

Current Distortion and Sensitivity Calibration Problems of Rogowski Coil

Jiezheng Bi¹, Lumeng Ge² and Ziyi Wang^{3,*}

¹ School of Electrical and Automation Engineering, Nanjing Normal University, Nanjing, China

² School of Automation, Nanjing Institute of Technology, Nanjing, China

³ College of Automation, Shenyang Aerospace University, Shenyang, China

* Corresponding Author Email: 1912211118@mail.sit.edu.cn

Abstract. Driven by technology, China's power system has been greatly improved, and has been gradually transformed and upgraded, bringing great improvements to performance in all aspects. Current distortion and sensitivity misalignment of Rogowski coils have always been the key problems to be solved in practical applications. This paper summarizes the methods of calibrating the sensitivity of the Rogowski coil in the shape of the single ring arbitrary skeleton, the Rogowski coil of the double ring skeleton and the Rogowski coil in the shape of the round skeleton, which provides the basis for other improvements of the Rogowski coils. The existing method to solve the current distortion of the Rogowski coil has a single method in the output of the differential current signal, which will reduce the limitation of the measurement range, and the suppression problem still cannot be solved well. This paper summarizes the solutions to current distortion in Rogowski coils, introduces the causes and solutions of current sensor and transistor current distortion, and puts forward certain correlations to provide reference and direction for follow-up research.

Keywords: Rogowski coil, current distortion, sensitivity.

1. Introduction

China's power system has experienced arduous exploration and development from the 1990s to the present and has made great achievements and progress. In particular, the continuous promotion of reform and innovation has enabled the power system to be gradually transformed and upgraded, realizing the transformation from traditional thermal power to multiple energy sources, from simple long-term contracts to more flexible multiple trading methods, and from traditional manual management to digital and intelligent upgrading. These changes have greatly improved the supply capacity, safety, stability and environmental protection of China's power system, and have made important contributions to the country's economic and social development. However, with the development of new energy power systems, the accuracy of current values in circuits has become an issue that needs special attention.

With the development of the times, modern power systems and experimental research have increasingly increasing requirements for flexible, accurate and safe current measurement. As a miniaturized, non-contact, broadband response and high-precision current sensor, Roche coil needs continuous improvement and innovation in its performance and function.

"Rogowski coil" is a sensor for measuring current, which is used to measure the size and waveform of AC current. Power system, power distribution, motor control, and electronic equipment testing are mainly used fields, which are mainly used to measure and monitor currents to meet the needs of overload protection, power load analysis and fault detection. As a whole, the Roche coil is a spiral sleeve, which is composed of insulated wires. Most of the coils are arranged in a flat or spiral shape, but there are also other shapes [1].

Current distortion refers to the phenomenon of Rogowski coil output signal distortion caused by power supply interference, transformer internal leakage, power supply harmonics, noise and other factors. Distance causes a deviation between the measurement result and the actual current value, thus reducing the measurement accuracy of the system. The main distortion sources include power supply frequency, power supply harmonics, capacitive coupling interference and common-mode noise.

The current distortion of the Rogowski coil refers to the deviation or distortion between the output signal of the Roche coil and the actual current value due to different factors. In order to accurately measure the current of the Roche coil, the calibration of its sensitivity is very important.

The sensitivity of the Roche coil refers to the rate of change of the output signal per unit time. Correct evaluation of the sensitivity of the Roche coil is essential for accurately measuring the current. However, the sensitivity of the Rogowski coil may be affected by several factors, such as the parameters of the coil itself, the length of the connector and the change of the power supply [2]. Therefore, before using Roche coils for current measurement, sensitivity tests must be carried out to ensure accuracy and reliability.

Through the summary method, this paper sorts out the methods of calibrating the sensitivity of the Roche coil in the shape of a single ring arbitrary skeleton, the Roche coil in the double ring skeleton and the Roche coil in the shape of the round skeleton and explores more solutions and directions of current distortion in the Rogowski coil by combining other types of current distortion solutions.

2. Sensitivity calibration of Rogowski coils

Sensitivity (also known as conversion ratio in some cases) is an important parameter of the Rogowski coil, which refers to the conversion ratio of the Roche coil corresponding to the primary current through the secondary output voltage of the integrator, unit mV/A. The nominal sensitivity value is determined according to the process and current measurement range or range of the Rogowski coil. Generally, the sensitivity range value of the Rogowski coil is 0.02~200 mV/A [3]. When calibrating, the stability of the high-power AC current source, the determination of the standard primary current, and the selection of the secondary monitoring digitizer, etc. are mainly considered [4].

