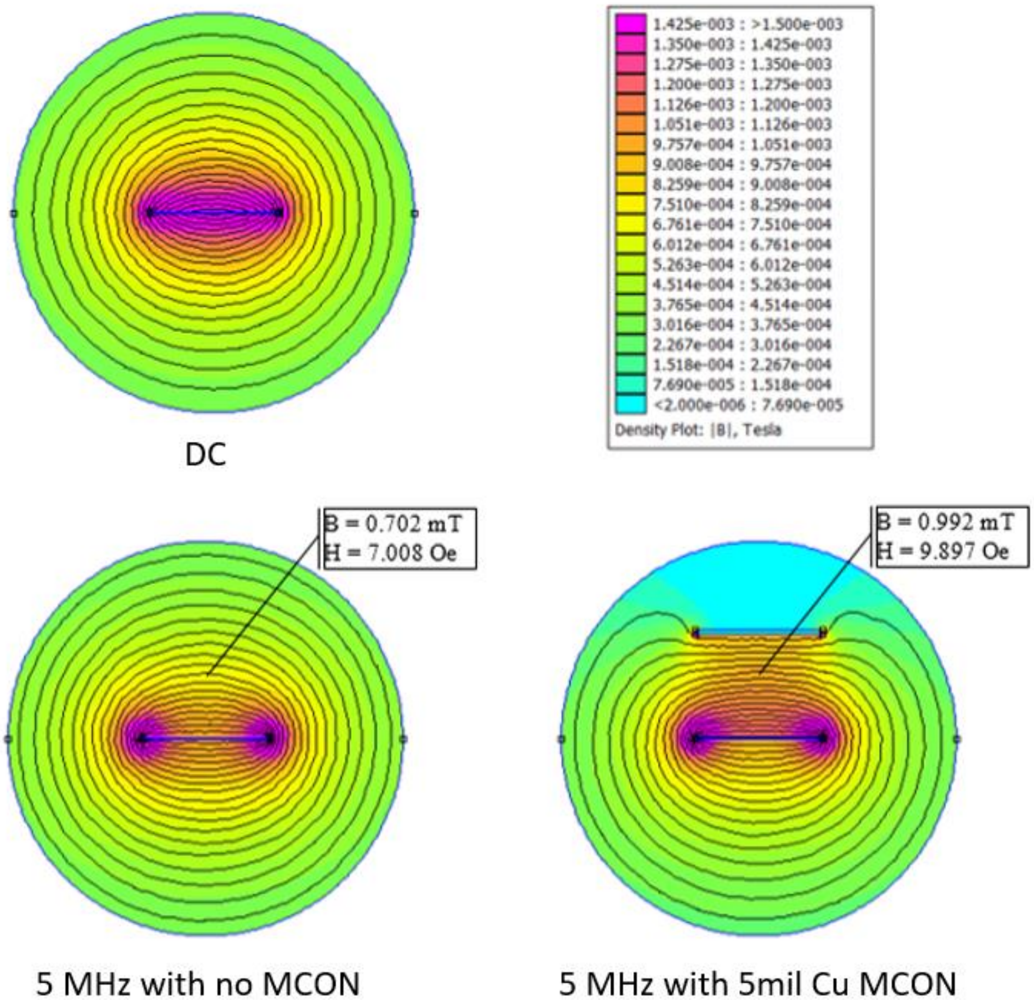


Figure 3.5: Simulation results for 5mil copper MCON on magnetic field distribution at 10A current

In [26] the AMR sensor used in developing the proposed wideband current sensor has been characterized in detail. The bandwidth of the sensor mentioned in the reference datasheet is 5MHz. However, due to the skin effect and the resulting non-uniform magnetic field distribution around the PCB trace, the effective detection bandwidth of the AMR sensor is limited to only 1.21MHz. In [21] the concept of MCON has been experimentally verified and the performance of the AMR sensor with six different

MCON configurations having various thickness and materials (Cu and Al) are evaluated. The detailed study involving high frequency Finite Element Method (FEM) simulation and experimental verification, identified a copper (Cu) MOCN having 5 mil thickness as the most suitable material to be used as MCONs for magnetoresistor sensors. Figure 3.5 shows the simulation results in FEMM solver showing the magnetic field distribution around a 1 oz copper trace for 10A current running at DC and 5MHz frequency with and without the MCON. It can be clearly seen that, the magnetic field through the sensing element is significantly enhanced and normalized at high frequency by using 5mil copper MCON. The implementation of the 5mil copper MCON resulted in an improved sensing bandwidth of around 1.61MHz from the AMR sensor which contributes to around 33% improvement in sensing bandwidth. In the proposed hybrid sensor, a 5mil thick copper MCON having length and width of 0.19” and 0.15” respectively is used with the AMR sensor to achieve maximum magnetic field normalization in the frequency range of interest.

B. PCB Embedded Planar Rogowski Coil

The Rogowski coil is a simple, lossless and accurate current sensing method for detecting currents and is investigated and implemented in many applications. A Rogowski coil delivers an output signal which is ideally proportional to the time derivative of the input current. Rogowski coil based current sensing, due to its inherent simplicity, and no theoretical bandwidth limitation is among the most popular techniques for current measurement in high frequency power electronic converters. The Rogowski coil typically consists of an air-core inductor coil with a few number of turns, which is placed around the main current carrying conductor. The air core Rogowski coil is induced by current of the main conductor by utilizing Faraday's law of induction. Then the picked up current information is transformed to equivalent voltage through an integrator circuit. In some applications, the coil is equipped with a periodic reset signal to indicate the start and end point for the integration of the coil output.

