Temperature and nonlinear compensation of Hall current sensor based on least square method

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Abstract. In view of the temperature characteristics and non-linear problems of Hall current sensor, this paper introduces a method of temperature and nonlinear compensation based on least square method. On the basis of the curve fitting by the least square method, it is verified by the test data. This method can better compensate the influence of temperature and nonlinearity on the measurement errors of the Hall current sensor.

1. Introduction

As a basic signal detection component, sensor is an important part of intelligent automation equipment. Accuracy, digitalization and miniaturization are its current development direction [1]. Hall current sensor, with its superior adaptability and load capacity, plays an important role in the development and application of intelligent energy sensors, and the degree of linearization and temperature variation are the main factors affecting the accuracy. The data deviation caused by the temperature on the Hall current sensor will affect the overall performance and accuracy of the device itself; Linearity is also an important indicator to describe its static characteristics, and its size directly affects the measurement accuracy.

In the traditional energy sensor, the symmetrical nature of the structure is mainly used to eliminate the errors; In the primary form of intelligent sensors, the "patchwork compensation" is mainly carried out by adding hardware circuit, which not only has unsatisfactory compensation effect, but also has disadvantages such as cumbersome circuit and high cost [2]. In the intelligent era of combining sensors and microprocessors, it is more suitable to use the method of software level to compensate the measured data. There are many methods of error compensation. This paper introduces a kind of compensation method which uses the least square method to fit the curve. After the curve relation between output and variable is obtained by fitting, the embedded software algorithm is used to automatically compensate the output value under different variables.

2. Working principle of Hall current sensor

Hall sensor uses Hall effect to measure current or voltage [3]. The physical principle of Hall effect is shown in figure 1. An additional electric field is added between the electric field and the magnetic field. When the current $I_H$ passes through the semiconductor or conductor of the external magnetic field $B$, the semiconductor hole carriers are deflected by the Lorentz force, resulting in potential difference, that is, the Hall voltage $U_{H}$, across the semiconductor or conductor.
Hall voltage reflects the proportional relationship between magnetic field and induced voltage, and its expression is shown in formula (1):

\[ U_H = \frac{R_H}{d} \times I_H \times B \]  

(1)

Where, \( I_H \) is the current through hall material, \( B \) is the applied magnetic field strength, \( d \) is the thickness of the Hall material, \( R_H \) is the Hall coefficient of the Hall element and is related to the Hall element material itself.

The overall principle of the Hall current sensor is shown in Figure 2. The measured current \( I \) produces a magnetic induction intensity \( B \) in the iron core, and \( B \) is proportional to \( I \). Magnetic field \( B \) passes through Hall element to generate Hall voltage. The expression of Hall voltage can be written as follows:

\[ U_H = \frac{R_H}{d} \times I_H \times K \times I \]  

(2)

Where, \( I \) is the measured current; \( K \) is a constant.

Let \( \frac{R_H}{d} \times I_H \times K = C \)  

(3)

Namely, \( U_H = C \times I \)  

(4)

If the influence of magnetization of iron core and temperature is not considered, \( C \) is a constant, but because Hall current transformer is greatly affected by temperature, and there is inevitably excitation current in the system, the formula (4) is not completely consistent with the actual situation [4, 5]. Therefore, it is necessary to compensate the temperature drift and linearity of the system when high-precision measurement is required [6, 7].
3. The principle of least square curve fitting

As a mathematical optimization technique, the least square method can find the best matching function of a set of data by minimizing the sum of squares of errors, which is widely used in curve fitting and error compensation in engineering. The least square method uses the simplest method to obtain some absolute unknowable truth values, thus obtaining the minimum sum of squared errors [8, 9].

Assuming the final fit function is \( f(x) \), the sum of squared errors is:

\[
S_E = \sum_{i=1}^{m} (f(x_i) - y_i)^2 \tag{5}
\]

If \( f(x) \) is selected as the straight line \( y = Ax + B \) as the best fit function for the given data \((x_i, y_i)\), \(i=0,1,...,m\), it is called straight line fitting or linear fitting.

Then the sum of the square errors of formula (5) can be expressed as:

\[
R(A, B) = \sum_{i=1}^{m} (Ax_i + B - y_i)^2 \tag{6}
\]

Obviously, this problem can be transformed into extremum problem. According to the conditions of extremum of multivariate function, we can get:

\[
\begin{align*}
\frac{\partial R(A, B)}{\partial A} &= 2\sum_{i=1}^{m} (Ax_i + B - y_i)x_i = 0 \\
\frac{\partial R(A, B)}{\partial B} &= 2\sum_{i=1}^{m} (Ax_i + B - y_i)y_i = 0
\end{align*}
\]

After finishing, there are:

\[
\begin{align*}
\left( \sum_{i=1}^{m} x_i^2 \right) A + \left( \sum_{i=1}^{m} x_i \right) B &= \sum_{i=1}^{m} x_i y_i \\
\left( \sum_{i=1}^{m} x_i \right) A + mB &= \sum_{i=1}^{m} y_i
\end{align*}
\]

Equation (8) is the linear equations of parameters A and B, and its matrix expression is as follows:

\[
\begin{bmatrix}
\sum_{i=1}^{m} x_i^2 & \sum_{i=1}^{m} x_i \\
\sum_{i=1}^{m} x_i & m
\end{bmatrix}
\begin{bmatrix}
A \\
B
\end{bmatrix} =
\begin{bmatrix}
\sum_{i=1}^{m} x_i y_i \\
\sum_{i=1}^{m} y_i
\end{bmatrix}
\tag{9}
\]

