Current Measurement for Curved Conductor based on 3-D Coreless TMR Sensor Array

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Abstract. Magnetic sensor arrays have been widely used in current measurement due to their advantages of small size, low power consumption, high sensitivity, wide bandwidth, and large dynamic range. However, researches in recent years all assume that the conductor is long-straight, while in actual engineering the conductor is usually curved. And the error introduced by curvature has not been searched until now. In this paper, a correction method based on circular 3D magnetic sensors array is proposed. The simulation results show theoretically that the method can greatly reduce the error. 3-D tunnel magnetoresistance (TMR) chip is selected as the magnetic sensors of the circular array in laboratory experiment, and the experiment errors can be reduced to around 1%. The simulation and experiment results verify that the correction method can improve the accuracy of the current measurement.

1. Introduction

In the power system, safety and stability are the most important considerations [1,2]. Thus the detection of current is an important object. Current transformers must be able to detect the fault current immediately in order to maintain the stability of the distribution network [3].

Traditional current transformers have low bandwidth, saturated cores, and large size, which cannot meet the needs of measurement [4,5]. Rogowski coils are not very accurate, and cannot measure direct current flow [6,7]. Conventional Hall current sensors are open-loop (direct-discharge) [8] and closed-loop (magnetic-balanced) [9], but the range of applications is limited by possible core saturation and remanence problem (especially at high currents).

Nowadays abundant studies have focused on coreless magnetic sensor array to measure the current. AMR and GMR sensors are widely used as the chips of the arrays [10]. TMR sensors [11,12] have better linearity, higher sensitivity, excellent temperature stability, and ultra-low power consumption. So in this paper TMR chips are selected as the magnetic sensors chips.

Most of the existing studies are based on the assumption that the conductor is long-straight. While in actual engineering, conductors will have a certain degree of curvature due to the gravity and the physical properties. The curvature of the conductor influences greatly to the accuracy of the current measurement. Thus it is very necessary to find a new method to reduce the measuring error caused by the curvature. Therefore, this paper proposed a correction algorithm for curved conductor based on 3-D TMR magnetic sensors array. The paper presents theoretical and experimental results subsequently.
2. Principle
The 3-D TMR sensor array was adopted and its structure is shown in Figure 1.

![Figure 1. Structure of 3-D TMR sensor](image)

2.1. Method for Curved Conductor
In actual engineering, the conductor will have a certain degree of curvature due to gravity and physical properties. The main current measurement method is a one-dimensional non-positioning algorithm, which means that the sensors can only measure the magnetic field in the tangential direction. In this paper, a model for non-positioning algorithm is set up as shown in Figure 2.

![Figure 2. The model of 3-D TMR array for curved conductor using non-positioning algorithm](image)

In the 3-D space, the algorithm is based on Biot-Savart law which is shown as

\[
B = \frac{\mu_0 I}{4\pi} \times \frac{d\vec{l} \times \vec{\rho}}{\rho^3}
\]  

where \( \mu_0 \) is the vacuum permeability, \( \rho \) is the vertical distance between field point and conductor. \( d\vec{l} \) is the current segment.

As shown in Figure 2, the conductor I is a circular arc with radius b, the curved angle is \( \phi \) (\( \phi_1, \phi_2 \)), the conductor and the sensor array intersect at point A, the radius of the circular array is \( R_0 \), the centre of the circle is point B. Set the centre of curvature of the curved conductor the coordinate origin point
O, the sensor is located in the plane of the x-y, the coordinates of point A are (b, 0, 0), the coordinates of the conductor source point P' are (b\cos \varphi, 0, b\sin \varphi). If point A is deviated from the sensor center B, assuming the eccentric radius is r and the eccentric angle is \alpha, then the coordinates of point B are (b-b\cos \alpha, -b\sin \alpha, 0). \theta_p is the angle between the x-axis and the line between TMR chip S_1 and B, then the coordinates of TMR chips S_k are as follows.

\[ S_k = (b-r\cos \alpha + R_s\cos(\frac{2\pi(k-1)}{N_1} + \theta_p), -r\sin \alpha + R_s\sin(\frac{2\pi(k-1)}{N_1} + \theta_p), 0) \]  

(2)

where \( k = 1, 2, 3, ... N_1 \) and \( N_1 \) is the total number of TMR chips on the sensors array. \( IdI \) is the source current segment of the source point P'.

