Accuracy analysis of current sensor based on magnetic field

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Abstract. Current is the most important parameter in power system, and its accurate measurement is the basis of system operation. With the research of new current measurement technology based on magnetic field, such as Hall effect and giant magnetoresistance, the current can be measured without contact with the conduct. However, due to the different wire diameters and the deviation of wire position, it is impossible to measure the multi-range current through the sensor with a single structure in practical use. In this paper, the error analysis of current technology based on magnetic field is studied. First, the measurement model is analyzed, and the measured wire current and magnetic field measuring point model is established. Through simulation, the influence of wire diameter and position deviation on the measurement accuracy is tested, which supports the design of current sensor based on magnetic field.

1. Introduction

Current is one of the important observable state parameters in power system. The transient current concludes a wealth of information, including waveform, frequency, amplitude and other characteristics. Therefore, current is an important parameter to reflect the disturbance and fault process of power system. Real-time observation of current is an important demand for power grid transient information acquisition, accident traceability, power big data technology, transparent grid and energy Internet. Traditional electromagnetic current transformer is still has many disadvantages in the measurement of current, such as high insulation cost, magnetic saturation, small measuring range, narrow band, remanence, slow dynamic response, and higher harmonic problems, these defects seriously affect the real-time accurate to obtain the current data.

Compared with traditional current measuring devices as electronic current transformers, magnetoresistance sensor has more engineering applicability with small volume, light weight, good linearity, large dynamic range and other advantages.. The measurement basis of magnetoresistance sensor is that its sensing matrix is sensitive to the magnetic field, and the current can be calculated by various changes [1-3].

Current sensors based on magnetic field are used as follows:
(1) Current sensor based on Hall effect;
(2) Current sensor based on anisotropic magnetoresistance intrinsic (AMR) effect;
(3) Current sensors based on giant magnetoresistance (GMR) effect;
(4) Current sensors based on tunnel magnetoresistance, including intrinsic TMR effect.

However, in the application of power grid engineering, the electromagnetic environment is complex and there are many interference sources, which will affect the accuracy of current detection. In the
measurement, the magnetic field at the measurement place of the induction element will change due to the deviation of the wire and the change of the wire diameter, which will have an impact on the measurement accuracy \cite{4,5}. In this paper, the magnetic field error analysis of current technology based on magnetic field is studied. First, the measurement model is analyzed, and the measured wire current and magnetic field measuring point model is established. Through simulation, the influence of wire diameter and position deviation on the measurement accuracy tested, which supports the design of current sensor based on magnetic field.

2. Principle of current sensor based on magnetic field measurement

In a wire of power system, due to the presence of current, a magnetic field will be generated around the wire. The magnitude of the magnetic field of an infinite wire can be calculated by the following formula.

\[ H = \frac{I}{2\pi d} \]

In the formula, \( I \) represents the current through the wire, \( d \) represents the distance between the sensor and the wire, and \( H \) represents the magnetic field intensity at the sensor.

At this time, the sensor is placed in the distance from the wire \( D \), and the size of the magnetic field is sensed through the size of the resistance, and then the current is calculated. This is shown in figure 1.

![Figure 1. Principle of measurement](image1)

A single induction element is placed near the wire at an open magnetic field, and then the wire shape and small displacement have a great influence on the magnetic field. Therefore, the influence of spatial position variation on the measurement must be reduced by external means. In practical application, the magnetic field measurement architecture based on magnetic agglomeration ring is usually adopted. This is shown in figure 2.

![Figure 2. Architecture of measurement with magnetic ring](image2)

According to Ampere Loop Theorem, there are:

\[ \oint B \cdot dl = N \mu_0 I \]  \hspace{1cm} (1)

In the formula, \( L \) is the length of the closed path, and \( N \) is the number of wires crossing the closed loop. In practice, \( N \) can be equivalent to 1.

Since \( B = \mu_0 H \), the above equation is equivalent to:
∮ \( H \cdot dl = I \)  \hspace{2cm} (2)

So, we can calculate:

∮ \( H \cdot dl = H_1 \cdot (2\pi r_0 - d) + H_2 \cdot d = I \)  \hspace{2cm} (3)

In the formula, \( H_1 \) represents the magnetic field intensity in the magnetic ring, \( H_2 \) represents the magnetic field intensity in the air gap, and \( r_0 \) represents the average radius of the magnetic ring.

Due to the equation below:

\[
B = \mu_0 H_2 = \mu H_1
\]

\( \mu_0 \) is the permeability of vacuum and \( \mu \) is the permeability of magnetic ring.

Then, the formula can be solved as below:

\[
B = \frac{\mu \mu_0}{2\pi \alpha_0 (\mu - \mu_0) d} I
\]

Since \( \mu \) is much larger than \( \mu_0 \), the formula can be simplified as:

\[
B = \frac{\mu_0}{d} I
\]

Then the current of conduct can be measured.

Therefore, the size of the magnetic field is only sensitive to the gap at the induction element with the magnetic concentration ring. In practice, the center of the wire does not coincide with the center of the magnetic ring completely. Since the induction element is only set at a single air gap, the offset of the wire will affect the size of the magnetic field at the air gap. Therefore, the effect of conductor offset can be reduced by arranging multiple air gaps and induction elements. The magnetic concentration measurement architecture with two air gaps and induction elements is shown in Figure 3.

