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The Rogowski Coil Design Software

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Abstract **-** The Rogowski coil is a current measuring element, galvanic separated from measured current. Account on structural simplicity and low price of electronic devices processing its output signal, the Rogowski coil is more used in electroenergetics. The paper deals with the design of the Rogowski coil in wider frequency range. Required parameters of the Rogowski coil – its geometry limits, input current and output voltage are entered into developed program. The results are proportions of the Rogowski coil and parameters of the wire used for the coil winding. It is possible to use presented findings for construction of Rogowski coils during the development of these current measuring elements.

I. Introduction

The aim of presented work was the realization of program for the Rogowski coil (RC) design with respect to the amplitude and shape of the measured current and parameters of circuits for output voltage evaluation. There was taken into consideration closed non-ferromagnetic toroidal RC wound as one-layer homogenous winding. The program for RC design is able to calculate coil dimensions to obtain required value of mutual inductance between conductor with measured current and the sensing winding. The goal is to reach defined amplitude and time course of induced output voltage when measuring impulse current. The defined amplitude should be appropriate to the input sensitivity of evaluation circuits. There are respected many adjacent parameters, for example insulation distance between conductor with measured current and sensing winding, on the assumption that RC is used in high-voltage power grids. Leakage capacitances of sensing winding are not respected at the moment. The computation was verified by measurement of the harmonic current with power frequency, while dimensions and number of RC turns were optimized to suppress leakage capacitances [3]. In addition, the program can calculate the output impedance of sensing winding that is important parameter for selection of evaluation circuits.

II. Theoretical fundamentals for Rogowski coil design

Basic setup of closed toroidal Rogowski coil [2] is on the Figure 1.

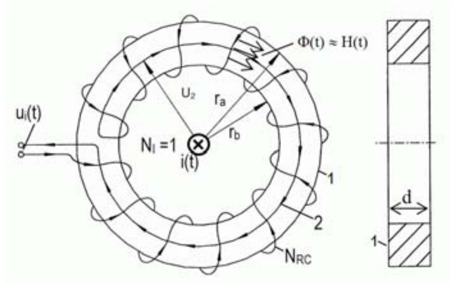

Figure 1. Basic setup of the Rogowski coil

The measured value is current i(t) flowing in conductor $N_1 = 1$ that is along the main axis of toroidal coil. Magnetic field intensity H (t) excited by this current and corresponding time variable magnetic flux Φ (t) is inducing voltage $u_i(t)$ into the sensing winding of the RC. Measured current is possible express as

$$i(t) = \frac{1}{M}\int_0^T u_i(t)\, dt \ , \tag{1}$$

where *M* (H) is mutual inductance of conductor with measured current and the sensing winding of the RC.

If the current is harmonic with angular frequency ω, the measured current is

$$I_1(\omega) = \frac{U_i(\omega)}{j\omega M} \ . \tag{2}$$

In ideal case of the harmonic current waveform the induced voltage has phase shift π/2 to measured current. Value of the mutual inductance is expressed in the form

$$M = \frac{U_i}{\omega I} \ . \tag{3}$$

This expression is used for calibration of RC's with harmonic current.

III. Fundamental expressions for computing of Rogowski coil mutual and output impedance

It is evident from expressions (1) to (3) that RC basic parameter is mutual inductance between the conductor with measured current and the sensing winding. The mutual inductance value and sensing winding resistance are necessary for determination of RC output impedance. It is important to know the impedance value for selection of measuring device input impedance, which is connected to the RC output and evaluates its output signal.

A. Rectangular cross-section of toroidal sensing winding

The construction of rectangular cross-section sensing winding is shown on the Figure 2.

