The Existing Types, Advantages, and Disadvantages of Rogowski Coils and Application Scenarios

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Abstract. Rogowski coil is a kind of high-precision current measuring tool, mainly used to measure Alternating Current (AC). It has been widely used in power systems, electronic equipment monitoring, and high current measurement. This paper systematically reviews the existing types of Rogowski coils. There are three commonly used Rogowski coils: traditional rigid Rogowski coils, flexible Rogowski coils, and PCB (Printed Circuit Board) Rogowski coils. Rogowski coils can be classified into self-integrating Rogowski coils and external-integrating Rogowski coils according to different integration methods. According to the different skeleton materials used, Rogowski coils can be classified into annular air-core Rogowski coils for measuring large amplitude currents and magnetic core Rogowski coils for measuring small amplitude currents. This paper mainly introduces the traditional air-core Rogowski coils, flexible Rogowski coils, and PCB Rogowski coils, and analyzes their basic principles, structural characteristics, and application scenarios. The advantages and limitations of each type of Rogowski coil in specific applications are further discussed.

Keywords: Rogowski Coils, Current Measurement, Integration Methods

1 Introduction

In modern power systems and power electronic devices, current measurement is an important part of control system stability, equipment operation safety, and fault detection and protection. Traditional current measurement devices, such as current transformers and Hall effect sensors, although they perform well in many applications, are limited in performance under high frequency, transient current measurement, or high electromagnetic interference environments. For example, current transformers often suffer from nonlinear errors due to core magnetic saturation, while Hall effect sensors are limited by low bandwidth and sensitivity [1, 2]. To solve these problems, Rogowski coils have become an important development direction for high-performance current sensors due to their coreless design, wide bandwidth, and non-contact measurement capabilities [3, 4].

The basic principle of the Rogowski coil is based on Faraday's law of electromagnetic induction and Ampere's loop law. When the measured current changes,

J. Iqbal (ed.), *Proceedings of the 2025 2nd International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2025)*, Advances in Engineering Research 272,
https://doi.org/10.2991/978-94-6463-821-9_11

the change in the surrounding magnetic field induces an electromotive force in the Rogowski coil, which is proportional to the rate of change of the current, and the original current waveform can be restored by integrating the circuit [1, 5]. Its coreless structure enables it to avoid magnetic saturation problems and exhibits extremely high linearity and accuracy in high-frequency and high-current measurements [6, 7]. In recent years, with the widespread application of new energy technologies, high-voltage transmission equipment, and power electronic switching devices, the demand for Rogowski coils has increased, and various types have gradually developed to meet the needs of different application scenarios [8, 9].

Due to the increasing demand for Rogowski coils in various applications, to solve the problems of weak anti-interference ability, low measurement accuracy, and poor stability of traditional Rogowski coils, many researchers have developed different Rogowski coils to meet the growing needs of different applications. Shen et al. proposed a rectangular PCB Rogowski coil suitable for industrial frequency AC measurement, and their experimental results verified that the designed coil can achieve stable and accurate current measurement and can be integrated with thermal release molded case circuit breakers [10]. Xu et al. proposed a twisted pair type four-layer printed circuit board (PCB) Rogowski coil with strong anti-interference and high bandwidth characteristics [11]. However, more accurate Rogowski coils suitable for different specific scenarios still need to be developed and studied.

Starting from the definition and working principle of Rogowski coil, this paper reviews the existing main classifications, including air-core type, PCB type, flexible type, etc., and analyzes their respective advantages and disadvantages as well as their applicability in different application scenarios. By systematically summarizing the research progress in recent years, this paper aims to provide a theoretical basis and technical guidance for the further development of the Rogowski coil.