Figure 3. Architecture of measurement with magnetic ring and double sensing elements

According to the Ampere Loop Theorem, when the center of the conductor coincides with the center of the magnetic ring, the following calculation results can be obtained:

\[
B = \frac{\mu \mu_0}{2\pi \alpha_0 (\mu - \mu_0) (d_1 + d_2)} I
\]

In other words, the magnetic field at the induction element is still related to the size of the air gap. When the center is offset, the error can be balanced by measuring the sensor in two different positions. Similarly, the measurement error can be reduced by increasing the number of sensing elements.

3. Simulation model of magnetic concentration measurement

3.1. Calculation principle of finite element method

Finite element method (FEM) will divide the solution area into different small areas through grid division, and the small area is called "finite element". According to Maxwell's equation, the solution of
the whole solution area can be obtained by mathematical method for each element column system. The basic analysis process is shown in figure 4.

![Figure 4. Process of finite element calculation](image)

### 3.2. Simulation model

The simulation models of single and double sensing elements are shown in figure 5

![Figure 5. Simulation models: (a) single element, (b) double elements](image)

### 4. Accuracy analysis in multiple scenarios

#### 4.1. Analysis of single element measurement

In the single element mode, there is only a single air gap in the magnetic ring. Compare the deviations caused by the lead deviation of two different diameter conductors. The diameter of the wire is 10mm and 28mm, and the inner diameter of the sensor magnetic ring is 29mm, so the maximum distance of the wire moving inside is about 10mm and 1mm. The current is set at 600A (RMS), and the deviation of the wire from the center of the circle along the directions of +x, -x, +y and -y is recorded respectively to calculate the deviation. The magnetic field distribution of the magnetic ring is shown in the figure 6. The magnetic field in the air gap is weak, and the magnetic field on the side without the air gap is strong.

![Figure 6. Simulation result: (a) mesh generation, (b) magnetic field distribution](image)
According to the simulation data, when the wire moves 10mm inside, the maximum deviation is 4.3%, and when the wire moves 1mm inside, the maximum deviation is 1%. It is easy to find that the deviation caused by the deviation of the wire in the direction of the air gap is greater, and the closer the diameter of the wire is to the inner diameter of the sensor, the smaller the deviation is. The data is in the tables below.

| Position  | Magnetic field intensity in the gap / Gs | Relative deviation / % |
|-----------|----------------------------------------|------------------------|
| (0, 0)    | 618.3                                  | 0                      |
| (0, 10)   | 648.6                                  | 4.9                    |
| (0, -10)  | 590.7                                  | 4.5                    |
| (10, 0)   | 591.9                                  | 4.3                    |
| (-10, 0)  | 592.6                                  | 4.2                    |

Table 2. Simulation result (wire diameter 28mm, maximum offset 1mm)

| Position  | Magnetic field intensity in the gap / Gs | Relative deviation / % |
|-----------|----------------------------------------|------------------------|
| (0, 0)    | 605.9                                  | 0                      |
| (0, 1)    | 613.97                                 | 1.3                    |
| (0, -1)   | 613.6                                  | 1.2                    |
| (1, 0)    | 606.9                                  | 0.2                    |
| (-1, 0)   | 604.7                                  | 0.2                    |

4.2. Analysis of double element measurement

When the conductor is offset, the magnetic field in the air gap on one side becomes larger and the magnetic field in the air gap on the other side becomes weaker. Therefore, the average value of the magnetic fields in the two air gaps can be used as the measurement value to improve the accuracy effectively. Simulation is used to verify the deviation. The magnetic ring size remains unchanged, and the upper and lower half rings open the same size air gap with a width of 4mm. The bus current is set to 600A (RMS).

![Figure 7. Simulation result: (a) mesh generation, (b) magnetic field distribution](image-url)
According to the simulation data, when the wire moves 10mm inside, the maximum deviation is 1.23%; when the wire moves 1mm inside, the maximum deviation is 0.53%. It can be seen that the sensor with double air gap has a higher measurement accuracy.

Through the simulation analysis of single and double element, it can be found that when the conductor sloshes in the measured ring, the measurement accuracy will change, and the more the center deviation, the greater the error. Therefore, in practical use, one type of magnetic ring should be fixed for only several types of wires to reduce the error caused by sloshing due to the differences in wire diameter. At the same time, in order to improve the measurement accuracy, the displacement error can be reduced by increasing the number of air gap to place more sensing elements.

5. Conclusion
In this paper, the accuracy analysis of current technology based on magnetic field is studied. First, the measurement model is analyzed, and the measured wire current and magnetic field measuring point model is established. Through simulation analysis, the influence of wire diameter and position deviation on the measurement accuracy is tested, which supports the design of current measurement sensor based on magnetic field.

1) When the conductor sloshes in the measured ring, the measurement accuracy will change, and the more the center deviation, the greater the error. In practical use, one type of magnetic ring should be fixed to only several types of wires to reduce the error caused by sloshing due to differences in diameter of wires.

2) The double elements sensor has higher measurement accuracy. In order to improve the measurement accuracy, the displacement error can be reduced by increasing the number of air gap to place more sensing elements.

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