The Research on Anti-DC current Transformer of Dual Iron Core Structure with Air Gap

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Abstract. Current transformer (CT) is wildly used in electrical measurement and relay protection. In order to improve the power system stability in DC bias, the CT performance of anti-DC is necessarily to be enhanced. Based on the Jiles-Atherton theory, the magnetization characteristics of iron core with different air gap was analyzed in this paper. A simulation model was established using the Simulink toolbox, and the ratio error and angle error were investigated in different air gap length. Simulation result shows that the maximum magnetic density of iron core almost stays unchanged with the addition of air gap. Furthermore the slope of magnetization curve decreased, which leads to the increase of iron core saturation current. Current transformer with closed and air gap iron core possesses a stable measurement error in condition of severe DC bias.

1. Introduction

Current Transformer (CT) is the basic component of power system measurement and protection. It is widely used in metering, maintenance, state assessment and other scenarios, and its accuracy and reliability are very important [1-2]. Normally, the current transformer core works in the unsaturated region, and the output waveform error is small. However, in the case of serious DC magnetic bias, the iron core will enter the saturation state with the joint action of AC and DC magnetic flux, and the excitation current will have a sharp peak and distortion at half cycle, showing a positive and negative asymmetric shape, and produce a large number of harmonics [3-4]. At this time, the current transformer error increases significantly, affecting the subsequent measurement and protection device. With the increasing of DC engineering in our country, the problem of DC magnetic bias becomes more and more prominent, so the ability of current transformer to resist DC magnetic bias should be improved.

The basic requirements of the anti-DC bias magnetic current transformer are that it has good transmission characteristics in an AC environment with DC components, high saturation magnetic induction intensity, high permeability and low iron loss, and the measurement accuracy of large DC
components and small or no DC components [5-6]. At present, there are two main schemes for this type of transformer: 1) Optimized iron core material, using high magnetic conductivity core and anti-saturation core to form composite core or double core; 2) Improved iron core structure, iron core is formed by the superposition of magnetic core with air gap and magnetic core without air gap. Because the production of iron core with air gap is more convenient and the cost is lower, it has been studied and applied more. Literature [7] builds the equivalent circuit model of iron core open air gap current transformer, and analyzes the influence of air gap on current transformer performance. In literature[8], J-A model was used to establish a simulation model of iron-core open-air gap CT, and the influence of different air-gap sizes on transient characteristics of CT was analyzed. Based on the basic magnetic circuit and circuit time domain equation of open current transformer, the analytical model of open current transformer is established in literature [9], and the influence of secondary side load effect is taken into account. Literature [10] analyzes the influence of air gap on the accuracy of clamp current sensing head, and provides relevant methods to improve the accuracy. Literature [11] proposed a wide range current transformer with open air gap structure, and verified the effectiveness of the new current transformer through simulation calculation. Literature [12] analyzes the influence of DC component on current transformer in principle. By studying the DC resistance of iron core material, a low-voltage DC resistance of composite magnetic core is developed, and the detection method of it's DC resistance is also studied.

Most of the existing researches have analyzed the influence of air gap on magnetization characteristics of single iron core, but there is a lack of research on measurement error of CT with double iron core structure. Therefore, based on Jiles-Atherton theory, magnetization characteristics of iron core with air gap are analyzed. With the help of Matlab Simulink toolbox, the double core current transformer model is established based on the \( \phi-I \) curve of different core, and the dc resistance effect of current transformer under different core configuration is analyzed.

2. Simulation of magnetization characteristics of iron core with air gap

2.1. Analysis of magnetization characteristics of closed iron core

The magnetization characteristic of iron core is the basis of current transformer analysis. Based on jiles-Atherton theory [13-14], magnetization of iron core \( M \) is composed of irreversible component and reversible component.

\[
M = M_{irr} + M_{rev}
\]  

(1)

In the formula, \( M_{irr} \) represents irreversible component and \( M_{rev} \) represents reversible component. \( M_{irr} \) is caused by domain closure caused by discontinuous material structure, while \( M_{rev} \) is caused by domain walls bending in an elastic way [15]. Where, \( M_{irr} \) of irreversible component of magnetization is calculated by the following formula

\[
\frac{dM_{irr}}{dH} = \frac{1}{\delta k} \left( M_{an} - M_{irr} \right)
\]  

(2)

In the formula, \( \delta \) represents the sign of \( dH/dt \) and can be 1 or -1. \( k \) is the parameter reflecting the restraining effect of magnetic domain movement. \( \mu_0 \) is the vacuum permeability.

