A new complementary symmetrical structure of using dual magnetic cores for open loop Hall-Effect current sensors

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Abstract

In this paper, a new complementary symmetrical structure of using dual magnetic cores for open loop Hall-Effect current sensors is proposed to reduce the influence of the position change of primary current carrying conductor, which cannot be compensated in signal processing circuit. Magnetic field simulations by using Ansoft Maxwell are made to evaluate the influence from the magnetic fields of the core air gap, as the conductor changes its position inside the core. Both simulation and the testing results show that the influence is obviously reduced by a dual cores structure, and the accuracy of open loop Hall-Effect current sensor is improved to ±0.5%.

Keywords *– dual magnetic cores; primary current carrying conductor position; Magnetic field simulation; open loop Hall-Effect current sensor; accuracy improvement*

1. Introduction

Current measurement is always one of the most necessary tasks in electrical equipment, especially in power devices [1]. Comparing to other current measuring products, Hall-Effect current sensors enjoy the best price versus performance ratio, low cost, small size and weight, non-contact, galvanic isolation and non-insertion losses, low power consumption, suitable for both DC and AC, high capability of overload, good linearity and accuracy [2, 3].

Though open loop Hall-effect sensors have advantages mentioned above, they only have a common accuracy of ±1.0%, which is relative low compared with that of closed loop Hall-Effect current sensors of ±0.5% (even ±0.2%).

The following figure (Fig. 1) shows a brief block diagram of the operating principle of open loop Hall-effect current sensor.

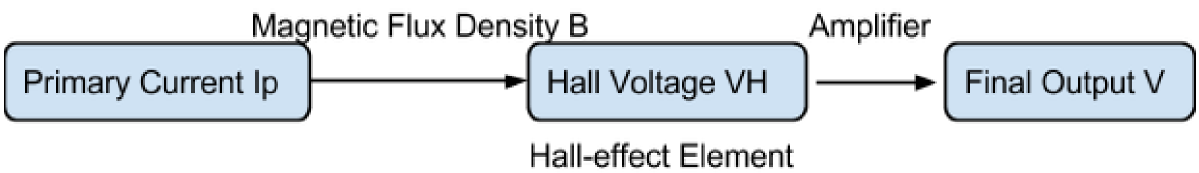

Fig. 1 Block diagram of open loop Hall-effect current sensor

In a Hall-effect current sensor, the magnetic flux density B generated by the primary current I_P under measurement is detected with a Hall-Effect element. The output voltage of the Hall-Effect element is boosted by a high gain amplifier. The output of the amplifier is the final output of the current sensor. There are various kinds of accuracy improving methods. However, most of them locate in the amplification part, and it cannot deal with the errors from the parts that influence the magnetic flux density in the air gap.

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Actually, a magnetic core is an especially important part in Hall-effect current sensors since it concentrates the magnetic flux produced by the primary current conductor placed through the aperture of the core. Position change of the primary current carrying conductor does affect the accuracy. Therefore, the relationship between the position of primary current carrying conductor and the magnetic field in the air gap of the magnetic core is investigated by magnetic field simulation under using Ansoft Maxwell, and a new dual cores structure is proposed to reduce that affect to improve the accuracy of open loop Hall-effect current sensors from ±1% to ±0.5%.

2. Magnetic Circuit in Hall-Effect Current Sensor

The magnetic core is used to capture and concentrate the magnetic flux generated by the primary conductor. An air gap inserted magnetic core causes much more leakage magnetic flux (named fringing flux) and side magnetic effect [3, 4]. When the primary conductor changes its position inside the magnetic core, it will affect the leakage magnetic flux around the air gap, so change magnetic flux density through the air gap. Hence, the sensor output is also influenced. For a current sensor with a higher precision level, this affect must be taken into account.

Fig. 2 displays a magnetic core model used in current sensors. The parameter will be used in the following analysis.