The output of an ideal Rogowski coil is proportional to the time derivative of the current and can be approximated as equation (4).

$$V_{coil} = M\frac{di}{dt} \tag{4}$$

where, V_{coil} is the Rogowski coil output and M is the mutual inductance of the Rogowski coil.

As can be seen from (4), an integration of the coil output voltage is required to extract the actual current information. However, in practice, there are several non-idealities such as the coil resistance, coil leakage inductance and inter-winding capacitance of the coil that need to be taken into consideration when approximating the actual output from a Rogowski coil.

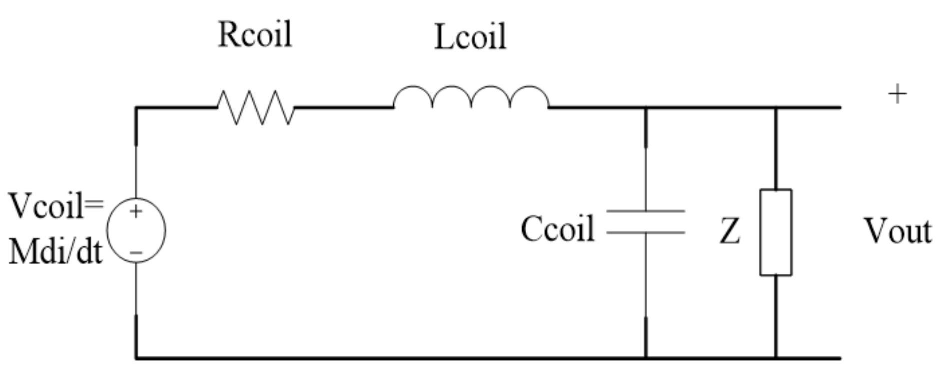


Figure 3.6: Equivalent circuit diagram of a Rogowski coil

The equivalent circuit of a Rogowski coil is presented in Figure 3.6. Here, R_{coil} is the coil resistance, L_{coil} is the coil leakage inductance and C_{coil} is the aggregated inter-winding capacitance of the coil as shown in Figure 3.6. Z is the terminating impedance of the Rogowski coil which is usually very high. By analyzing the equivalent circuit shown in Figure 3.6, the transfer function of the Rogowski coil can be obtained from the equivalent circuit as (5).

$$H_{coil}(s) = \frac{V_{out}}{I_{in}} = \frac{ZMs}{ZL_{coil}C_{coil}s^2 + (L_{coil} + ZR_{coil}C_{coil})s + (R_{coil} + Z)} \approx \left. \frac{Ms}{L_{coil}C_{coil}s^2 + R_{coil}C_{coil}s + 1} \right|_{Z\to\infty} \quad (5)$$

Assuming very high terminating impedance for the Rogowski coil, one should design the coil such that 1) sufficient mutual inductance to maintain the required sensitivity at a particular frequency range is obtained, and 2) the natural frequency of the resonance for the coil as seen in (5) is located far enough from the required sensor bandwidth.

For the proposed wideband sensor, a custom designed PCB embedded planar Rogowski coil is utilized as the high frequency sensor. The selection of a high bandwidth AMR sensor in conjunction with the planar magnetic field concentrators (MCON) enables the Rogowski coil to be designed for very high frequency transients. This advantage allows the implementation of planar and PCB embedded Rogowski coils and the size of the coil to be shrunk significantly as well. The inductance of the Rogowski coil depends on the design and size of the coil. The inductance of the PCB embedded

Rogowski coil utilized for the proposed wideband hybrid sensor is designed to be around 220nH for signal pickups in the megahertz range current transients.

The integrator for the designed PCB embedded Rogowski coil is designed using passive components. For high frequency applications, the passive integrator has more advantage compared to the active integrator due to its non-dependency on the active components and gain bandwidth limitations. Hence, in the proposed wideband sensor development, a simple passive low pass filter is utilized as an integrator at higher frequencies. The cut-off frequency of the low pass filter needs to be selected very carefully to match the cut-off frequency of the AMR sensor response approximated by first order terms. Referring back to the theoretical analysis presented in section II, any mismatch in the corner frequency adjustments of the two individual sensing elements will result in a loss of linear response from the hybrid sensor over the frequency bandwidth.

The AMR sensor used in the development of the wideband hybrid sensor is carefully analyzed in detail and the results are presented in the authors' previous studies [26]. Also, utilization of the planar magnetic concentrators (MCON) enhances the sensing bandwidth of the AMR sensors to approximately 1.61MHz [21]. Hence the corner frequency of the designed passive low pass filter is selected to be exactly 1.6MHz to match the corner frequency of the AMR sensor response. Finally, the gains of the two discrete sensing elements are gain adjusted and aggregated using high-speed active components to achieve a linear flat-band response from the proposed sensor over a wide frequency range.