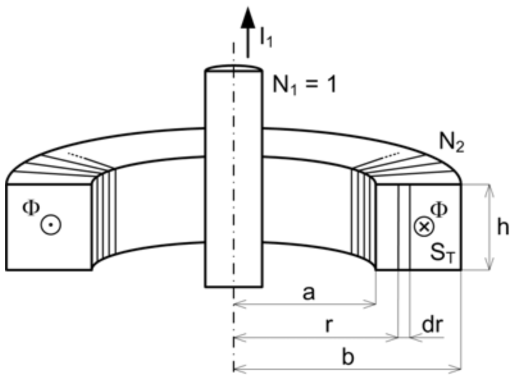

Figure 2. Rogowski coil arrangement with non-ferromagnetic rectangular core cross-section

This arrangement of the sensing winding is not optimal from the design point of view. The main disadvantages are sharp edges of the rectangular cross-section, where the winding insulation may be damaged. This is the reason why the circular or oval cross-section is usually used.

The final term for mutual inductance M_{21} between the sensing winding N_2 and the conductor with measured current I_1 , in arrangement according to Figure 2, is

$$M_{21} = \frac{\mu_0}{2\pi} N_2\, h \ln\left(\frac{b}{a}\right) \ . \tag{4}$$

Self inductance L_2 of the sensing winding with rectangular cross-section of toroidal core is

$$L_2 = \frac{\mu_0 N_2{}^2 h}{2\pi} \ln\frac{b}{a} \ . \tag{5}$$

Impedance magnitude of sensing winding N_2 is calculated by

$$Z_2 = \sqrt{R_2^{\ 2} + (\omega L_2)^2} \ , \tag{6}$$

where R_2 is the sensing winding resistance and ω (rad.s^{-1}) is the angular frequency of the current, resp. voltage on the sensing winding.

B. Circular cross-section of toroidal sensing winding

The construction of circular cross-section sensing winding is shown on the Figure 3.

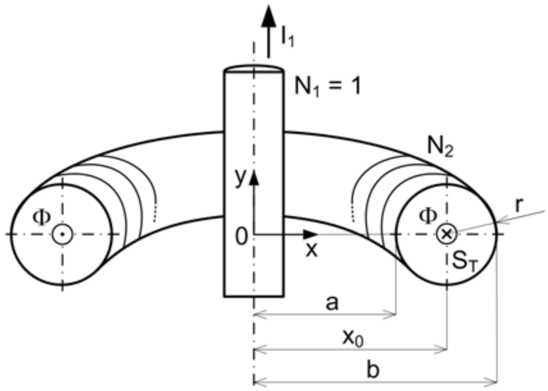

Figure 3. Rogowski coil arrangement with non-ferromagnetic circular core cross-section

Mutual inductance M_{21} between the sensing winding N_2 and the conductor with measured current I_1 , in arrangement according to Figure 3, is

$$M_{21} = \frac{\mu_0 N_2}{2}\left(a + b - 2\sqrt{ab}\right) \tag{7}$$

Self inductance L_2 of the sensing winding with circular cross-section of the toroidal core is

$$L_2 = \frac{\mu_0 N_2^{\ 2}}{2}\left(a + b - 2\sqrt{ab}\right) . \tag{8}$$

Impedance magnitude of sensing winding N_2 is calculated by (6).

C. Oval cross-section of toroidal sensing winding

The construction of oval cross-section sensing winding is shown on the Figure 4.

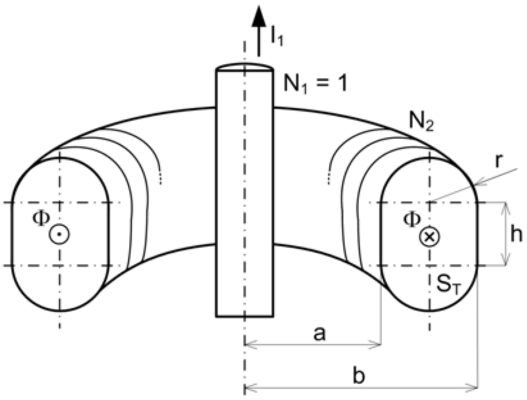

Figure 4. Rogowski coil arrangement with non-ferromagnetic oval core cross-section

Mutual inductance M_{21} between the sensing winding N_2 and the conductor with measured current I_1 , in arrangement according to Figure 4, is

$$M_{21} = \frac{\mu_0 N_2}{2}\left[\left(a + b - 2\sqrt{ab}\right) + \left(\frac{h}{\pi}\ln\left(\frac{b}{a}\right)\right)\right] \tag{9}$$

Self inductance L_2 of the sensing winding with oval cross-section of toroidal core is

$$L_2 = \frac{\mu_0 N_2^{\,2}}{2}\left[\left(a + b - 2\sqrt{ab}\right) + \left(\frac{h}{\pi}\ln\left(\frac{b}{a}\right)\right)\right] \cdot \tag{10}$$

Impedance magnitude of sensing winding N_2 is calculated by (6).

