JPE 9-1-8

Coreless Hall Current Sensor for Automotive Inverters Decoupling Cross-coupled Field

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ABSTRACT

Automotive inverters may require current sensors for motor torque control, especially, in applications of hybrid electric vehicles or fuel cell vehicles. In this paper, to achieve a compact, integrated and low cost current sensor, a hall current sensor without magnetic core is introduced for integrating an automotive inverter. The compactness of the current sensor is possible by using integrated magnetic concentrators based on the Hall effect. Magnetic fields caused by three-phase currents are analyzed and a magnetic shield design is proposed for decoupling the cross-coupled field. It offers galvanic isolation, wide bandwidth (>100kHz), and accuracy (< 1%). Using 2D FEM analysis, its performance is demonstrated with design parameters at a U-shaped magnetic shield. The proposed coreless current sensor is tested with rated current to validate the linearity and accuracy.

Keywords: Hall current sensor, Magnetic core, Integrated magnetic concentrators(IMC) chip, Automotive inverter, Magnetic field analysis

1. Introduction

Current sensors are widely used in automotive inverters for motor torque control in hybrid electric vehicles (HEVs) or fuel cell electric vehicles (FCEVs), as well as motor driven power-steering systems.

The Hall effect, giant magneto-resistive(GMR) effect, current transformer(CT), and optical current transformer (OCT) are well known methods for sensing current[2-5] Singh[2] and Olson[1-3] utilized the GMR magnetic field effect by current sensing in applications with DC-DC converters and inverters, respectively. Imamura [4-5] analyzed magnetic field effects caused by three phase currents for OCT sensors. They proposed a double shield structure to reduce magnetic coupling. But, GMR and OCT sensors need to decouple the cross coupled field and disturbance fields due to neighboring current and eddy current paths. To overcome the cross coupling between magnetic fields, the field detector array and a complicated decoupling matrix for a GMR sensor[1] and the dual core shield for a OCT sensor[2] are utilized.

Specifically, since the Hall effect current sensor using a magnetic core is superior to the others in respect of the decoupling of the magnetic field, it is usually adopted for automotive inverters in HEVs or FCEVs. But, it makes current sensors bulky and more costly due to the presence of a magnetic core. To achieve a compact, integrated and low cost current sensor as well as magnetic field decoupling as in GMR and OCT sensors, in this paper, a

Manuscript received Aug. 4, 2008; revised Nov. 3, 2008
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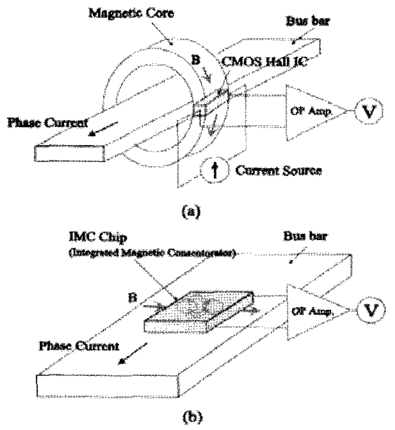

Fig. 1 Hall current sensors: (a) Hall current sensor with on magnetic core and (b) coreless current sensor based on IMC chip

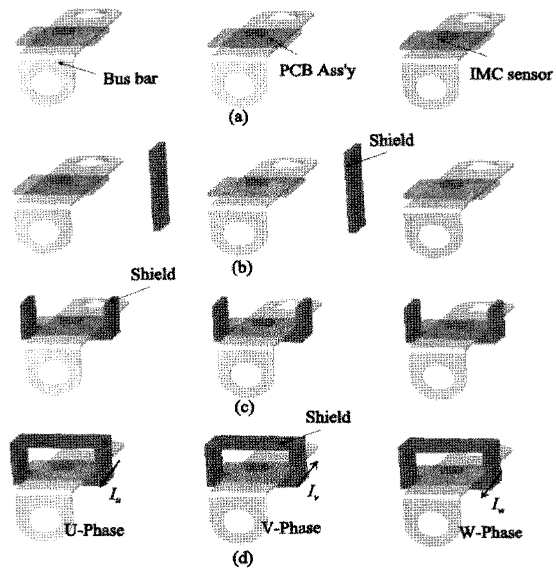

Fig. 2 Magnetic Shield Cases for the coreless current sensor for a PWM inverter: (a) No shield, (b) I-shaped shield, (c) U-shaped shield, (d) Closed-type shield