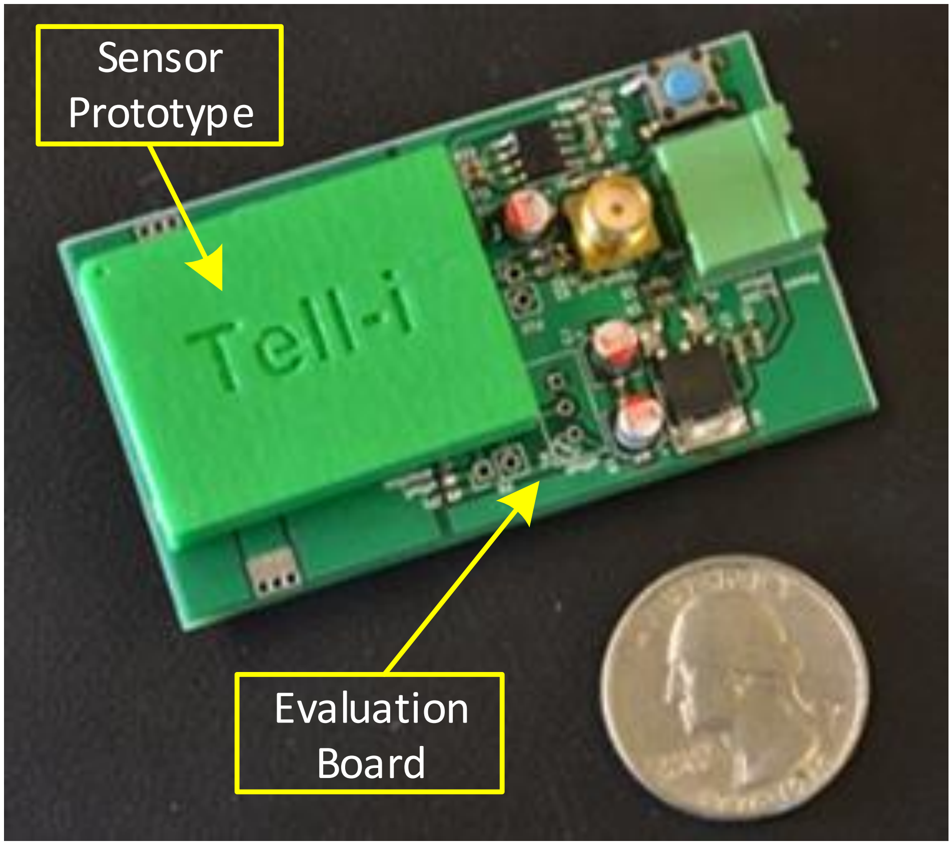


Figure 3.7: Developed hardware prototype of the proposed wideband current sensor with custom designed evaluation board.

Implementation of The Proposed Wideband Current Sensor

The proposed wideband current sensor consisting of the AMR sensor and the PCB embedded Rogowski coil is designed on a 4-layer Printed Circuit Board (PCB). Several iterations of the sensor design are performed to achieve the desired performance in the smallest possible form factor. Figure 3.7 shows the developed hardware prototype of the proposed wideband AMR-Rogowski hybrid sensor. The low frequency sensing element which is the AMR sensor is characterized in detail and the cut-off frequency of the AMR sensor response is experimentally determined [26]. The AMR sensor is also implemented with the planar magnetic field concentrators (MCON) to achieve more normalized magnetic fields through the sensing element and consequently the higher sensing bandwidth [21]. The corner frequency of the AMR sensor with the 5mil copper MCON is also determined experimentally [21]. The high frequency sensing element which is the PCB embedded Rogowski coil is realized on inner layers of the 4-layer PCB. The coil traces are designed using 1oz copper traces having a trace width of 5mils. The clearance between the windings are maintained at 10mils. The interwinding connections are continued using buried via holes between the layers.

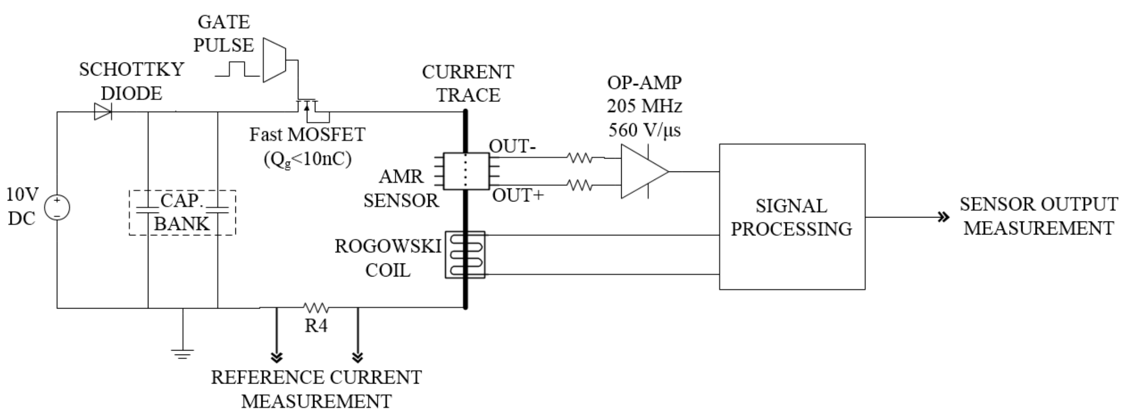


Figure 3.8: Test circuit diagram of the proposed wideband AMR-Rogowski hybrid current sensing scheme.

The AMR sensor output was amplified using a differential amplifier. On the other hand, the Rogowski coil signal is passed through a passive low pass filter which also acts as the integrator. The cut-off frequency of the passive low-pass filter is matched with the AMR sensor used in conjunction of the MCON to achieve a linear flat-band response in the frequency range of interest. Finally, the AMR and Rogowski coil conditioned outputs are gain adjusted and aggregated to obtain a wideband current measurement output from the sensor. The conditioning circuits are designed with high speed op-amps (205MHz, 506V/us) and components so that they don't limit the frequency range of interest for the hybrid current sensor.