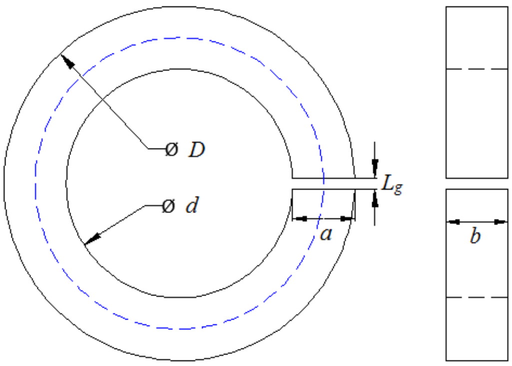

Fig.2 Dimensions of the magnetic core used in current sensors

For an ideal magnetic core model, applying the Ampere's law, one gets [4, 5]:

$$NI=H_cL_c+H_gL_g \tag{1}$$

with H as magnetic field strength, L as path length, I as primary current and N as turns of primary coil. The turn in our case is equal to 1. The subscript c refers to the core and g to the air gap.

The path L_c in the core can be calculated by the length measured along the center of the cross section of the core, as the blue line shown in Fig.2. H_c and H_g can be written in terms of the magnetic flux as

$$H_c=\frac{B_c}{\mu_c} \tag{2}$$

$$H_g=\frac{B_g}{\mu_g} \tag{3}$$

According to Gauss's law of magnetism, the magnetic flux Φ must be the same through any cross section of the magnetic circuit and

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$$\oint_S \vec{B} \bullet d\vec{s} = 0 \tag{4}$$

$$\Phi_c = \Phi_g = \Phi \tag{5}$$

$$B_c A_c = B_g A_g \tag{6}$$

where A_c and A_g are the cross sections of the core and of the air gap, respectively.
Combining (2) to (6) gives [7]

$$B_g A_g \left[\frac{L_c}{\mu_c A_c} + \frac{L_g}{\mu_0 A_g} \right] = I \tag{7}$$

The magnetic flux density of the air gap is determined by

$$B_g = \frac{I}{A_g \left[\frac{L_c}{\mu_c A_c} + \frac{L_g}{\mu_0 A_g} \right]} \tag{8}$$

The path length of the core is calculated by

$$L_c \approx 2\pi \frac{\frac{d}{2} + \frac{D}{2}}{2} - L_g = \frac{\pi}{2}(d + D) - L_g \tag{9}$$

Hence, the magnetic flux density of the air gap becomes

$$B_g = \frac{I}{A_g \left[\frac{\frac{\pi}{2}(d + D) - L_g}{\mu_c A_c} + \frac{L_g}{\mu_0 A_g} \right]} \tag{10}$$

In order to reduce Eddy current losses, the magnetic core is made by a set of laminations of soft materials. As a result, the effective cross-section area of magnetic core is [6]

$$A_{ec} = K_c A_c = K_c ab \quad (K_c<1) \tag{11}$$

Another key point is how to describe and explain fringing effect of the air gap. A simple method is that the effective area of air gap should be regarded [6]

$$A_{eg} = (a + g)(b + g) \approx ab + (a + b)g = K_g ab \quad (Kg>1) \tag{12}$$

Where *a* and *b* are the length and width of the air gap, respectively.
Hence, (10) can be simplified as:

$$B_g = \frac{I}{\frac{\frac{\pi}{2}(d + D) - L_g}{\mu_c} \frac{\mathrm{K_g}}{K_c} + \frac{L_g}{\mu_0}} \tag{13}$$

According to these equations, it is obvious that the magnetic flux density will not change if the value of primary current does not change. In fact, due to the leakage magnetic flux, the magnetic flux density at the air gap will change even when the primary current is kept constant. If the primary current carrying conductor changes its position inside the magnetic core, it does have influence on the magnetic flux density in the air gap. It is very difficult to find out the real value of the leakage magnetic flux, but a more accurate model can be used to

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estimate the fringing effect of the air gap. In this way the problem can be considered as how the cable position affects the fringing effect of the air gap.

An approximate and very useful method exists, which seems to have been first used by Herbert C. Roters, in his book "Electromagnetic Devices" [7]. The model is shown in Fig. 3.

