

Study on the Performance of Magnetic Shielding Materials for Rogowski Coils in Distribution Line Current Measurement

Naming Zhang¹, Yangcheng Liu¹, Shuhong Wang¹ and Shuya Ning²

¹The School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, 710049, China;

²The School of Electronic Information and Artificial Intelligence, Shaanxi University of Science and Technology, Xi'an 710021, China

This paper conducts a simulation analysis on the performance of magnetic shielding materials under different interference magnetic field intensities. A finite element model of the magnetic shielding structure is established within the context of actual distribution line current measurement environments. The finite element analysis results show that magnetic shielding significantly enhances measurement accuracy. At low interference levels, permalloy exhibits better magnetic shielding performance compared to silicon steel, while silicon steel proves more effective under higher interference levels. This study underscores the importance of selecting shielding materials and structures based on the measurement environment, offering valuable insights for optimizing current measurement in smart grids.

Index Terms—power distribution lines, current transformers, magnetic shielding, finite element analysis

I. INTRODUCTION

CURRENT is a critical electrical parameter in distribution lines, serving as the foundation for calculating line loss rates and power consumption. Accurately collecting current data is an essential aspect of smart grids. Compared to traditional iron-core transformers, Rogowski coils utilize a non-magnetic framework, eliminating the issue of magnetic saturation. They offer a wider dynamic range, higher accuracy, and broader response bandwidth, along with both measurement and protection functions [1]. When the conductor under test passes through the center of the Rogowski coil's non-magnetic framework, its magnetic field induces an electromotive force across the coil ends. This electromotive force is proportional to the rate of change of the current, allowing quantitative analysis of the original current through integrator processing [2]. Considering that current research on Rogowski coils primarily focuses on improving their structural design to enhance measurement accuracy, there has been relatively little exploration into shielding against external interference magnetic fields [3]. In particular, there is a notable lack of simulation analysis on the performance variations of magnetic shielding materials under different interference field intensities. Based on the working principles of the Rogowski coil, this paper establishes a finite element model (FEM) that takes into account the core material and coil parameters. By simulating a more realistic interference magnetic field environment for distribution lines, this study investigates the impact of magnetic shielding materials on measurement accuracy under various interference intensities. The findings contribute to the design of high-precision Rogowski coils for current measurement in distribution lines.

II. PRINCIPLES AND ANALYSIS

A. The basic principle of the Rogowski coil

The main structure of the Rogowski coil is shown in Fig 1. Enamel-coated copper wire is uniformly wound around a non-

magnetic material frame, with the measured current passing through the center of the coil.

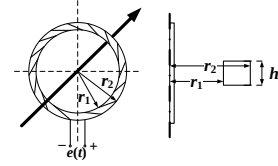


Fig. 1. Structure of a typical Rogowski coil with a rectangular cross-section

The principle of the Rogowski coil is primarily based on Ampère's Circuital Law and Faraday's Law of Electromagnetic Induction:

$$\oint B \cdot dl = \mu_0 \sum_{i=0}^n I_i \quad (1)$$

$$B = \frac{\mu_0 I(t)}{2\pi r} \quad (2)$$

$$\Phi = \int_S B(x, y, z, t) ds \quad (3)$$

$$e(t) = -\frac{Nd\Phi}{dt} = -M \frac{dI(t)}{dt} \quad (4)$$

where B is the magnetic flux density, μ_0 is the permeability of free space, I is the primary current, r is the distance to the measured conductor, S is the enclosed loop area of the Rogowski coil, Φ is the magnetic flux, and M is the mutual inductance between the Rogowski coil and the measured conductor.

Based on the geometric parameters in Fig. 1, the mutual inductance M of a Rogowski coil with a rectangular cross-section and ideally uniformly wound toroidal core can be derived as:

$$M = \frac{\Psi}{I} = \frac{N\Phi}{I} = \frac{N \int_{r_1}^{r_2} \frac{\mu_0 I}{2\pi r} h dr}{I} = \frac{\mu_0 h}{2\pi} N \ln \frac{r_2}{r_1} \quad (5)$$

where Ψ represents the total magnetic flux linkage, N is the number of coil turns, h is the height of the coil, and r_1 and r_2 are the inner and outer radii of the coil, respectively [4].

B. The influence of magnetic shielding enclosures

In practical distribution line applications, Rogowski coils are highly susceptible to power-frequency magnetic interference. Employing high-permeability magnetic shielding materials

(e.g., silicon steel, permalloy) as enclosures is an effective method to improve measurement accuracy. As illustrated in Fig. 2, these materials form a parallel magnetic circuit with air. Due to their significantly lower magnetic reluctance, most magnetic flux is confined within the shielding material, effectively reducing interference. Thicker enclosures and higher permeability lead to better shielding performance [4].

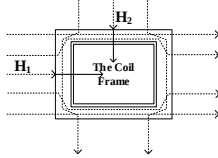


Fig. 2. Principle of magnetic field shielding.