To examine the performance of the proposed AMR-Rogowski hybrid current measurement scheme, several circuits were designed and implemented. Figure 3.8 presents the circuit diagram of the hardware setup designed to evaluate the performance of the proposed sensor. The left side of the circuit diagram shows the custom designed fast rise step current generator circuit for bandwidth evaluation of the proposed sensing scheme. The right side of the circuit shows the proposed wideband AMR-Rogowski hybrid sensing scheme. The step current generator delivers a 10A current pulse having 5ns rise time which allows us to comment on the sensing bandwidth for more than 50MHz. Figure 3.9 shows the test circuits and experimental hardware prototypes for the step current test utilized for the evaluation of the response time and detection bandwidth of the proposed AMR-Rogowski wideband current sensing scheme. To evaluate the performance of the hybrid sensor in a practical power converter, a high frequency H-bridge inverter is reconfigured as a half bridge DC-DC converter running at 1MHz frequency. The same H-bridge inverter is utilized to test the performance of the proposed sensor in detecting the sinusoidal output current of the inverter with a high frequency ripple. Figure 3.10 shows the experimental setup utilized for the evaluation of the proposed wideband sensor in a high frequency power converter.

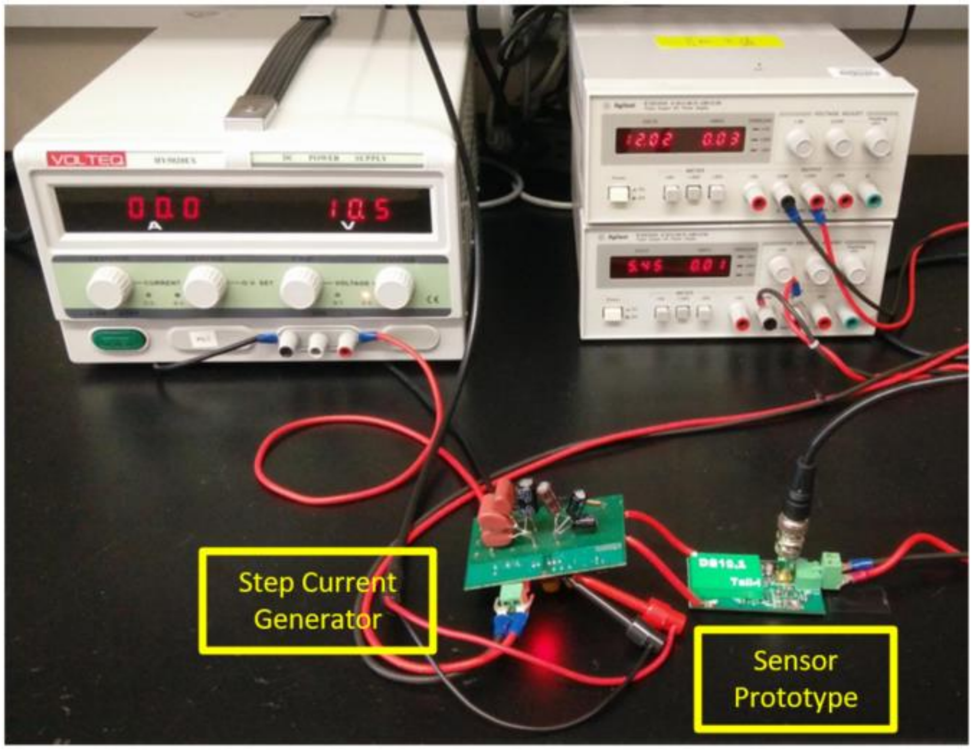


Figure 3.9: Test circuits and experimental setup used for the step current test

