Offset Error reduction in Open Loop Hall Effect Current Sensors Powered with Single Voltage Source

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***Abstract* - For precise current measurement with Open Loop Hall Effect current sensors, zero offset error is problematic. With double voltage supplies, this offset can be adjusted near to zero. However for sensors powered with a single voltage supply, a remarkable amount of voltage offset still remains. This undesired rest offset causes inaccuracy in most applications. In this paper a novel method is proposed to minimize voltage offset error of Open Loop Hall Effect Current sensors powered with single voltage supply. Experiment results show that the offset error of current sensors under using the proposed method can be controlled within 0.2% so that the measuring accuracy of 0.5% is realizable for open loop current sensors.**

Keywords – Hall Effect Sensor, Zero Offset Adjustment, Accuracy Improvement, Single Voltage Supply, Open Loop Current Sensor, Offset Reduction

I. INTRODUCTION

Current sensing is an important operation for many electric power, driving and communication systems. Traditionally, it was primarily intended for circuit protection and control. With the technological development, current sensing has appeared as a method for monitoring and performance enhancing. Therefore, current sensors are widely applied to power systems, current and voltage regulators, linear and switch-mode power supplies, inverters, rectifiers, motor drives, generators, automotive power electronics, electric powered locomotives, telecommunications, transformer substations, battery management systems, wind turbines and photovoltaic equipment etc.

Hall Effect current sensors are preferred towards other competitive technologies like shunt resistors, because they provide many benefits such as wide measuring range, good linearity, high accuracy, Galvanic isolation between input and output, and wide variation of sensor configurations etc. [1, 2].

There exist two kinds of current sensors based on the Hall Effect principle: Open Loop current sensors and Closed Loop current sensors. Each technology offers its own advantages. The Open Loop model provides excellent performance with respect to price and is preferable for battery-operated applications where power consumption, size, and weight are dominant concerning. Moreover, it can be used even at excessive overcurrent without significant damages. Due to its good cost-benefit ratio, Open Loop Hall Effect current sensors are preferred for many applications.

In order to get a useful analog output signal for controlling systems and measuring instruments, the Hall voltage of Hall Element has to be further processed by a differential amplifier with high input impedance, gain and zero offset adjustments [3]. Under using double voltage supplies, adequate results can be realized. Nevertheless, double voltage supplies are exceptions in many applications, where low power consumption, easy handling, small size and low costs are requested. Thus sensors with single voltage supply can be the solution of such applications.

When the Hall Effect element is powered with a single constant voltage source, the sensor output will get a remarkable offset voltage even after a normal offset adjustment. For reducing the offset output voltage, various kinds of efforts are done, for instance, by using a DC-DC-voltage converter in order to generate an internal additional negative power supply. This causes a higher current consumption, more complicated circuit, and higher costs of the sensor system.

This paper proposes a novel method of zero offset error reduction in Open Loop Hall-Effect current sensors with single voltage supply. This method consists of a coarse zero compensation and a fine zero adjustment. By using the proposed method the zero output offset of Hall Effect current sensors under using single voltage supply can be controlled within 0.2%. This method can be applied to all Hall Effect sensors with analog output and other similar sensors, which are powered with a single voltage source.

II. ZERO OFFSET REDUCTION METHOD

A. Principle of Open Loop Hall Effect Current Sensor

An Open Loop Hall Effect current sensor consists of three main components: a toroid core with high permeability, a Hall element and electronics for signal processing etc. Fig. 1 shows the structure of an Open Loop Hall Effect current sensor. The toroid core with the effective permeability μ_r boosts the magnetic flux produced by the primary current carrying conductor [1, 4]. A Hall element is placed in the air gap of the core for sensing the flux. In order to get a reliable signal output, amplification is needed for signal processing.

