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Minrui Xu ; Zhixin Li ; Shufeng Lu ; Tianchao Huang ; Guangchen Ma ; Jiajia Liu ;
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Minrui Xu,[1] Zhixin Li,[1] Shufeng Lu,[1] Tianchao Huang,[1] Guangchen Ma,[2,3,a)] Jiajia Liu,[2] Hang Zhou,[2] and Jiaxin Yuan[2]

AFFILIATIONS

[1] State Grid Jiangsu Electric Power Co., Ltd. Marketing Service Center, Nanjing 210026, China
[2] State Key Laboratory of Power Grid Environmental Protection, School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China
[3] Department of Electrical and Electronic Engineering, The Hong Kong Polytechnic University, Hong Kong 999077, China

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[a)] **Author to whom correspondence should be addressed:** MegrayChan@whu.edu.cn

ABSTRACT

In low-frequency transmission, traditional current transformers face the problem of saturation distortion issues, while utilizing materials with high magnetic saturation intensity could add measurement errors. In order to solve this problem, the mixed materials current transformer (MMCT) is proposed, which uses two cores, one made of conventional silicon steel with an air gap and the other made of nanocrystalline alloy material without an air gap. Theoretical analyses and finite element method simulations are carried out to validate the practicability and effectiveness of the proposed MMCT. Furthermore, the performance is optimized to address the effect of the air gap. The results manifest that the transmission characteristics of the MMCT are outstanding.

I. INTRODUCTION

With large-scale power electronics technology advancements, alternative transmission methods at different frequencies have gained traction, such as High Voltage Direct Current (HVDC) and Low-Frequency Alternating Current (LFAC). Research indicates that LFAC transmission can outperform HVDC by enhancing transmission capacity and improving power flow control in offshore wind energy, rail systems, and mining applications while also being more cost-effective.[1]

However, at the same voltage level, lower frequencies result in a greater magnetic flux passing through the core cross-section, making it more susceptible to core saturation issues, significantly impacting current transformers. And core saturation can lead to secondary current distortion, increased measurement errors, and compromised accuracy in energy metering, which may even trigger erroneous actions in relay protection devices, thus threatening the safe and reliable operation of power systems.

Early studies proposed compensation algorithms to correct distorted currents;[2] however, these algorithms depend heavily on hardware devices. Techniques like genetic neural networks require extensive specific data support, rendering them unsuitable for widespread application.[3] Recently, researchers have introduced methods utilizing adjustable switched resistors[4] or tunneling magnetoresistance (TMR)[5] to compensate for transformer outputs. While these methods demonstrate high accuracy and adequate compensation, they are constrained by sensor measurement ranges and precision, with algorithm design and sensor installation positioning also influencing compensation effectiveness.

Reference 6 improved sensor measurement range limitations by adding extra air gaps. However, this approach complicates transformer design and manufacturing due to multiple air gaps and different sensor placement, which will influence the measurement data and might cause the instability of the output.

This study proposes a novel type of current transformer based on mixed magnetic materials (Mixed Materials Current

Transformer, MMCT), leveraging the sensitivity differences of two materials with distinct *B-H* characteristics to achieve measurement without additional sensors. Initially, the basic structure of the MMCT is introduced, followed by establishing its equivalent model and a theoretical analysis of its operational principles. Subsequently, the measurement performance of the MMCT is compared with that of traditional current transformers. Finally, parameter optimization of the MMCT is conducted. The results indicate that the MMCT exhibits optimal performance with an air gap width of 0.04 mm, achieving a measurement error of approximately 0.11% and a phase angle error of approximately $-9'$ at 20 Hz, thereby meeting a class 0.2 accuracy standard.

II. PRINCIPLE OF MMCT

A. Equivalent circuit analysis

The MMCT comprises two concentric ring-shaped cores. The inner core is constructed from normal silicon steel and features an air gap segment, while the outer core is made of nanocrystalline alloy[7] and is devoid of any air gaps. The primary conductor passes through the center of the cores, while the secondary windings are uniformly wrapped around the two cores, encapsulating them together. During the ordinary manufacturing procedure, the silicon steel core, the nanocrystalline alloy core, and the secondary windings are poured together with epoxy resin, and the secondary windings have two ports connected to the external circuit.

