Simulation and Design of DC Sensor Based on Tunnel Magnetoresistance

Zechun Chen¹, Hong Shi¹, Cong Zhao¹ and Yue Chen²,*
¹Marketing Service Center (Measurement Center) of State Grid Hubei Corporation, Wuhan, China
²Heilongjiang Electrical Instrument Engineering Research Center Co., Ltd., Harbin, China.

*Corresponding author email: 736057854@qq.com

Abstract. In order to measure the DC current measurement, a method of current measurement and interference error elimination based on tunnel magnetoresistance (TMR) DC sensor is established. Firstly, the basic principle of TMR sensor is described, and its open-loop transfer function is derived, and the parameter variables related to its open-loop gain are analyzed; an adaptive filtering algorithm based on least mean squares (LMS) is proposed to detect the magnetic induction intensity. Taking three magnetic sensors as an example, the magnetic field estimation value under this condition is calculated. Finally, the correctness and effectiveness of the design method are verified by simulation.

1. Introduction
Magnetoresistive sensor has the characteristics of small size, low cost, low power consumption and high response frequency, which has been widely used in the industrial field. Magnetoresistive sensors include anisotropic magnetoresistance sensor (AMR), giant magnetoresistance sensor (GMR), and tunnel magnetoresistance sensor (TMR) [1-4]. Compared with AMR sensor and GMR sensor, TMR sensor has higher sensitivity and lower temperature error. However, the linearity of TMR sensor is not ideal and the hysteresis error is large, which affects the measurement accuracy. In order to solve the interference of magnetic field and other factors on measurement accuracy, In [5], the optimal and suboptimal steady-state filtering schemes based on Kalman filtering algorithm are designed. However, the optimal steady-state filter is limited because it depends on the system state characteristic information, because in the actual system, the state information is unknown, which is also the reason for the need to measure the current information. As classical adaptive algorithm, the least-mean-squares (LMS) algorithm is linear to the complexity of adjustable parameters and has good robustness to external disturbances.

In this paper, the basic principle of TMR sensor is analyzed firstly, and the adaptive algorithm based on LMS is deduced according to the magnetic field environment to improve the measurement accuracy. Then, the estimation results are obtained by combining the adaptive algorithm with the sensor model. Finally, the correctness and effectiveness of this algorithm are verified by simulation.

2. Basic Principle Of TMR Sensor
Fig. 1 shows the open-loop structure of TMR current sensor. The structure of TMR current sensor is used with high-permeability open magnetic concentrating ring. The current-carrying wire passes through the inner part of the magnetic concentrating ring, and there is a rectangular air gap on the
magnetic concentrating ring. The TMR chip is placed in the air gap, and the size of the air gap depends on the size of the TMR chip. The current flowing through the conductor is $I_p$. Because the magnetic focusing ring uses high permeability materials, its permeability is far greater than that of air. Therefore, the magnetic field generated by conductor current is gathered in the magnetic concentrating ring. The TMR chip in the air gap converts the magnetic field strength into the output voltage signal. At the same time, the output voltage is amplified to the appropriate level through the signal amplification circuit, which is convenient for subsequent measurement. In the linear region of the hysteresis loop, the magnetic induction strength $B_p$ in the air gap of the magnetic concentrating ring is directly proportional to the current $I$ to be measured, while the output voltage of the TMR chip is proportional to the magnetic induction strength $B_p$. Therefore, the output voltage of the TMR current sensor is linearly related to the measured current $I_p$.

![Figure 1](image)

**Figure 1.** Open-loop structure diagram of TMR current sensor.

Fig. 2 shows the Open-loop junction transfer function of TMR current sensor. In order to further analyze the characteristics of the open-loop structure, a mathematical model is established. The voltage $V_{out}$ is the output of the system and the primary current $I_p$ is the input of the system. $B_p$ represents the magnetic induction intensity produced by the primary current $I_p$ in the magnetic concentrating ring. The coefficient $K$ is used to define the relationship between $I_p$ and $B_p$: $K=\frac{B_p}{I_p}$. According to Ampere's loop theorem, $K$ can also be expressed as:

$$KV = \frac{\mu_0}{d}$$  \hspace{1cm} (1)