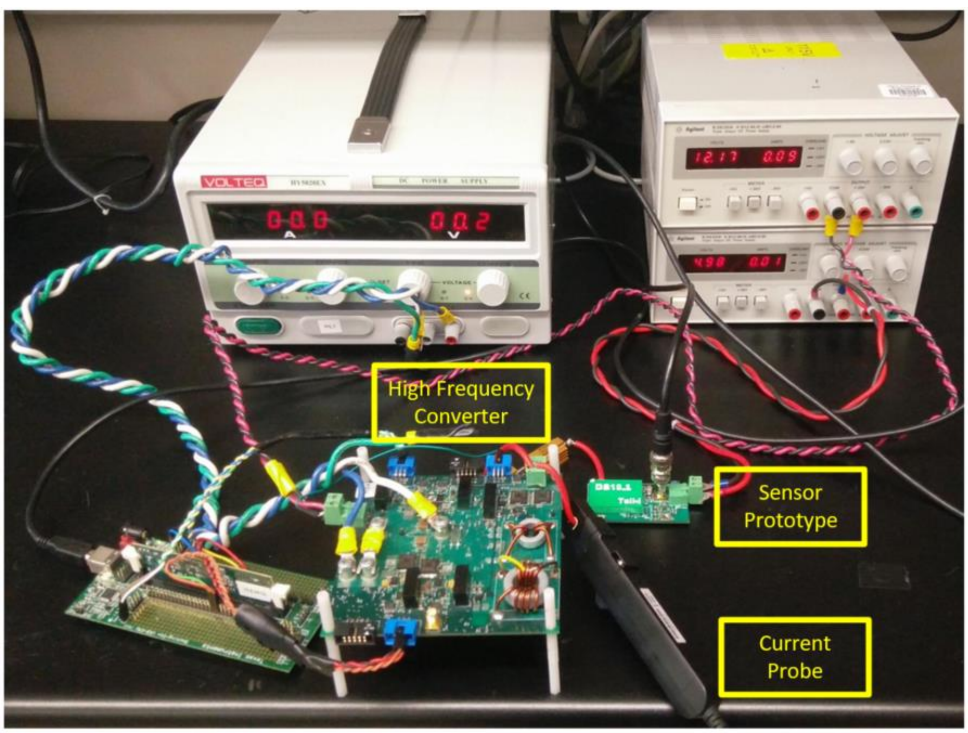


Figure 3.10: Test circuits and experimental setup used for the converter test

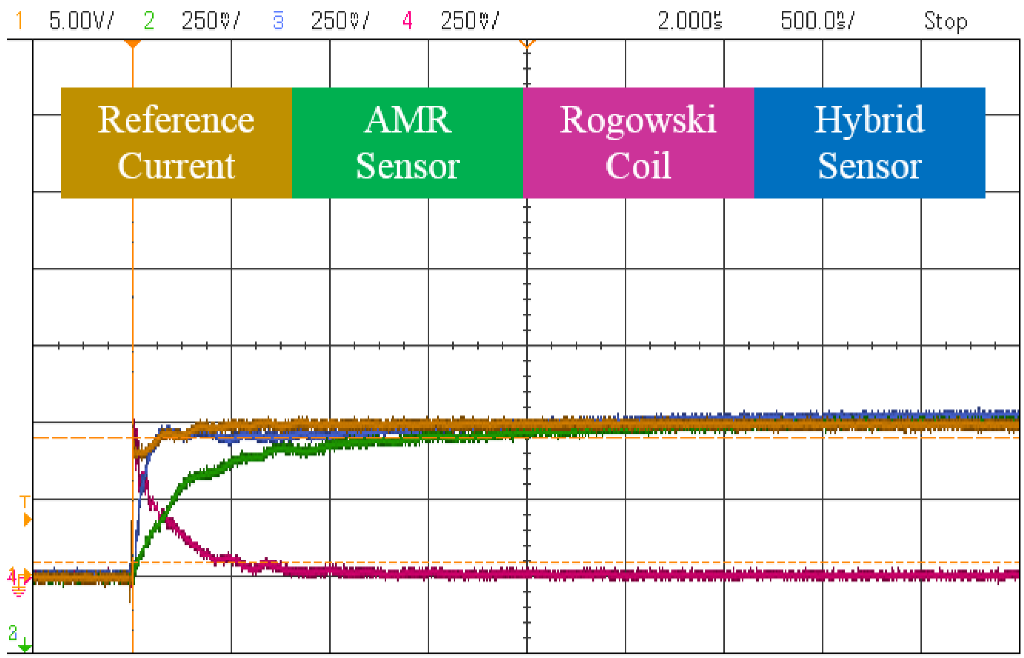


Figure 3.11: Hybrid sensor response for a fast 10A step current.

Experimental Results

The proposed hybrid sensor prototype is tested with the custom designed step current generator with a fast-rise step current of 10A magnitude. The current is passed through a 1oz PCB trace placed on the sensor prototype board. The distance between the current trace and the sensing elements are maintained at 1.57mm. The current trace is placed on the evaluation board while the sensor is placed on top without any physical contact with the current trace as shown in Figure 3.7. The responses of the individual sensing elements with respect to the fast 10A step current are conditioned and aggregated in the on-board signal conditioning circuits. Figure 3.11 shows the results of the hybrid sensor response with respect to a 10A step current. It can be observed from the results presented in Figure 3.11 that, the AMR sensor (Green) and the Rogowski coil sensor

(Pink) responses are complementary in nature. The AMR sensor is responding to the DC and low frequency components while the Rogowski coil picks up the high frequency components. After filtering, gain adjusting and aggregating the two individual sensor responses, the hybrid AMR-Rogowski sensor response (Blue) is much faster and closer to the reference 10A step current (Yellow).