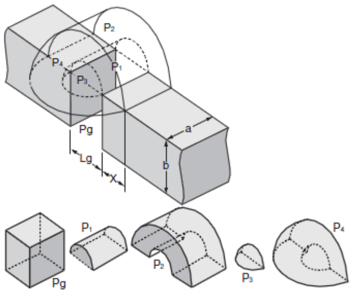


Fig. 3 Herbert C. Roters' model [8]

Herbert C. Roters wrote an equation for the reluctance of a uniform gap, which is [7]

$$R' = \frac{1}{\mu_0}\frac{\hat{l}}{\hat{A}} \tag{14}$$

Where *R'* is an approximation to reluctance

l is an average flux-path length

A is an average cross-sectional area to the path

Therefore, (7) turns

$$B_g A_g [R_c + R_g] = I \tag{15}$$

Rc and Rg can be calculated using (14) and finally, the magnetic flux density of air gap is [9, 10]

$$B_g = \frac{1}{A_g}\frac{I}{\frac{1}{P_c}+\frac{1}{P_g}} = \frac{1}{A_g}\frac{I}{\frac{2\pi L_c}{\mu_r\mu_0 abK_S}+\frac{1}{\mu_0(\frac{ab}{L_g}+0.528(a+b)+\frac{1.28(a+b)}{L_g/x+1}+0.308L_g+x)}} \tag{16}$$

In order to solve the influence of the position change, a "distance factor" could be used to connect the position of the cable and the magnetic flux density. One hypotheses is that the cable position affects the permeability of P1, P2, P3 and P4, especially P2 and P4 inside the magnetic core, shown in Fig. 3. In mathematics, functions *f(s)* is used as the expression of the distance (from cable center to air gap center) coefficient. Since the air gap is divided into 5 subparts, almost 17 portions, it is impossible to give every portion a distance coefficient, based on the truth that the influence of the cable position on the 17 portions is different, with completely certainty. Hence, function *f(s)* will be considered as an overall coefficient.

Hence, the magnetic flux density could be rewritten as:

$$B_g = \frac{1}{A_g}\frac{I}{\frac{1}{P_c}+\frac{1}{\mathrm{f}(s)\bullet P_g}} = \frac{1}{A_g}\frac{I}{\frac{2\pi L_c}{\mu_r\mu_0 abK_S}+\frac{1}{f(s)}\frac{1}{\mu_0(\frac{ab}{L_g}+0.528(a+b)+\frac{1.28(a+b)}{L_g/x+1}+0.308L_g+x)}} \tag{17}$$

The function *f(s)* could be estimated by magnetic flux density simulation, which is discussed in the following section.

3. Magnetic Flux Density Simulation

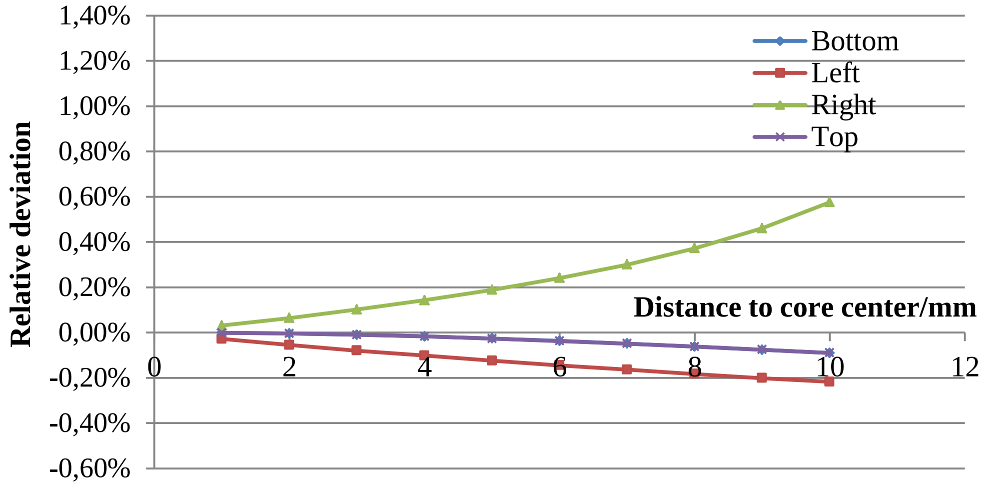
3.1 Magnetic Flux Density Simulation

The magnetic flux density of the air gap is simulated as the primary current carrying conductor changes its position inside the magnetic core in both vertical and horizontal directions.

