Layout Study of Contactless Magnetoresistor Current Sensor for High Frequency Converters

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***Abstract*— In this paper, we present a new technique to unify and intensify the magnetic fields that results in higher performance of Anisotropic Magneto-Resistive (AMR) current sensors and consequently develop a closed loop controller for 100W synchronous GaN buck converter at 1MHz. The closed loop operation of high switching frequency converters at high power has always been a big challenge due to lack of access to current information. The proposed method that also intensifies the magnetic fields through the sensor, significantly improves the bandwidth limits, and reduces electromagnetic interference (EMI) on AMR sensors, making them applicable for high switching frequency and high current power electronics converters. After verifying uniform distribution concept through simulation, we also implemented a prototype of AMR current sensors onto Printed Circuit Board (PCB) for verification of the concept at high frequency converter. We then present the design procedure and associated challenges of an integrated analogue peak current controller for creating the closed loop operation of a GaN buck converter at high switching frequency.**

Keywords— Anisotropic Magneto-Resistive; high frequency; peak current control; synschrnous GaN buck converter

I. Introduction

To enhance the performance of switching converters along with improving their efficiency in power electronics applications, a need for higher switching frequency is inevitable. Knowing the difficulties for hardware implementation of high switching frequency/high-current converters to overcome layout issues, EMIs, thermal dissipations, and finding alternatives for passive components, effective techniques to control a converter will always be challenging. In this area, current sensing is one of the most important parameters for controlling of power electronics converters. In many articles, different digital control techniques such as predictive methods, DC-DC converters on chip, and nonlinear digital control to predict the inductor current are widely proposed. The other approaches such as digital signal processors (DSP), FPGAs, and sensor-less current mode control are also successfully implemented [1]-[3]; however, all of these techniques are useful for low power applications (<20W and <30V). On the other side, average current and peak current mode are among the typical approaches to control converters by analogue circuits, especially at high current applications. For instance, the peak current controller method not only helps to increase the controller bandwidth, robustness, and simplicity, it also adds a potential to inherently overcurrent protection. In all of high switching frequency/high current applications, for effective controlling of the converter, a need to have an accurate current sensor with a higher bandwidth limit to capture ripple current information is necessary [4], [5].

Modern research in the field of high frequency current sensing is now more focused on the investigation of alternative approaches to current sensing and measurement. These techniques should yield to have current sensors that are fast, accurate, topology-independent and lossless. In addition, having higher voltage devices (>30V) using Wide-Bandgap (WBG) semiconductors that allow high frequency power converters (>1MHz) necessitates to have isolated current sensors for closed loop controls. Among the many different types of sensors, hall-effect sensors, magnetic field induction-based transducers, and magnetoresistance (MR) based sensors has observed significant performance improvement over the years [6], [7]. In modern Hall-effect sensors, using high carrier mobility material such as GaAs/InAs, are biased by electrical current which is exposed to a magnetic field; however, their tendency to suffer from drift and lesser noise immunity as well as EMI generated by high frequency power electronic converters, affect the sensing accuracy of Hall-effect based sensors [8]-[10]. The most advanced Hall-effect based current sensor available in the market has limited bandwidth of 1MHz. On the other side, magnetic field induction-based transducer sensors have no technical limitation to reach high bandwidth, but their sensitivities with respect to magnetic components and having signal condition to bring low pass filters create a lot of challenges and complex layout considerations and especially for the power electronics converters [11]-[13].

The contribution of this work is to develop a closed loop controller for high power applications (>100W) of high frequency converters (>1 MHz) introducing a new technique to increase the bandwidth limit of the contactless AMR current sensor. This paper has organized in five main parts: In Section II, the characterization of standard AMR current sensor is defined. In Second III, the proposed method for enhancing the sensor performance, including all the simulations and experimental results in a step input and converter operation is explained. In Section IV, the infrastructure of the analogue peak current controller for the closed loop performance of GaN synchronous buck converters is described and the second PCB prototype is proposed with describing a novel layout recommendation to reduce EMI and noises are briefly explained following with the conclusion of the research work.