Hall current sensor excluding a magnetic core, so called, a coreless Hall current sensor is proposed. It consists of an integrated magnetic concentrator(IMC) chip based on the Hall effect [3].

By using conventional CMOS technology with an additional ferromagnetic layer, it uses the ferromagnetic layer as a magnetic flux concentrator providing a high magnetic gain. Thus, the IMC chip transforms a lateral field locally into a vertical field. The coreless current sensor based on an IMC chip has a conductor below or above the printed circuit board (PCB). Thus, the sensor features high magnetic sensitivity, low offset, and low noise.

In this paper, three shield techniques for an I-shaped, U-shaped, and rectangular permalloy are introduced for a coreless hall current sensor. The magnetic shield guides the external flux around the sensor, and it increases magnetic susceptibility for the flux lines emanating from the current conductor. Thus, it enhances its sensitivity. Consequently, magnetic fields using a U-shaped magnetic shield are analyzed by using the 2D finite element method (FEM) and its performance is validated by experimental tests.

2. Coreless Hall Current Sensor Using IMC Chip for Automotive Inverter

Hall current sensors using a magnetic core have been developed for automotive or industrial inverters. However, a magnetic core for the flux concentration is not always necessary because the IMC chip enables direct measurement of the field.

Fig. 1 shows the configuration of the Hall current sensor. It is classified into a conventional Hall current sensor using a magnetic core and the proposed coreless one. Requirements of a Hall current sensor for an automotive inverter are summarized as follows:

- High linearity : Linearity of current sensor should be less than $\pm 1\%$ for rated current.
- Wide bandwidth : Bandwidth of >100kHz and response time of <10 μs should be satisfied.
- Low cost, small size, and simple construction.

The IMC chip converts the magnetic field generated by current flowing through a bus bar to a voltage proportional to the field. The magnetic field generated by a bus bar is given by

$$H(r) = \frac{I}{2\pi r} , \qquad (1)$$

where I denotes the carrying current in a bus bar and r the distance from the bus bar. And flux density in the air is given by $B = \mu_0 H$ with magnetic permeability $\mu_0 = 4\pi / 10^{-7}$ H/m. Placing the flat bus bar over the IMC chip, the output

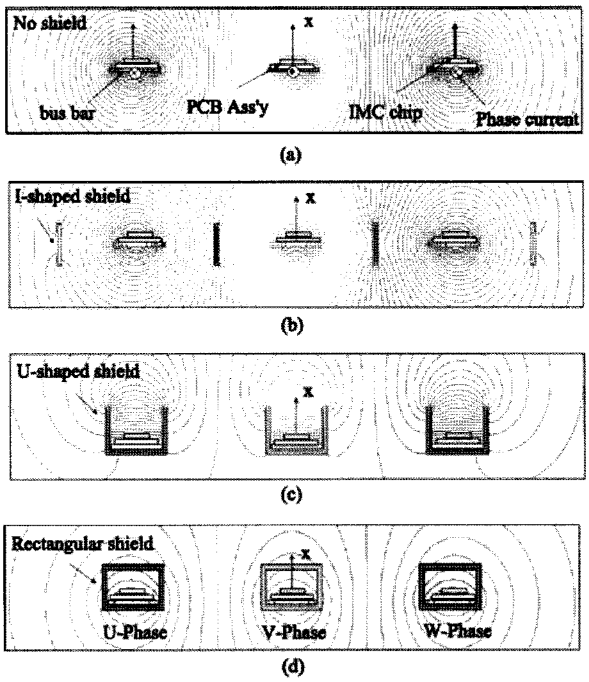

Fig. 3 Magnetic flux distribution when current flows bus bar with *Iu*=-400A, *Iv*=400A, and *Iw*=-400A: (a) No shield, (b) I-shaped shield, (c) U-shaped shield, (d) Rectangular shield

voltage of IMC sensor depends on the flux density at the distance from the top of the bus bar to the surface of the IMC sensor[7].