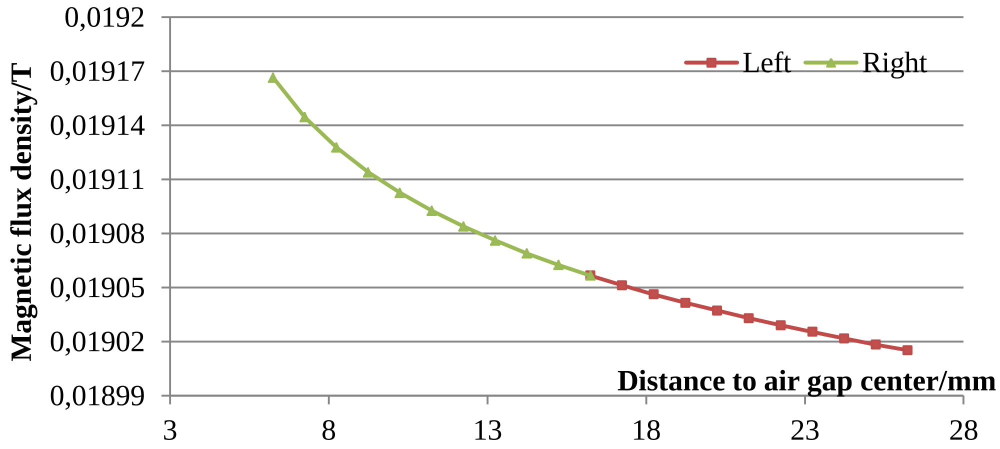
The influence of conductor position in the horizontal direction is much higher than in the vertical direction, see Fig. 4(a). The closer the conductor to the air gap, the greater the influence is. The influence of the conductor position in the horizontal direction is shown in Fig. 4(b). With the assistance of MATLAB, using Fig. 3 (b), *f(s)* in (17) can be estimated as:

$$\mathrm{f}(s) = \frac{1.273}{0.0476 * s - 28.0118} \tag{18}$$

where *s* is the distance between conductor and air gap center.



(a) Relative deviation at different conductor positions



(b) Magnetic flux density as function of the horizontal distance

Fig. 4 Simulation results at different conductor positions

3.2 A New Complementary Symmetrical Structure of Using Dual Cores

One solution to reduce the influence from the position of the primary current carrying conductor is to use two same magnetic cores, which are coupled by positioning the air gaps reversely. A ring air gap between the two cores is necessary, in order to form two independent magnetic circuits. Fig. 5 shows the complementary symmetrical structure.