2 Principle of Rogowski Coil

The Rogowski coil is a coreless current sensor designed based on Ampere's loop law and Faraday's law of electromagnetic induction. When the measured current passes through the conductor, the magnetic field around it changes and generates an induced electromotive force in the Rogowski coil winding, which is proportional to the rate of change of the current:

$$\mathrm{v(t)} = -\mathrm{M}\frac{\mathrm{di(t)}}{\mathrm{dt}} \tag{1}$$

Where: $\mathrm{v(t)}$ is the induced voltage, M is the mutual inductance, which is related to the geometry and material of the coil. $\frac{\mathrm{di(t)}}{\mathrm{dt}}$ is the time derivative of the current. The output voltage signal can be processed by the integration circuit to restore the original current waveform:

$$\mathrm{i(t)} = -\frac{1}{\mathrm{M}}\int \mathrm{v(t)dt} \tag{2}$$

Where $\mathrm{i(t)}$is the original current, $\int \mathrm{v(t)dt}$ is the integral of the induced voltage over time. Fig. 1 shows the measurement principle of the Rogowski coil.

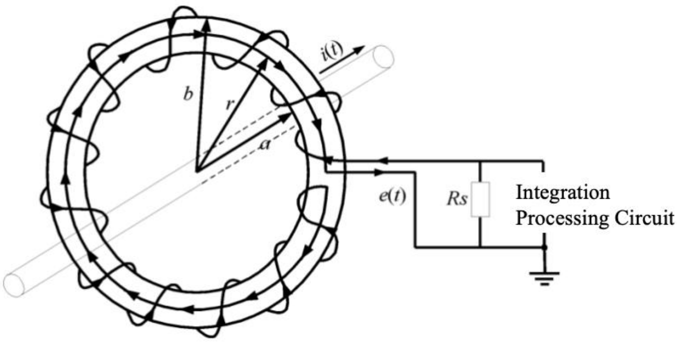

Fig. 1 Rogowski coil measurement principle diagram [11]

This principle gives the Rogowski coil extremely high linearity and wideband characteristics, making it excellent in large current, high frequency, and transient current measurement [1, 2, 4]. Fig. 2 shows the structure of the Rogowski coil.

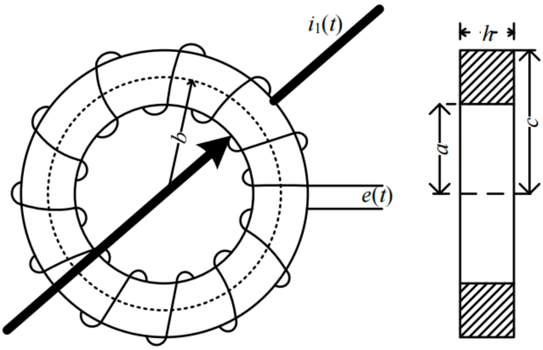

Fig. 2 Structure of Rogowski coil [3]

3 Classification and Application Characteristics of Rogowski Coil

In recent years, according to different application requirements, Rogowski coils have gradually developed into various types, including air-core type, flexible type, and PCB type. Each type has its own advantages and limitations in structural design, performance characteristics, and applicable scenarios.

3.1 Air-core Rogowski Coil

The air-core Rogowski coil is the earliest developed form, which is characterized by a simple structure, low cost, and high linearity. Due to the coreless design, the air-core coil can avoid magnetic saturation problems and is particularly suitable for transient measurement of large currents and short-circuit protection scenarios. The annular air-core Rogowski coil has advantages that other current sensors do not have when measuring nanosecond pulse currents: the skeleton is not easily damaged, the response time is short, the impact on the main circuit is small, and it is safe, simple, and easy to manufacture [6]. However, due to its low sensitivity, the air-core coil has obvious shortcomings in small current measurements [1, 8]. Fig. 3 shows the structural schematic diagram of the air-core Rogowski coil.