3. Design of Coreless Hall Current Sensor and its Magnetic Field Analysis

Fig. 2 shows the magnetic shield cases of the coreless current sensor for a PWM inverter. This current sensor consists of bus bars, a PCB substrate, and IMC current sensors. The bus bar is conducting three phase currents and the PCB assemblies provide electrical insulation between bus bars and sensor. It is also utilized to control the distance from the bus bar to the IMC chip. Further, the magnetic shield guides external fluxes around the sensor and decouples the cross-coupled field. It is made of a permalloy core. In cases where there is no shield in Fig. 1(a), since there is no magnetic barrier between the bus bars, the magnetic field caused by a phase current affects not only its own sensor but also the sensors for the other phases. To decouple the cross-coupled field, the I-shaped, U-shaped and rectangular magnetic shields are

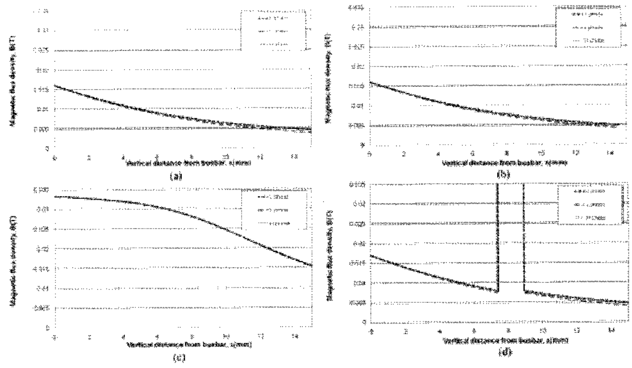

Fig. 4 Magnetic flux density according to vertical distance from bus bar when current flows bus bar with *Iu*=-400A, *Iv*=400A, and *Iw*=-400A: (a) No shield, (b) I-shaped shield, (c) U-shaped shield, (d) Rectangular shield

suggested as shown in Fig. 2(b)-(d).

To analyze the interference effect of the magnetic field among bus bars, we performed a 2D FEM analysis. Fig. 3 shows the magnetic flux distribution with *Iu*=-400A, *Iv*=400A, and *Iw*=-400A in cases of no shield, I-shaped shield, U-shaped shield, and rectangular shield, respectively. Magnetic flux density around V-phase is mainly influenced from the fluxes caused by U- and V-phase currents.

Fig. 4 shows the magnetic flux density B according to vertical distance x from bus bar. The four cases are shown in Fig. 3 (a)-(d). As shown in Fig. 4 (a), in the case of no shield, the magnetic fluxes of U-, V- and W-phase bus bars at x=5mm are 9.9, 9.6, and 9.9mT, respectively. The flux difference between V-phase and U- or W-phases is about 3%. The accuracy is not satisfied with the specification below ±1%. The current errors for 400A of rated current corresponding to 4.5V of output voltage are approximately 12A, respectively.

Similarly, the current errors between V-phase and the other phases for 400A are approximately 10A at x=5mm in case of the I-shaped shield shown in Fig. 4(b). In the case of the U-shaped magnetic shield, the flux density at x=5mm are almost the same irrespectively of phases as shown in Fig. 4(c). The magnetic shield becomes almost saturated due to the closed shape, since the flux leads to 0.68T from x=7.5 to 9mm in Fig. 4 (d), the magnetic shield looks like air. The flux difference between the U-phase and the others is similar to the no shield case.