\[ IdI = I \cdot e \cdot b \cdot d\varphi = I \cdot b \cdot d\varphi \cdot (-\sin \varphi, 0, \cos \varphi) \]  

(3)

Substituting (3) into (1), the magnetic susceptibility \( B_k \) of the point where the TMR chip \( S_k \) is located can be obtained.

\[ B_k = \frac{\mu_0 I}{4\pi} \int_{\theta_p}^{\pi} (-\sin \varphi, 0, \cos \varphi) \times |R_s|^2 d\varphi \]  

(4)

where \( R_s \) is the displacement from the field point \( S_k \) to the source point \( P' \).

\[ R_k = P' S_k = (b-r\cos \alpha + R_s\cos(\frac{2\pi(k-1)}{N_1} + \theta_p), -b\cos \varphi, -r\sin \alpha + R_s\sin(\frac{2\pi(k-1)}{N_1} + \theta_p), -b\sin \varphi) \]  

(5)

The tangential vector of the point where the TMR chip is located is

\[ e_t = (\cos(\frac{2\pi(k-1)}{N_1} + \theta_p), \frac{\pi}{2}, \sin(\frac{2\pi(k-1)}{N_1} + \theta_p), \frac{\pi}{2}, 0) \]  

(6)

The tangential component of \( B_k \) along the circle is

\[ B_{tk} = B_k \cdot e_t \]  

(7)

Then the value of the current obtained is

\[ I_c = \frac{2\pi R_e}{N_1 \mu_0} \sum_{k=1}^{N_1} B_{tk} \]  

(8)

Obviously, the obtained current is somewhat different from the measured current value, with an error

\[ e_c = \frac{I_c - I_1}{I_1} \cdot 100\% \]  

(9)

In the above equation, \( I \) represents the actual current of the conductor.

2.2. Correction Method for Curved Conductor

In this paper, a correction method for curved conductor is proposed based on 3-D TMR chips to reduce the error. The 3-D TMR chips can measure magnetic flux density in the x, y and z directions simultaneously. The model is shown as Figure 3.
Figure 3. The model of circular 3D TMR array for curved conductor using the correction algorithm.

The unit vectors for $x'$, $y'$, and $z'$ are $e_{x'} = (\cos \theta_p, \sin \theta_p, 0)$, $e_{y'} = (-\sin \theta_p, \cos \theta_p, 0)$, and $e_{z'} = (0, 0, 1)$, respectively, and the measured magnetic field components are

$$
\begin{align*}
B_{x'} &= B \cdot e_{x'} \\
B_{y'} &= B \cdot e_{y'} \\
B_{z'} &= B \cdot e_{z'}
\end{align*}
$$

According to equation (10), there are 12 nonlinear groups of equations. There are seven unknown variables: $I$, $b$, $\varphi_1$, $\varphi_2$, $r$, $\alpha$, and $\theta_p$. Since the group of equations is nonlinear, its numerical solution can be obtained by nonlinear least squares method, with steps shown in Figure 4.

![Schematic diagram of current measurement method for bent conductor](image-url)
Then the measurement error is as follows:

\[ \varepsilon_s = \frac{I_s - I_i}{I_i} \times 100\% \]  \hspace{1cm} (11)

3. Simulation

3.1. Effective Range of Conductors

When calculating the magnetic field around a long-straight conductor, the length of the conductor is limited. Using equation (1) will inevitably bring some calculation error. Therefore, this paper analyses the relationship between the length of the conductor and the calculation error, and finds out the length of the conductor when the error is no larger than 1%. The range between this length is the object that the paper needs to study. The magnetic field generated by conductor currents outside this range has a negligible effect on the TMR sensors.

Figure 5 shows the difference between the calculation of the surrounding magnetic field for the infinite long straight conductor and the finite long straight conductor.

![Figure 5. Infinite and finite long straight wire](image)

Calculate the magnetic field around the conductor based on Biot-Savart law, for infinite long straight wire, the result can be obtained by equation (12)

\[ B_1 = \frac{\mu_0 I}{2\pi \rho} \]  \hspace{1cm} (12)

For finite long straight conductor, the result can be get by equation (13)

\[ B_2 = \frac{\mu_0 I}{4\pi \rho} (\sin \alpha_1 + \sin \alpha_2) \]  \hspace{1cm} (13)

Suppose the array radius \( r = 15.6 \) mm where the 3-D TMR sensors are placed, \( I_{exact} = 100 \) A. \( L = 0.05 \) m-1m. The error between \( B_1 \) and \( B_2 \) is calculated by equation (14)

\[ e = \left| \frac{B_1 - B_2}{B_1} \right| \times 100\% \]  \hspace{1cm} (14)

The result is shown in Figure 6.
Figure 6. Error of B with the variation of wire length

It can be seen from the figure that the error of B decreases as the length of the wire increases. When the length of the wire is 0.21m, the error approaches 1%. Therefore, only the variation of B in the range of 0.21 m is considered.