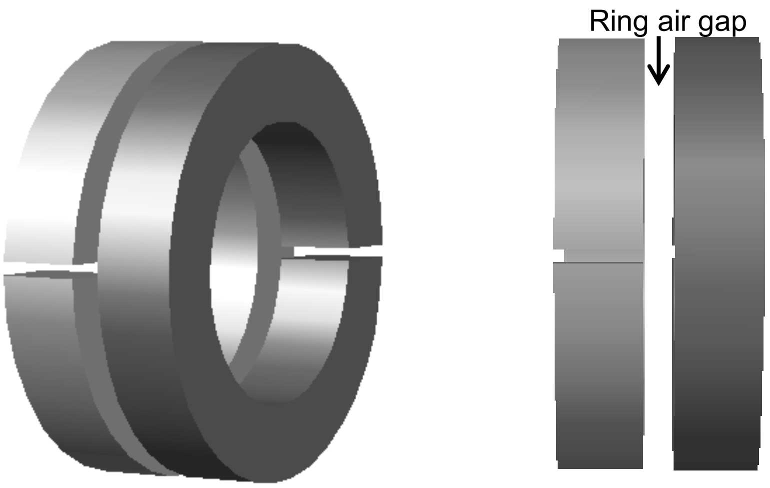


Fig. 5 A new complementary symmetrical core structure

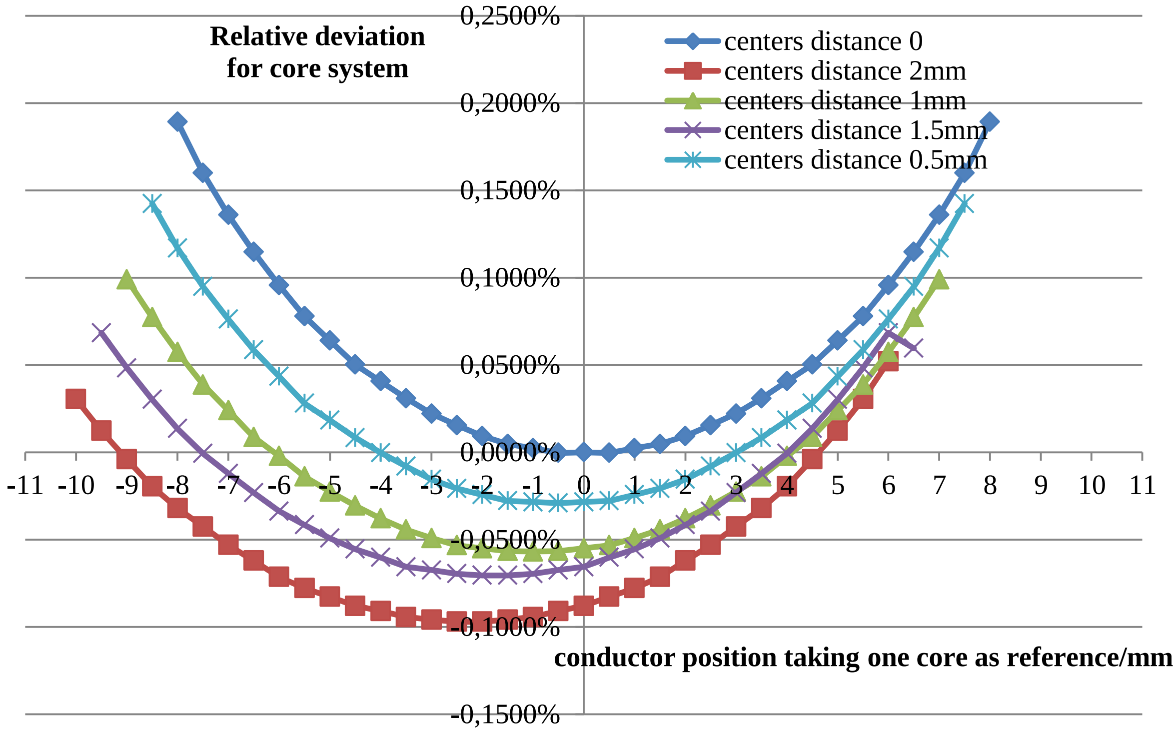


Fig. 6 Relative deviation under using two cores structure

The distance between the center of the sensor aperture and centers of the cores ranges from 0 to 2mm. The system's relative deviation for the different centers distance is shown in Fig. 6. It is obvious that the relative deviations at the center distance of 1mm and 1.5mm are smaller than those at other distances.

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4. Experimental Results of the New Complementary Symmetrical Structure

Experiments are done with a same circuit by using single core and dual cores to make a comparison. The results are shown below.

