# Investigation of the thermal drift of open-loop Hall Effect current sensor and its improvement

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***Abstract*— Linear Hall IC can be used for the low price open-loop Hall Effect current sensor thanks to its high sensitivity. However, according to the experimental results, its thermal performance is greatly related to the thermal drift coefficient of linear Hall IC and the gain of the amplifying circuit. In this paper, the thermal drift of the zero offset will be improved by two methods. One is to use two Hall ICs, the thermal drift coefficients of which are similar, to build up a differential amplifying circuit to compensate the common thermal drift of the two Hall ICs. Another one is to add a magnetic core for concentrating the magnetic flux. In this way the gain of the amplifying circuit is reduced by increasing the magnetic flux density passed through the Hall IC. Experimental results show that the thermal performance of the optimized current sensor is reasonably improved by the proposed methods.**

**Keywords— linear Hall IC, open-loop Hall Effect current sensor, thermal drift improvement, thermal drift coefficient, amplifying circuit gain.**

## I. INTRODUCTION

Electrical current sensors are well known and find a wide range of applications to the electronics industry [1]. There are a lot of current sensors such as current transformers, shunt resistors and Hall Effect current sensors, etc. [2-7]. Among these current sensors, Hall Effect current sensors have more advantages in good linearity, wide measuring range, high isolation between input and output, relative high accuracy, diverse sensor configurations and applications [5,6,7].

With the development of the semiconductor integrated circuit industry, Hall IC, which integrates a Hall Effect element and its signal processing circuit in one chip, is also quickly developed. It has been widely used since it has a lot of advantages, such as high sensitivity, long life, easy installation, low power consumption, high frequency, shock-resistant and low cost [8,9].

According to previous studies [7], the linearity of Free-space Hall Effect current sensor by using a Hall Effect element is not good and its sensitivity is not high enough for industrial applications. In this paper, a higher sensitivity Hall IC is used to improve the linearity and sensitivity of this sensor. It is known that temperature is a major factor affecting the accuracy of a Hall current sensor [10]. It is verified by temperature experiments that the zero offset thermal performance of the sensor depends on the thermal drift coefficient of linear Hall IC and the gain of the amplifying circuit.

In this paper, the thermal performance of low-cost current sensors will be improved by two methods. The first one is to use two Hall ICs to build up a differential amplifying circuit to compensate the thermal drift of the two Hall ICs. The second one is to integrate a magnetic core to increase the magnetic flux density passing through the Hall IC, and consequently to reduce the gain of the amplifying circuit. Hall Effect current sensors developed according to these methods can be used in solar energy system and other systems which need sensors to have a wide operating temperature range.

## II. OPEN LOOP HALL EFFECT CURRENT SENSOR BASED ON LINEAR HALL IC

### A. *Free-space Hall Effect open-loop current sensor*

A single linear Hall IC and a U-shaped copper wire are used to build a Free-space Hall Effect current sensor. The distance between IC and copper wire is 2mm and 10A primary current flows through the U-shaped copper wire. The model of the sensor is shown in Fig.1.

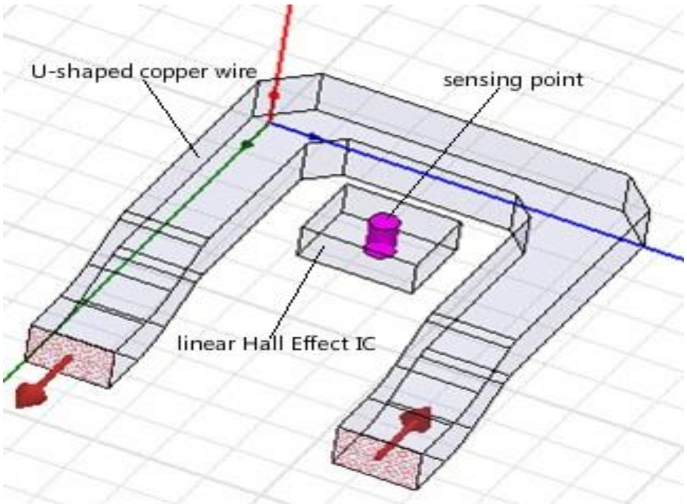

Fig.1 Current sensor model of using a single linear Hall IC and a U-shaped copper wire

Fig.2 shows the relationship between the magnetic flux density at the sensing point and the simulation region of the solution domain. It indicates that as the solving region gradually increases, the magnetic flux density becomes more and more accurate. The magnetic flux density B is finally equal to 0,98mT, which is approximate to the real value.