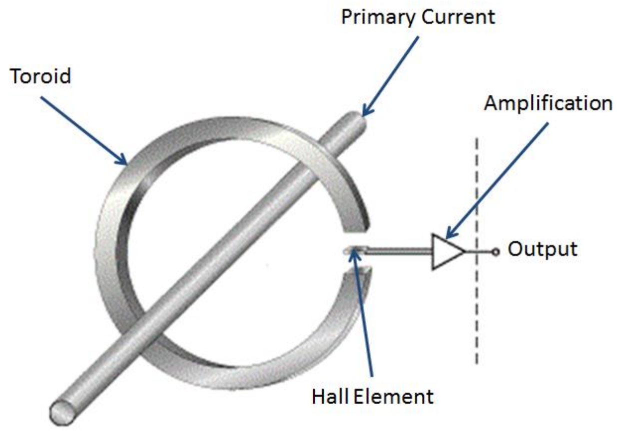

Fig. 1. Structure of an Open Loop Hall Effect current sensor

B. *Zero Offset Origin*

Fig. 2 shows a SIP package of a Hall sensor element, which has two supply input pins (+Vcc, –Vcc/GND) and two output pins (+Vh, -Vh). The Hall element is powered with one or two constant voltage (or current) sources through its input pins, in order to get a reliable linear output voltage for measuring a magnetic field. In absence of magnetic field, a voltage difference exists between the two output pins (+Vh, -Vh), due to manufacturing tolerances and inhomogeneity in the semiconductor material [1].

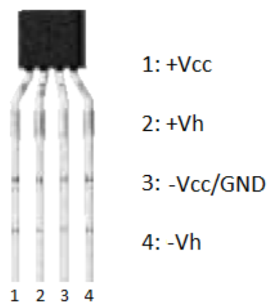

Fig. 2. Pin assignment of a Hall element

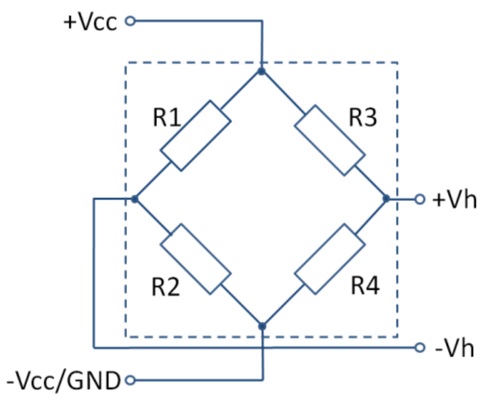

Fig. 3 Equivalent circuit of a Hall element

A Hall element can be modeled as a resistive bridge (see Fig. 3). The output voltage difference is the result of mismatches between the resistances R1, R2, R3 and R4 [6]. When the output pins (+Vh, -Vh) are connected to a differential amplifier, a zero offset voltage at the amplifier output will be caused by the voltage difference mentioned above. Therefore zero offset adjustment circuit must be built in the signal processing unit of the sensor, see Fig. 4.

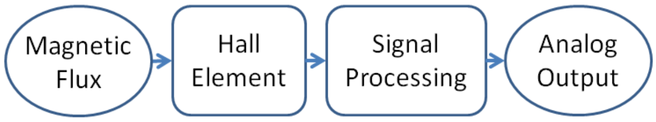

Fig. 4. Magnetic flux detection and signal processing

C. *Conventional Zero Offset Adjustment*

If the Hall element is powered with double voltage sources, the zero offset voltage can be easily eliminated by using an operational amplifier and a potentiometer (see Fig. 5).

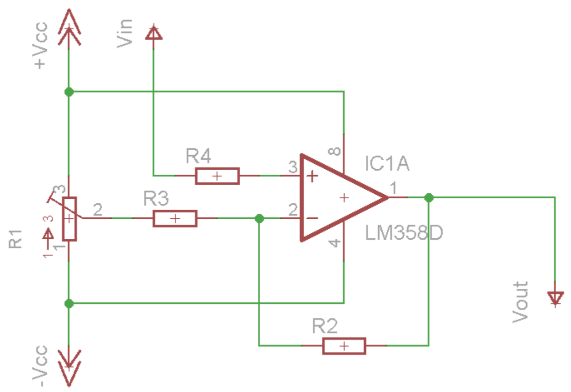

Fig. 5. Zero Offset Adjustment with Double Voltage Supplies

However, the zero offset voltage is difficult to reduce to zero under using a normal adjustment circuit (see Fig. 6) if the Hall element is powered with a single voltage source, i.e. the pin 3 and 4 are connected to the ground GND, see Fig. 2 and 3. In this case, -Vh=0 and the output voltage +Vh can be written by

$$+Vh = Vcc \times R3 / (R3+R4) \quad (1)$$

One gets +Vh=Vcc/2 when R3=R4. So a compensation voltage close to the voltage +Vh is needed for the zero offset adjustment. However, a remarkable rest offset after the compensation cannot be avoided in this case. For proving this, an experiment is done with a test circuit shown in Fig. 6.