To minimize distortion of the coil's measurement field, the enclosure design should be symmetric, with an internal magnetic path reserved and left unshielded to block eddy current loops. However, materials with high permeability may have lower saturation magnetic induction. Once magnetic saturation is reached, their permeability decreases rapidly, leading to a decline in magnetic shielding effectiveness. The measured B-H curves of the silicon steel and permalloy used in this study are shown in Fig. 3.

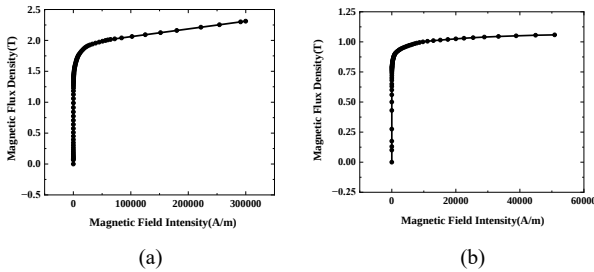


Fig. 3. B-H curves of the silicon steel (a) and permalloy (b).

III. SIMULATION RESULTS

Based on the design principles and actual structure of the Rogowski coil, a FEM for measuring distribution line current was developed. Since the current measurement of distribution lines is primarily affected by the power-frequency interference magnetic fields from nearby lines, two additional power-frequency current-carrying conductors were placed in the surrounding air environment in both horizontal and vertical directions to simulate the influence of the surrounding interference magnetic fields. The 3D model of the Rogowski coil is shown in Fig 4.



Fig. 4. The finite element model (a) and mesh division (b).

The Rogowski coil is configured with 300 turns, an inner diameter of 40 mm, an outer diameter of 89 mm, and a height of 25 mm. The current of the three-phase conductors in the distribution line under test is set to an AC current of 50 Hz and 300 A. The initial amplitudes of the currents in two nearby interfering conductors are 5000 A at the power frequency, and the interference strength is gradually increased by amplifying it in multiples. The induced voltage amplitudes measured by the Rogowski coil under a 2 mm thick non-magnetic shielding

material and two magnetic shielding materials enclosures were simulated and compared with theoretical values. The simulation results are shown in Fig. 5.

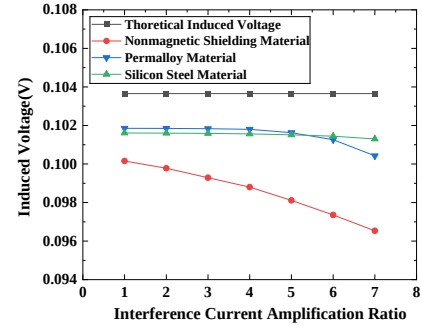


Fig. 5. Variations in induced voltage for the three enclosures.

As shown in Fig. 5, the measurement results using a magnetic shielding material shell are closer to the theoretical values compared to those using a non-magnetic shielding shell. Under low-intensity interference magnetic fields, the measurement results using permalloy as the magnetic shielding material are closest to the theoretical values. However, under high-intensity interference magnetic fields, the measurement results using silicon steel as the magnetic shielding material are the most accurate.

IV. CONCLUSION

The theoretical analysis and simulation results demonstrate that, under conditions where magnetic saturation is not reached, permalloy exhibits higher magnetic permeability and better magnetic shielding performance than silicon steel. However, in the presence of a strong interfering magnetic field, permalloy is more prone to magnetic saturation, which leads to a rapid decline in its permeability and results in inferior magnetic shielding performance compared to silicon steel. Therefore, it is essential to consider the actual measurement environment and accuracy requirements when selecting magnetic shielding materials. In some cases, a multi-layer magnetic shielding enclosure may be employed to enhance the measurement accuracy of Rogowski coils.

ACKNOWLEDGEMENT

This work was supported by the National Key R&D Program of China (2022YFB2403600).

REFERENCES

- [1] M. H. Samimi, A. Mahari, M. A. Farahnakian and H. Mohseni, "The Rogowski Coil Principles and Applications: A Review," in *IEEE Sensors Journal*, vol. 15, no. 2, pp. 651-658, Feb. 2015.
- [2] W. Xing, Y. Li, M. Li. Analysis of Current Detection Technology of Rogowski Coil [J]. *Integrated Circuits*, 2021, 38(9): 192-193. 1674-2583.2021.09.094.
- [3] W. Yang, K. Song, L. Zhou. Design and Research of the Magnetic Shielding Box of the Rogowski Coil [J]. *High Voltage Apparatus*, 2018, 54(12): 158-164+173.
- [4] X. Lu, Z. Bai, Y. Huangfu and S. Wang, "Characterization Study on an Air-Core Rogowski Coil Based Current Transformer," *2024 IEEE 7th International Electrical and Energy Conference (CIEEC)*, Harbin, China, 2024, pp. 5183-5187.