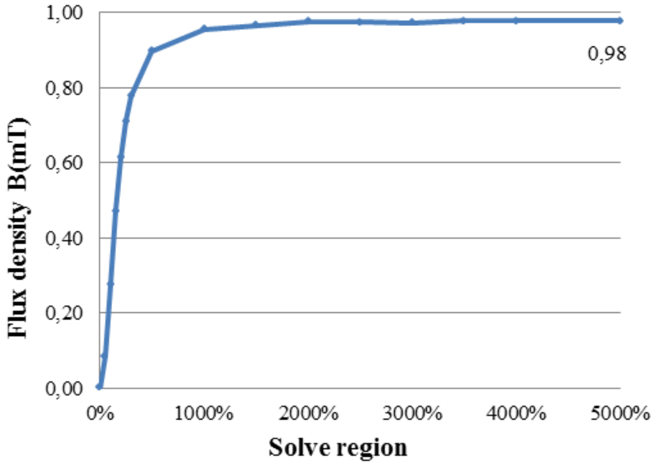

Fig. 2 The relationship between the magnetic flux density and the solution domain

The gain of the amplifying circuit should be set to 45 so that the sensor can give an output voltage of 2.5V±1V when the primary current is 10A. Fig. 3 shows the linearity error of the sensor, the measurement is repeated for 9 times to get a reliable result. One can get that the linearity error is less than ± 0.40%, which is better than that of the current sensor based on Hall Effect element in previous studies (± 0.60% ) [7].

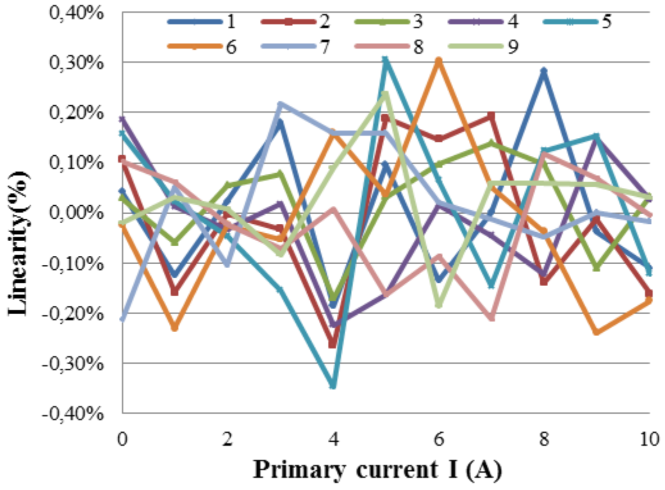

Fig. 3 Linearity of current sensor of using a single Hall IC and a U-shaped copper wire

### *B. Zero offset temperature experiment of the Free-space Hall Effect open-loop current sensor*

Experiments have been done in order to find the zero offset thermal drift of the sensor. The results of current sensor under using a Hall IC are shown in Tab I. The thermal drift coefficient ($TCV_o$) of the zero offset of the sensor is calculated by considering 25°C as reference temperature. This parameter is expressed in ppm/°C (ppm is an abbreviation for "part per million") and is determined by:

$$TCV_o\left[\frac{ppm}{^\circ C}\right]=\frac{V_o\left(T_1\right)-V_o\left(25^\circ C\right)}{V_o\left(25^\circ C\right)*\left(T_1-25^\circ C\right)}\times 10^6 \qquad (1)$$

where $Vo(25°C)$ is the zero offset output voltage at 25°C, $Vo(T_1)$ is the zero offset output voltage at temperature $T_1$.