The voltage input Vin, which comes for instance from the output of the Hall element, is connected to the non-inverting input of the operational amplifier through the resistor R4. The voltage *Vc* at the inverting input can be adjusted by the potentiometer R1 in order to get a output voltage of the amplifier approximate to zero, i.e., to the minimum of zero output voltage. Table 1 shows the minimum zero output voltage Vout in dependence to the input voltage Vin.

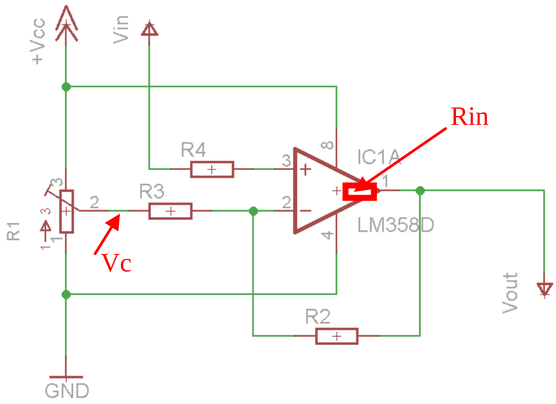

Fig. 6. Zero Offset Adjustment with Single Voltage Supply

TABLE 1. EXPERIMENT RESULTS ON TEST CIRCUIT

Compensation Voltage Vc (V)	*Input Voltage Vin (V)*	*minimum zero output Vos (mV)*
0.1008	0.09532	0.40
0.2003	0.09600	0.70
0.5000	0.47297	1.80
1.0052	0.94541	0.50
1.5028	1.4133	1.00
2.0197	1.8993	1.10
2.5066	2.3568	1.50
3.0776	2.8886	4.50
3.5032	3.2797	14.0
4.0000	3.7906	21.0
4.5083	4.2388	28.5
5.0345	4.7016	35.0

From the experiment results, one can obtain that the minimum zero offset voltage Vos at Vout increases with the input voltage Vin. The compensation voltage Vc at the inverting input is optimized in this case.

The voltage at the non-inverting port of the amplifier is approximately to Vin. The voltage at the inverting port is the same. Therefore, a higher feedback loop current at the resistor R2 is caused as follows:

$$Ic = Vin / R2 = Vcc / (2 \times R2) \quad (2)$$

Due to the exist of inner resistance Rin at the output of an operational amplifier [4], this feedback loop current Ic causes a rest offset voltage V_{off}:

$$V_{off} = Ic \times Rin \quad (3)$$

$$V_{off} = Vcc \times Rin / (2 \times R2) \quad (4)$$

Dependent on the necessary amplification factor, the zero offset voltage of an Open Loop Hall Effect current sensors can be only controlled within 30-50mV for an output voltage range of 0-5V. This means that the relative zero offset voltage is 0.6-1.0%, which is not acceptable in many current sensing applications. Thus a new solution is needed for reduction of the zero offset error.

D. Novel Method of Zero Offset Reduction

The proposed novel method for zero offset error reduction contains two stages of signal processing, see Fig. 7.

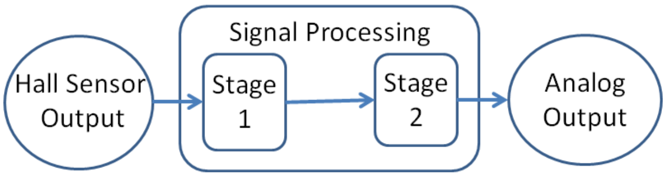

Fig. 7. Description of a novel zero offset reduction method

In the first stage, a relative high zero offset voltage under single power supply can be reduced by a coarse zero offset compensation. After the compensation there is still a rest offset voltage V_{off1}, which is caused by the feedback loop current I_{c1} at the inner output resistance Rin of the operational amplifier in the first stage, and can be calculated by equations (3) and (4). The rest zero offset voltage V_{off1} is as the input voltage Vin2 of the second stage (see Fig. 8.). It is now lower, so that the feedback loop current I_{c2} at R8 is much smaller than that in the first stage or in conventional zero offset adjustment.