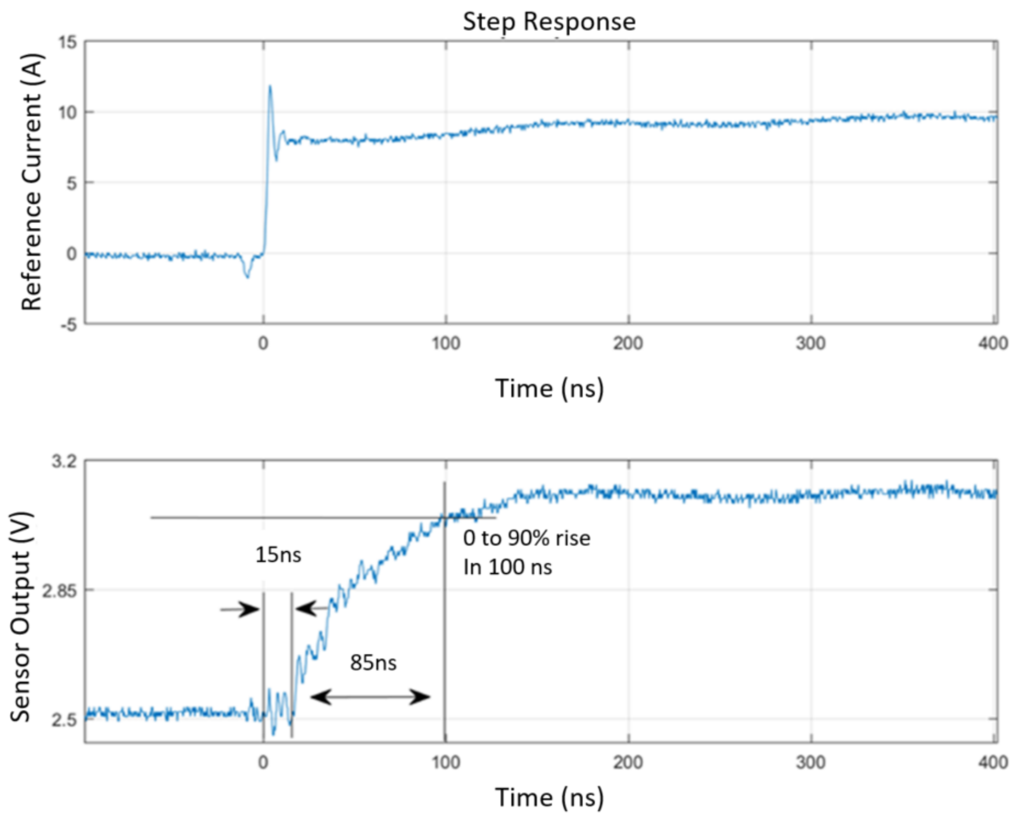


Figure 3.12: Hybrid sensor response for 10A step current (zoomed).

Figure 3.12 presents the zoomed in figure of the proposed hybrid sensor response with respect to a 10A fast rise step current shown in Figure 3.11. The zoomed results from Figure 3.12 shows that the reference current has a rise time of around 5ns as mentioned before. Analyzing the hybrid sensor response in more detail shows that the sensor has a 15ns response delay which is limited by the propagation delay of the op-amps used in the conditioning circuits. The sensor reaches from zero to 90% of the steady state value for 10A current in 85ns. This shows the ultra-fast characteristic of the proposed wideband hybrid sensor.

For further analysis of the observed sensor response and to comment on the sensing bandwidth of the proposed sensing scheme, the data captured from the step current test is exported and a detailed frequency analysis is performed. Figure 3.13 shows results of the frequency analysis for the hybrid sensor response from the step current test shown in Figure 3.11. It can be observed that, the bandwidth of sensing for the hybrid sensor is significantly increased compared to the raw AMR sensor bandwidth. This is because the Rogowski coil sensor responds to high frequency transients and when combined with the AMR sensor, it generates a flat-band response till much higher frequency. The sensing bandwidth for the proposed hybrid sensor is calculated at 10.78MHz.

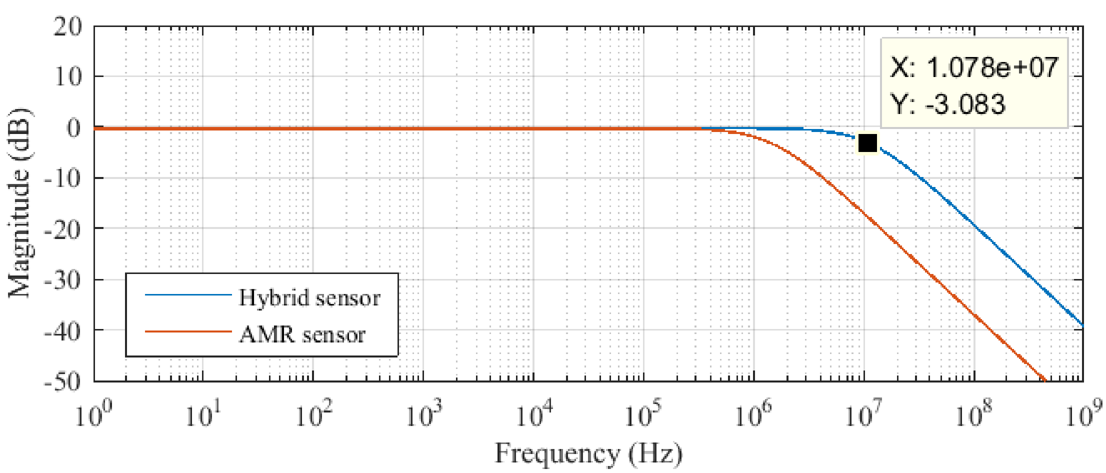


Figure 3.13: Frequency response for the step current response shown in Figure 3.11.

The developed sensor prototype is then tested with a H-bridge inverter reconfigured to work as a half bridge running at 1MHz switching frequency. The converter is set up with a very low inductance to achieve high transients in the inductor current. In fact, the inductor is bypassed and the only inductance present in the current path is the inductance in the wires and traces. The sensor prototype board is placed in series with the load resistance to measure the current flowing through the load. Here, the inductor current is measured using four different sensing methods – a shunt resistor, a Hall-effect sensor (1MHz bandwidth), a Tektronix current probe (50MHz bandwidth) and the designed hybrid sensor. This is done to compare the responses of the proposed hybrid sensor with the commercially available sensing technologies.