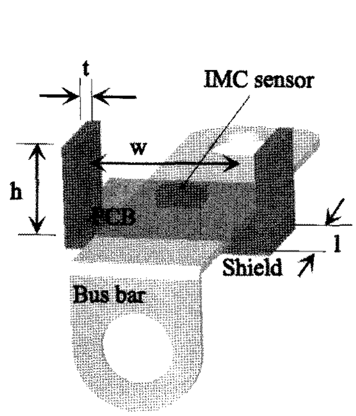

Fig. 5 Configuration of the coreless current sensor using a U-shaped magnetic shield

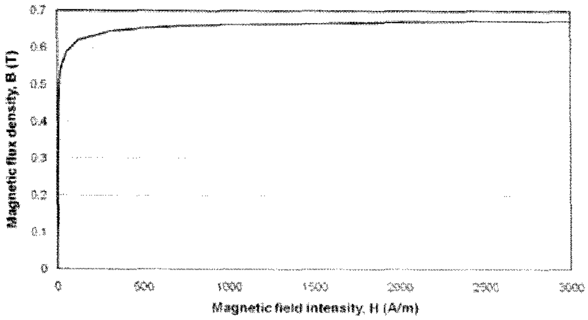

Fig. 6 *B/H* Curve of magnet shield

Compared with other shields, the current sensor with a U-shaped magnetic shield has locally high increased flux density. It could achieve high output voltage and low field equivalent offset. As a result, the U-shaped magnetic shield is selected for coreless current sensors in automotive PWM inverters.

4. Simulation Analysis and Experimental Results

In this section to find a way to minimize the interference of each bus bar in the U-shaped shield, 2D FEM analysis will be performed with various shield cases from Fig. 2(c). Fig. 5 shows the configuration of the coreless current sensor using the U-shaped magnetic shield. The *B/H* curve of the magnet shield is shown in Fig. 6. The design parameters of the U-shaped shield are listed in Table 1. The parameters are extracted with the actual package of a HEV inverter.

Table 1 Design parameters of magnetic shield

Shield width (w, mm)	15, 20, 25
Shield height (h, mm)	0, 5, 10
Shield thickness (t, mm)	1, 1.5, 2
Shield lenght (l, mm)	12

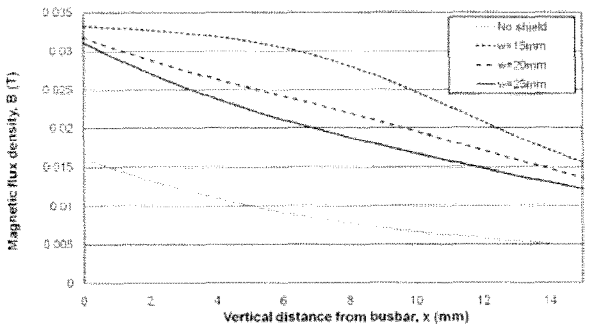

Fig. 7 Flux density versus vertical distance with w=10, 15, 20mm in case of h=10, t=1.5, l=12mm at 400A

To analyze the effects of the magnitude and the slope of the flux density at the IMC chip, we utilized the parameters of the magnetic shield for magnetic field analysis in Table 1. In this simulation, the magnitude of the phase current is set to be the rated value of 400A and the exciting frequency is set to be 0Hz.

4.1 The Effects of U-shaped Magnetic Shield

Fig. 7 shows the flux density versus vertical distance when the shield width w is set to at 15, 20 and 25mm in cases of h=10, t=1.5 and l=12mm at 400A, respectively. At shield width w=15mm, the flux density is 31mT at x=5mm considering the distance between the PCB substrate and chip. And the slope of the flux density from x =4 to 6mm is approximately -0.75mT/mm, while those of the flux density at no shield, w=20, 25mm are -1.15 and -1.35mT/mm at same condition, respectively. This means that the larger width is more sensitive for different vertical distances. But, the shield width is limited to bus bar size in practical package design.