This paper lists three sensitivity calculation methods for current sensors of Rogowski coils: single-ring arbitrary skeleton-shaped Rogowski coil (not closed), double-ring skeleton Rogowski coil (unclosed), and round skeleton-shaped Roche coil [5-7].

2.1. Rogowski Coil of Any Skeleton Shape of a Single Ring

The Rogowski coil of any skeleton shape of a single ring is shown in Figure 1.

The first step is to find a random origin in the rogowski coil and set up a three-dimensional rectangular coordinate system with the origin and write the geometric center line parameter equation of the Rogowski coil. The geometric center line also passes vertically through the geometric center of the line turn section.

Step 2: The intersection point between the line turn section at the β position and the geometric center line of the skeleton is O' , the center of the line turn section O' is projected to the xOy plane is O , and the angle between the line $O'O''$ and the x -axis is β , and the point P is taken on the circular section located in the vertical distance of the straight conductor, get the coordinates of point P ;

Step 3: When the measured conductor is a straight conductor, the coordinates of both ends of the finite long current-carrying straight conductor are $A(a, b, c)$ and $B(d, e, f)$, and the current of the current-carrying conductor is I , and the unit vector of the current-carrying conductor is obtained.

Step 4: θ_1 and θ_2 are the angle between the straight line from both ends of the current carrier to point P and the direct current conductor respectively. By the law of Biosavart, the magnetic induction intensity generated by the current-carrying direct conductor at point P is calculated.

Step 5: Calculate the magnetic flux passing through the linear cross-section at the β position.

Step 6: Add the magnetic flux of each wire turn in step 5 to get the magnetic flux of the entire Roche coil. The number of turns of the Rogowski coil is N , and then the mutual insensitivity coefficient M between the Rogowski coil and the direct current conductor described in step 3 is obtained.

Step 7: When the measured wire is a curved wire, the spatial parameters of the curved Equation; divide the current-carrying conductor into n current elements and add all the current elements on all the bending wire to get the magnetic flux of the whole bending wire passing through the whole coil.

Step 8. The basic working principle of the Roche coil current transformer can be seen. Combined with the mutual inductance between the current-carrying conductor and the Roche coil, the measured current is calculated to calculate the open-circuit induction voltage at two sides of the Roche coil, so that the sensitivity of the Roche coil can be measured at any position and shape of the wire can be obtained.

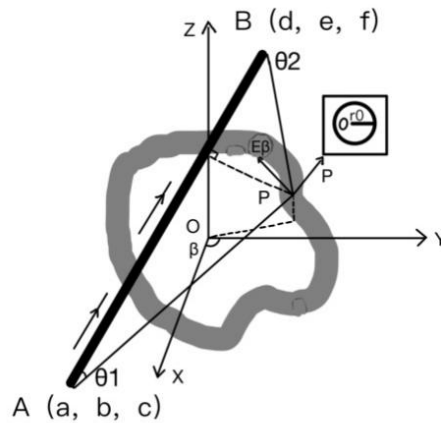


Fig. 1 The rogowski coil of any skeleton shape of a single ring [5]

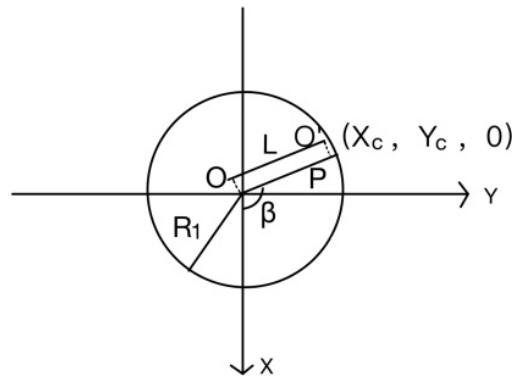


Fig. 2. The double-ring skeleton rogowski coil [6].