The rest offset voltage can be reduced by a fine zero offset adjustment in the second stage. The feedback current I_{c2} is now dependent on the rest offset voltage V_{off1} and can be calculated by

$$I_{c2} = V_{off1} / R8 \quad (5)$$

The resulting voltage drop V_{off2} on the inner resistor Rin of the operational amplifier is determined as follows:

$$V_{off2} = I_{c2} \times Rin \quad (6)$$

$$V_{off2} = V_{off1} \times Rin / R8 \quad (7)$$

$$V_{off2} = Vcc \times Rin^2 / (2 \times R2 \times R8) \quad (8)$$

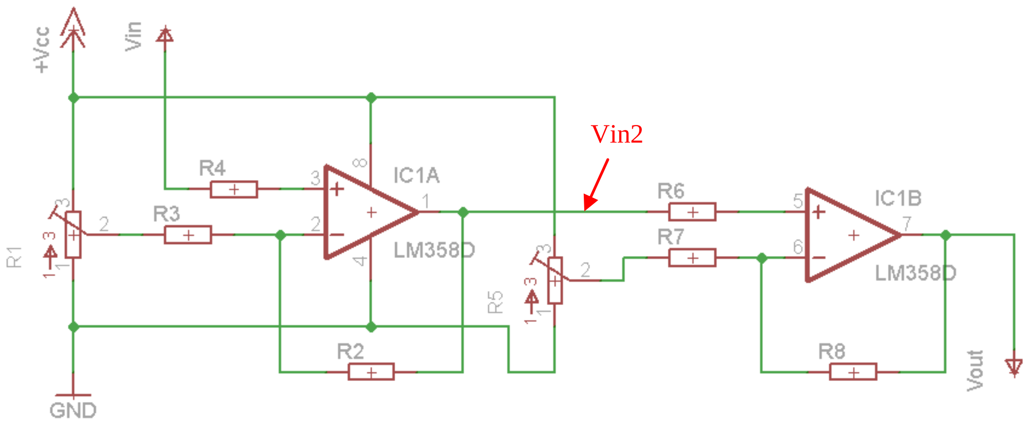

Fig. 8. Possible Implementation of the novel Zero Offset Reduction method

The inner resistance Rin of the most operational amplifier is very small, and the feedback resistors R2 and R8 are relative high. Therefore the offset after the fine adjustment is reduced to the wished level. Experiment shows that the zero offset voltage can be reduced within 10mV. This means a relative zero offset of 0.2% in the range of 0-5V, which can be tolerated in the most applications.

The use of two stage amplifications has also its benefit. According to (4), the same effect of zero offset reduction can also be achieved by choosing a very high feedback resistor R2. Nevertheless, an optimal gain factor cannot be guaranteed in this way. So for optimal gain and zero offset adjustment, the two-stage amplification according to (8) provides better results. Both feedback resistors R2 and R8 can be chosen more moderate in order to achieve the desired gain factor. Moreover, the zero offset error is reduced by the factor R8/Rin according to (4) and (8).

The advantages of this method are less power consumption, simplified circuit and higher reliability in comparison to other zero offset adjustment techniques with single power supply, e.g. by using an internal negative power supply. Compared to one stage amplification, the two-stage amplification topology provides better gain and zero offset adjustment.

III. EXPERIMENTAL SETUP

Experiments are done with an automatic testing system which is especially designed for Hall Effect current sensors [11]. Figure 9 shows the automatic testing system. It consists of a digital multimeter (1), a DC current source (2), a PC system (3) and a data acquisition device with analog and digital outputs (4).

In our experimental setup, an Agilent 34401A digital multimeter is used which provides a 6½ digit resolution and many measurement functions. It has a basic accuracy 0.0035% for DC measurements and 0.06% for AC measurements [7]. The DC current source is an EA-PS 8080-120 which has a DC current output of 0-120A. According to the data sheet, it has an accuracy ≤0.2% [8]. The NI USB-6008 is a data acquisition device, but also offers two analog outputs and 12 digital I/O pins [9]. So it can be used for system controlling with software which runs on the PC system.