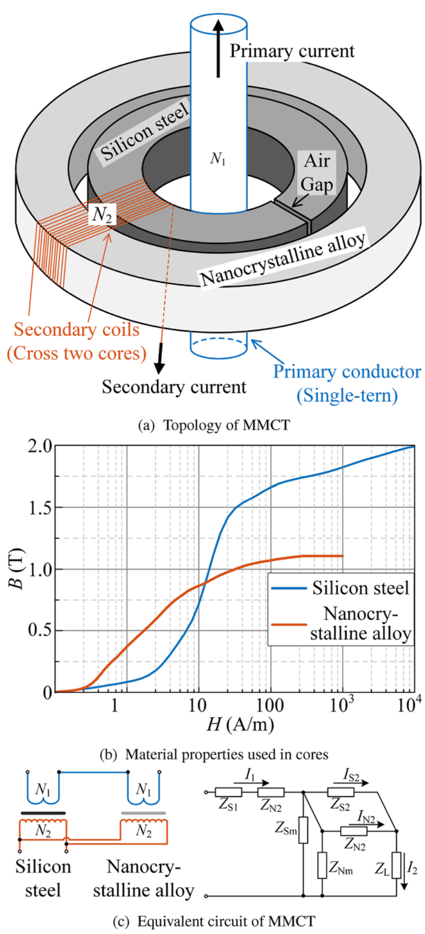

FIG. 1. Structure and equivalent circuit of the MMCT.

Figure 1(a) illustrates the physical structure of the MMCT. Figure 1(b) presents the *B-H* curves of the two different materials utilized in the MMCT. Figure 1(c) depicts the equivalent circuit of the MMCT, which represents two transformers connected in series on the primary side and in parallel on the secondary side, and the Z_L is the equivalent impedance of the external circuit.

According to Ampere's law, we can get:

$$\begin{cases} (2\pi r_S - w)H_S + H_0 w = N_1 I_1 - N_2 I_{S2} \\ 2\pi r_N H_N = N_1 I_1 - N_2 I_{N2} \end{cases} \tag{1}$$

where H_S, H_0, H_N are the magnetic field strength of the inner core, air gap, and outer core, respectively. w is the width of the air gap. r_S, r_N are the average radii of the inner and outer cores, respectively. N_1 and N_2 are the number of coil turns on the primary and secondary sides.

Using Faraday's law of induction, the electrical circuit equation on the secondary side can be written as

$$N_2 A_S \frac{dB_S}{dt} + N_2 A_N \frac{dB_N}{dt} = I_2 Z_L \tag{2}$$

where A_S and A_N are the inner and outer cores' cross-sectional areas. B_S, and B_N are the magnetic flux density of the cross-sectional areas of the inner and outer cores, respectively.

In addition, the analysis of the interface between the air gap and the inner core and the inside of the core:

$$\begin{cases} H_0 = \dfrac{B_0}{\mu_0} = \dfrac{B_S}{\mu_0} \\ H = \dfrac{B}{\mu} \\ \dfrac{dH}{dt} = \dfrac{1}{\mu}\dfrac{dB}{dt} \end{cases} \tag{3}$$

where B_0 is the magnetic flux density of the air gap. μ_0 is the magnetic permeability of air. H and B represent the magnetic field strength and magnetic flux density inside the core, respectively, and their subscripts can be S or N. Notably, although the *B-H* relationship within the core is nonlinear, the permeability can be effectively treated as a constant in the time domain for a transformer operating at a specific working point.

According to formulas (1)–(3), we can get:

$$\frac{I_2}{I_1} = \frac{N_1/N_2}{1 + \frac{Z_L}{j\omega N_2^2}\left(\frac{(2\pi r_S - w)B_S/\mu_S + wB_0/\mu_0 + 2\pi r_N B_N/\mu_N}{A_S B_S + A_N B_N}\right)} \tag{4}$$

where ω is the angular velocity of the input current and the j operator indicates that the phase has changed by 90°.