2.2. Double-Ring Skeleton Rogowski Coil

As shown in Fig. 2, the first step is to set up a coordinate system. The central axis of the double-ring skeleton coil coincides with the z -axis. The geometric centerline of the multi-ring skeleton projected on the xOy flat surface is a circle $C1$ with a radius of $R1$, and the radius of the skeleton circular cross-section is $r0$. The geometric center line also crosses The spatial parametric equation to the geometric center line of the spiral skeleton;

Step 2: When the measured conductor is a straight conductor, the coordinates of both ends of the finite long current carrier straight conductor are $A(a, b, c)$ and $B(d, e, f)$, respectively. the current carrier conductor is I , and the unit vector of the current carrier conductor is obtained.

Step 3: Take any point P on the circular cross-section located in the β position. IP is the vertical distance from any point P to conductor on the line-ring cross-section. The unit normal vector of the line-section corresponding to the β angle where the point P is located is obtained and the expression of point P is obtained;

Step 4: θ_1 and θ_2 are the angle between the straight line from both ends of the current-carrying direct conductor to the point P and the direct current conductor. By the law of Biosavart, Calculate the magnetic induction intensity generated by the current carrying straight conductor at point P;

Step 5: Calculate the magnetic flux passing through the linear cross-section at the β position;

Step 6: Add the magnetic flux of each line turn in step 5 to get it of the entire Roche coil. , and then the mutual inductance coefficient M Divide the current carrying conductor into n current elements between the Roche coil and the direct current conductor described in step 2 is obtained;

Step 7: When the measured wire is a curved wire, the spatial parametric equation of the curved conductor is obtained. Adding all the current elements on all the curved wires to obtain the magnetic flux of the entire curved wire passing through the whole coil;

Step 8: According to the basic working theory of the Roche coil current transformer, combined with the mutual inductance from the current carrier to the Roche coil, the measured current calculate the open induced voltage at both ends of the Roche coil, so as to obtain the sensitivity of the Roche coil at any position and shape of any wire.

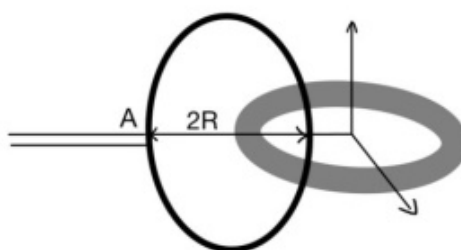


Fig. 3. Circular skeleton shape [7]

2.3. Roche Coil in the Shape of a Circular Skeleton

The Roche coil in the shape of a circular skeleton is shown in Fig. 3. Firstly, the equivalent radius of the circular skeleton of the Roche coil is R , and a three-dimensional Cartesian coordinate system is set up with the geometric center of the circular skeleton of the Roche coil as the coordinate origin, with the z-axis of the Cartesian coordinate system passing vertically through the center of the coil;

Step 2: The intersection of the linear turn cross-section at the β position and the geometric center line of the skeleton is O' , and the angle between the straight line $O'O$ and the x-axis is also β . The unit normal vector of the cross-section at the β position is any point P on the circular section at the β position, the distance from the For $(l\cos\beta, l\sin\beta, z)$;

Step 3: When the measured conductor is a straight conductor, the straight conductor is regarded as a finite long current-carrying direct conductor, and the unit vector of the current-carrying conductor is calculated.

Step 4: θ_1 and θ_2 are the angle between the straight line from both ends of the current-carrying straight conductor to point P and the direct current-carrying conductor. By Biosavalt's law, the magnetic induction strength generated by the current-carrying straight conductor at point P is calculated;

Step 5: Using the idea of microelement, divide the circular section of the line turn into rectangular surface elements whose area tends to zero, and calculate the magnetic flux on the line turn section corresponding to the angle β ;

Step 6: Add the magnetic flux of each wire turn in step 5 to get the magnetic flux of the entire Rogowski coil. The number of turns of the Roche coil is N , and then calculate the mutual inductance coefficient M between the Rogowski coil and the current-carrying straight conductor described in step 3.

Step 7: When the measured conductor is a curved wire, write the spatial parameters of Equation; divide the current-carrying conductor of the measured wire into n current elements, calculate, and use steps 5 and 6 to obtain the mutual inductance from Obtain the magnetic field of the current element at point p the curved wire to the Rogowski coil;

Step 8: According to the basic working principle of the Rogowski coil current transformer, calculate the open-circuit induced voltage at both ends of the Rogowski coil, so as to obtain the sensitivity of the Rogowski coil when measuring any wire in any position and shape, and to explore the influence of the shape and position of the measured wire on the sensitivity of the coil.

