Performance Study of Magnetic Field Concentration Techniques on Magnetoresistor/Rogowski Contactless Current Sensor

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***Abstract*— Magnetoresistor/Rogowski coil can be utilized as a wideband contactless current sensor in power electronic converters. However, the magnetic field detected by these sensing devices varies with frequency due to skin effect. This paper presents an investigation on two Magnetic field Concentration (MCON) techniques using conductive plates and power trace. These MCONs result in a more uniform magnetic field seen by the sensing elements over the frequency range of interest. Simulation and experimental results are presented to demonstrate the efficacy of the proposed MCONs and their impacts on performance of the sensors.**

***Keywords*— Current sensor, Anisotropic Magnetoresistor, Rogowski coil, Isolated current sensing**

I. INTRODUCTION

High frequency current sensing is one of the most challenging aspects of advanced power electronic circuits. In power electronics circuits that contain high common-mode voltage, isolated current sensors are required. Among the many different types of sensors, magnetic field induction-based current transducers, hall-effect based current sensors and Rogowski coil-based current sensors are among the most popular choices, where significant improvements have been achieved over the years in terms of performance, accuracy and bandwidth [1-6]. Si-based hall-effect sensors have a limited bandwidth of a few kHz, but recent developments in the field have enabled detection bandwidth of around 1 MHz by taking advantage of materials with high carrier mobility such as GaAs and InAs. Researchers have also demonstrated the potential to combine hall-effect and Rogowski coil-based detection methods to achieve a bandwidth of tens of MHz [7].

Magnetoresistor (MR) based sensors are fabricated from semiconductors and metal alloys to ensure maximum sensitivity and accuracy. MR sensors suffer from less drift and are more immune to EMI, which make it an attractive choice for high frequency current measurement. Several research groups are exploring different aspects of improving the accuracy and sensitivity of current sensing by MR based devices [8-15]. On the other hand, magnetic field induction-based transducers such as Current Transformer (CT) and Rogowski coil use Faraday's law of induction. Implementation of the Rogowski coil based sensing schemes are less challenging than CTs and there is added advantage of having no saturation issue (air-core).

Comparable researches on merging Hall-effect sensor and CT have been reported in [16], [17]. The ideal characteristics of the sensing elements and the proposed scheme are depicted in Fig. 1. AMR detects currents from DC to a certain frequency. As the frequency increases, the induced voltage in the Rogowski coil increases. These two responses are conditioned and aggregated to obtain a current sensing scheme with wideband characteristic. The focus of this paper is to analyze the performance of Magnetic CONcentrators (MCON) on contactless current sensors combining two complementary current sensing techniques: AMR (Anisotropic Magneto-Resistor) and Rogowski coil for wideband current measurement purposes. This paper has organized as: In Section II shows the configurations and simulation characterization of MCON at low and high frequency operation. In section III, the experimental and hardware results of the proposed method will be presented following with section IV, for the conclusion and future works.

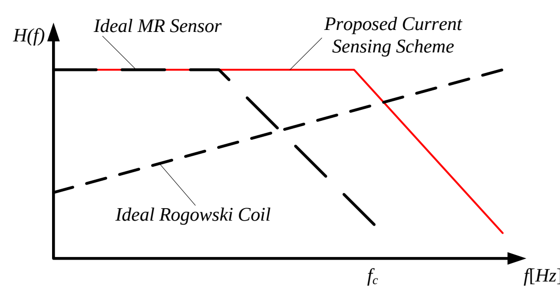

Fig. 1. Ideal characteristics of Magnetoresistor current sensor, Rogowski coil response and the proposed hybrid current measurement scheme.

II. MAGNETIC CONCENTRATORS CONFIGURATIONS

In a general case, MR-based current sensor is placed on top or underneath a Printed Circuit Board (PCB) trace carrying the current without any conductive contact with the trace. At low frequencies, the magnetic field is distributed uniformly around the trace and it intersects the sensor along the default axis generating a response. However, at high frequencies, especially above 1 MHz, due to 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. But, the MR 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. Normalizing the magnetic field over the frequency range of interest with MCON using conductive materials as simple as the folded trace technique [18]. The results show the increase of the bandwidth of the sensor in the range of DC to a few MHz [19], [20].