The calculation formula of reversible component \( M_{rev} \) is

\[
M_{rev} = c \left( M_{an} - M_{irr} \right)
\]  

(3)

In the formula, \( c \) is the reversible motion parameter of the magnetic domain.

In combination with the above types, the functional relationship between \( M \) and \( H \) can be obtained:
When \((M_{an} - M) \delta < 0\), Equation (4) can be simplified as

\[
\frac{dM}{dH} = \frac{c}{1 - \alpha c} \frac{dM_{an}}{dH_e}.
\]

According to Jiles-Atherton theory, the shape of magnetic hysteresis curve of iron core is controlled by \(M_s\), \(\alpha\), \(k\) and \(c\) parameters. After these parameters are determined, the fourth-order Runge-Kutta method is used to solve differential equation (5), and the relationship curve between \(M\) and \(H\) can be obtained. According to the measured magnetization curve of iron core, the above parameters are adjusted to make the simulated magnetization curve approach the measured curve, so as to obtain the magnetization characteristic parameters of iron core.

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2.2. Analysis of magnetization characteristics of iron core with air gap

Fig. 1 shows the structure of iron core with air gap. \(l_a\) is the length of the air gap part of magnetic circuit, which is only a few thousandths of the average magnetic circuit length of iron core \(l_i\). Based on this, the following assumptions can be made: the air gap section is parallel and perpendicular to the magnetic field line; The magnetic field lines at the edge of the air gap do not bulge. That is, the average magnetic field line length in the air gap is the same as the geometric design length \(l_a\), the cross-sectional area of the magnetic circuit in the air gap is the same as the cross-sectional area of the magnetic circuit in the iron core, and the magnetic induction intensity on the cross section of the iron core is the same as the magnetic induction intensity on the cross section of the air gap \([16]\).

![Fig.1 Diagram of iron core with air gap](image)

If the magnetic field intensity in the iron core is \(H_i\) and the magnetic field intensity in the air gap is \(H_a\), then the excitation current when the current transformer is converted to one turn is

\[
e = H_i l_i + H_a l_a.
\]

The formula of magnetic field intensity in the air gap is

\[
H_a = B / \mu_0
\]
The units of cross-sectional area and magnetic circuit length of the core are m² and m, the magnetic flux density is T, the magnetic field intensity is A/m, and the vacuum permeability \( \mu_0 = 4\pi \times 10^{-7} H/m \). The excitation characteristic curve of iron core with air gap can be equivalent to

\[
H = i_e/i_1 = H_i + \frac{l_a}{l_i} H_u
\]

Then,

\[
H = F(B) = f(B) + BN_p
\]

Where \( N_p = \mu_0 I_a/I_i \) is the demagnetization coefficient of the iron core. The magnetization curve of iron core CT with air gap \( H=F(B) \) is obtained. Two kinds of iron cores (as shown in Table 1) are selected for magnetization curve analysis. Sample 1 is ultra fine iron core, and Sample 2 is silicon steel sheet iron core. Take \( \lambda = I_a/I_i \) and change the value of \( \lambda \) to obtain the magnetization characteristics as shown in Fig.2.