IV. Description of the Rogowski coil Design Program

The software for Rogowski coil parameters computation was realized in accordance with theoretical formulas derived in previous chapters. The software consists from a three main parts. In the first part the measured current waveform is defined. In case of harmonic waveform by means of magnitude and frequency, in case of impulse waveform by means of magnitude, rise time and half of fall time. Inserted current waveforms are displayed in graphical window as well. Initial parameters for computation and shape of non-ferromagnetic toroid are inserted in the second part of software. In current software version is possible to work with rectangular, circular and oval shape of toroid. The enumeration of output values and output impedance is in the last part of the software.

Impulse current waveform is usually characterized by peak value, rise time and half of fall time. The mathematical model of impulse waveform can be described as

$$i(t) = A(e^{-\alpha_1 t} - e^{-\alpha_2 t}) \ , \tag{11}$$

where A (A) is peak value parameter,

α_1 (s^{-1}), α_2 (s^{-1}) are shape parameters

t (s) is time in range $<0, T_{imp}>$, where T_{imp} is duration time.

Model parameters are determined by nonlinear regression (least squares method). The resulted model of current waveform is consequently numerically derived and the maximal value of derivation *max_der* is founded. This value is input data for design of RC for impulse current waveforms.

The computation of mutual inductance between wire and sensing winding *M_rc* is choosed in accordance with selected current waveform (harmonic or impulse). The iteration process is applied when the input and initial values are entered. This process takes into account selected shape of nonferomagnetic toroid as well.

On the basis of output values the computation of real resistivity and self inductance of winding is done. These values are used for computation of input impedance, which is important parameter of the designed RC. The main window of the RC design software in Matlab environment is shown on the Figure 5.