3.2. Simulation Results

From the previous section, it can be deduced that the magnetic field generated by the out-of-range current has a negligible effect on the TMR component when the wire lengths are greater than 0.21 m. Therefore, the currents measured in the experiments in this paper are within this range.

When N1=4, this paper studies whether the three parameters of the bending radius b and bending angle φ (φ1, φ2) of the wire are related to the measurement error, and how much they affect the measurement error.

For non-positioning algorithm, the simulation results are shown as Figure 7.

Figure 7(a). Error $\varepsilon_c$ varies with bending radius b when $\phi_1$, $\phi_2$ are -45° and 45° respectively
The figures above that the curvature of the conductor has a great influence on the accuracy of the current measurement. The absolute errors can be as high as 50%, and the smallest error is around 6%. For the correction algorithm, 3-D TMR chips can be easily influenced by the background magnetic field. 60DB noise is added. The simulation results are shown as Figure 8.

**Figure 7(b).** Error $\varepsilon_C$ varies with bending angle $\phi_1$ when $b$, $\phi_2$, are $10R_0$ and $45^\circ$ respectively.

**Figure 7(c).** Error $\varepsilon_C$ varies with bending angle $\phi_2$ when $b$, $\phi_1$, are $10R_0$ and $-45^\circ$ respectively.

**Figure 8(a).** Error $\varepsilon_a$ varies with bending radius $b$ when $\phi_1$, $\phi_2$, are $-45^\circ$ and $45^\circ$ respectively.

**Figure 8(b).** Error $\varepsilon_s$ varies with bending angle $\phi_1$ when $b$, $\phi_2$, are $10R0$ and $45^\circ$ respectively.

**Figure 8 (c).** Error $\varepsilon_a$ varies with bending angle $\phi_2$ when $b$, $\phi_1$, are $10R_0$ and $-45^\circ$ respectively.
It can be seen from the simulation results that when 60dB noise is added, the absolute value of the error $\varepsilon_s$ is within 1.5%, which shows that this method can reduce the measurement error greatly when the parameters vary within a certain range for curved conductor. The results verify the effectiveness of the correction algorithm.

4. Experimental Results

In this section, a circular TMR sensor array was developed. The circle radius is 15.6mm, four ultra-low power triaxial TMR sensors were fixed on PCB. The selected TMR type is TMR2301.

The diagram of the experimental system was shown in Figure 9.

![Figure 9. Diagram of the experimental system](image)

In the following experiments, the current was set $I=100A$ and the conductor was curved as shown in Figure 10. The magnetic field data was obtained by acquisition card and then the current correction algorithm was performed in Matlab.

![Figure 10. Experimental demonstration of current measurement](image)

The calculated currents by correction algorithm were shown in Table 1.
From Table I, the average current errors are 1.16%-2.01% for curved conductor. The errors increase with the increasing of the current. The largest error is 2.01%, which is much smaller than that of the non-positioning algorithm. The results show the effectiveness of the correction algorithm.

5. Conclusion
A correction algorithm based on a 3-D coreless TMR sensor array scheme is introduced to perform current measurement for curved wire in this paper. The conclusions are as follows:

- When the length of the wire is 1m, the error approaches 0.1%. For this paper, when the length of the wire is equal to 0.21m, the error is 1%. The error of current measurement caused by the curvature of the wire within this range needs to be considered.
- It can be seen from the results that when measured with non-positioning algorithm, measurement error is very large and the maximum is as high as 50%, this shows that the curvature of the conductor brings a great influence on the accuracy of the current measurement. While for the correction algorithm, the measurement error is around 1%, which is much smaller. The simulation results indicate the effectiveness of the correction algorithm.
- It can be seen from the experimental results that the curvature of the wire brings a large error to the measurement of the current, and the larger the current is, the bigger the error is. The experimental errors are between 1%-2%, which are much smaller than that of the non-positioning algorithm. And the results verify the effectiveness of the correction algorithm.

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