Fig. 8 shows the flux density versus vertical distance when the shield height h is set to be 0, 5, and 10mm in cases of w=15, t=1.5, and l=12mm at 400A, respectively. If the height is lower, it is more sensitive for different vertical distances due to the product deviation. It is similar to cases of shield width variation.

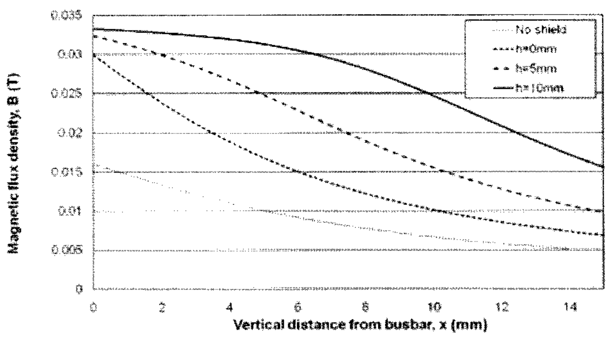

Fig. 8 Flux density versus vertical distance with h =0, 5, 10mm in case of w=15, t=1.5, l=12mm at 400A

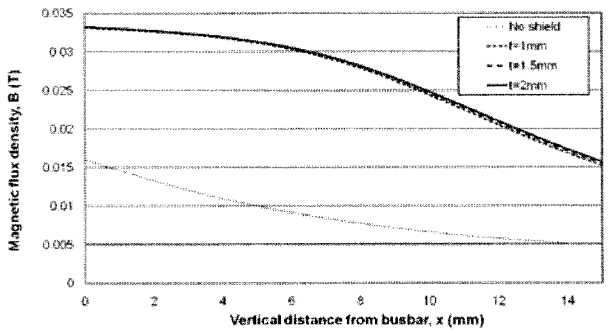

Fig. 9 Flux density versus vertical distance with t =1, 1.5, 2mm in case of =15, h=10, l=12mm at 400A

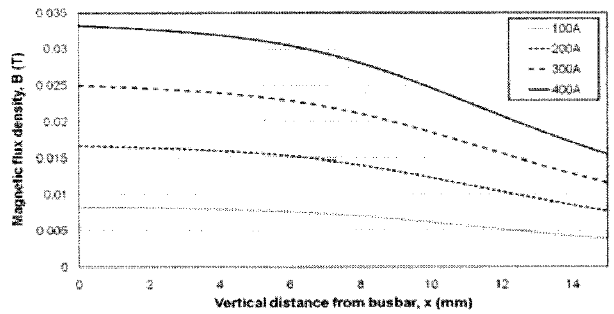

Fig. 10 Flux density versus vertical distance when current flows from 100A to 400A in case w=15, h=10, t=1.5, and l=12mm

Fig. 9 shows the flux density versus vertical distance when the shield thickness t is set to be 1, 1.5, and 2mm in cases of w=15, h=10, and l=12mm at 400A, respectively. Irrespective of the thickness of the magnetic shield, the flux density versus vertical distance is almost the same. We can see that the magnetic interference between the phase currents depends on the width and height of the magnetic shield.

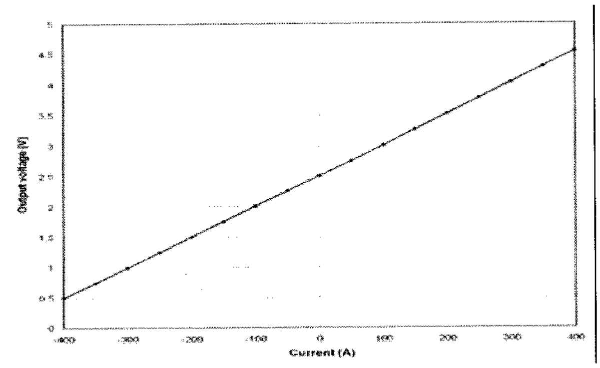

Fig. 11 Experimental results: Measured output voltage versus phase current when current flows from -400A to 400A in case of by w=20, h=15, t=1.5, and l=12mm

