High-Frequency Current Measurement and Signal Error Analysis Based on Rogowski Coil

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Abstract. The traditional current measurement technology faces issues such as slow response speed and bandwidth limitations in high-frequency signal measurements. The Rogowski coil, with its wide bandwidth response characteristics, is a reliable tool for high-frequency current measurement. This article aims to explore the advantages of the Rogowski coil in high-frequency current measurement and its applicability in power electronics technology. First, the working principle of the Rogowski coil and its characteristics in high-frequency current measurement are introduced. Then, the methods for processing the output signal of the Rogowski coil and the sources of error in the output signal are analyzed, along with a summary of some signal analysis techniques. Several methods for optimizing the accuracy of the output signal are discussed. Finally, the application effects of the Rogowski coil in high-frequency current sources such as power electronic converters and switch-mode power supplies are discussed, along with the existing advantages and disadvantages of the Rogowski coil, and its potential for high-precision current measurement in the future is anticipated.

Keywords: Rogowski Coil, High-Frequency Current Measurement, Measurement Accura Optimization

1 Introduction

In power electronics and switching power supplies, the demand for high-frequency current measurements is increasing. Traditional methods, while accurate for low-frequency currents, suffer from bandwidth limitations, slow response, and reduced accuracy when handling high-frequency signals. These limitations hinder their application in scenarios requiring precise capture of high-frequency waveforms or rapidly changing signals. The Rogowski coil, a non-contact current sensor, demonstrates significant potential for accurate high-frequency current measurement.

The Rogowski coil generates an induced electromotive force (EMF) based on Faraday's law of electromagnetic induction [1]. Compared to traditional Hall-effect sensors, it offers wider bandwidth and greater stability at high frequencies. However, its weak output signal is susceptible to interference, making signal processing critical for extracting valid information. Digital signal processing (DSP) and wavelet transform

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techniques have been applied to enhance precision and real-time performance.
This paper analyzes the principles of Rogowski coils, discusses their advantages in high-frequency measurement, and explores signal processing techniques to improve accuracy. It aims to provide insights for optimizing Rogowski coil applications and outlines future research directions.

2 Principles and Advantages of Rogowski Coil

2.1 The Working Principle of Rogowski Coils

When alternating current flows through a conductor, it generates a varying magnetic field. According to Faraday's law, this field induces an EMF in the Rogowski coil, producing a voltage signal proportional to the current's rate of change. An integrator converts this signal into one proportional to the current itself.

Under ideal conditions, the induced EMF $e(t)$ is:

$$e(t) = -\frac{d\psi}{dt} = -\frac{\mu_0 NS}{2\pi R}\frac{di(t)}{dt} \quad (1)$$

where N is the total number of turns of the Rogowski coil and S is the cross-sectional area of the Rogowski coil.

Make:

$$M = \frac{\mu_0 NS}{2\pi R} = \mu_0 nS \quad (2)$$

M is the mutual inductance between the Rogowski coil and the current-carrying conductor, and n is the number of turns per unit length of the Rogowski coil, that is, the line turn density.

If the distributed capacitance of the Rogowski coil is not considered, the mutual inductance L of the Rogowski coil is:

$$L \approx NM \quad (3)$$

The EMF $e(t)$ can be abbreviated as [2]:

$$e(t) = -M\frac{di(t)}{dt} \quad (4)$$

There is a trade-off between the bandwidth of a Rogowski coil and its sensitivity and immunity to interference. In general, a higher bandwidth of a Rogowski coil means that the coil has fewer turns, which not only reduces its sensitivity but also weakens its immunity to interference. Especially for low-frequency and low-current measurements, the signal-to-noise ratio of the output-induced voltage generated by the Rogowski coil is low, which limits the measurement accuracy. On the contrary, Rogowski coils, which have higher sensitivity or stronger anti-interference ability, have relatively narrow bandwidths due to the large number of coil turns. As a result, in high-frequency current measurements, the output-induced voltage may produce large errors, which can affect the accuracy of the measurement results.

2.2 Advantages of Rogowski Coils Over Traditional Current Measurement Methods

Most of the traditional low-frequency current measurement methods, such as Hall-effect sensors, rely on magnetic fields and core materials to measure current, and core materials are prone to magnetic saturation effect and high-frequency loss under high-frequency currents, resulting in reduced measurement accuracy [3]. However, the Rogowski coil has a wide frequency band response because it has only wound wires in its structure, no core material, and no magnetic saturation effect. At the same time, due to the distributed winding structure and coreless structure of the Rogowski coil, it has relatively small parasitic inductance and parasitic capacitance, which makes the Rogowski coil not cause signal distortion or interference when measuring high-frequency currents [4].