The parameter in ppm/°C is a relative value and independent on the output voltage. For instance, the thermal drift coefficient of a current sensor with an output voltage of +2.5VDC±2V under using a power supply of +5VDC is the same as that of a current sensor with an output voltage of +5VDC±4V under using a power supply of +10VDC. Therefore it is better to use the unit ppm/°C than using the unit µV/°C or mV/°C.

The results show that the thermal drift of zero offset $V_o$ can reach about 6533 ppm/°C as the temperature changes from -40°C to 85°C.

Table I. THERMAL DRIFT COEFFICIENT OF A CURRENT SENSOR BASED ON THE MODEL SHOWN IN FIG. 1

| **Tempera-ture (°C)** | **Thermal drift coefficient of the sensor** | | | |
|---|---|---|---|---|
| | **$V_{zd}$(ppm/°C)** | **$V_h$(ppm/°C)** | **$V_{ref}$(ppm/°C)** | **$V_O$(ppm/°C)** |
| -40 | 10,5229 | 226,056 | 81,5168 | 5829,88 |
| -20 | 4,55994 | 261,133 | 103,946 | 6182,34 |
| 0 | 0,879417 | 275,236 | 108,831 | 6533,56 |
| 25 | 0 | 0 | 0 | 0 |
| 60 | 11,8652 | 209,348 | -69,1458 | 5224,92 |
| 85 | 16,0412 | 222,088 | -79,8486 | 5375,29 |

Similar experiments of Free-space current sensor under using a Hall Effect element are also done to make a comparison between the two types of sensors. A Hall Effect element has two output pins, it can Fig. 4 shows the thermal drift coefficients of the two output pins.

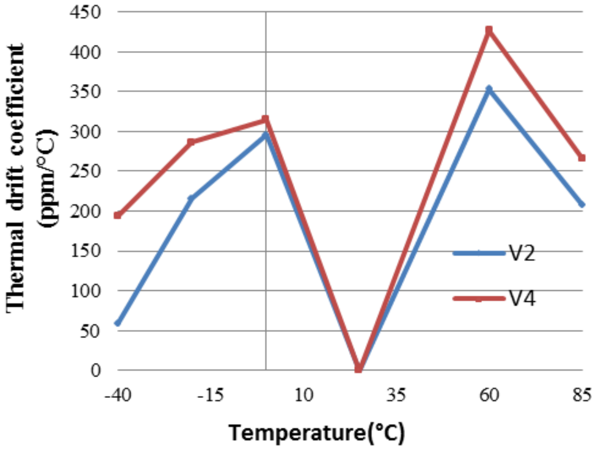

Fig.4 Thermal drift coefficients of two output pins of a Hall Effect element

The thermal drift coefficients of the output pins are very similar so that the thermal drifts can be compensated by a differential amplifier circuit. However, due to its low sensitivity of a Hall Effect element, the gain of the amplifying circuit must be very high. It can reach 320 when using the same U-shaped copper wire. Fig. 5 shows a comparison of the sensors based on a Hall Effect element and a Hall IC under using the same U-shaped copper wire. The thermal drift coefficient of current sensor using a Hall IC is better than that of current sensor by using a Hall Effect element.

Hence, an improvement of the thermal performance of current sensors is necessary for the industrial applications.

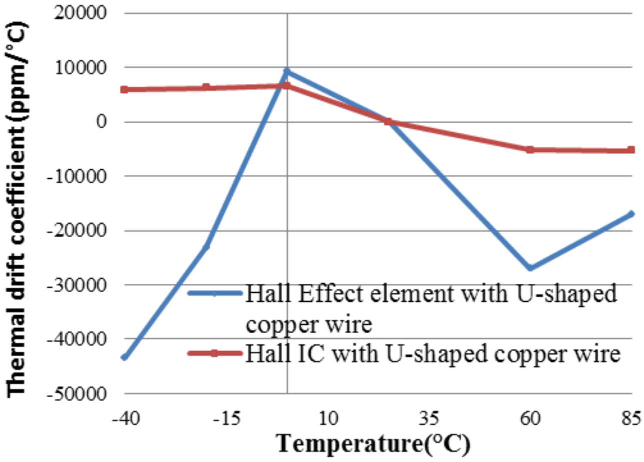

Fig.5 Thermal drift coefficients of two types of current sensors

## III. THERMAL PERFORMANCE IMPROVEMENT OF THE ZERO OFFSET OF THE SENSOR

The circuit used in the current sensor is shown in Fig. 6.

