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INDUCTIVE CURRENT TRANSDUCERS IN THE FREQUENCY RANGE UP TO 150 kHz

GRZEGORZ KOSOBUDZKI, DANIEL DUSZA

Wrocław University of Science and Technology.
Department of Electrical Machines, Drives and Measurements,
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland,
e-mail addresses: grzegorz.kosobudzki@pwr.edu.pl; daniel.dusza@pwr.edu.pl

Abstract: The article presents the results of the research on inductive current transducers in the form of a uniform winding non-magnetic ring with a rigid and flexible construction encompassing the flow of processed current in the frequency range of up to 150 kHz. The results for the developed transducer were related to the results obtained in simulations conducted on the transducer simplified model. The frequency tests of this type of transducers are of key significance in the assessment of the applicability of a given transducer in the measurements of network signals with high-order harmonics, and particularly in the assessment of the construction capacity of inductive current transducers in the form of the Rogowski coil.

Keywords: *current, Rogowski coil, inductive current transducer*

1. INTRODUCTION

Energy in an electric power system is transported in conductors whose potentials significantly differ from the zero potential. Thus, a current transducer must first of all provide galvanic insulation between the signal circuit and the current circuit as it is necessary in measurement systems. Natural galvanic insulation is obtained by inductive circuit coupling.

Current transformers are commonly used to process current. The circuits in the current transformer are coupled with a magnetic flux closed in a ferromagnetic circuit. The current in the signal circuit (secondary) is approximately proportional to the processed current. A processing error is caused by polarization current which is necessary to create the magnetic flux in the ferromagnetic circuit. The polarization current and hence also the processing error depend mainly on the permittivity of the magnetic circuit and transformer parameters. For the purpose of limiting the influence of the magnetizing current, two-core transformers are made. However, the transformer has a limited linearity range,

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a narrow frequency band and it does not carry the measurement information about the DC component. Special current transformers are built with a magnetic circuit made of a nanocrystalline material and these correctly transport measurement information in a wide frequency range (up to 150 kHz), however, due to their high price they are used only in specialist measurement systems.

The circuits in an inductive current transducer are coupled with a magnetic flux proportional to the processed current. The signal induced in the transducer output circuit is precisely proportionate to the current derivative and the coefficient of proportionality is also constant for a random value of current in the acoustic frequency range.

Inductive transducers are commonly used to process current in the form of a flexible Rogowski coil [4] which can encompass conductors passing current. However, the Rogowski coil requires the exactly uniform distribution of winding in a closed circuit so as to prevent the induction of external signals from interfering fields. High frequency coils have occasionally been reported [3, 5], however, due to their construction their sensitivity is not sufficient for industrial frequency waveforms. This article presents the results of comparative studies for a rigid coil constructed by the authors and a flexible construction available on the market. Both simulation and real-time tests were performed in the frequency band up to 150 kHz.

2. CONSTRUCTION OF THE TESTED TRANSDUCERS

A non-magnetic ring with a constant cross-section and the following dimensions: inner diameter d_1 = 80 mm, outer diameter $d_2 = 2d_1$, cross-section area $S \cong 1500$ mm^2 (Fig. 1a), was uniformly wound with two layers of silver plated wire ∅ 0.3 mm in Teflon insulation. The first layer is wound in such a way that the winding precisely fills the internal circumference of the ring which is twice as short as the external one. The second layer has return winding so that the winding can fill in the gaps in the external circuit. Thanks to this, in the external circumference there is one completely filled layer and in the internal one there are two such layers. The total number of turns is $N_2 = 1000$. The other coil is a typical commercial solution in a flexible form, it is shown in Fig. 1b.