In which, $d$ is the width of air gap of the magnetic concentrating ring, and $\mu_0$ is the permeability of vacuum. The TMR chip is placed in the air gap of magnetic concentrating ring and its output voltage is in exact proportion to the magnetic strength in the air gap, i.e.

$$V_{s} = K_s B_p$$  \hspace{1cm} (2)

In the formula, $K_s$ is the sensitivity of TMR chip in open-loop structure. Hence, the transfer function of the whole open-loop system is

$$S_p(s) = \frac{V_{out}(s)}{I_p(s)} = KK_s G_a$$  \hspace{1cm} (3)

In this equation, $G_a$ is the transfer function of operational amplifier. Operational amplifier can be regarded as first-order system to represent its open-loop system:

$$G_a = \frac{K_a}{1 + \tau_a s}$$  \hspace{1cm} (4)

In the formula, $K_a$ is the static gain of operational amplifier, $\tau_a$ is the time constant of operational amplifier in open-loop system.

Hence, the first-order transfer function of open-loop TMR current sensor can be gotten:

$$S_p(s) = \frac{V_{out}(s)}{I_p(s)} = \frac{KK_s G_a}{1 + \tau_a s}$$  \hspace{1cm} (5)

It can be seen that the gain of open-loop TMR current sensor is related to the sensitivity of TMR chip, the gain of operational amplifier circuits and the air gap width of magnetic concentrating ring.
3. Adaptive Filtering Algorithm Based on LMS

3.1. The Fundamental Principles of LMS Algorithm

In the non-contact current measurement method based on magnetic sensor, the measurement accuracy is disturbed by external magnetic field, in this paper, the adaptive elimination of magnetic interference is realized by using the least-mean-squares (LMS) algorithm, which can be shown by the following equation:

\[
\begin{align*}
\bar{B}(t) &= \sum_{k=1}^{M} w_i(t) B_i(t) \\
B_i(t+1) &= w_i(t) + \mu B_i(t) e(t) \\
e(t) &= B_{\text{tar}}(t) - \bar{B}(t)
\end{align*}
\]  

(6)

In this equation, \( \bar{B}(t) \) represents the filtered magnetic induction intensity, \( w_1(t), w_2(t),...w_M(t) \) is the weight at time \( t \), \( M \) is the number of filter taps, \( \mu \) is the learning rate, which is a constant, \( B_{\text{tar}}(t) \) is the true value of the magnetic induction intensity generated by the current to be measured, and \( B_i(t) \) is the output value of magnetic sensor, which means the detected magnetic induction intensity.

3.2. The Fundamental Principles of LMS Algorithm

In consideration of the limited space and the power consumption, we make three magnetic sensors uniformly distributed around the conductor to be tested, as Fig.4 shown, and use the output of the magnetic sensor within a period of time as the input of the filter system. In theory, based on Biot-Savart Law, the magnetic induction intensity detected by magnetic sensor \( S_i \) \( (i = 1,2,3) \) can be depicted as

\[
B_i(t) = \frac{\mu}{2\pi R} \left[ I_i(t) + \frac{(D \cos \phi - 1)}{(D^2 + 1 - 2D \cos \phi)} I_i(t) \right]
\]

(7)

It is defined that

\[
\phi = \phi_0 + \frac{2\pi}{N}(i-1), i = 1,2,3
\]

(8)
The current flowing through conductor 1 is the target current and the current in conductor 2 is the disturbance current. $D$ is the distance from conductor 1 to conductor 2. $B_\phi$ and $B_r$ are components parallel to TMR sensor sensitive direction, $B_r$ is the component along the radial direction of the target current-carrying conductor, and $B_1$ is the current detected by sensor $S_1$. Taking the output of a magnetic sensor over a period of time as input, it can be gotten that:

$$\begin{align*}
\vec{B}_1(t) &= \sum_{k=1}^{M} w_{1k}(t) \vec{B}_i(t) \\
\vec{B}_2(t) &= \sum_{k=1}^{M} w_{2k}(t) \vec{B}_i(t) \\
\vec{B}_3(t) &= \sum_{k=1}^{M} w_{3k}(t) \vec{B}_i(t) \\
e(t) &= \frac{B_1(t) + B_2(t) + B_3(t)}{3} - \vec{B}(t) \\
\{ w_{ik}(t+1) = w_{ik}(t) + \mu B_i(t)e(t), i = 1, 2, 3 \} \tag{9}
\end{align*}$$