II. MAGNETORESISTIVE SENSOR CHARACTERIZATION

Anisotropic Magneto-Resistors (AMR) are based on metal alloys as opposed to MRs which are based on low bandgap semiconductors such as InSb/InAs. The most widely used AMR devices developed and integrated into a chip is composed of four Permalloy (Ni0.81F0.19) AMRs in a full sensitivity Wheatstone bridge configuration [13]-[15]. In the AMR element shown in Fig. 1, ***M*** and biased ***I*** are shown in their default directions when no magnetic field is applied. ***M*** is aligned with the easy axis, and ***I*** is directed along the shortest distance between the conducting strips. If the material is designed such that the contacts are at an angle to the easy axis, and initially when no field is present the magnetization is oriented along the easy axis, the conduction path is the shortest distance between the contacts. By applying a magnetic field, the magnetization is rotated from the easy axis towards the direction of current flow, in effect changing the orientation of dipoles and increasing the current path, which translates into an increase in resistance of the material as a function of the applied magnetic field. When the magnetization is aligned with the direction of current flow, the resistance reaches its maximum value. This is 'type a' AMR element. Since 'type b', which has the conducting strips placed in the opposite diagonals, the applied field reduces the angle between ***M*** and ***I***, increasing the resistance. By combining 'type a' (Fig. 1) and 'type b' (mirror-imaged along the vertical axis) of AMR elements in a Wheatstone bridge, the output can be further amplified.

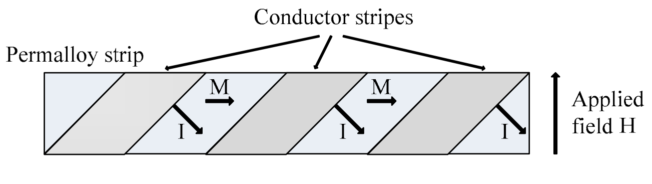

Fig. 1: Permalloy strip with conducting stripes such as Aluminum. M and I are shown in their default directions (no magnetic field is applied)

MR based current sensors work on the principal of detecting the magnetic fields generated by current travelling through a trace on the Printed Circuit Board (PCB). Generally, the MR based current sensor is placed on top or underneath a trace carrying the current without any conductive contact with the current trace. The low frequency current through the PCB trace generates a uniformly distributed magnetic field, which passes through the sensor along the default axis and thus the sensor responds by sensing the magnetic field. For high frequency current, especially above 1 MHz, the generated magnetic field is concentrated mostly on the edges of the trace due to skin effect that results in a non-uniform magnetic field distribution around the PCB trace. Consequently, the detected magnetic field by the sensor is very weak at higher frequencies. Therefore, the application of AMR based sensors using standard configuration is limited to about 1 MHz. Placing the sensor on the opposite side of the PCB with respect to the current trace provides the easiest solution to the magnetic field detection generated by current. However, the relatively higher distance between the sensing element and the current trace results in a weak and non-uniform magnetic field distribution through the default axis of the sensing element at higher frequencies. As a result, while detecting currents in high frequency power electronic converters, the sensor suffers from loss of sensitivity and accuracy. Placing the MR based current sensor right on top of the current carrying trace on the same side of the PCB results in a significantly better sensitivity and detection accuracy. This is due to the fact that, the close proximity of the sensor to the current trace results in higher magnetic field density through the default axis and consequently better sensitivity. To further improve the sensitivity of the sensor, smart and effective layout considerations are taken into account. The sensor is positioned in such a way that it is free from unwanted EMI from other components on the PCB. Also, any copper pour is avoided both on the outer and inner layers of the PCB underneath the sensor to eliminate the effects of circulating Eddy currents which is detrimental to the performance of the sensor.

III. PROPOSED METHOD FOR WIDEBAND CURRENT SENSING

For high frequency applications, due to skin effect, the magnetic field distribution is non-uniform and affects the sensitivity of the AMR based current sensors. Therefore, placing the sensor on the opposite side of the PCB with respect to the current trace is not effective for accurate sensing above 1MHz. For better detection bandwidth and sensitivity, the magnetic field passing through the default axis of the sensor needs to be concentrated to make the field uniform. By moving the trace right underneath the sensor on the same side of the PCB enables the sensor to detect relatively stronger magnetic field and hence improve the sensitivity. However, this method does not allow for higher trace widths and hence can only be applied to measure currents up to a certain value limited by the trace.