From (4), it is evident that the denominator of the equation primarily influences the error of the MMCT. Operating under low-frequency conditions, the characteristics of the MMCT ensure that the inner silicon steel core does not saturate, resulting in a minimal value for BS; if an ideal *B-H* curve is assumed, then B_S equals

TABLE I. Parameters in FEA simulation.

Parameter	Value
Primary rated current (I_1)	500 A
Secondary rated current (I_2)	5 A
Turns of primary (N_1)	1
Turns of secondary (N_2)	100
Silicon steel core cross-sectional area (A_S)	200 mm^2
Nanocrystalline alloy core sectional area (A_N)	80 mm^2
Current frequency (Hz)	20
Length of air gap (w)	1 mm
Distance between inner and outer cores (d)	2 mm

zero. Conversely, the outer nanocrystalline alloy core operates in a saturated state, with B_N approximately equal to B_0. Thus, the principal factor affecting error is the nanocrystalline alloy's permeability μ_N. Given that the permeability of the amorphous material is several times lower than that of silicon steel, this enables effective control of the error. Should the operating environment be altered to prevent saturation of the outer core, B_N would similarly approach a negligible value, thereby making the entire denominator very close to zero and the error exceedingly small.

B. Finite element analysis (FEA)

Build FEA 3D models of MMCT and several currently used current transformer structures and compare their performance differences, and electromagnetic transient simulations are performed. The currently used current transformer structures are dual-core configuration without air gap, single silicon steel core with air gap, and single silicon steel core without air gap. The detailed parameters and operating conditions are shown in Table I.

Figure 2 compares the measurement results of the MMCT with those of several other transformer structures, with the secondary current values normalized to the primary side. Structures 1, 2, and 3 represent a dual-core configuration without an air gap, a single silicon steel core with an air gap, and a single silicon steel core without an air gap, respectively.

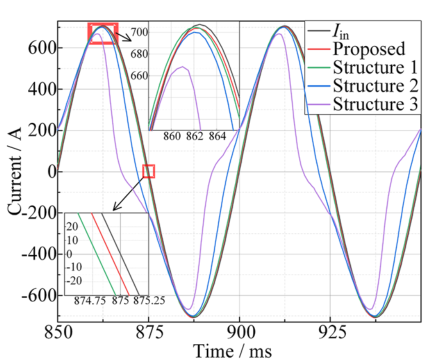

FIG. 2. Comparation between MMCT and other typical structure CT (Structures 1, 2, and 3 represent dual-core configuration without air gap, single silicon steel core with air gap, and single silicon steel core without air gap, respectively.).

As illustrated in Fig. 2, the proposed structure exhibits a low ratio of measurement error, approximately −0.45%, with a phase angle error of about −90′, indicating potential for further improvement. Nonetheless, it satisfies the requirements for a Class 3 current transformer, making it suitable for line protection. Although Structure 1 demonstrates a measurement error ratio comparable to the MMCT, its phase angle error is significantly greater. The other two structures experience varying saturation under low-frequency conditions, particularly Structure 3, which employs a single silicon steel core without an air gap and exhibits no capacity for low-frequency restoration. Structure 2, due to the presence of an air gap, has some low-frequency response capability; however, the waveform remains distorted, and the phase angle error is considerably high.

III. PERFORMANCE OPTIMIZATION

A. Air gap length of silicon steel core

Considering that the air gap's presence or absence, as well as its width, significantly influences the current transformer's performance and recognizing that the sensing results in Fig. 2 are not entirely satisfactory, it is essential to investigate the impact of air gap width on the transmission characteristics of the MMCT. As depicted in Fig. 3(a), the air gap width w varies from 0.01 mm to 10 mm, with the trends in the ratio of secondary current measurement error and phase angle error showing similar behavior. And three typical situations, which are w = 0.01, 0.04, 0.1, and 1 mm, were demonstrated in Fig. 3(b) to illustrate the tiny difference between different situations.

