

Evaluating Nonlinear Characteristics of Rectangular Rogowski Coils: Effects of Skin, Proximity, and Crosstalk

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Air-core Rogowski coils (RCs) have been massively adopted in switchgears in smart distributions owing to various advantages, for instance non-magnetic saturation, non-contact measurement, light weight as well as low cost. Nevertheless, the measuring accuracy of the RC based current transformer (CT) at harmonics in general suffers from the skin effect, proximity effect, and crosstalk effect. In this paper, a rectangular RC (RRC) is designed and the degradation on the measuring accuracy caused by diverse effects is further analyzed. Initially, to consider the impact of the skin effect of a single-phase rectangular busbar, the analytical solutions for the computations of the distribution of the magnetic field and of the induced voltage are derived. Subsequently, for a three-phase rectangular busbar system the combined influence of skin effect, proximity effect, and crosstalk effect are assessed by using finite element method (FEM). The nonlinearity of the RRC at harmonics are then evaluated by considering the amplitude of the excitation and the central distance between two adjacent busbars. The results can be employed for the optimal design of the linearity for the RRC based CT.

Index Terms—crosstalk, proximity effect, rectangular Rogowski coil, skin effect.

I. INTRODUCTION

Intelligent measuring instruments have been massively employed with the evolution towards smart distribution grids. In particular, the Rogowski coil (RC) based low power current transformer (LPCT) has experienced a huge penetration owing to various advantages compared with conventional magnetic-core based CTs [1]. Nevertheless, the measuring accuracy of the RC in general suffers from the skin effect, proximity effect, and crosstalk effect. Nonlinear behavior pronounces especially at higher harmonics [2]. To address this limitation, in this paper, a rectangular RC (RRC) is designed and the degradation on the measuring accuracy caused by diverse effects is further analyzed.

II. ANALYTICAL MODEL OF THE IMPACT OF THE SKIN EFFECT ON THE RRC

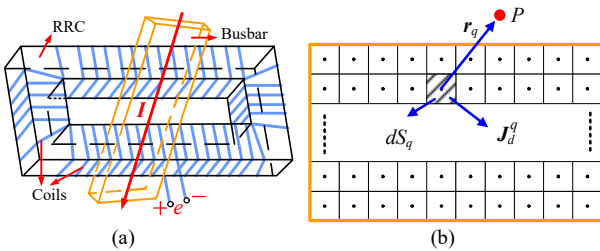


Fig. 1. (a) Typical construction of an RRC and (b) illustration of current distribution on the cross-section of a single rectangular busbar with skin effect.

Fig. 1 (a) shows a typical construction of an RRC. Suppose the rectangular busbar is infinitely long. Essentially, the current density in the cross-section of the rectangular busbar varies with the excitation frequency due to the skin effect. Particularly, the skin depth is defined as a depth at which the current density decreases to $1/e$ of the surface current density [3].

$$\delta = \frac{1}{\sqrt{\pi f \gamma \mu}} \quad (1)$$

where δ is the skin depth; f is the frequency of the excitation current I ; γ and μ are the conductivity and permeability of the conductor, respectively.

Fig. 1 (b) illustrates the current distribution on the cross-section for a single rectangular busbar with skin effect. The relationship between the surface current density $\mathbf{J}_s$ and the current density $\mathbf{J}_d$ at a depth d beneath the conductor's surface is given by

$$\mathbf{J}_d = \mathbf{J}_s \cdot e^{\left(-\frac{d}{\delta}\right)} \quad (2)$$

Assume the cross-section S of the rectangular busbar is divided into Q subsections, each element with an area of dS . In this case, the current element on the q th subsection dS_q can be expressed as $\mathbf{J}_d^q \cdot dS_q$, where $\mathbf{J}_d^q$ represents the current density on dS_q . As a consequence, the total current I flowing through in the busbar is the summation of all the current elements. For simplicity, it mathematically yields

$$I = \sum_{q=1}^Q \mathbf{J}_d^q \cdot dS_q \quad (3)$$

Referring to Fig. 1 (b), the magnetic flux density at a given observation point P can be obtained with respect to the Superposition Principle

$$\mathbf{B} = \sum_{q=1}^Q \frac{\mu_0 \mathbf{J}_d^q \cdot dS_q}{2\pi r_q^2} \times \mathbf{r}_q \quad (4)$$

where $\mathbf{B}$ is the magnetic flux density produced by all of the current element; $\mathbf{r}_q$ represents the vector from the q th current element to the observation point P .

Suppose the cross-section area A of a single turn of the coil winding is uniformly divided into M elements, that is, each with an area of dA_m . It is illustrated in Fig. 2. Therefore, the total magnetic flux Φ_n within the n th turn of the coil can be expressed as:

$$\Phi_n = \sum_{m=1}^M \mathbf{B}_m \cdot d\mathbf{A}_m \quad (5)$$

where $\mathbf{B}_m$ is the magnetic flux density at the center of $d\mathbf{A}_m$.

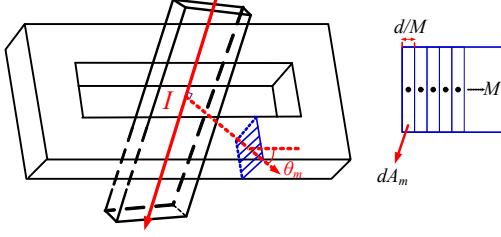


Fig. 2. The cross-section of a single turn of the RRC winding.