At much higher frequencies, especially above 1 MHz the magnetic field is more non uniform due to skin effect and hence the sensitivity of the MR based sensor also suffers. Therefore, alternative and innovative magnetic concentration techniques need to be implemented to make the field normalized and more uniform. One of the techniques that can be utilized effectively to enhance the sensing bandwidth of the MR based sensors is the 'folded trace' method, which addresses the challenges related to high frequency current detection by modifying the layout of the current trace. The current trace is wrapped around the top and bottom of the sensor so that the magnetic field through the sensor is uniform in the high frequency range (>1MHz). The folded trace method is visualized in Fig. 2 where the sensor is practically sandwiched between current traces and generated magnetic field is uniform and amplified, which results in better sensitivity of the sensor. The proposed folded trace method also provides shielding for the sensor from external EMI generated in the high frequency power converter circuits. The results from the implementation of the folded trace method show significant improvement in the detection bandwidth and sensitivity of the MR based sensor.

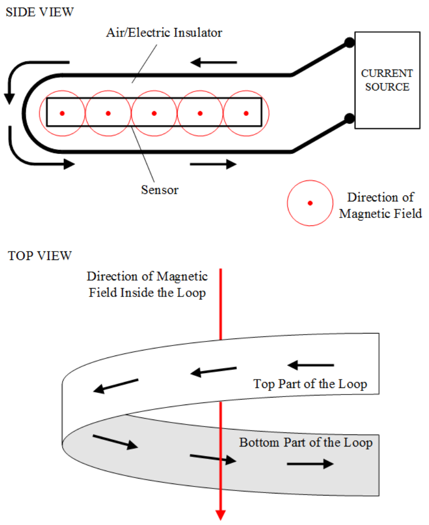

Fig. 2: Folded trace technique to normalize and intensify the fields near sensor

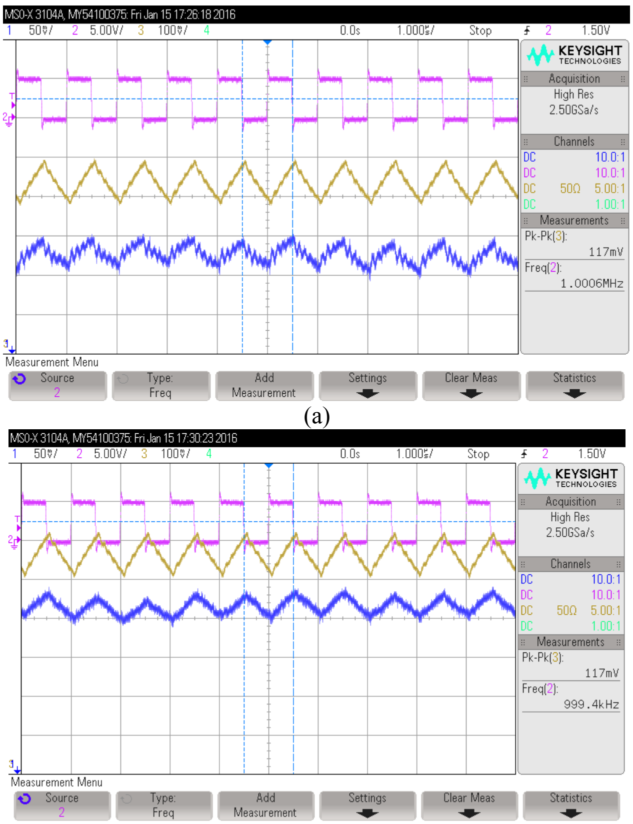

Fig. 3. Experimental results: Open loop operation of half-bridge GaN converter at 3A, 30V and 1 MHz is compared with strategies: bare trace (a) and folded trace (b). Significant improvement of the current sensor measurement in proposed method is observed. Pink: Gate Signals, Yellow: Actual Current measured from current gun Blue: AMR sensor measurement.