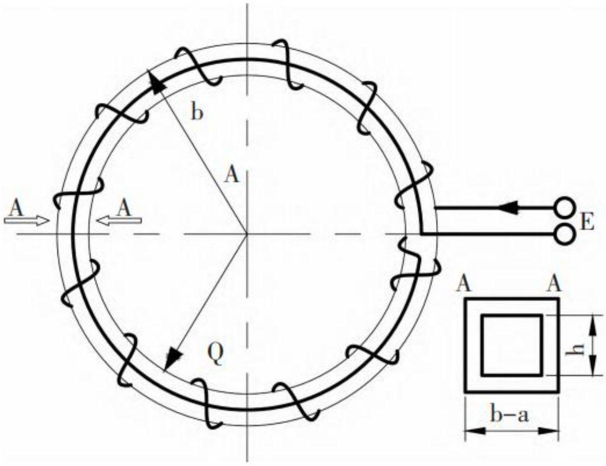

Fig. 3 Schematic Diagram of Air-core Rogowski Coil Structure [8]

3.2 Flexible Rogowski Coil

Flexible Rogowski coils usually adopt a hollow core structure with a flexible material such as silicone rubber as the skeleton. They are light, easy to bend, easy to install, easy to carry, and highly adaptable. Therefore, they are widely used in leakage current detection of overhead lines [3]. Their high sensitivity makes them excellent in the measurement of small currents in new energy equipment (such as photovoltaic and wind power systems) [7, 11]. However, flexible materials are susceptible to mechanical deformation, which may cause measurement errors. In addition, it is difficult for flexible Rogowski coils to achieve uniform winding and skeleton cross-sectional areas, and their ability to resist external magnetic field interference is weak, so their measurement accuracy and stability are low [3]. In addition, the durability and environmental adaptability of flexible coils need to be further improved [5, 9].

3.3 PCB Rogowski Coil

There are three typical types of PCB-type Rogowski coils, namely two-layer, four-layer, and six-layer PCB-type Rogowski coils. PCB-type Rogowski coils use printed circuit board technology to achieve a compact and highly integrated design. This coil adopts a multi-layer PCB structure, which effectively improves the anti-interference ability and measurement accuracy, and is suitable for switching current measurements of high-frequency power electronic devices [3, 6]. PCB-type Rogowski coils are drawn by computer, which gets rid of the cumbersome manual winding process of traditional Rogowski coils, and can ensure the uniform winding of the coil and set the return turns of equal area, thereby improving its ability to resist external interference and measurement accuracy. In addition, the application of digital signal compensation technology can significantly reduce integral errors and improve the accuracy of low-frequency measurements. However, due to the limitations of space size and manufacturing process, the number of turns of PCB Rogowski coils is relatively small [12]. The manufacturing cost of PCB-type coils is high, and performance fluctuations may occur under extreme temperatures [4, 9]. Fig. 4 shows the structure and equivalent circuit of PCB Rogowski coils.

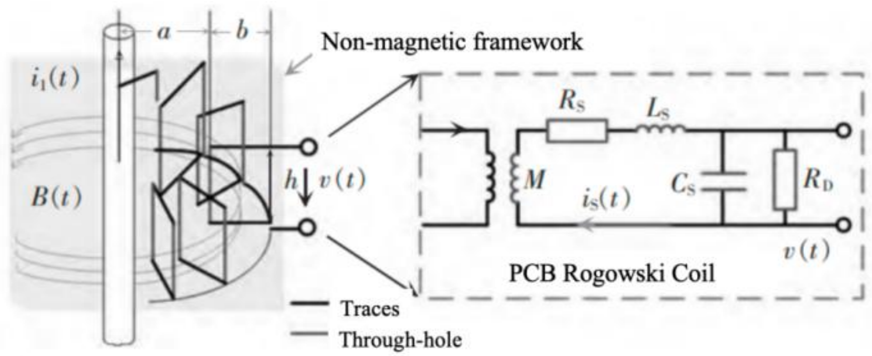

Fig. 4 PCB Rogowski coil structure and equivalent circuit [10]

3.4 Self-Integrating Rogowski Coil

Rogowski coils can be divided into self-integration and external integration modes according to their working modes. In the self-integration mode, the measured current can be output at a certain ratio. The self-integration type Rogowski coil simplifies the signal processing process by integrating the integration circuit into the coil. This design is particularly suitable for high-speed transient current measurement and high-frequency pulse current monitoring [2, 6]. However, due to the limitations of the built-in integration circuit, the self-integration type coil has poor performance in low-frequency measurement and cannot meet the precise measurement requirements of some scenarios [8, 9]. Fig. 5 shows the basic structure of the self-integration type Rogowski coil.