Energized semiconductors in magnetic fields generate a voltage at the poles, which is the Hall potential, due to the different Lorentz forces exerted by the magnetic field on the electrons and holes in the semiconductor. The formula for calculating the Hall potential U is:

$$U = KB \tag{5}$$

where K is the product of the sensitivity of the Hall element and the driving current of the Hall chip, and B is the magnetic induction intensity of the Hall element. According to Ampere's law, the magnetic induction intensity B of the Hall element can be obtained:

$$B = \frac{\mu_0}{2\pi R} I \tag{6}$$

where I is the current passing through the current-carrying wire, and R is the distance between the Hall element and the current-carrying wire [5].

3 Error Source and Processing Method of Rogowski Coil Output Signal

3.1 The Source of the Data Error

In the environment of high-frequency signal circuits, the signal output by the Rogowski coil will be introduced into noise errors, and the parasitic inductance and parasitic capacitance generated by the structure of the Rogowski coil will also affect the output signal in the high-frequency environment.

Under the influence of temperature, the geometrical parameters of the Rogowski coil also change. In addition, the fact that the object to be measured is not in the center of the coil or is not perpendicular to the plane where the coil is located can also cause errors. The interference of external electromagnetic fields should also not be ignored for the interference of the output signal [6]. The above errors can be reduced by optimizing the data integration algorithm, optimizing the integration circuit and optimizing the Rogowski coil design.

3.2 Error Handling Methods

3.2.1 Accuracy Compensation Circuit:

Due to the external integration mode of the Rogowski coil, the transient high-current signal is differentiated through the Rogowski coil and then enters the integration circuit to be integrated and restored. Subsequently, the integrated signal can be introduced into an ultra-low-pass filter to filter out the ultra-low-frequency interference components generated by the op-amp and other white noise, and the integration circuit can be negatively adjusted in reverse.

This design can solve the problem of noise integration of the signal while maintaining the stability of the static operating point of the entire integration circuit, and eliminating the influence of the delay generated during signal feedback processing on the signal phase [7].

3.2.2 Optimize the layout of the Printed Circuit Board (PCB):

The influence of parasitic parameters on signal conditioning circuits can be mitigated by optimizing the PCB layout and employing passive components.

Optimize the power supply layout. Considering that the switching power supply generates high-frequency electromagnetic interference by adjusting the voltage through high-frequency switching, the integrated switching power supply is moved to a part away from the circuit, and the regulator circuit part is moved closer to the operational amplifier.

To reduce voltage drop due to wire resistance and electromagnetic noise interference from wire coupling. A 100nF filter capacitor is placed directly on the op-amp power pins to minimize the effect of the power supply ripple on the op-amp.

Replace the high-capacitance electrolytic polarity capacitor with a tantalum capacitor. Compared with conventional electrolytic capacitors, the main feature of tantalum capacitors is that they use tantalum metal as the medium, rather than the electrolyte in ordinary electrolytic capacitors. Therefore, tantalum capacitors have almost no inductance and have a certain degree of defect self-healing ability, so they are more suitable as filter capacitors.

By optimizing the traces and reducing the length of the signal line, the electromagnetic interference of the signal line as an antenna coupling to the outside world can be reduced, and the parasitic inductance capacitance on the wire can also be reduced.

Arc routing is used for turning. Conventional chamfered traces will result in a change in the width of the wire at the chamfer, which will cause a change in the impedance of the wire. Transient high-current signals are distorted when they are routed through a large number of chamfered corners [7].

3.2.3 Use Wavelet Filtering Analysis to Reduce White Noise:

By using wavelet threshold filtering, the "ambiguity" of the sensor output signal caused by the signal detection device at a small primary current can be suppressed. This "fuzziness" is mainly manifested as "Gaussian white noise".

The basic idea of wavelet filter analysis is to decompose a signal using wavelet transform. Through transformation, the signal is broken down into different components, and these components are able to reveal the local characteristics of the signal at different locations in time or space. On this basis, the signal can be filtered at various scales of the wavelet transform to reduce the influence of noise on the output signal [8].

3.2.4 Using Special Materials to Reduce Temperature Effects:

Temperature changes can cause thermal expansion and contraction in the skeleton of the Rogowski coil, the wound copper wire, and the insulating layer surrounding the coil. The geometric parameters of the entire coil must also change accordingly, directly leading to alterations in the mutual inductance of the coil, which in turn affects the accuracy of the measured data and the sensitivity of the coil. Thermal expansion results in relative errors in the induced voltage, with the magnitude of these errors increasing with rising temperatures.

To mitigate the impact of thermal expansion changes caused by environmental temperature on the relative mutual inductance error of the Rogowski coil, the most straightforward method is to seek high-performance materials for the coil skeleton, specifically materials with a low-temperature coefficient.