It is important that the test equipment should be more accurate than the sensor under test. The measuring error of the testing system should be lower than one-fourth of the error of the sensor [10]. Due to the deviations of the DC current source (±0.2%) and the DMM (±0.01%), the measuring deviation of the whole testing system is higher than 0.2%. The most Hall Effect current sensors are defined with accuracy from ±1.0% to ±0.2%. Consequently, this system is normally not suitable for testing Hall Effect current sensors.

But with our error correction method which is described in [11], the accuracy of our testing systems can be improved to ±0.03%. Hence our experimental setup fulfills the criterion for testing and calibrating Hall Effect current sensors.

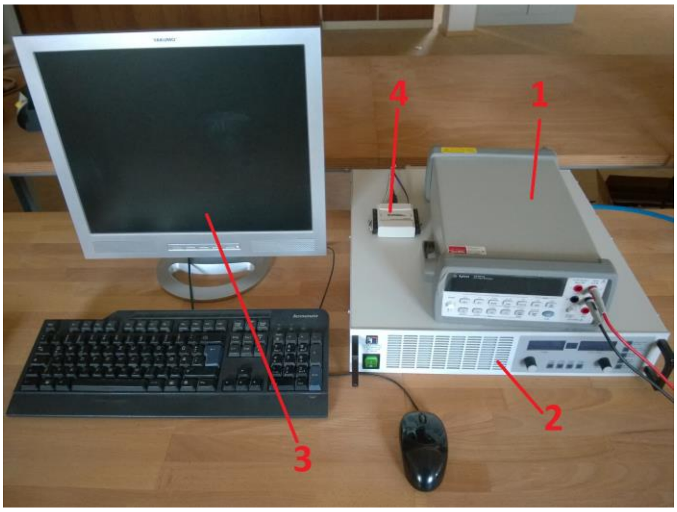

Fig. 9. Experimental Setup with Automatic Testing System for Hall Effect Current Sensors

IV. EXPERIMENT RESULTS

This novel zero offset error reduction method has been applied to an Open Loop Hall Effect current sensor powered with a single voltage supply of +12VDC. The output range is

0-10V for different measuring ranges. In the following, some experiment results are given.

For evaluating the measurement results, the accuracy and the linearity are calculated. The accuracy f_e is defined as the relative deviation between the measured and the true values:

$$f_e = 100\% \times (V_{meas} - V_{true}) / V_{range} \qquad (9)$$

The linearity error f_l describes the relative deviation of the measured values and a straight line which can be determined by the least-squares method under using all measured values. The linearity can be calculated as follows:

$$f_l = 100\% \times (V_{meas} - V_{line}) / V_{range} \qquad (10)$$

In table 2 and Fig. 10, the experiment results of the measuring range 0-30A are presented.

TABLE 2. EXPERIMENT RESULTS FOR 0-30A

Current (A)	*Voltage Output (V)*	*Accuracy (%)*	*Linearity (%)*
0.000	0.008	0.080	0.180
3.750	1.240	-0.100	0.003
7.500	2.482	-0.180	-0.074
11.25	3.729	-0.210	-0.102
15.00	4.982	-0.180	-0.069
18.75	6.232	-0.180	-0.066
22.50	7.484	-0.160	-0.044
26.25	8.743	-0.070	0.049
30.00	10.00	0.000	0.122

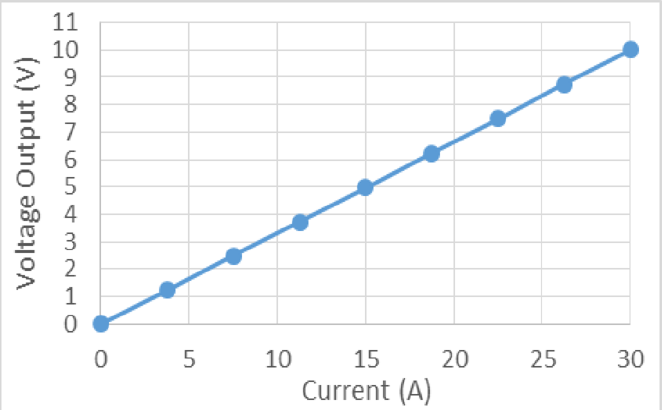

Fig. 10. Experiment results for 0-30A

In this measuring range, the accuracy of the sensor is defined with ±0.25% and the linearity is about ±0.2%.