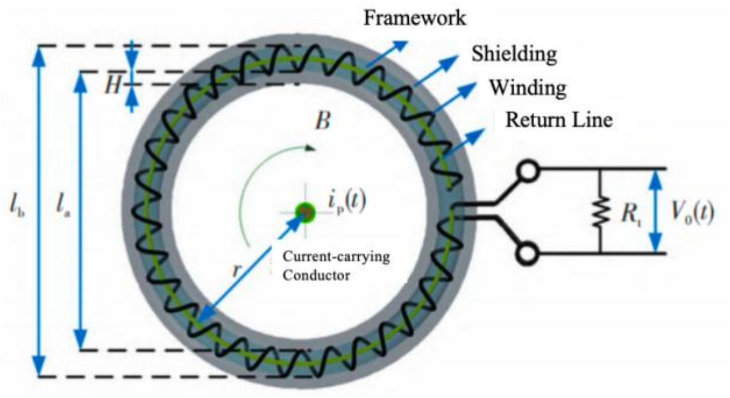

Fig. 5 Basic structure of self-integrating Rogowski coil [6]

4 Improvement of Rogowski Coil

Rogowski coils do not have a magnetic core, so there is no problem with core saturation. They can be used to measure small currents and pulsed large currents. In addition, their measurement frequency band is very wide, ranging from a few tenths of a hertz to tens of megahertz, with higher measurement accuracy and a wider measurement frequency band. They have no direct electrical contact with the primary current loop being measured, ensuring personal and equipment safety. However, Rogowski coils can only have theoretically high accuracy when the cross-sectional area of the skeleton is consistent, the coil is wound evenly and densely, and a return turn is set. The actual Rogowski coil is easily affected by various interferences. Internal factors: inconsistent cross-sectional area of the skeleton, uneven winding of the coil; external factors: eccentricity of the primary current being measured, crosstalk of adjacent phase currents, and interference from external stray magnetic fields. Given these problems, research and improvement of Rogowski coils are still important issues [3].

Given the problem of insufficient sensitivity of air-core coils, it can try to combine signal amplification and optimization technology to improve their small current measurement capabilities. Given the current situation of insufficient durability of flexible coils, it can try to improve the mechanical strength and environmental adaptability of flexible coils by improving material science and technology. For PCB-type Rogowski coils, it can try to reduce manufacturing costs while improving their temperature stability to adapt to extreme environments and optimize their performance. It can also develop intelligent applications, that is, combine artificial intelligence and digital compensation technology to develop an intelligent current monitoring system based on Rogowski coils to meet the needs of complex power environments.

5 Conclusion

This paper comprehensively reviews the existing types, advantages and disadvantages, and applicable scenarios of Rogowski coils. By analyzing the principles and application characteristics of different types of Rogowski coils, such as air-core type, flexible type, PCB type, and self-integral type, the wide applicability and technical challenges of Rogowski coils in current measurement are revealed. Air-core coils are suitable for high-voltage transmission systems due to their simple structure and reliability of large current measurements, while flexible coils are ideal for small current monitoring of new energy equipment due to their high sensitivity and convenient installation. PCB coils achieve high-frequency and high-precision measurement through integrated design, which is particularly prominent in the field of power electronics, while self-integral coils have unique advantages in high-frequency transient measurement due to their efficient signal processing capabilities.

Although Rogowski coil technology has made significant progress, it still faces the limitation of accuracy due to internal and external interference in practical applications, as well as the need for performance optimization under specific environments. Given the shortcomings of different types of coils, future research should focus on breakthroughs in material science, improvements in manufacturing processes, and the integration of intelligent technologies to develop high-performance current sensors that adapt to complex power environments.

In conclusion, the Rogowski coil has become an indispensable core component in modern power systems and power electronic devices with its excellent wide-band, large-current, and high-precision measurement capabilities. In the future, by continuously improving its performance and applicability, the Rogowski coil will play an important role in a wider range of fields.

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