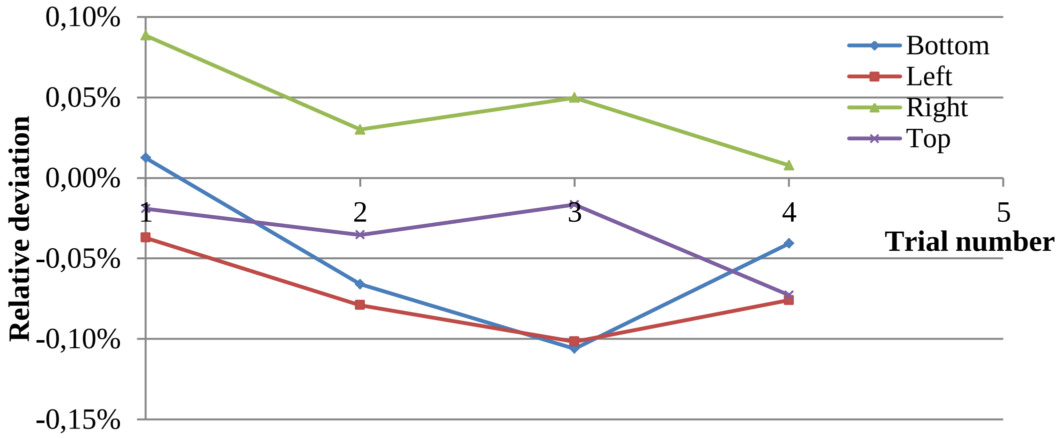

Fig. 7 Experiment results for single core

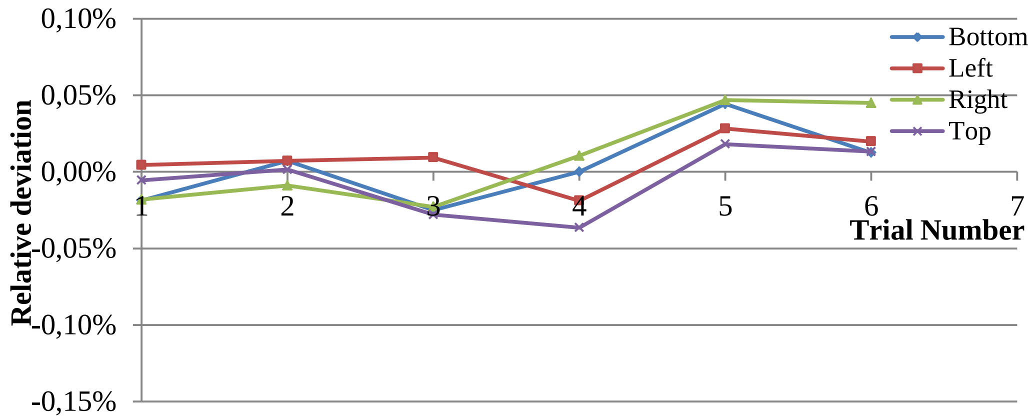

Fig. 8 Experiment results for dual cores

Fig. 7 shows that the magnetic flux density varies as the conductor position changes inside the core aperture. Apparently the fours curves are in different levels, which mean the deviation is more dependent on the conductor position. The curve at right position has a larger relative deviation than the other three positons. Those are the same with the simulation results. A difference from simulation is that the influence of the left is not always bigger than the top and bottom in experiments and it will be smaller. Another is the top and bottom curves obviously have the different influence. They are not at the same level.

Fig. 8 shows the results of sensors with dual cores. Obviously, the four curves are near identical. It means that the influence is near the same. Compared with single core structure, influence of the conductor position is reasonably reduced by the dual cores structure.

5. Conclusions

From theoretical analysis, simulation and experimental results, the following conclusions can be drawn:

- The magnetic flux density of the air gap is mainly determined by the air gap length, and it is nearly inversely proportional to the air gap.

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- The position of the primary conductor affects the magnetic flux density in the air gap, especially in the horizontal direction
- The closer the conductor is to the air gap , the higher influence it has
- The influence from the position change of the primary current carrying conductor can be reasonably reduced by the new complementary symmetrical structure by using dual cores.
- The accuracy of the open loop hall-effect current sensor can be controlled within ±0.5%. This has been proved by a new developed current sensor.

Further work should be done to find out the reason for the different magnitude of conductor positon influence between simulation and experimental results. The model should be further applied to the full area inside the sensor aperture so that a more complete and accurate relationship would be found for this model, which then will also take the width of the magnetic core, the effective length of the cable into consideration.

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