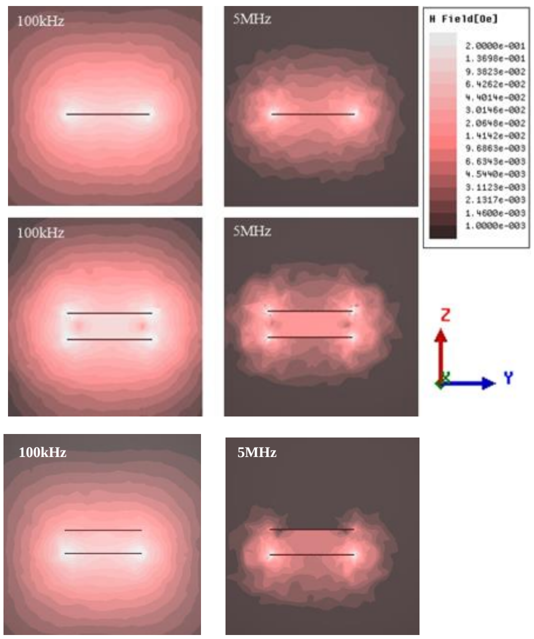

Fig. 2. Simulation results: magnetic field distribution of bare trace (top), folded trace (middle) and MCON with copper plate (bottom) at 100 kHz and 5 MHz.

Normalization of the magnetic fields generated by the current carrying PCB trace can also be realized by placing a copper sheet as a concentrator on the opposite side of the sensor. It eliminates the complexity of changing the current path, while still maintaining good enough normalizing property to achieve a higher detection bandwidth. To better understand the effect of MCON on the magnetic field distributions over the frequency range, a detailed simulation study is performed by using a full-wave commercial electromagnetic solver, Ansys-HFSS. Fig. 2 presents some results of the simulation study showing the change in magnetic field distribution for different MCON techniques compared to the regular current trace. It can be noted that, increasing the thickness of copper plate increases the uniformity of the field compared to regular and reaching to 35um thickness has nearly the same effect as the folded trace. The simulation results verify the advantage of using MCON to normalize the magnetic field and making it more uniform hence, can be effectively implemented to enhance the detection bandwidth and sensitivity of contactless current sensors.

III. Experimentation and Results

Several circuits were designed to examine the performance of different MCON techniques. Fig. 3 presents the circuit diagram of the hardware setup designed to evaluate the performance of the MCON. A fast high-rise (8 ns) current step function generator was developed allowing to comment on the bandwidth of the sensing scheme up to 25MHz. A commercially available AMR sensor [20], and a custom-designed PCB embedded Rogowski coil was used to evaluate the MCON technique with folded trace and copper sheet and normalize the magnetic fields. The AMR sensor output as well as the induced voltage in the custom designed PCB embedded Rogowski coil was taken to a digital signal-processing tool for filtering and aggregation.

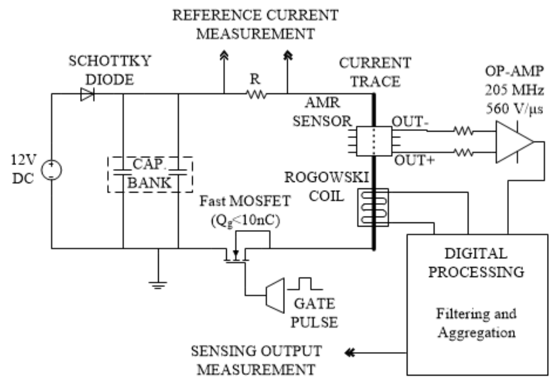

Fig. 3. Test circuit diagram of the proposed wideband AMR-Rogowski current sensing scheme.

The current carrying trace with 1Oz copper thickness was implemented onto the bottom layer of the PCB. Copper foil with 35µm (1Oz) thickness and one sided insulator is used to implement the MCON to cover the AMR sensor and Rogowski coil . The Rogowski coil has been developed on a two-layer PCB with 30 mils (0.76mm) wide traces. Both sensing elements take the advantage of two different MCON techniques that intensify and make uniform fields in a wider frequency range, and enhance the sensitivity of the sensing element.