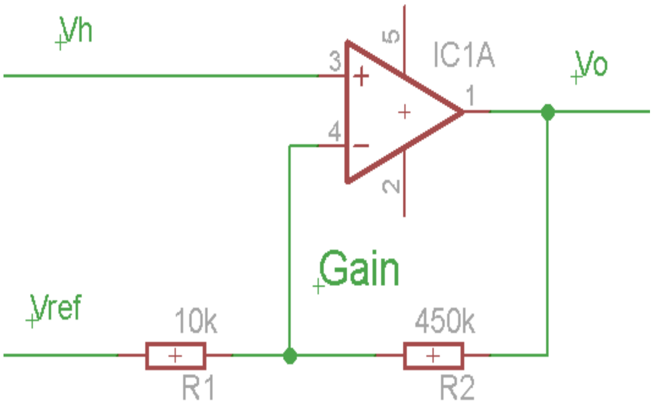

Fig. 6 Circuit of the Hall Effect current sensor

The zero offset output voltage $V_O$ of the sensor can be expressed as

$$V_O = K * \left( V_h - V_{ref} \right) + V_h \qquad (2)$$

Where $K$ is the gain of the amplifying circuit, $V_h$ is the output voltage of linear Hall IC, and $V_{ref}$ is the constant voltage reference.

The derivative of the sensor output with respect to the temperature is given as:

$$\frac{dV_O}{dT} = \left( K+1 \right) * \frac{dV_h}{dT} - K * \frac{dV_{ref}}{dT} \qquad (3)$$

From (2), it can be seen that the thermal drift coefficient of the zero offset of the sensor is proportional to the gain of the circuit and to the thermal drift coefficient of linear Hall IC under using a constant reference voltage $V_{ref}$. Therefore, the thermal drift of zero offset should be reduced by using the following methods.

### A. *Hall Effect Current Sensor by using two Hall ICs*

The linear Hall IC has only one output pin. Two Hall ICs should be used to build a differential amplifying circuit (see Fig. 7[11]). The zero offset output voltage $V_O$ of the sensor in this case can be expressed by

$$V_o = K * \left( V_{h1} - V_{h2} \right) + V_{ref} \qquad (4)$$

Where $K$ is the gain of amplifying circuit, $V_{h1}$ and $V_{h2}$ are output voltages of linear Hall IC1 and IC2 respectively, and $V_{ref}$ is the constant voltage reference.

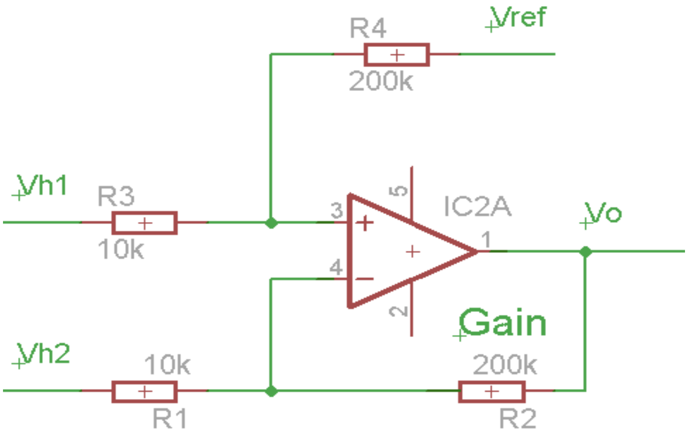

Fig.7 Differential amplifying circuit [11]

The derivative of the sensor output with respect to the temperature is given as:

$$\frac{dV_O}{dT} = K * \left( \frac{dV_{h1}}{dT} - \frac{dV_{h2}}{dT} \right) + \frac{dV_{ref}}{dT} \qquad (5)$$

Under assuming that $V_{ref}$ is constant and $K$ does not change with temperature, the thermal drift coefficient of the sensor is proportional to the difference between the thermal drift coefficients of the two Hall ICs.