Fig. 10 shows the flux density versus vertical distance when the phase current flows from 100 to 400A in cases of w=15, h=10, t=1.5, and l=12mm. The flux density has the linearity of <±1% at x=5mm which are obtained by 7.8, 15.6, 23.5, 31.3mT at 100, 200, 300, 400A.

4.2 Experimental Results

In practical applications, the magnetic shield should be designed not to be saturated at the rated current. Further, the flux density of IMC chip should not exceed its limit. Due to limitation of magnetic range in IMC chip, a magnetic shield for a PWM inverter are designed by w=20, h=15, t=1.5, and l=12mm, respectively.

Fig. 11 shows the experimental results of the measured output voltage versus the applied current from -400 to 400A. The supply voltage has a single output from 5V and the output voltage ranges from 0.5 to 4.5A for ±400A. As a result, the linearity of the current sensor could be less than ±1%. This demonstrates that experimental results support the conclusion that the current sensor yields are accurate.

5. Conclusions

A U-shaped shield for a coreless current sensor was used to reduce magnetic coupling caused by three phase currents. The shield's width and height turned out to have robust design parameters for location variation between the IMC chip and bus bar. The simulation study shows that the proposed shield outperforms in cases with no shields in measuring current, and looks robust in the cross-coupled field caused by motor phase currents. Furthermore, the performance of the current sensor was experimentally verified on an automotive inverter with adaptable shield structure and material. Since the proposed current sensor does not include a magnetic core, the inverter package is more compact and the implementation cost is therefore lower than conventional ones. Thus, the coreless current sensor is adoptable for PWM inverters in HEVs or FCEVs.

Acknowledgment

The authors would like to thank Mr. S. Kim and Mr. S. Jung from the New Technology R&D Center, Woory Industrial Company for their support.

References

[1] E. R. Olson and R. D. Lorenz, "Effective use of miniature, multi-point, field-based current sensors without magnetic cores", *in Conf. Rec. IEEE-IAS Annu. Meeting*, pp. 1426-1433, 2007.

[2] R. P. Singh and A. M. Khambadkone, "Giant Magneto Resistive (GMR) Effect Based Current Sensing Technique for Low Voltage/High Current Voltage Regulator Modules", *IEEE Trans. Powor. Electron.*, Vol.23, pp. 915-925, Mar. 2008.

[3] E. R. Olson and R. D. Lorenz, "Integrating giant magnetoresistive current and thermal sensors in power electronic modules", *in Proc. IEEE APEC*, pp. 773-777, 2003.

[4] M. Imamura, M. Nakahara, T. Yamaguchi, and S. Tamura, "Analysis of magnetic fields due to three-phase bus bar currents for design of an optical current transformer", *IEEE Trans. Magnetics.*, Vol. 34, pp. 2274-2279, July 1999.

[5] M. Imamura and M. Tokubuchi, "Magnetic fields analysis for the optical current-transformer used for three-phase bus-bars arranged longitudinally", *IEEE Trans. Magnetics.*, Vol. 32, pp. 4962-4964, Sept. 1996.

[6] N. McNeill, G. Iordanidis, D. Holliday, and P. Mellor, "Low-cost high-bandwidth current transducer for automotive applications", *IEEE Trans. Powor. Electron.*, Vol. 21, pp. 832-835, Sept. 2006.

[7] "IMC hall current sensor datasheet", Melexis Semiconductors, http://www.melexis.com/sensor.

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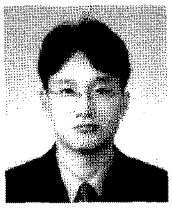

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