When the air gap is tiny, the inner silicon steel core struggles to effectively handle low frequencies, leading to a tendency toward

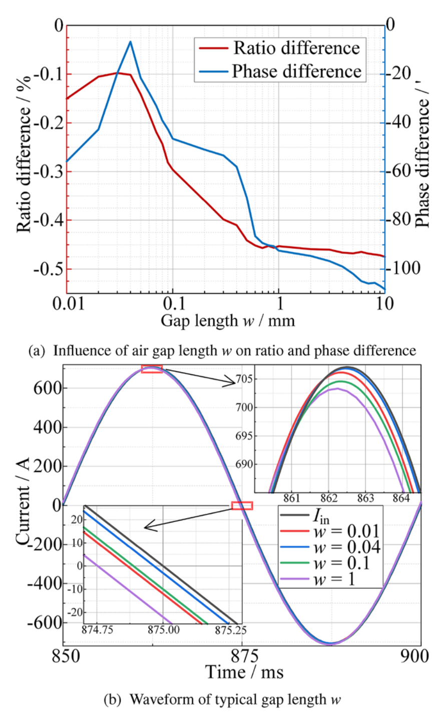

FIG. 3. Effect of air gap length w on MMCT performance.

TABLE II. Effect of d on MMCT performance.

d	Ratio difference (%)	Phase difference
1 mm	−0.103	−9.812′
2 mm	−0.101	−6.698′
3 mm	−0.100	−5.234′
4 mm	−0.102	−9.243′
5 mm	−0.097	−11.34′
6 mm	−0.106	−8.732′
7 mm	−0.099	−12.15′
8 mm	−0.093	−7.987′
9 mm	−0.104	−9.012′
10 mm	−0.096	−10.67′

critical saturation or full saturation, which results in increased measurement and phase angle errors. Conversely, when the air gap is enormous, the magnetic pressure drop is predominantly localized within the air gap, diminishing the functional contribution of the inner silicon steel core. Notably, when the air gap exceeds 1 mm, the role of the inner silicon steel core becomes negligible, approaching an infinite impedance (Z_{Sm}) as illustrated in Fig. 1(b), thereby causing the MMCT to exhibit characteristics similar to a single-core transformer.

Under the operational parameters outlined in Table I, the MMCT achieves optimal performance with an air gap size of 0.04 mm, yielding a measurement error ratio of approximately −0.11% and a phase angle error of about −9′, thus meeting the standards for a Class 0.2 current transformer.

B. Distance between inner and outer cores

Considering that the distance between the inner and outer cores, i.e., the silicon steel core and nanocrystalline alloy core, may influence the performance of MMCT, further analysis is done using the best parameter in Subsection III A, i.e., $w = 0.04$ mm.

Table II shows that the distance between the inner and outer cores almost does not impact performance. It can be explained from the Fig. 1(c). The slight change of d mainly influences the average magnetic path length of the nanocrystalline alloy, which will influence the Z_{Nm} and Z_{N2} slightly. However, the length changes in millimeters are almost negligible, and the variation of the FEA results can be explained as calculation error.

IV. CONCLUSION

This study presents a novel current transformer based on mixed magnetic materials (MMCT) designed to address measurement errors caused by core saturation in traditional transformers during low-frequency transmission. By implementing a dual-layer core structure and utilizing a combination of materials with differing permeabilities, the MMCT significantly enhances accuracy under low-frequency conditions. Simulations at 20 Hz demonstrate that with an air gap width of 0.04 mm, the MMCT achieves a measurement error ratio of merely −0.11% and a phase angle error of approximately −9′, meeting the standards for a Class 0.2 current transformer. In contrast to traditional compensation algorithms or sensor-based methods, the MMCT design does not rely on additional sensors, offering improved applicability and stability.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Minrui Xu: Conceptualization (equal); Funding acquisition (equal); Methodology (equal); Project administration (equal). **Zhixin Li**: Formal analysis (equal); Methodology (equal). **Shufeng Lu**: Formal analysis (equal); Methodology (equal). **Tianchao Huang**: Investigation (equal); Project administration (equal); Validation (equal). **Guangchen Ma**: Data curation (equal); Software (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Jiajia Liu**: Software (equal); Writing – original draft (equal). **Hang Zhou**: Supervision (equal); Writing – review & editing (equal). **Jiaxin Yuan**: Funding acquisition (equal); Project administration (equal); Resources (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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