Influence of winding and positioning defaults on current measurement with a Rogowski coil

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The Rogowski coil is a well-known transducer device use for its linear or large bandwidth characteristic, but it's quiet a challenge to wind a perfect Rogowski coil to minimize the current measurement error. In this paper, we will discuss the influence of different winding and positioning defaults such as coil and turn tilt, turn density, and conductor positioning on current measurement. Using Sobol's method combined with Monte Carlo method, the aim of this study is to put the light on the manufacturing defaults that have the worst influence on the actual current measurement accuracy.

***Index Terms*—Analytical model, Rogowski coil, magnetic flux measurement.**

I. Introduction

A ROGOWSKI COIL is an electrotechnical device consisting of a toroidal non-magnetic support on which a copper wire is wound. Based on Ampère's and Faraday's laws, it generates a voltage proportional to the variation of the magnetic flux [2]. This variation of flux is generally due to an alternating current or a current peak. A device similar to a Rogowski Coil first appeared in 1887 during an experiment carried out by P. Chattock of Bristol to measure a reluctance, with the aim of improving dynamos [1]. Subsequently, W. Steinhaus and W. Rogowski used and improved this device to measure magnetic fields, validating its performance through various experiments. The coil was then named after the German physicist Walter Rogowski [5]

Until 2000, the Rogowski coil was largely overlooked due to its low output voltage. However, advances in modern microprocessors now enable the exploitation of low signals, paving the way for the Rogowski coil to be utilized in current measurement, with all its advantages: linearity in current and frequency, allowing for the measurement of currents over a wide range, as well as being lightweight, cost-effective, and compact. Nevertheless, a significant drawback lies in its manufacturing challenges, which is why this paper examines the impact of defects or combinations of defects on current measurement. [6, 3]

II. Analytical model

The analytical model developed for this study is based on the vector potential. This approach involves integrating the vector potential A along the path traced by the wire winding around the non-ferromagnetic core. The wire's path is divided into straight segments, enabling the calculation of each segment's contribution to the total flux. Consequently, the total flux ϕ_{total} is determined by summing the contributions from all segments. The resulting formula is as follows:

$$\phi_{total} = \sum_{i=1}^{m} \int_{l} A_i \cdot dl_i \tag{1}$$

with A_i the vector potential of the i^{th} segment and dl_i the unit vector indicating its direction. The calculation of A_i is based on Biot-Savart law as in [4].

$$A_i z = \frac{\mu_0 I}{4\pi} \int_{l_{cond}} \frac{1}{PM} dl_{cond} \tag{2}$$

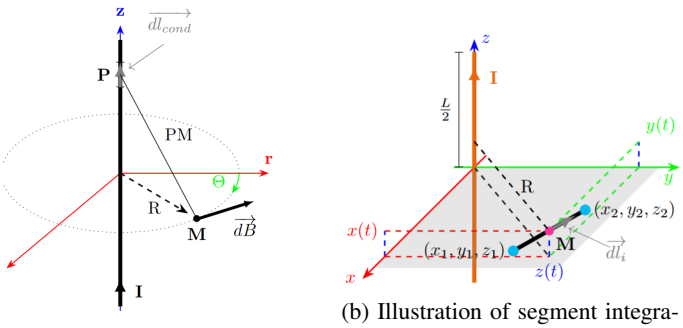
Then, using $PM = \sqrt{R^2 + (l_{cond} - z)^2}$ and integrating A_i along the conductor, we obtain :

$$A_i z = \frac{\mu_0 I}{4\pi} \left[\ln \left((l_{cond} - z + \sqrt{R^2 + (l_{cond} - z)^2} \right) \right]_{-\frac{L}{2}}^{\frac{L}{2}} (l_{cond}) \tag{3}$$

We replace R, x, y and z with $R = \sqrt{x(t)^2 + y(t)^2}$, $x(t) = x_1 + t(x_2 - x_1)$, $y(t) = y_1 + t(y_2 - y_1)$ and $z(t) = z_1 + t(z_2 - z_1)$. Points (x_1, y_1, z_1) and (x_2, y_2, z_2) represent the coordinates defining the segment. The expression is then simplified and integrated by focusing solely on the logarithmic term $I.1$ along the segment (refer to diagram 1b).