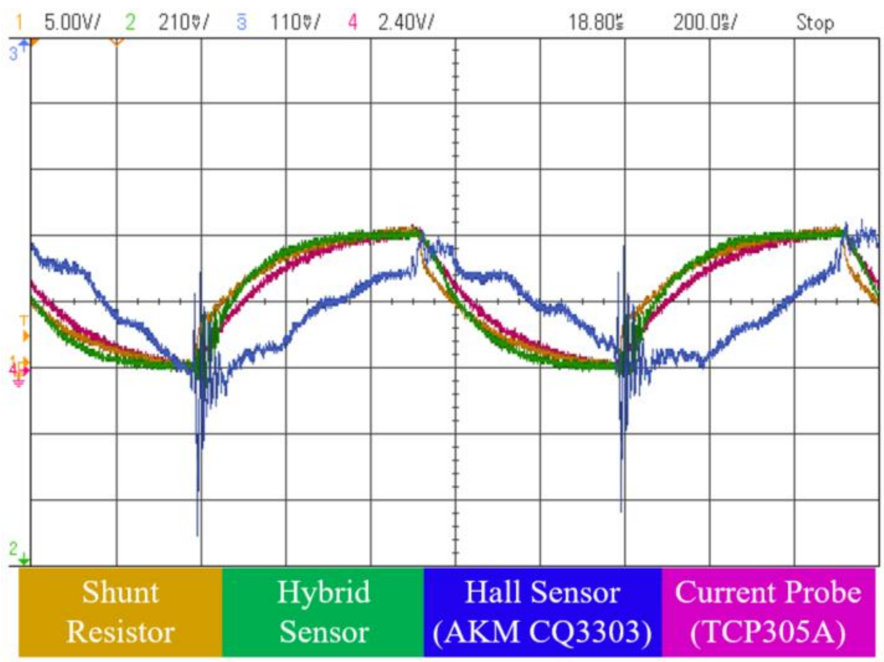
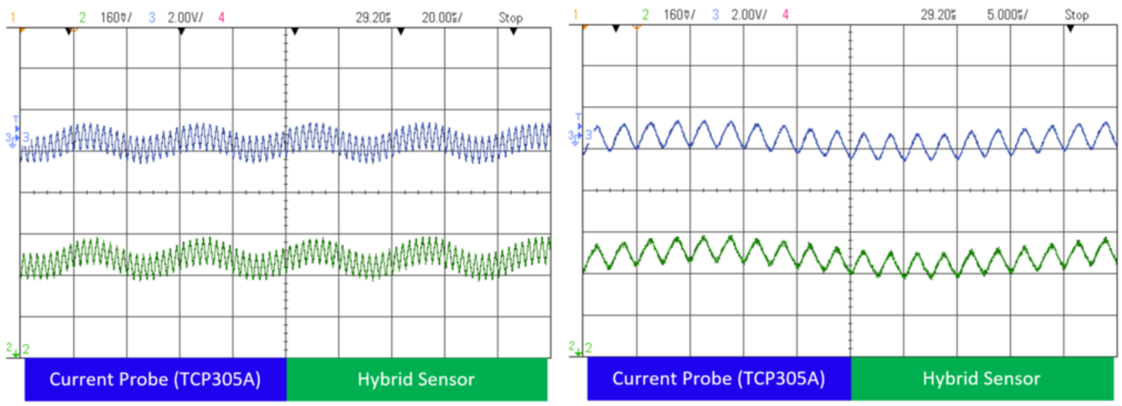


Figure 3.14: Different sensor responses for inductor current measurement in a 1MHz half bridge converter.

Figure 3.14 shows the results for the 1MHz converter test. It can be observed that, the shunt resistor has the fastest transient response and is taken as the reference. The

Tektronix TCP305A current probe is made based on Rogowski coils and has a bandwidth of 50MHz and is able to measure the fast transient of the converter output current (pink). The 1MHz bandwidth Hall-effect sensor response (blue) is clearly suffering from delay and is unable follow the fast transient current. The hybrid sensor has minimal delay and closely matches the shunt resistor and current probe measurements and is able to respond to the fast transient of the current. The peak of the converter output current is also detected by the hybrid sensor more accurately compared to the state of the art Hall-effect sensor.



(a) (b)

Figure 3.15: Performance of the proposed wideband AMR-Rogowski current sensor in measuring high frequency inverter output current compared to a current probe: (a) regular and (b) zoomed

The H-bridge used in the previous experiment is then reconfigured to work as a hard-switching inverter. The inverter is run with unipolar sinusoidal PWM switching at 400kHz. The inverter input voltage is selected to be 10V and the output load resistor is selected as 2 ohms. The proposed hybrid sensor is placed in series with the load resistor to measure the load current. The high frequency current probe from Tektronix (TCP305A) is also placed in the same path to be taken as the reference current measurement. Figure 3.15 presents the results from the hard-switched high frequency inverter test comparing the performance of the proposed wideband current sensor and the commercial current probe. It can be observed from the results presented in Figure 3.15(a) that, the proposed current sensor accurately responds to both the fundamental and ripple frequency currents and the responses from the proposed sensor and the current probe are identical. When zoomed in to investigate details as shown in Figure 3.15(b), it is noted that the peaks and troughs of the ripple current are also detected accurately and without any delay. Hence, the developed AMR-Rogowski hybrid sensing scheme offers an alternative loss-less current sensing solution for high frequency power converters.

Conclusion

In this paper, we have proposed and detailed a contactless and loss-less hybrid current measurement scheme based on two complementary characteristics. The main sensing element is a Magnetoresistive (MR) sensor which responds to constant DC fields as well as low frequency transients. The secondary sensing element is a PCB embedded Rogowski coil sensor which is responsible for picking up high frequency transients. The proposed hybrid sensor combines these two sensing techniques to achieve a wideband response from DC to multi megahertz. The detailed theoretical analysis of the proposed sensing scheme is presented in the paper and the design of the proposed sensor has been discussed in detail. The proposed wideband current sensing scheme is experimentally using hardware prototypes. The proposed hybrid sensor response is tested with a fast-rise step current generator and the response is analyzed further to obtain the sensing bandwidth and the response time of the sensor. The sensor is also tested in a 1MHz half bridge DC-DC converter and the performance is compared with other commercially available state of the art current sensors. The sensor performance is also evaluated with a high frequency hard switching inverter and the results are compared with commercially available current probes. It has been verified through experiments and tests that, the proposed AMR-Rogowski hybrid sensor offers an isolated, loss-less and contactless current sensing solution for power converters operating from DC to 10MHz.