Fig. 4 presents the experimental results captured from the prototype testing with the folded trace and copper plate MCON techniques. As shown in the top picture, very fast rising current with less than 10ns rise time for 12A is achieved,which allows comfortably to characterize the sensing scheme up to 25MHz. The middle and the bottom pictures show the effect of MCON on the output of the sensor. Data from the prototype testing shows,while the MCON-equipped with AMR sensor, it follows the reference current from DC to certain transients; however, the Rogowski coil can only detect the fast AC transients of the current. The response from the AMR sensor without any MCON (Standard AMR) shows at high transients, the sensor output is out of phase and unable to follow the reference current.

Considering MCONs with both folded trace and copper plate techniques, the magnetic fields generated by the current trace are normalized. The field normalization achieved with the folded trace MCON is much higher compared to copper plate MCON, hence the response follows the reference more closely. On the other hand, the response from the sensor with the copper plate MCON shows significant improvement in comparison to the reference. When this combines with the Rogowski coil response, much better response is achieved, which corresponds to a higher detection bandwidth from the AMR sensor.

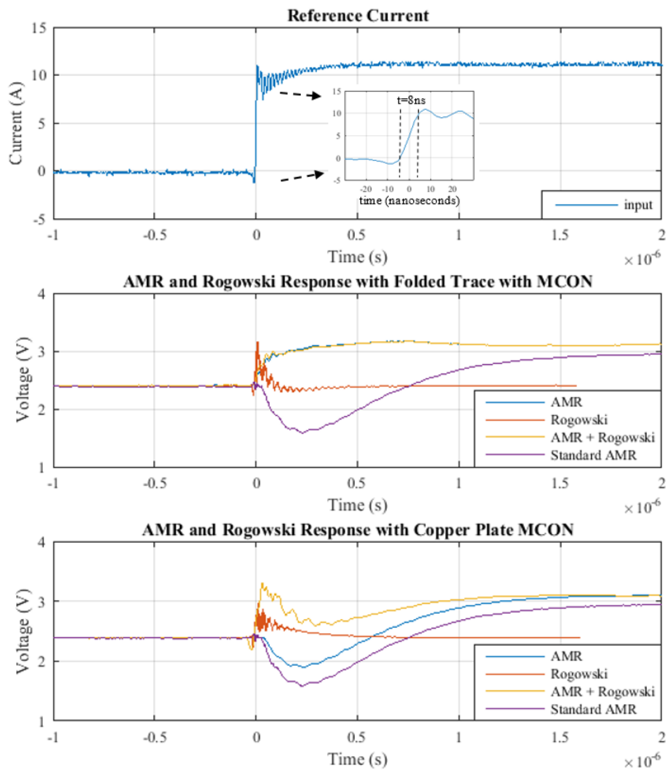

Fig. 4. Step response of the AMR-Rogowski sensing scheme with the folded trace (middle) and copper plate (bottom) MCON technique.

Both the folded trace and the copper plate MCON methods show great potential in high frequency current sensing applications. The higher sensitivity achieved by applying MCON techniques for MR and Rogowski coil sensors enables current monitoring with extreme accuracy and precision. An effective implementation of the folded trace and copper plate MCON in conjunction with the MCON equipped embedded Rogowski coil gives a solution to the true contactless wideband current sensing scheme for current measurements in very high frequency power electronics converters.

IV. Conclusion

This paper studied the impacts of two magnetic field concentration techniques on the performance of a hybrid current measurement scheme consisting of Magnetoresistor sensor and planar Rogowski coil. These MCONs shaped the magnetic fields and made it uniform in a limited frequency range in both cases. In the first approach, the current carrying trace was folded around the sensing elements to make the uniform and intensify the magnetic fields. In the second approach, the MCON was investigated by using a conductive material, copper without any contact to the power trace. The performances of both MCON methods were compared and it has been shown through the experiments, implementation of the proposed techniques significantly increased the bandwidth of the current sensing.

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References

[1] M. Banjevic, “High bandwidth CMOS magnetic sensors based on miniaturized circular vertical hall devices,” PhD Dissertation, No. 5144(2011), EPFL, Switzerland, 2011.

[2] N. Karrer and Patrick Hofer-Noser, “A new current measuring principle for power electronic applications”, The 11th International Symposium on Power Semiconductor Devices and ICs, 1999, pp. 279-282.