Tab.1 Magnetization characteristics of two iron cores based on Jiles-Atherton theory

| No. | Ms | a  | k   | c   |
|-----|----|----|-----|-----|
| 1   | 0.4E6 | 27 | 30  | 5E-5  | 0.55 |
| 2   | 1.5E6 | 1600 | 1500 | 1.6E-3 | 0.15 |

The influence of air gap on the maximum magnetic density of the two cores is small and basically unchanged. It mainly affects the slope of magnetization curve, and the air gap makes the slope of magnetization curve smaller. For an iron core, the larger the added air gap, the smaller the slope of the linear part of the magnetization curve, and the larger the magnetization current required for saturation, the more difficult the core is to be saturated. In addition, different cores have different sensitivity to air gap. When \( \lambda \) is 0.0005, the slope of magnetization curve of sample 1 iron core changes obviously, but sample 2 iron core needs \( \lambda \) greater than 0.01 to achieve the same effect.

3. Simulation model of double iron core current transformer

3.1. Basic principle of double iron core current transformer

The addition of air gap will improve the anti-saturation ability of iron core, but reduce the magnetic permeability of iron core and affect the accuracy of current transformer. To meet the measurement accuracy requirements under different conditions, the iron core with air gap and the closed iron core are superimposed to form the double iron core current transformer (as shown in Fig.3). The closed iron core is used to meet the accuracy of conventional conditions, and the iron core with air gap is used to meet the accuracy requirements of current transformer with DC component. For dual-iron core CT, the
The process of superposition of DC shunt and gradual increase can be equivalent to increasing magnetic field intensity. The closed iron core plays a major role before saturation, and the iron core with air gap plays a major role after saturation.

**Fig.3 Diagram of current transformer with double cores**

### 3.2. Simulation model of current transformer with double iron core structure

The current transformer used for simulation is 500 A/5 A, rated capacity 25VA, primary winding 1 turns, secondary winding 100 turns. The transformer has two iron cores, each with an average magnetic circuit length of 220mm and a cross-sectional area of 1750mm². After obtaining the magnetization characteristics of the iron core, the current transformer simulation modeling is carried out with the help of Matlab Simulink toolbox. The current transformer model is built in Simulink, the sinusoidal signal generator is used to simulate the power supply, and the circuit breaker is opened and closed. Two saturation transformer modules are connected in series to simulate the double iron core current transformer. The primary and secondary time constants of the current transformer's primary and secondary side impedance control system. Observe the current transformer flux, magnetization current, primary measurement current and secondary side current waveform changes, and obtain the transformer Angle difference and ratio difference through calculation.

**Fig.4 Current transformer simulation model based on simulink toolbox**
The magnetization curve of the iron core is simulated by HYSTERESIS DESIGN. Firstly, five parameters of the Jiles Atherton model were adjusted according to the magnetization B-H curve of iron core material, and the best parameters were obtained by approximating the measured curve. According to the parameters of the Jiles-Atherton model, the B-H curve considering hysteresis is obtained. According to the structural parameters of the current transformer, it is transformed into a basic magnetization curve in the plane, where $\phi$ is the magnetic flux and $i$ is the magnetizing current.

$$\phi = BS$$ (10)

$$i = (Hli)/N1$$ (11)

Where, $li$ is the average magnetic circuit length of the current transformer core, m; $S$ is the cross-sectional area of the current transformer core, m$^2$; $N1$ is the number of primary winding turns of the current transformer.

According to the curve, in the matlab software HYSTERESIS DESIGN, adjust the residual magnetic flux of the magnetization curve, the saturation magnetic flux, the saturation current, the coercivity current, the slope of the coercivity current, the saturation area current, the saturation area magnetic flux, the rated parameters of the transformer, then the magnetization characteristic curve obtained by Jiles-Atherton model is approached.

