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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1109/CPEM.2010.5544836>

2010 Conference on Precision Electromagnetic Measurements (CPEM 2010), pp. 541-542, 2010

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TO WHAT EXTENT CAN ROGOWSKI COIL CURRENT AMPLITUDE LINEARITY BE VERIFIED?

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Abstract

Calibrations of Rogowski coils at power frequencies are often performed at currents of only tens of amperes even though the coils are used at currents larger by two to three orders of magnitude, or even greater. The underlying assumption of an ideal linearity versus current amplitude is true for ideal coils. This paper addresses the question of practical significance as to what extent the linearity of real Rogowski coils versus current can presently be verified at power frequencies. For this task several different types of Rogowski coils were evaluated using a digital sampling system, with the best calibration uncertainties ($k=2$) of $50 \mu\text{A/A}$ for magnitude and $50 \mu\text{rad}$ for phase.

Introduction

Rogowski coils are widely used by electric utilities, manufacturers of electrical equipment, smelters and the automotive industry for monitoring/measurement of high, impulse, and transient currents in protective relaying, circuit breakers, arc furnaces, resistance welding, and plasma physics [1],[2]. New materials and manufacturing methods developed in the last decades have been implemented in the design of Rogowski coils. Because of these improvements, the earlier prevailing perception of the coils as relatively inexpensive and low-accuracy devices is no longer valid. The improved coils increased the need for calibrations with low uncertainties and traceability [3].

Precision Rogowski coils have been used for on-site calibrations of metering or protection current transformers in power systems [4],[5]. On-site calibrations reduce service interruption and the cost of transporting transformer to a calibration laboratory. In some cases, Rogowski coils have also been used in current transformer measurement comparisons by national measurement laboratories [6].

Calibrations of Rogowski coils at power frequencies are often performed at currents in the range of 250 A to 500 A [7]. However, calibrations are also performed at currents of only tens of amperes and the

calibration results extrapolated to currents larger by two to three orders of magnitude, or even more [5]. The underlying assumption is an ideal linearity versus current amplitude. Although the coils wound on air-cores have, in principle, such an inherent linearity, the question still arises how true this is in practice for real coils where materials and fabrication processes include imperfections. In spite of numerous papers on Rogowski coils, few have addressed this issue of linearity versus current [8],[9].

An amplitude linearity test of a calibrated split-core coil revealed a mean deviation of $0.005 \text{ \%/kA}$ in the current range of 1 kA to 10 kA at 50 Hz [8]. The verification of Rogowski coil linearity from 200 A to more than 100 kA at power frequencies using ratio methods with reference coils and pulsed currents in the range of 1:500 has been examined in [9]. In the range 50 kA - 100 kA, a maximum cumulative nonlinearity of less than $200 \cdot 10^{-6}$ was reported, well within an estimated combined uncertainty ($k=2$) of $950 \cdot 10^{-6}$.

This paper addresses the question as to what extent the Rogowski coil linearity versus current can presently be verified at power frequencies. For this task several different types of Rogowski coils were evaluated using the low-uncertainty digital sampling system described in [10].

Calibration System

A simplified block diagram of the automated Rogowski coil calibration system used for the verification is shown in Fig.1. It consists of a signal generator SG, power amplifier PA, current step-up transformer ST, reference current transformer CT, reference AC shunt S as in [11], Rogowski coil under test RC, two digitizers DS1 and DS2, and a computer PC which control the calibration process.

The signal generator SG provides a low-voltage signal of stable frequency for driving the power amplifier PA. The power amplifier drives the single turn primary of a current step-up transformer ST, which forms the main current loop. The reference current transformer CT scales down the current from the main loop and provides it to the reference AC

current shunt S. The voltage across the shunt is thus a replica of the current generated in the main current loop which threads the Rogowski coil under test. The shunt voltage and the voltage at the output of the Rogowski coil are sampled by the digitizers. The mutual inductance of the Rogowski coil is derived from these samples by means of nonsynchronous multi-rate digital filtering [10].

Fig.1 Block Diagram of the Rogowski Coil Calibration System with Digital Sampling.

For currents above 2,000 A, different ST and CT transformers were used, and in place of the power amplifier PA, a high current source supplied from the mains at 60 Hz, or from a synchronous generator at 50 Hz, was used.

Testing and Results

To extract meaningful results from the testing, a number of constraints related to the calibration system and the Rogowski coils under test had to be taken into account. The voltage at which dielectric breakdown in the Rogowski coil winding or the cable occurs limits the maximum operating coil primary current. More importantly, physical dimensions of the coil's opening (window) limit the primary current conductor dimensions and lead to thermal limits in the primary current circuit. Due to these thermal limitations, most of the coils were tested at continuous currents up to 24,000 A.

The temperature coefficient of the Rogowski coil mutual inductance has to be taken into account as it may mask the coil's current amplitude nonlinearity. Even for high-precision coils, changes of $\pm 0.5^\circ\text{C}$ can have an impact of the order of $\pm 30 \cdot 10^{-6}$ on the measurements. To mitigate the impact of changing temperature, the Rogowski coils under test had to be temperature compensated, or thermally isolated from the primary conductor and the ambient, or both. The compensation is somewhat a tedious process and involves determining the coil temperature coefficient

and a selection of a compensating load resistor value [4]. Since the Rogowski coil positional sensitivity could easily mask current nonlinearity, it is essential that the coils be kept in the same fixed position during the coil temperature compensation and the testing. Additionally, the return primary current conductors must remain in a fixed geometry. A thorough testing has been performed and the results obtained indicate that any possible coil nonlinearities are within the calibration system estimated uncertainties. Detailed results obtained from the measurements on different types of Rogowski coils will be presented at the conference.

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