As a result, the induced voltage $e(t)$ of the RRC can be expressed as:

$$e(t) = - \frac{d \left(\sum_{n=1}^N \Phi_n \right)}{dt} \quad (6)$$

where N is the total number of turns.

III. NUMERICAL ANALYSIS OF THE RRC

For the validation purpose of the analytical model for a single-phase RRC, a numerical model is implemented by using FEM. For simplicity, the construction of the RRC is shown in Fig. 3 (a). A current excitation with RMS value of 500A is imposed to the busbar.

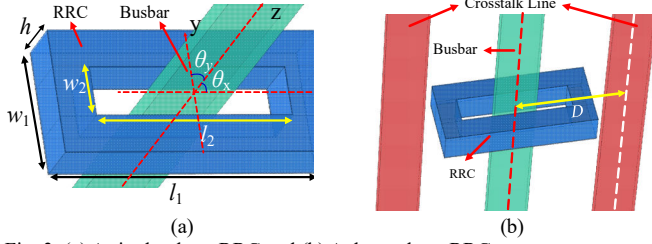


Fig. 3. (a) A single-phase RRC and (b) A three-phase RRC.

Fig. 4 presents the relative error of the output induced voltage in amplitude between the analytical solution and the numerical solution. In this case, a frequency sweep test from 50Hz to 5000Hz with a step of 50Hz is applied.

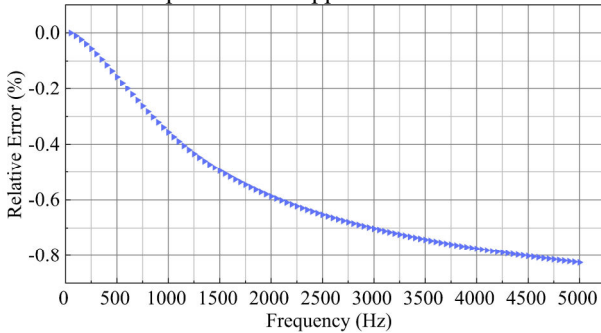


Fig. 4. Amplitude error at different frequencies.

Fig. 5 (a) and (b) show the distribution of the current density in the busbar and the magnetic field distribution of the RRC at 5000Hz. This behavior clearly explains that the amplitude error increases with the increase of the harmonic frequency due to the more pronounced skin effect. Of course, this is also corresponds to the mesh density of the developed FEM model.

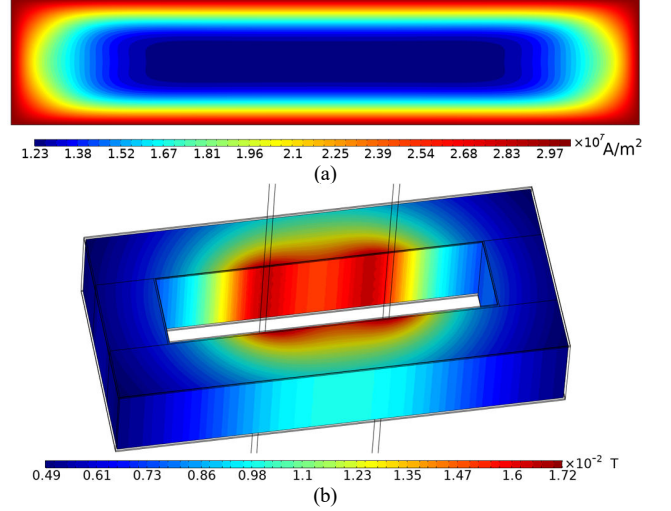


Fig. 5. (a) The distribution of the current density in the rectangular busbar and (b) the magnetic field distribution in the RRC at 5000Hz.

In order to take the combining influence of the skin effect, proximity effect, and the crosstalk effect into account, a numerical model based on the FEM is implemented. For brevity, a three-phase RRC is illustrated in Fig. 3 (b). Fig. 6 demonstrates the error caused by RRC in measuring the bus under different crosstalk distances.

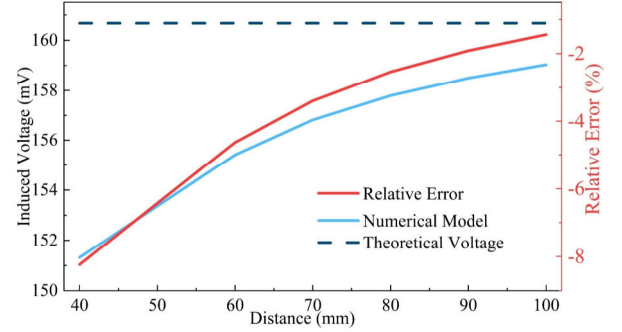


Fig. 6. The impact of different crosstalk distances.

REFERENCES

- [1] C. Chou and C. Chen, "Measurement and analysis of partial discharge of high and medium voltage power equipment," *2018 7th International Symposium on Next Generation Electronics (ISNE)*, 2018, pp. 1-4.
- [2] Q. Guo, P. Fu, G. Gao, L. Jiang, L. S. Wang and Y. R. Bai, "Rectangular Magnetic Sensor Array for Current Measurement by the Quadrature Method," *IEEE Trans. Plasma Sci.*, vol. 46, no. 5, pp. 1227-1233, May 2018.
- [3] J. S. Jiao, X. Liu and Z. Zeng, "Intensive study of skin effect in eddy current testing with pancake coil," *IEEE Trans. Magn.*, vol. 53, no. 7, pp. 1-8, July 2017.