### 4. Analysis of anti-DC effect of double iron core current transformer

In order to analyze the anti-DC effect of the dual-iron core current transformer, the amplitude of the original AC current of the transformer is set to 500 A, so that the transformer works in the critical saturation state. The DC current component is superimposed to make it appear saturated, and the Angle difference and ratio difference of the current transformer are analyzed under different iron core combinations and different air gaps. Fig 6-8 show the current wave-forms of the primary and secondary sides of the dual ultra micro crystal iron core current transformer under different DC magnetic bias. The values of the iron core with air gap are 0, 0.0005 and 0.001. Without DC component, the output waveform of each current transformer is standard sine wave without distortion. When the DC component is 100A, after 0.15s, the core of the no-air gap iron core current transformer is saturated, and the waveform of the secondary side appears obvious distortion. With the increase of DC component, the distortion of secondary waveform becomes faster and more serious. No air gap iron core current transformer is difficult to work under the condition of DC magnetic bias. For the current transformer $\lambda = 0.0005$, under the same DC component, the secondary side waveform distortion is slightly better than that of the current transformer without air gap, but the anti-DC effect is not obvious. When $\lambda = 0.001$ and above, the secondary side current waveform can also ensure small distortion when the amplitude of
the DC component is 200A, but obvious distortion only occurs when the DC component is 300A. For ultra micro crystal core, in order to obtain better dc resistance, the length of air gap is long, which will affect the measurement accuracy of unsaturated section.

Fig. 9 shows the current waveform of the primary and secondary side of the ultra micro crystal plus silicon steel sheet iron core current transformer under 300A DC bias. Because the silicon steel sheet has a good anti-DC effect, even if the iron core has no air gap, this set of transformers can guarantee a good output under the DC bias of 300A. Adding a small gap ($\lambda = 0.01$) in the core can effectively improve the dc resistance of the current transformer and shorten the time for the output waveform to reach stability.

Table 2~ Table 3 show the errors of dual ultra micro crystal iron core and ultra micro crystal plus silicon steel sheet iron core CT under different DC bias magnetic field respectively. Dual ultra micro crystal iron core current transformer has the smallest error in the case of no DC magnetic bias, but its DC resistance is average. Even if the air gap is increased, the effect is not significant. Ultra micro crystal plus silicon steel sheet iron core current transformer, only need to set a small gap in the silicon steel sheet iron core, can meet the demand of better resistance to DC magnetic deviation, improve the measurement accuracy of the transformer under DC magnetic deviation.
Tab. 2 Current transformer error of two ultra crystalline core

| DC Amplitude/A | Iron core      | Ratio error/% | Angular error/° |
|---------------|----------------|---------------|-----------------|
| 0             | No air gap     | -0.5          | 0.01            |
|               | Small air gap  | -0.54         | 0.02            |
|               | Big air gap    | -0.56         | 0.03            |
| 150           | No air gap     | -33           | 25              |
|               | Small air gap  | -21           | 18              |
|               | Big air gap    | -3.2          | 8.7             |
| 300           | No air gap     | -69           | 48              |
|               | Small air gap  | -57           | 39              |
|               | Big air gap    | -27           | 26              |

Tab. 3 Current transformer error of ultra crystalline and silicon steel sheet core

| DC Amplitude/A | Iron core      | Ratio error/% | Angular error/° |
|---------------|----------------|---------------|-----------------|
| 0             | No air gap     | -0.8          | -0.1            |
|               | Small air gap  | -1.1          | -0.1            |
|               | Big air gap    | -1.2          | -0.2            |
| 150           | No air gap     | -2.0          | 4.7             |
|               | Small air gap  | -2.0          | 4.8             |
|               | Big air gap    | -3.4          | 9.0             |
| 300           | No air gap     | -2.6          | 7.0             |
|               | Small air gap  | -2.6          | 5.0             |
|               | Big air gap    | -3.4          | 9.0             |
| 500           | No air gap     | -20.0         | 30.0            |
|               | Small air gap  | -2.8          | 5.0             |
|               | Big air gap    | -3.8          | 10.0            |

5. CONCLUSION

Based on Jiles-Atherton theory simulation, the addition of air gap has little effect on the maximum magnetic density of iron core, but lowers the slope of the linear part of magnetization curve and increases the current required for core saturation, thus improving the anti-saturation ability of iron core. The longer the air gap, the harder the core is to saturate. The addition of air gap can improve the measurement error of CT in the absence of DC bias, but can improve the measurement error of CT in the absence of DC bias. Under the same size, the effect of air gap added by different cores is not consistent. The combination of ultra micro crystal and silicon steel sheet iron core is selected. As long as a relatively small gap is set in the silicon steel sheet iron core, it can have a good dc resistance.

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