Table 1 lists the thermal expansion coefficients of some commonly used insulating non-magnetic materials for easy observation, comparison, and selection. Choosing cost-effective materials will significantly reduce the errors caused by changes in environmental temperature.

Table 1 Coefficients of Thermal Expansion for Commonly Used Insulating Non-Magnetic Materials

Insulating non-magnetic materials	Coefficient of thermal expansion (/°C)
Phenolic plastic	1.9×10^{-5}
Quartz glass	5.5×10^{-6}
Electrical ceramics	0.5×10^{-6}
Fiber materials	4.5×10^{-6}
Common ceramics	$1.0\sim7\times10^{-6}$

Epoxy resin	$5.6 \sim 6.7 \times 10^{-5}$

The actual production of the Roach coil will also take into account the cost-effectiveness and characteristics of the materials.For example, ceramic materials are relatively brittle, but they have a very low thermal expansion coefficient, and it is often necessary to add moderate oxides to these materials to increase their toughness, making them suitable for practical use and convenient for production and transportation [9].

3.2.5 Introducing Return Lines and Differential Design Reduces External Electromagnetic Field Interference:

A differential design can be introduced, dividing the even block insert into two parts to form two independent composite PCB Rogowski coils, one above the other. One end of the first coil is grounded to the other end of the second coil, ensuring that the main circuit direction of one coil is the same as the magnetic field direction, while the other is opposite to the magnetic field direction.

During measurement, an induced voltage U of equal magnitude but opposite direction is generated, which can reduce parasitic parameters without decreasing the number of coil turns, thereby expanding the measurement bandwidth of the Rogowski coil without compromising sensitivity.

At the same time, the differential circuit design can ensure that the two coupling capacitances formed between adjacent wires and electrical equipment and the coils, as well as the parasitic parameters between the two coils, are equal, resulting in coupling capacitance voltages of the same magnitude and consistent polarity. These two voltage signals belong to common-mode noise and will cancel each other out when entering the subsequent differential amplification circuit, thereby reducing the electric field interference caused by the coupling capacitance.

A return line design can be introduced, by adding a return line at the bottom layer. The return line at the bottom layer will sense a voltage equal in magnitude but opposite in direction to that of the main circuit at the top layer, theoretically completely canceling out the magnetic field interference perpendicular to the plane of the coil.

When measuring current, the induced voltages generated between the various plug board coils will superimpose on each other. When facing external parallel interference magnetic fields, the induced voltages of each plug board coil will cancel out during the superimposition process. This can reduce the induced voltage from external parallel interference magnetic fields, thereby significantly diminishing the impact of the parallel magnetic field on the measurement results [10].

4 Conclusion

In this paper, the principle of the Rogowski coil and its data processing method are discussed and analyzed. Through a literature review, the advantages of Rogowski coil and the error treatment method are discussed. In this paper, the principle of measuring current from Rogowski coil and Hall effect sensor is compared, and the advantages of

Rogowski coil in measuring high-frequency current are illustrated. Then, the possible interference in the output signal of the Rogowski coil is analyzed, and then different ways can be used to reduce or avoid the interference for different signals. For example, design and build integration compensation circuits to reduce integration noise.

It is also possible to optimize the PCB layout and use passive components to avoid the electromagnetic noise interference of the switch and weaken the interference of parasitic parameters on the signal conditioning circuit. In addition, the high-frequency noise of the output signal can be reduced by wavelet filter analysis, and the influence of ambient temperature on the parameters of the Rogowski coil can be reduced by selecting the appropriate material to make the Rogowski coil.

Due to its simple structure, fast response, high measurement accuracy, and the fact that it can be measured without interfering with the current, it has been widely used in the field of current measurement. Examples include high-current measurement, current waveform analysis, and rectifiers and inverters in substations and large power plants.

However, there is still much room for improvement. For example, the output signal strength of Rogowski coils is usually small, and the use of signal amplifiers to increase the strength will also increase the signal noise, which will affect the measurement accuracy. In addition, the Rogowski coil has a poor response to low-frequency DC current and AC current and is also prone to external electromagnetic interference, which requires additional shielding design.

The development prospects of Rogowski coils are very broad. With the development of power electronics, it is possible to further improve the frequency band response range of Rogowski coils, or integrate more sensors to provide more comprehensive detection capabilities. Or the development of modular Rogowski coils, so that users can flexibly adjust the size, shape, or working frequency of Rogowski coils according to different applications.

With the advancement of power electronics and integration technology, the application of the Rogowski coil will be more extensive. By continuously optimizing the design of the Rogowski coil, the Rogowski coil will play an even more important role in the current measurement technology of the future.

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