3. Current Distortion in Rogowski Coil

3.1. Direct Output Current Differential Signal

There are some problems in the application of Rogowski coil current transformer in differential protection. Expanding the transmission error generated by the Roche coil and the sampling process in the integration process can cause severe distortion of current transmission, resulting in protection malfunctions [3]. In differential protection, as shown in Fig. 4, when the sampling frequency of the analogue-to-digital transformation link is lower than the frequency of the high-frequency signal in the measured signal and the frequency of the two meets a certain relationship, the digital signal will be approximately.

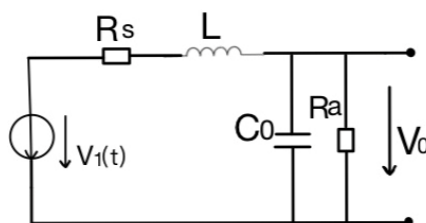


Figure. 4 The schematic diagram of the internal integral Rogowski coil [3].

3.2. Direct Flow

At the same time, because of the inherent variable nature of the Roche coil, under the influence of high-frequency transient signals, the output of the Roche coil will superimpose a decaying DC component. These two DC components will be amplified after subsequent integration processing, which will cause bad distortion of current transmission.

When the current through the Rogowski coil changes, an electromotive force will be generated inside the coil, which is proportional to the rate of change of the current. Then the electromotive force signal is input into the integrator for integration to obtain the accurate value of the current. The function of the integrator is to perform an integral calculation of the voltage to restore the original current signal. The actual integrator has limited bandwidth and response time, which cannot fully realize the ideal integration characteristics. In the process of integrating the electromotive force signal by the integrator, the integrator may not be able to fully track the high-frequency change of the electromotive force signal, resulting in an error in the integral value.

The electromotive force of the Rogowski coil is proportional to the current rate of change, but with the increase of the current rate of change, the relationship between the electromotive force and the current may become nonlinear. This nonlinear response will introduce current distortion, so that the integral result is different from the actual current. The structure of the Rogowski coil has a certain attenuation effect on high-frequency signals. When there is a high-frequency component in the current, the Roche coil may not be able to accurately capture these high-frequency signals, resulting in an error in the integral result.

An integrator may be very sensitive to noise and interference signals as it integrates these signals into the output. Noise and interference signals can come from external environments, the noise of the sensor itself, and other components in the circuit. They will be superimposed on the original signal during the integration process, causing distortion in the current measurement results. Taking differential protection as an example, differential protection is a type of relay protection, as shown in Figure 5. It starts the action element when the vector difference of the current at both ends of the input current transformer (CT) reaches the set action value, protecting the equipment at both ends of the

input CT. Differential protection is formed by the theory of "the sum of the incoming node currents in the circuit is equal to zero". Electrical protection equipment is an important part of differential protection. Under normal circumstances, the guaranteed current will flow out like the normal current, and the differential current is zero [2]. After the device encounters a problem, the current flowing into the protection device and the current flowing out differ in value, and the differential current is greater than zero. After the differential current exceeds the set value, the upper computer issues a warning and performs a protective exit action, disconnecting the problematic machine from the power supply after disconnecting the circuit breaker.

According to the transmission theory of transmission lines, the current directly adopts the current differential signal output by the Roche coil, and the voltage also passes through the virtual Roche coil with the same transmission characteristics. The voltage and current relationship after the transmission link is compensated, which still meets the distribution parameter model of the original transmission line. The current of equal transmission differential protection directly adopts the current differential signal output by the Roche coil, which eliminates the impact of the transmission error introduced in the integral link on protection and improves the reliability of protection, as shown in Fig. 5 [8].

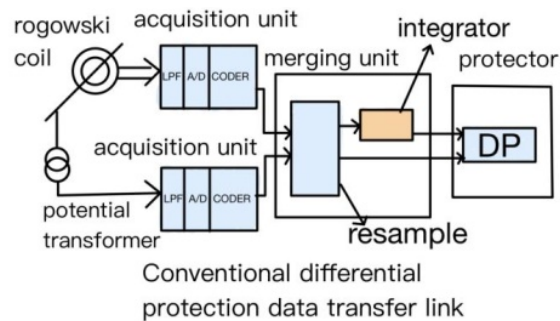


Fig. 5. Conventional differential protection data transfer link [8]