To understand the effect of the folded trace technique for high bandwidth current measurement, the sensor is tested under different ranges of switching frequency in a GaN converter (LMG 5200) at half-bridge configuration with both bare and folded trace configurations. Fig. 3 shows the results of the AMR sensor on a 1 MHz synchronous buck converter running at 30V and 3A with 50% duty ratio. It is clear that, by improving the sensor positioning with respect to the current trace and also by implementing the folded trace method, the AMR based sensor can be accurately used in current sensing and control applications in power electronic converters.

IV. Closed Loop Operation of GaN Converter in HBridge Configuration

In this section, analogue peak current controller method to regulate inductor current of 1MHz GaN converter in half bridge configuration will be explained. In the continuous conduction mode operation of the synchronous buck converter, the peak of current can be calculated by (1):

$$i_{peak} = \frac{V_{in} - V_{out}}{L} T_{on} = \frac{V_{out}}{L} T_{off} \qquad (1)$$

where V_{in} and V_{out} are input and output voltage of the converter, and T_{on} and T_{off} are the operation time of switches during on and off, respectively. L also presents the series inductor in the output. Based on outer loop controller and current command, the current reference is calculated by microprocessor (TMS320F28335). Since this microcontroller is not equipped to Digital-to-Analog Converter (DAC), this current reference is generated as a High Resolution Pulse Width Modulation (HRPWM), which is filtered by a fourth order Butterworth low-pass filter. The output of filter is amplified with proper gain and directed to analogue circuitries as shown in Fig. 4. After measuring the inductor current using the AMR sensor, explained in details in the previous sections, the current will be compared with current reference in high-speed analogue comparator. Once the current peak hit the reference limit, the fast comparator provides reset signals, which goes to the input of latch circuitries implemented in Altera MAX II CPLD. Ideally, the reset signals from the output of the comparator needs to be sent to gate signals of the power driver immediately. However, due to calculation delays in controller system and propagation delay in circuit components, switching signals are generated with delay. Therefore, the reference needs to be adjusted based on delay prediction methods. As shown in (2), the total switching period of the converter is:

$$T_{sw} = T_{on} + T_{off} + T_{delay} \qquad (2)$$

Here, T_{delay} shows all the delays associated with AMR current sensor and the whole analogue circuitries (comparator, subtractor, DAC, slope compensator, CPLD). This delay needs to be compensated in the controller section to provide proper gate PWM signals for the converter. In order to mitigate the effect of harmonics and from the current feedback loop, avoiding sub-harmonic oscillation and delays in the analogue circuit, the slope compensator is also considered in this design, which brings the opportunity of adjusting the reference signal. The slope compensation also provides the capability of leading reference to overcome the mentioned delays.

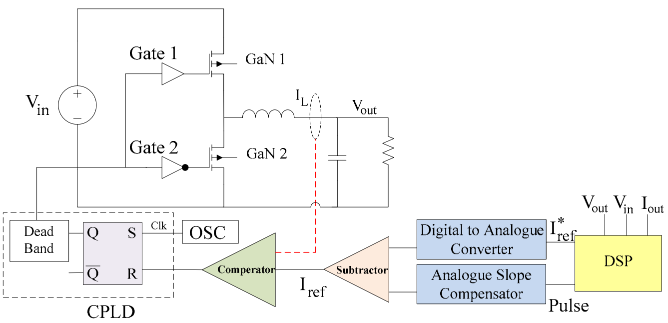

Fig. 4. Proposed digital/analogue controller to implement peak current controller for 1 MHz buck converter with a technique to measure current ripple by AMR sensor

To produce a linear ramp, a capacitor in parallel with the transistor is provided. The capacitor will be charged by the constant current source and then the transistor creates a path for the capacitor to flow; since the transistors operate at their saturation points to create a linear ramp, essentially the offset will be created that needs to be addressed in the reference. The offset can be varied depending on switching frequency, maximum output current, and ramp amplitude; however, additional circuities are brought to modify the offset for unbiased waveforms. Finally, the analogue subtractor circuit consisting of high speed Op-Amps provides the analogue reference which will be compared with the actual current in fast comparator. In addition, delays, offsets, and temperature characteristics of the sensor should be taken into account in various conditions to adjust the controller accordingly that all will be possible in this configuration.