Fig.8 shows the thermal drift coefficients of the zero offset of different ICs. Hall IC1 and IC2 have a different coefficient; IC1 and IC3 have a similar coefficient. Theoretically, the common thermal drift can be compensated when the output signals of the two Hall ICs are processed with a differential amplifier.

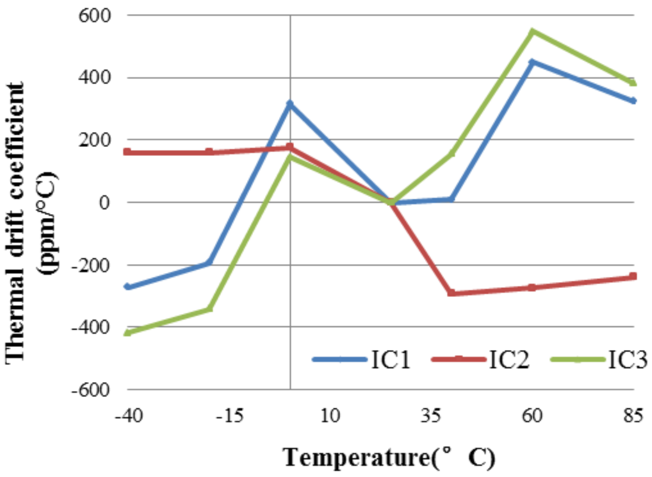

Fig.8 The thermal drift coefficient of different ICs

Furthermore by using two ICs the output signal of the differential amplifier can be doubled in comparison to that by using a single Hall IC. Therefore the gain of the amplifying circuit can be reduced from 45 to 20. Fig.9 shows thermal drift coefficients of the zero offset of different sensors. The first sensor uses a single Hall IC and U-shaped copper wire. The second sensor is built with the same U-shaped copper wire and Hall IC1 and IC2, while the third sensor consists of Hall IC1 and IC3. The output signals of both Hall ICs are connected to a differential amplifying circuit. Comparing these three curves, it is obvious that the differential amplifier circuit can improve the temperature characteristics of the sensor when the thermal drift coefficient of two Hall ICs is approximately the same. Otherwise the thermal drift coefficient will not be reduced or even be worse.

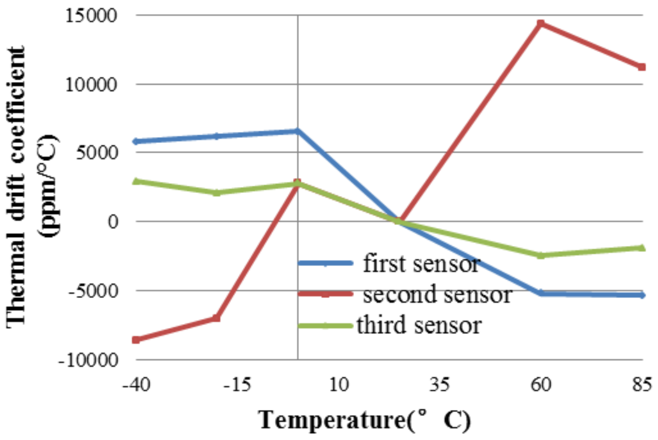

Fig.9 Thermal drift coefficients of sensors

### B. *Hall Effect Current Sensor by using a Magnetic Core*

In order to reduce the gain of the amplifying circuit of the current sensor, a magnetic core should be used to concentrate the magnetic flux generated by the primary current conductor in the air gap of magnetic core, where the Hall IC is positioned. From experimental results the gain of the amplifying circuit is reduced from 45 to 4.8 with using a magnetic core instead of the U-shaped copper wire. Fig.10 shows the linearity error of the sensor which uses a single Hall IC with a magnetic core. The measurement here is also repeated for 9 times to get a reliable result. The linearity is less than ± 0.30%, which is better than that of using a Hall IC with U-shaped copper wire (± 0.40%).