It can be proved that the coefficient matrix of this linear equation is a symmetric positive definite matrix, so its existence has a unique solution [10]:

\[
A = \frac{D_y}{D}, B = \frac{D_y}{D}
\tag{10}
\]

In equation (10),
4. Temperature compensation based on least square method

The Hall current sensor of model HOS-100C-SP2 produced by Shandong Yuanxing Electronics Co., Ltd. was selected as the test object. The input current of the sensor is fixed to 80A, and the primary/secondary ratio is 20:1. The temperature during the measurement gradually increases from the lowest temperature (-40℃) to the highest temperature (85℃) in the working range of the sensor, and the measurement results are shown in Table 1.

| Temperature (°C) | Output value (A) | Error value (A) |
|------------------|------------------|-----------------|
| -40              | 3.85085          | 0.14915         |
| -25              | 3.93319          | 0.06681         |
| 0                | 3.99531          | 0.00469         |
| 25               | 4.02466          | -0.02466        |
| 50               | 4.05716          | -0.05716        |
| 70               | 4.08411          | -0.08411        |
| 85               | 4.10263          | -0.10263        |

It can be seen that the sensor has different degrees of error at different temperatures, which may cause the secondary connection device to malfunction or refuse. Aiming at this problem, this paper adopts the compensation method based on the least squares method described above, and obtains the linear compensation coefficient by deriving the error value by curve fitting.

Suppose the fitting curve equation is:

\[ Y = AX + B \]  \tag{11}  

Substitute the calculated parameters into formula (8):

\[ A = \frac{D_1}{D} = -0.0018, \quad B = \frac{D_2}{D} = 0.0358 \]

Thus, the curve \( Y = -0.0018X + 0.0358 \) after error minimization is obtained. As can be seen from figure 3, the error points measured in the experiment are evenly distributed around the fitting curve.
As can be seen from table 2, after temperature compensation, the output value of the system is closer to the theoretical output, greatly reducing the influence of temperature on the output value of the sensor.

| Temperature (°C) | Output value after compensation (A) | Error value after compensation (A) |
|-----------------|-------------------------------------|-----------------------------------|
| -40             | 3.9587                              | 0.0413                            |
| -25             | 4.01399                             | -0.01399                          |
| 0               | 4.03111                             | -0.03111                          |
| 25              | 4.01546                             | -0.01546                          |
| 50              | 4.00296                             | -0.00296                          |
| 70              | 3.99391                             | 0.00609                           |
| 85              | 3.98543                             | 0.01457                           |

5. **Nonlinear compensation based on least square method**

In order to ensure the singularity of variables, when considering the nonlinear problems of the system, ensure that the test is always carried out at a normal temperature environment, namely 25°C. The Hall current sensor model HOS-100C-SP2 produced by Shandong Yuanxing Electronics Co., Ltd. is still selected as the test object. The current to be measured is gradually increased from 2.5A to 45A, and the primary/secondary ratio is 2:1. Also based on the least squares theory, the compensation coefficients $A'=0.499$, $B'=0.0023$ can be obtained by incorporating the actual test datas into formula (8) after processing, that is, the linearization function of the system is $Y=0.499X+0.00326$. After compensation, the degree of linearization of the system is improved, and the comparison of datas before and after compensation is shown in table 3. As can be seen from table 3, the maximum precision of the system was reduced from 0.4% to 0.2%.

![Figure 3 Output error curve after temperature compensation](image-url)

**Table 3 Results after temperature compensation of hall current sensor**
### Table 3 Results before and after nonlinear compensation of Hall current sensor

| The input values (A) | Output value before compensation (A) | Precision before compensation (%) | Output value after compensation (A) | Precision after compensation (%) |
|----------------------|-------------------------------------|-----------------------------------|-------------------------------------|----------------------------------|
| 2.5                  | 1.2531                              | 0.248                             | 1.2503                              | 0.024                            |
| 5                    | 2.4937                              | 0.252                             | 2.5028                              | 0.112                            |
| 15                   | 7.5044                              | 0.058                             | 7.5128                              | 0.170                            |
| 25                   | 12.552                              | 0.416                             | 12.503                              | 0.182                            |
| 40                   | 20.009                              | 0.045                             | 20.0378                             | 0.189                            |
| 45                   | 22.5518                             | 0.230                             | 22.5428                             | 0.190                            |

6. **Practical application of error compensation**

The error compensation based on the least squares method can be roughly divided into three cases in practical applications:

1. When the error of hall current sensor is mainly caused by temperature, a single temperature compensation can be adopted. The temperature compensation curve is stored in the single-chip microcomputer, and the current operating temperature of the Hall current sensor is detected by the temperature sensor, and the data collected by the sensor is corrected according to the change of the current working temperature, so as to realize the real-time temperature compensation.

2. When the temperature has little effect on the hall current sensor, temperature compensation is not needed, and the linearity is not within the allowable range, the nonlinear compensation formula is used to modify the measured data, so as to improve the measurement accuracy of the system.

3. When the Hall current sensor needs both temperature compensation and linearity correction, there are two variables, temperature and input. Theoretically, the problem should be solved by solving multivariable fitting equation, a binary linear regression equation is determined by least squares method [11], and the data can be compensated by this equation. The author will carry out further experimental research.

7. **Conclusion**

Based on the theory of least square method, this paper improves the algorithm on the software level of Hall current sensor. Taking the compensation curve method, the corresponding measurement data of different temperature and different input currents of the system are compensated accordingly. While improving the linearization level and temperature drift of the system, it does not add additional hardware circuits, the development direction of accurate, digital and miniaturized intelligent sensors is positively responded. The data analysis before and after compensation also shows that the method proposed in this paper is effective and feasible to improve the accuracy of Hall current sensor.

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