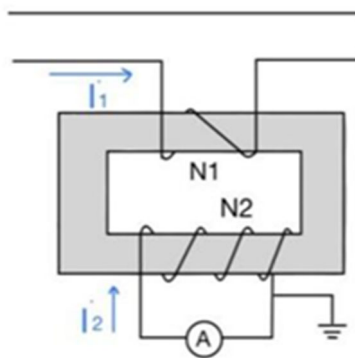


Fig. 6. The schematic diagram of current transformer [9]

4. Other Current Distortion Problems

4.1. Current Distortion of Current Transformer

Distortion problems of current transformers include nonlinear distortion and phase distortion, as shown in Fig. 6. In order to reduce the problem of current distortion, some measures can be taken when using current transformers. For example, reduce the contact resistance, reduce the circuit impedance, increase the transformer capacity, select the Hall element with less impact on the frequency change, and reduce the total circuit impedance, so that the transformer error moves in the positive direction, etc [9].

These solutions are also applicable to the current distortion problem in the Rogowski coil. By reducing the contact resistance and reducing the circuit impedance, the impact of nonlinear distortion in the Rogowski coil can be reduced. Increasing the capacity of the Rogowski coil and selecting suitable components can reduce the problem of phase distortion. In addition, reducing the total circuit

impedance also helps to reduce the occurrence of current distortion [10]. In summary, for the current distortion problem in the Rogowski coil, a solution similar to the current transformer can be adopted to improve the accuracy of the component, reduce the occurrence of current distortion, and improve the accuracy of the Rogowski coil.

4.2. Current Distortion of Transistor

Due to the life and reliability requirements of the transistor, when the current is reversed, it will not be cut off immediately. This will lead to the existence of reverse switching time, which will generate a sawtooth wave in the output signal. Because of the capacitance characteristics of the transistor, the high-frequency component of the input signal will be affected by the transistor capacitance. When the input signal frequency exceeds the cut-off frequency of the transistor, distortion will occur in the output signal. When the transistor current is large to a certain extent, the transistor will enter a saturated state. In this state, the magnification of the transistor is no longer proportional to the size of the input signal, resulting in the output not being able to accurately follow the change of the input signal, resulting in distortion [11].

4.2.1 Increase the design capacity of the power amplifier

One of the reasons why the harmonic distortion exceeds the standard is that the power amplifier is overloaded. One of the reasons why the harmonic distortion of the design capacity of the power amplifier exceeds the standard when the signal is too large to search and increase the power amplifier is working under overload. When the signal is too large to exceed the design capacity of the power amplifier, harmonic distortion will occur. Therefore, increasing the design capacity of the power amplifier is another way to solve the problem of harmonic distortion exceeding the standard. The working capacity of the amplifier can be improved by increasing the power supply voltage of the amplifier, improving the heat dissipation system, optimising the circuit design, etc., so as to reduce the degree of harmonic distortion.

4.2.2 Optimise the signal source

The quality and stability of the signal source have a great impact on harmonic distortion. If the signal source itself has harmonic components or poor frequency stability, it will lead to harmonic distortion exceeding the standard. Therefore, optimising the signal source is one of the key measures to solve the problem of harmonic distortion exceeding the standard. The performance of the signal source can be improved by replacing the high-quality signal source, improving the frequency stability of the signal source, increasing the filter circuit and other methods, so as to reduce the level of harmonic distortion.

In summary, for the current distortion problem in the Rogowski coil, a similar solution to the transistor can be used to amplify the power, increase the filter circuit to improve the signal source, and reduce the current distortion.

To a certain extent, all of these show that the solutions to other current distortion are related to the method of solving the distortion in the Roche coil, which provides a variety of possibilities for exploring more ways to solve the current distortion problem of the Roche coil.

5. Summary

In order to make the Rogowski coil more accurate in the measurement range when measuring the current, this paper summarizes the sensitivity quick calculation method of calibrating the Rogowski coil of the single ring arbitrary skeleton shape, the double ring skeleton Roche coil and the round skeleton shape of the Rogowski coil. And by combining the current sensor and the transistor current distortion solution, we can explore more directions and possibilities to solve the current distortion of the Rogowski coil. In a word, in the future, the development of Roche coil will continue to progress in the direction of miniaturization, high frequency, high precision, low distortion, new materials and intelligence. This will provide higher performance and more reliable induction devices in power

systems, electronic equipment and automation control. Solving the current distortion of the Rogowski coil is also an important part.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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