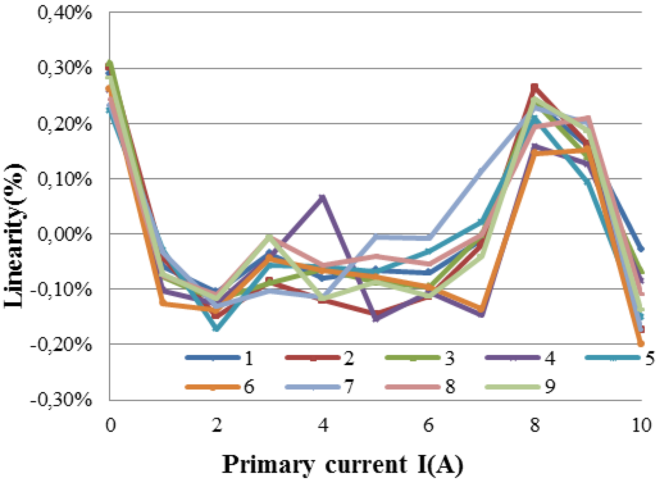

Fig.10 Linearity of the sensor using a single Hall IC with a core

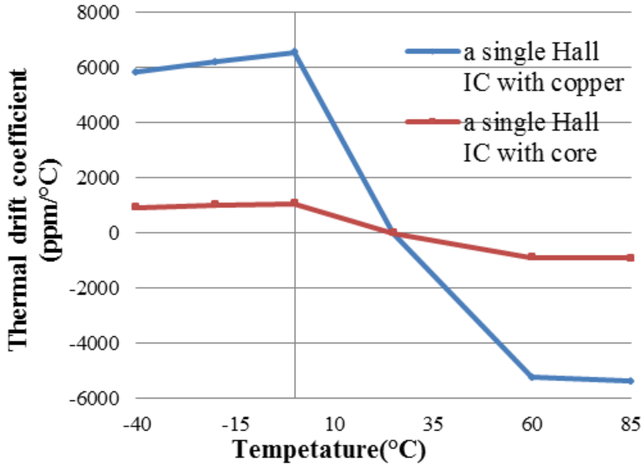

Fig.11 Thermal drift coefficients of the sensors with using a U-shaped copper wire and a magnetic core

Fig.11 shows the thermal drift coefficients of the sensors that magnetic flux density is generated by using a U-shaped copper wire and a magnetic core. The blue curve shows thermal drift coefficient of the sensor of using a U-shaped copper wire, while the red curve gives thermal drift coefficient of the sensor of using a magnetic core. One can see that the thermal drift of the sensor by using a magnetic core is much lower than that of using a U-shaped copper wire. The reason is that the magnetic flux density is increased by the magnetic core, and consequently the gain of the amplifying circuit is reduced reasonablely.

### *C. Hall Effect Current Sensor by using a Magnetic Core and two Hall ICs*

By combining the two sensors mentioned above, one can build an optimized current sensor with using a magnetic core and two Hall ICs. The gain of the amplifying circuit of this sensor is reduced from 45 to 1.5 and the thermal drift coefficient of the sensor can be greatly improved. Fig.12 shows the final results. The linearity error is less than ±0.20%.