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CONCLUSION AND FUTURE WORK

Conclusion

Current sensing techniques for high frequency power converters should yield to have some key characteristics such as – fast, accurate, isolated, loss-less and most importantly wide bandwidth. In this research, a detailed review of different traditional and advanced current measurement techniques has been performed. Starting from the very basic sense resistors to the most advanced wideband hybrid sensing technologies, each method offers its own advantages while having some limitations. Keeping in mind the future integration possibility of these current sensors in the high frequency power modules, isolated and loss-less current sensing techniques such as Hall-effect and Magnetoresistors provide the most efficient solution for current measurement in power converters. Magnetoresitive sensors has the advantage of responding to horizontal magnetic fields compared to the Hall-effect sensors which respond to the vertical components of the magnetic field. The sensing bandwidth of the MR sensors are much higher than the Hall-effect sensors which makes it an ideal candidate for applications such as high frequency power converters.

In this study, a novel technique for an AMR-based sensing circuit has been proposed which allows current measurements over a wide frequency range. This is achieved by folding the current trace on top of the AMR sensor for the purpose of intensifying and normalizing the magnetic field over the frequency range of interest. The concept has been verified by advanced simulations run in a full wave electromagnetic solver Ansys HFSS. The folded trace concept is tested with distinctly developed porotype circuits and verified experimentally by specific setup of the sensor and prototypes. The sensor, when implemented with the proposed method, shows an improved bandwidth of up to 5 MHz and enhanced sensitivity to high frequency currents. It is believed that the proposed method is applicable in high frequency power electronic converters, where the inductor current is used to control the ripple and transient response.

Also, a novel technique for enhanced bandwidth contactless current sensing using Magnetoresistive sensors with planar magnetic concentrators (MCON) utilizing conductive materials has been proposed in this work. The effect of different magnetic concentrators (MCONs) on the performance of a typical AMR sensors utilized as high frequency contactless current monitoring device has been investigated and analyzed. A detailed simulation study is performed to clearly understand the magnetic field distribution for current at very high frequencies with and without the proposed magnetic concentrators. The observations are experimentally verified and detailed analysis is performed. A fast rise step current generator is designed and utilized to generate a fast current step. To analyze the performance of the AMR sensor in detecting fast transient step current, four different MCONs made with copper and aluminum having different thicknesses are implemented. The sensor response equipped with different MCONs are recorded and presented accordingly. A frequency response of the sensor response with different MCONs is performed to analyze the effect of MCONs on the detection bandwidth of the AMR sensor. The use of MCONs normalized the magnetic field through the sensing element and improved the bandwidth of current sensing.

Implementation of the 5 mil copper MCON results in a significant improvement in the sensing bandwidth of around 400 kHz which translates into a 33.06% increase in detection bandwidth of the AMR sensor. It is believed that the proposed method is applicable for current sensing in high frequency power converters where the current information is used to control the ripple and transient response.

Finally, we have proposed and detailed a contactless and loss-less hybrid current measurement scheme based on two complementary characteristics. The main sensing element is a Magnetoresistive (MR) sensor which responds to constant DC fields as well as low frequency transients. The secondary sensing element is a PCB embedded Rogowski coil sensor which is responsible for picking up high frequency transients. The proposed hybrid sensor combines these two sensing techniques to achieve a wideband response from DC to multi megahertz. The detailed theoretical analysis of the proposed sensing scheme is presented in the paper and the design of the proposed sensor has been discussed in detail. The proposed wideband current sensing scheme is experimentally using hardware prototypes. The proposed hybrid sensor response is tested with a fast-rise step current generator and the response is analyzed further to obtain the sensing bandwidth and the response time of the sensor. The sensor is also tested in a 1MHz half bridge DC-DC converter and the performance is compared with other commercially available state of the art current sensors. The sensor performance is also evaluated with a high frequency hard switching inverter and the results are compared with commercially available current probes. It has been verified through experiments and tests that, the proposed AMR-Rogowski hybrid sensor offers an isolated, loss-less and contactless current sensing solution for power converters operating from DC to 10MHz. It is also believed that the proposed method can be utilized for the protection of power modules.

Future Work

The proposed wideband current sensing technique offers an alternative and loss-less solution to current measurements in high frequency power electronics converters. The developed board level prototype of the current sensor has been successfully demonstrated in step current and converter operations. Future developments in this research work will focus on developing integrated IC of the sensing technology. The analog signal processing circuits along with the high speed operational amplifiers and comparators can be implemented on chip using advanced CMOS processing technology. The sensing elements and the signal processing circuits need to be integrated together in a single IC using advanced packaging technologies. Different packaging technologies and options need to be evaluated in this regard. Finally, there has been significant progress in the area of MR technologies in recent years especially with the introduction of Tunneling Magnetoresitors (TMR) sensors. The TMR sensor offer much higher magnetic sensitivity compared to AMR and GMR sensors and are quickly becoming popular in the industry. The performance of TMR sensors should be evaluated as current sensor in power electronics applications and the feasibility of TMRs as a potential low frequency sensor in the proposed hybrid sensing scheme need to be evaluated. These new technologies can really unlock new design potentials and push the sensitivity and bandwidth of current sensors to a much higher boundary.

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