The same sensor has also been adjusted for the measuring range 0-52.5A. Table 3 and Fig. 11 give the experiment results. For this measuring range, an accuracy of ±0.3% and a linearity of ±0.25% are realized.

TABLE 3. EXPERIMENT RESULTS FOR 0-52.5A

Current (A)	*Voltage Output (V)*	*Accuracy (%)*	*Linearity (%)*
0.000	0.008	0.080	0.245
7.500	1.407	-0.216	-0.049
15.00	2.830	-0.271	-0.102
22.50	4.256	-0.297	-0.126
30.00	5.686	-0.283	-0.109
37.50	7.120	-0.229	-0.053
45.00	8.556	-0.154	0.024
52.50	9.999	-0.010	0.170

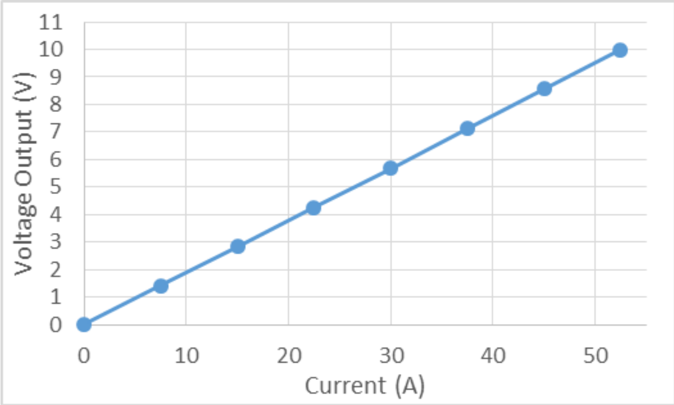

Fig. 11. Experiment results for 0-52.5A

In both experiments, the zero offset have been reduced to 8mV, which means 0.08% in the output range of 0-10V. These results indicate the significant reduction of zero offset error by the proposed novel method for Open Loop Hall Effect Current sensors with single power supply. Thanks to the reduction of the offset output voltage, the accuracy and linearity of the open loop current sensor under test can be controlled within 0.5%. It is a remarkable improvement for open loop current sensors. The accuracy and linearity of the most open loop current sensors is 1.0%.

This novel zero offset reduction method can be applied not only to Hall Effect sensors, but also to magnetoresistive sensors and inductive sensors for magnetic field measurement and current measurement etc.

V. CONCLUSIONS

In this paper, a novel zero offset reduction method has been proposed, which has been used in Hall Effect current sensors. From the results one can draw the following conclusions:

- Due to manufacturing tolerances and inhomogeneity in the semiconductor material, a voltage offset can be measured at the two output pins of a Hall Element in absence of magnetic field. This voltage offset has a negative effect on sensor linearity, accuracy and resolution.

- It is necessary to reduce the offset by a zero offset compensation method. Therefore, additional signal processing with zero offset adjustment is needed for Hall Effect current sensors.
- If the sensor is powered with double power supplies, the offset can be easily eliminated. However, double power supplies are exceptions in many applications.
- For single power supply, the zero offset adjustment is much more difficult. A compensation voltage near to one half of the supply voltage is needed. Nevertheless, a noticeable amount of zero offset voltage still remains in the level of 30mV~50mV after zero offset adjustment for an output range of 0-5V.
- Experimental results have shown that this rest offset increases with the voltage at the inverting port of an operational amplifier. This can be explained by the current of the feedback resistance and the voltage drop on the inner resistance of the operational amplifier, see equations (2)-(8).
- For eliminating this rest offset, a second zero offset adjustment stage is introduced. The offset voltage can be reduced within 10mV
- By using the proposed method the offset error of open loop current sensors can be controlled within 0.2% so that the linearity and accuracy of 0.5% is realizable.
- The advantages of this method are less power consumption, simplified circuit and higher reliability in comparison to other zero offset adjustment techniques with single power supply.
- The two stage amplification topology provides better gain and zero offset adjustment for the sensor production.

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