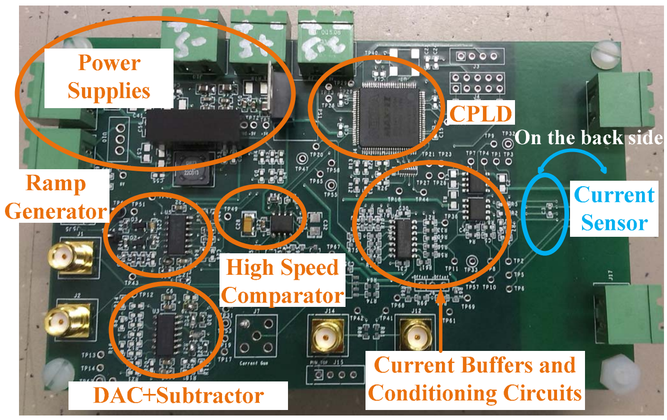

Fig. 5. Hardware setup: controller prototype with the novel ideas for shielding integrated with peak current controller and the AMR current sensor is designed at 4-layer PCB. Orange components are placed on top, cyan is on the back

In order to reduce the effect of EMI and noise in the controller circuit, especially in the vicinity of the sensor, the second prototype as a customized layout is designed. The controller board is implemented in 4-layer board with the virtual analogue and digital grounds are provided to keep all the signals in their domains to avoid noise radiations. An external shield layer underneath of power stage has also been provided. This helps to keep all the power traces are placed underneath the board to fully separate the control and power stage and reduce the effect of captured results at AMR current sensor as shown in Fig. 5.

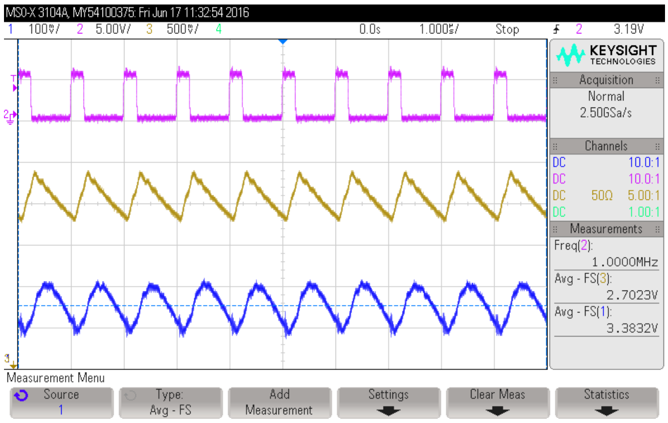

Fig. 6. Experimental results: Closed loop operation of half-bridge GaN converter at 3A, 30V and 1 MHz. Pink: Gate Signals, Yellow: Actual Current measured from current gun, Blue: AMR sensor measurement.

Considering the measured sensitivity of the sensor at different currents, offset level changes due to the intensifying the signal in the proposed method, the conditioning circuits are designed such that the actual reference current adjusting itself from DSP. Therefore, the closed loop operation of the 30V, 3A synchronous buck converter at 1MHz is successfully implemented as shown in Fig. 6.

V. Conclusion

This work has presented the development of a new technique to increase the bandwidth of AMR current sensors, which makes the implementation of closed loop operation of high switching frequency converters feasible, especially for high power applications. Effects of sensor positioning and effective layout considerations are deeply analyzed and an innovative folded trace technique is proposed for high bandwidth current measurement. The concept of folded trace to intensify the magnetic fields of the AMR current sensor for making uniform distribution has been verified through experiments and a new layout design is implemented onto PCB. The experimental results from the first prototype verified the concept of folded trace and reduced noise in AMR sensor significantly at 1MHz GaN buck converter; however, some modifications are brought for new conditioning circuits due to offset level changes and sensitivity of the sensor in the folded trace technique. Then, a prototype with novel layout considerations to reduce the effect of EMI was designed. This new prototype was including the analogue peak current controller circuits to make the closed loop operation of a synchronous buck converter feasible at 1 MHz, 3A and 30V. The digital and analogue circuits for generating PWM reset signals in the latch circuit (CPLD) needs to be tuned up according to delay, and sensor offset to provide proper gate signals for the converter. Due to delays in the current sensor and the controller components, software implementation of the controller need to be modified. In future work, the difficulties for running the controller will be raised and proper methods for solving these challenges will be presented.

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