Among them, $B_1(t), B_2(t), B_3(t)$ are the magnetic induction intensity measured by three magnetic sensors at time $t$, $\vec{B}_1(t), \vec{B}_2(t), \vec{B}_3(t)$ are the filtered value. The final estimate based on the above equation is:

$$B_c(t) = \frac{\vec{B}_1(t) + \vec{B}_2(t) + \vec{B}_3(t)}{3} \tag{10}$$

Figure 4. Magnetic array model based on LMS algorithm.

4. Result of Simulation

Based on the above theory, a numerical simulation of the ratio of the inter-conductor distance $D$ to the sensor's conductor distance to be measured, $R$, is required to analyze the effect of this ratio on the magnetic field at the test point location. It is assumed that the current to be measured, $I_1(t)$, and the disturbance current, $I_2(t)$, are sinusoidal signals at 50 Hz frequencies with amplitude magnitudes of 500A, 1000A and 1500A, respectively.

Case 1: Keeping $D$ constant at 0.12m, change the value of $D/R$ by changing the value of $R$. If $\Phi_1$ is 0, then the magnetic induction intensity is calculated by equation (7), and the estimated value of magnetic field is calculated by equation (9) (10), and the root mean square error between the estimated magnetic field and the target magnetic field is obtained, as shown in Figure 5, when $D/R$ is 2, root mean square error is minimized.
Figure 5. Root mean square error variation with $D/R$.
Case 2: Make the amplitude of both the measured current and the interfering current be 500A, keep the $D/R$ as 2, change the value of $R$, and the final result is shown in Figure 6. As we can see, when $R$ is 0.06m, the root mean square error is the smallest.

Figure 6. Variation of root mean square error with $R$.
Case 3: According to the simulation results of Case 1 and 2, set $R$ to 0.06m, $D$ to 0.12m, $\Phi_1$ to 0. Make the interference current from $I_2(t)$ from $I_1-250A$ to $I_1+250A$ change, The simulation results are shown in Table 1, where $B_c$ is the estimated value of the filtered magnetic inductance, and $B_0$ is the magnetic induction intensity generated by the target current. It can be seen that $I_1=1500\sin(100\pi t)$A, $I_2=1550\sin(100\pi t)$A, the root mean square error is the largest, 89.44%, at this time, the magnetic induction intensity waveform after filtering and the magnetic field waveform generated by the target current are shown in Fig. 7.

Table 1. Root mean square error at different amplitudes.

| $I_1$  | $I_2$      | $B_0$ | $B_c$ | RMSE% |
|-------|------------|-------|-------|-------|
| 500   | $I_1+50A$  | 16.67 | 16.63 | 3.64  |
|       | $I_1-250A$ | 16.28 | 28.08 |       |
| 1000  | $I_1+50A$  | 33.33 | 34.19 | 58.12 |
|       | $I_1-250A$ | 32.53 | 58.88 |       |
| 1500  | $I_1+50A$  | 50.00 | 51.34 | 89.44 |
|       | $I_1-250A$ | 49.59 | 33.72 |       |

Figure 7. Filtered magnetic field, target magnetic field and error curve.

5. Conclusions
In this paper, a direct current sensor based on tunneling magnetoresistance is designed. Based on the principle of TMR sensor, LMS combined with adaptive filtering algorithm can improve the anti-disturbance ability and measurement accuracy of the sensor. Then three magnetic sensors are taken
as examples to establish the magnetic array model, which can calculate the estimated value of magnetic induction intensity, that is, effectively reduce the hysteresis error; finally, the simulation results show that the design method can eliminate the magnetic field generated by external interference current at the sensor position.

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