[3] F. Costa, E. Laboure, F. Forest, and C. Gautier, “Wide Bandwidth, Large AC Current Probe for Power Electronics and EMI Measurements”, IEEE Transactions on Industrial Electronics, Vol. 44, No. 4, August 1997.

[4] D. Lawrence, J. S. Donnal, and S. Leeb, “Current and voltage reconstruction from non-contact field measurements,” IEEE Sensors J., Vol. 16, No. 15, August 2016.

[5] A. M. Bastos, J. W. M. Menezes, A. A Kamshilin, and A. S. B. Sombra, “Hybrid opto-mechanical current sensor based on Mach-Zehnder fiber interferometer,” IEEE Sensors J., Vol. 14, No. 4, April 2014.

[6] A. Ghosh, P. B. D. Gupta, and A. K. Mandal, “Development of a fiber-optic current sensor with range-changing facility using shunt configuration,” IEEE Sensors J., Vol. 13, No. 4, April 2013.

[7] S. Ziegler, R. Woodward, H. H. Iu, and L. J. Borle, “Current sensing techniques: A review,” IEEE Sensors J., Vol. 9, No. 4, April 2009.

[8] N. Karrer and P. Hofer-Noser, “A new current measuring principle for power electronic applications”, The 11th International Symposium on Power Semiconductor Devices and ICs, 1999, pp. 279-282.

[9] R. Singh and A. M. Khambadkone, “Giant Magneto Resistive effect based current sensing technique for low voltage/high current voltage regulator modules”, IEEE Trans. on Power Electronics, Vol. 23, No. 2, 2008.

[10] J. Han, J. Hu, Y. Ouyang, S. X. Wang and J. He, “Hysteric modeling of output characteristics of giant magnetoresistive current sensors”, IEEE Trans. on Industrial Electronics, Vol. 62, No. 1, January 2015.

[11] I. Jedlicska, R. Weiss and R. Weigel, “Linearizing the output characteristics of GMR current sensors through hysteresis modeling”, IEEE Trans. on Industrial Electronics, Vol. 57, No, 5, May 2010.

[12] F. Xie, R. Weiss and R. Weigel, “Hysteresis compensation based on controlled current pulses for magnetoresistive sensors,” in press, early access, IEEE Trans. on Industrial Electronics, 2015.

[13] P. E. Schneider, M. Horio, and R. D. Lorenz, “Integrating GMR field detectors for high-bandwidth current sensing in power electronic modules”, IEEE Trans. on Industry Applications, Vol. 48, No. 4, July/August 2012.

[14] P. E. Schneider, and R. D. Lorenz, “Evaluation of point field sensing in IGBT modules for high-bandwidth current measurement,” IEEE Trans. on Industry Applications, Vol. 49, No. 3, May/June 2013.

[15] M. Biglarbegian, S. J. Nibir, H. Jafarian, J. Enslin, and B. Parkhideh,“Layout study of contacless magnetoresistor current sensor for high frequency converters,” ECCE, September 2016 IEEE, In press

[16] L. Dalessandro, N. Karrer, and J. W. Kolar, “High-performance planar isolated current sensor for power electronics applications”, IEEE Trans. on Power Electro. Vol. 22, No. 5, September 2007.

[17] J. Jiang and K. Makinwa, “A Hybrid Multipath CMOS Magnetic Sensor with 210µTrms Resolution and 3MHz Bandwidth for Contactless Current Sensing”, IEEE Solid-State Circuits Conference, 2016, pp. 204–205.

[18] S. J. Nibir, E. Hurwitz, M. Karami, and B. Parkhideh, “A technique to enhance the frequency bandwidth of contactless magnetoresistive current sensors”, IEEE Trans. on Ind. Electron., Vol. 63, No. 9, September 2016.

[19] M. Biglarbegian, S. J. Nibir, H. Jafarian, and B. Parkhideh,“Development of current measurement techniques for high frequency power converters,” Intelec, October 2016 IEEE. In press.

[20] Honeywell (MN). 1-and 2-Axis Magn. Sens. HMC1001/1002/1021/1022, Datasheet, 2008. [Online]. Available: http://www51.honeywell.com/aero/common/documents/myaerospacecatalog-documents/Missiles-Munitions/HMC_1001–1002–1021–1022_Data_Sheet.pdf