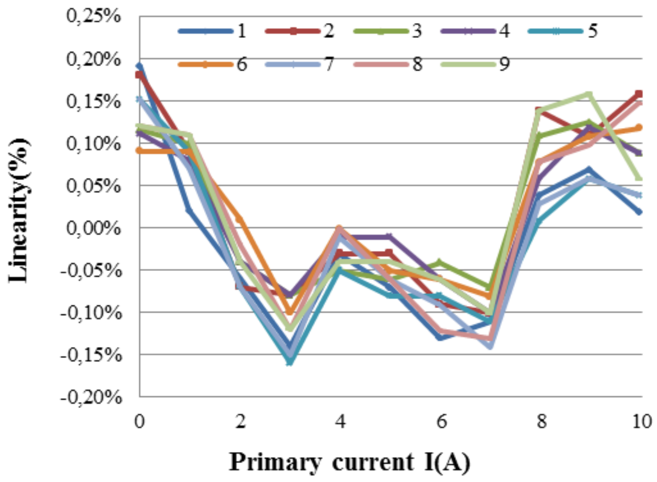

Fig.12 The linearity of the sensor using two Hall ICs with a magnetic core

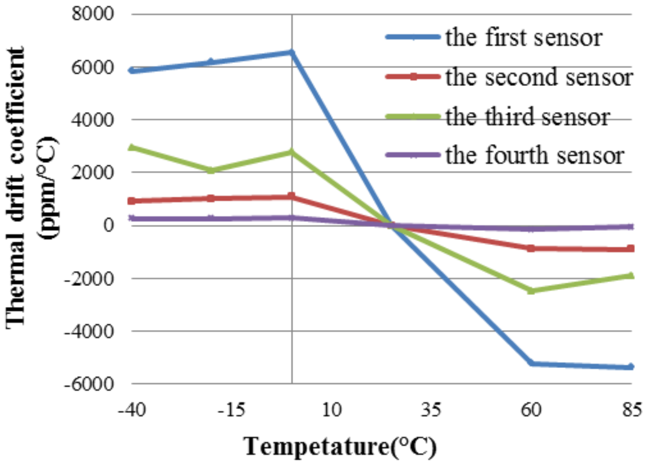

Fig.13 Thermal drift coefficients of four different sensors

The thermal drift coefficients of the zero offset of different sensors are shown in Fig.13. The first sensor consists of a single Hall IC and U-shaped copper wire. The second sensor uses a single Hall IC and a magnetic core. The third sensor is built with two Hall ICs and U-shaped copper wire. The fourth sensor is the optimized sensor with two Hall ICs and a magnetic core. It is obvious that the thermal drift coefficient of the optimized current sensor is much better than that of other three sensors. The maximum of the thermal drift coefficient of the optimized sensor is 289ppm/°C. This is the effect of using two Hall ICs and a magnetic core for reducing the thermal drift and improving the linearity.

If using another two Hall ICs, which have a similar thermal drift coefficient, do the same experiment, one gets the result shown in Fig.14. The thermal drift coefficient of the sensor is reduced in this case.

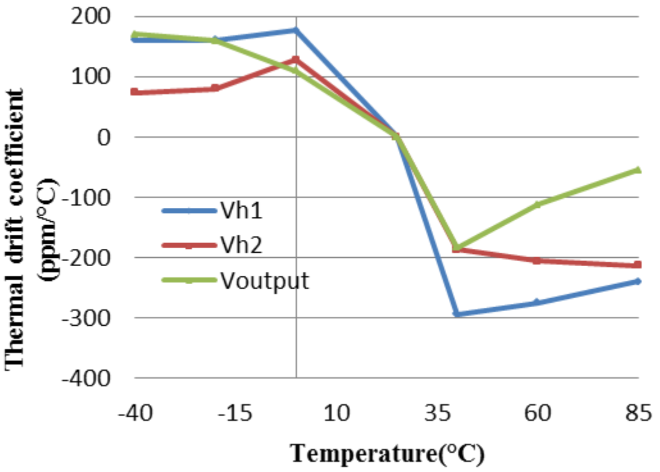

Fig.14 Thermal drift coefficients of an optimized current sensor under using two Hall ICs, which have a similar thermal drift coefficient

## IV. CONCLUSIONS

In this paper, the zero offset thermal performance of open-loop Hall Effect current sensors is improved by the proposed methods, which have been proved by experiments. The following conclusions can be drawn:

- The sensitivity of Hall IC is higher than that of Hall Effect element. It is suitable for current sensors.
- The thermal performance of an open-loop Hall Effect current sensor depends on the thermal drift coefficient of the linear Hall IC and the gain of the amplifying circuit
- Using two linear Hall ICs, the thermal drift coefficients of which are approximately the same, to build a differential amplifying circuit in the current sensor, it can not only compensate thermal drifts of the two Hall ICs but also increase the sensitivity of current sensor and reduce the gain of the amplifying circuit.
- Current sensor by using a magnetic core has a lower thermal drift than that of sensor by using a U-shaped copper wire thanks to the concentration of magnetic flux at the sensing point of the Hall IC.
- The linearity of the sensor can also be improved by using two Hall ICs and a magnetic core.

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