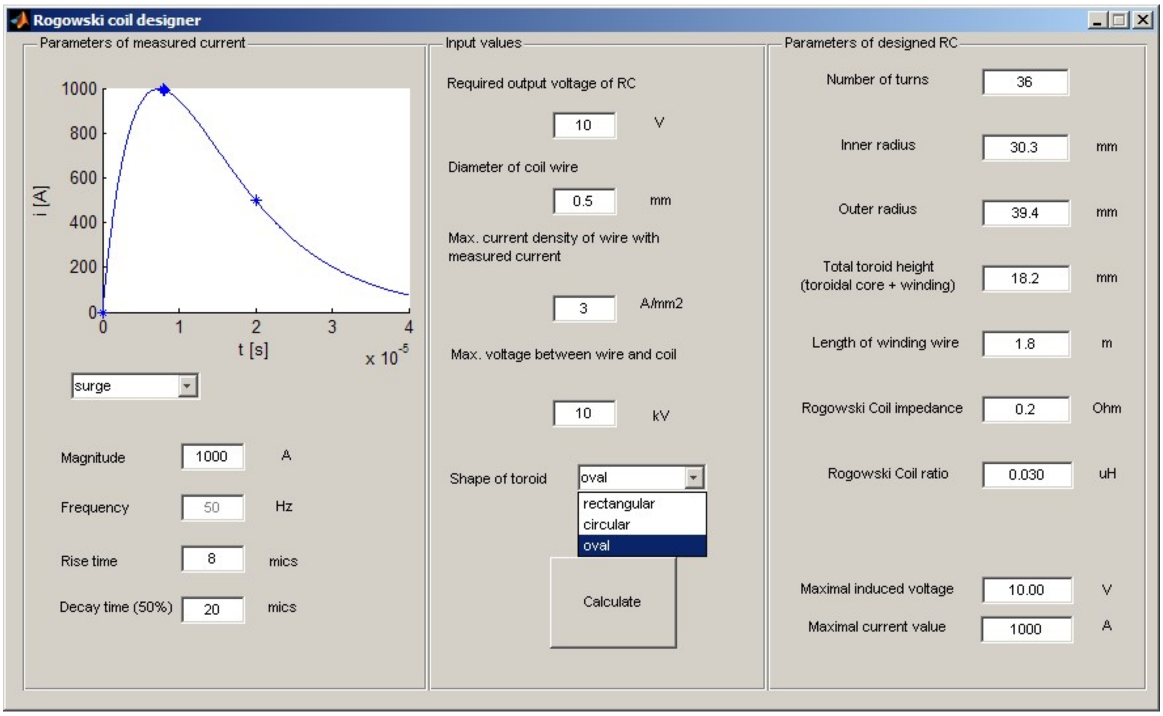

Figure 5. Main window of the software for Rogowski coil design

IV. Measurement results and comparison with calculated values

For the verification of the RC design program were used two types of Rogowski coils. The first one was the RC type KECA 80A1, produced by ABB EJF Brno, that is used in current protection systems. The second RC was designed and completed as an experimental coil for heavy impulse current measurements in the High Voltage Laboratory (HVL) at the CTU-FEE in Prague. Parameters describing RC's used for design program verification are listed in the Table 1. Electric parameters of both used RC's are listed in the Table 2.

Table 1. Parameters of Rogowski coils used for the RC design program verification

RC type:	**KECA 80A1 (ABB EJF Brno)**	**Experimental RC (HVL CTU-FEE)**
core profile:	**oval** - dimensions description - see fig. 4	circular - dimensions description - see fig. 3
dimensions:	a = 43,2 mm b = 63,2 mm h = 21,5 mm	a = 100 mm b = 135 mm
Sensing winding: number of turns wire diameter	 N_2= 2070 ± 9 turns d = 0,129 mm	 N_2= 30 turns d = 0,5 mm

Table 2. Electrical parameters of coils used for verification of the RC design program

Type of RC:	**KECA 80A1 (ABB EJF in Brno)**	**Experimental RC (HVL CTU-FEE in Prague)**
core cross-section type	**oval** - dimensions see fig. 4	**circular** - dimensions see fig. 3
RC constant **for freq. 50 Hz** measured calculated	 M_{21} = 5,968 μH M_{21} = 5,897 μH	 M_{21} = 0,0486 μH M_{21} = 0,0494 μH
K_{RC} deviation - measured from calculated value	**δ = 1,2 %**	**δ = 1,6 %**
output impedance **for freq. 50 Hz** calculated	 Z_2 = 300,3 Ω	 Z_2 = 0,31 Ω

When the RC type KECA 80A1 was verified, there were used its electric parameters listed on the RC name plate. Parameters of the experimental RC were measured in the Czech Metrology Institute (CMI), in the primary metrology laboratories in Prague, department of instrument transformers. The photo of the RC constant measurement realization in case of circular cross-section RC sensing winding is on the Figure 6.

Figure 6. Realization of the RC constant measurement (circular core cross-section)

IV. Conclusions

The aim of presented work was the theoretical determination of terms for mutual inductance and impedance of the Rogowski coil sensing winding. These terms were practically used in the software for Rogowski coil design. This program respects the amplitude and shape of the measured current, regarding to required parameters of circuits for the output voltage evaluation. Realized software will be applied for the design of Rogowski coils used in heavy impulse current measurements.

The software was realized in MatLab® environment. For the accuracy increase of the Rogowski coil output impedance computation was the winding length of lay and wire diameter taken into account. The winding leakage capacitances were not respected.

The program was verified for two types of Rogowski coils (KECA 80A1 with oval core cross-section and the experimental Rogowski coil with circular core cross-section) in the Czech Metrology Institute laboratory. There was verified the Rogowski coil constant only.

V. Acknowledgements

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VI. References

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