Finally, the total flux expression I is

$$\phi_{total} = \frac{\mu_0 I}{4\pi} \sum_{i=1}^{m} [I.1]_{-\frac{L}{2}}^{\frac{L}{2}} (l_{cond}) \cdot dl_i \tag{4}$$



(a) Illustration of Biot-Savart law

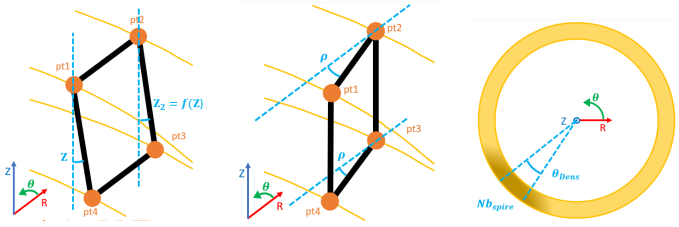
(b) Illustration of segment integration

Fig. 1: Synthetic geometric model

III. Defects managed by the model

This model is designed to address various defects, particularly those related to winding:

- The turn tilt, denoted by ζ in figure 2a, represents the inclination of a turn relative to the vertical Z axis occurring during the winding process.
- The turn tilt, denoted by ρ in figure 2b, represents the inclination of a turn relative to the radial R axis occurring during the winding process.
- The winding density defect, illustrated in figure 2c, represents irregularities in winding density, often caused by a localized excess or shortage of windings.

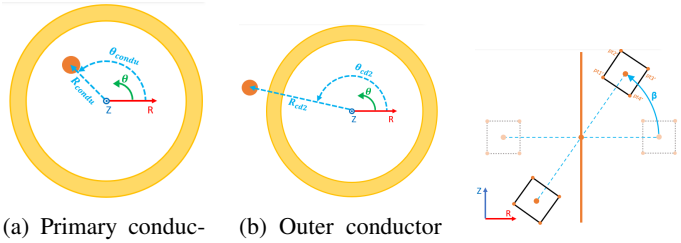


(a) Tilt turn ζ (b) Tilt turn ρ (c) Winding density

Fig. 2: Winding defects

It also accounts for positioning defects, such as:

- Rogowski coil decentering : This defect occurs when the conductor does not pass precisely through the center of the torus, as illustrated in figure 3a.
- Outer conductor position: Similar to the previous defect, this occurs when the Rogowski coil is positioned at varying distances from the outer conductor. This defect simulates crosstalk effects based on the outer conductor's position, as shown in figure 3b.
- Rogowski coil tilt: This defect represents a misalignment, where the normal axis of the toroid is not parallel to the conductor passing through its center, as depicted in figure 3c.



(a) Primary conductor position (b) Outer conductor position (c) Rogowski coil tilt

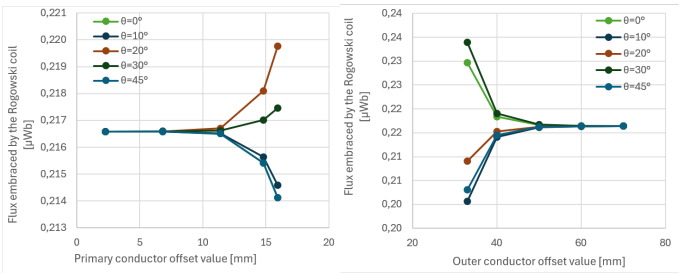
Fig. 3: Positioning defects

IV. Sensibility analysis

One way to identify the impacts of defects or combinations of defects is to conduct a sensibility analysis of our model. The Sobol method is a global sensitivity analysis technique that quantifies the impact of input variables on model output through variance decomposition. It computes Sobol indices to measure individual and interaction effects, making it ideal for identifying key defects in our Rogowski coils. And since our model is analytical and fast to compute, we can obtain accurate approximations of the magnetic flux distribution using a Monte Carlo method with a large set of generated parameters.

V. Results

The preliminary results highlight the impact of individual defects. As illustrated in Figures 4a and 4b, the position of the conductors emerges as a significant parameter. It has been observed that the influence of conductors increases rapidly as they approach either the inner or outer radius of the Rogowski coil. The other parameters in the study have a significantly lower impact compared to these.



(a) Embraced flux as a function of primary conductor position (b) Embraced flux as a function of outer conductor position

Fig. 4: Flux embraced by the Rogowski coil

VI. Conclusion

This work aims to clarify the most impactful defects in current measurement using Rogowski coils. Our results from a single-parameter study show that measurement errors increase significantly when a conductor gets too close to the coil. The other parameters studied do not have as much influence individually. We now need to conduct a more comprehensive sensitivity analysis using Sobol indices, which will help us identify the parameters to which the measurement device manufacturer should pay particular attention during the coil fabrication process.

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