The magnetic field generated by the current is a rotating one. Its strength satisfies the basic equation:

$$\oint H_l dl = i_1 N_1 \tag{1}$$

where H_l is the magnetic field strength component tangent to the closed path encompassing N_1 number of turns passing identical current i_1. The magnetic flux originating from field strength H_l and matched to transducer winding with N_2 number of turns is proportional to the current i_1

$$\psi = M i_1 \tag{2}$$

and the processing factor is:

$$M = \mu_0 \frac{N_1 N_2}{2\pi} \int_{y_1}^{y_2} \ln \frac{r_2(y)}{r_1(y)} dy \tag{3}$$

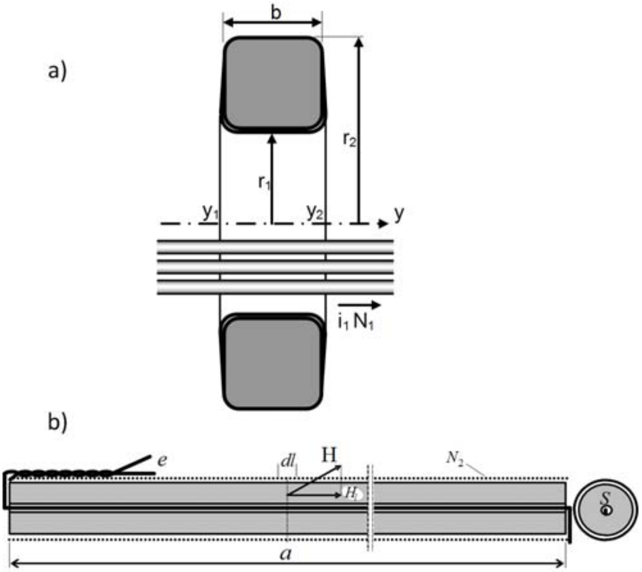

Fig. 1. Inductive transducer with a uniform magnetic circuit

Functions $r_1(y)$ and $r_2(y)$ describe the envelope of the transducer cross-section. In the case when the cross-section is a rectangle of width b (Fig. 1a), then:

$$M = \mu_0 \frac{N_1 N_2}{2\pi} b \ln \frac{r_2}{r_1} \tag{4}$$

For the Rogowski coil (Fig. 1b) encompassing the flow of current $i_1 N_1$, the processing factor is approximately defined by the following equation:

$$M = \mu_0 \frac{N_1 N_2}{a} S \tag{5}$$

According to Eqs. (4) and (5), the processing factor depends only on fixed parameters and not on the configuration of the current circuit or external magnetic fields.

If primary winding is evenly distributed, then the magnetic field strength generated by current i_1 is approximately perpendicular to secondary winding, hence the magnetic field component is close to zero, which significantly decreases the influence of interturn capacity on processing accuracy. However, the research showed that the influence of this capacity can be observed at high frequencies.

At constant winding density $\nu = N_2/2\pi r_2$ Eq. (4) takes the following form:

$$M = \mu_0 \nu \, N_1 r_2 b \ln \frac{r_2}{r_1} \tag{6}$$

Equation (6) shows that the processing factor, and hence also the sensitivity of transducers with bigger cross-sections, is larger. The approximate value of the processing factor of the transducer of the above given parameters is $M \cong 5.54$ μH, on the assumption that $N_1 = 1$ and that the sensor cross-section is a square of 40 mm side. The correct value of the processing factor is obtained using a measurement value.

3. MODEL OF THE TRANSDUCER

The Rogowski coil can be modelled using the substitution scheme [1, 2] shown in Fig. 2, where *R* is the coil resistance, *L* its inductivity and *C* capacity. The output signal of the transducer is described by the formula:

$$e_{in} = -M \frac{di_1}{dt} \tag{7}$$

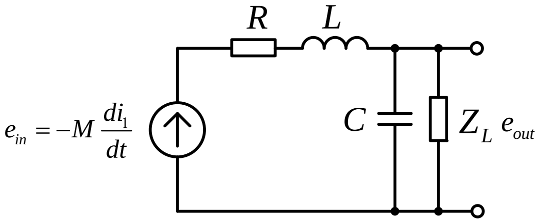

Fig. 2. Substitution scheme of an inductive current transducer

Load impedance Z_L results from the connection of the Rogowski coil output clamps to the measurement apparatus. The output circuit resistance is usually over 10 MΩ, while the capacity is estimated to be several dozen picofarads. The capacity of coil *C* is several hundred times higher and this is why the impedance Z_L can be neglected. The considered system, shown in Fig. 2, is simplified to an *RLC* series circuit usually described in electrotechnical handbooks. The dependence of the output voltage measured at transducer clamps on the voltage induced in the circuit, which is proportional to the current derivative as a frequency function (pulsation ω), is described by the following formula:

$$G(\omega)=\frac{|e_{\text{out}}|}{|e_{\text{in}}|}=\frac{|e_{\text{out}}|}{\left|M\,\dfrac{di_1}{dt}\right|}=\frac{\omega_0^{\,2}}{\sqrt{\left(\omega_0^2-\omega^2\right)^2+4\beta^2\omega^2}} \tag{8}$$

where $\omega_0 = 2\pi f_0 = 1/\sqrt{LC}$ is the resonance pulsation, while $\beta = 2R/L$ is the attenuation coefficient.

The actual values of flexible and rigid Rogowski coil parameters were measured with an RLC PM6304 electronic bridge, FLUKE. The parameter values, depending on frequencies, are presented in Fig. 3. The parameter tests were conducted in the frequency range from 50 Hz to 100 kHz.

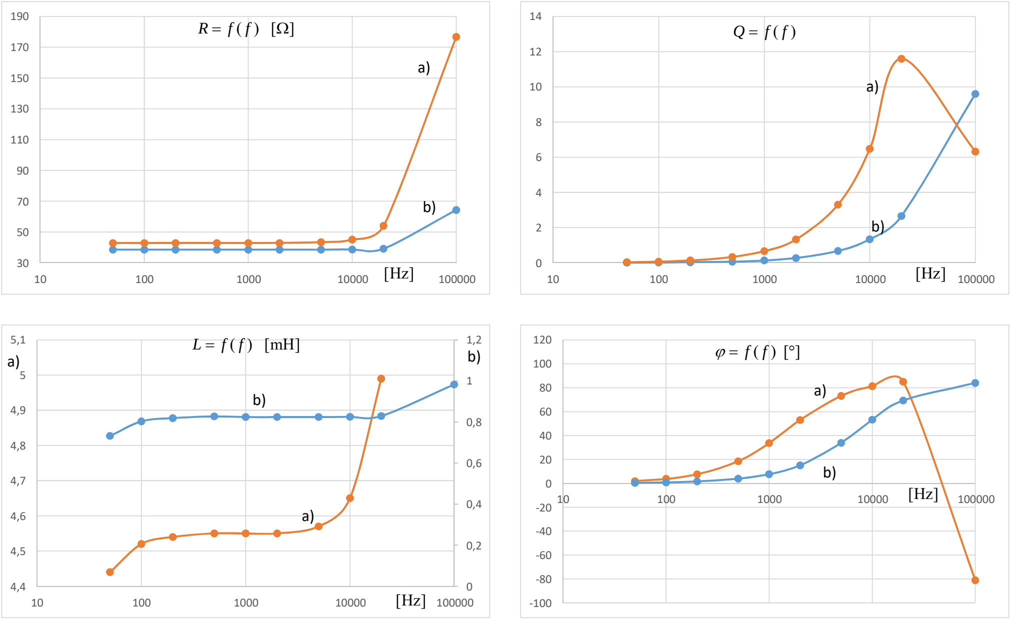

Fig. 3. Graphs for the rigid coil: a) soft coil, b) parameters R, L, Q and φ

The analysis of the above plots allows one to conclude that when the frequency exceeds 20 kHz, the current starts to penetrate the conductor material less, i.e., the skin effect occurs. The value of inductivity L changes in the acoustic frequency range similarly in both coils. In the case of the coil with rigid construction at the frequency of 100 kHz, the bridge changed the substitution scheme into RC and determined the capacity value $C = 1.42$ nF. The value of resonant frequency fr can be read directly from chart $Q = f(f)$ and $\varphi = f(f)$, or on the basis of the model presented in Fig. 2 it can be calculated from the formula:

$$f_r = \frac{\omega_r}{2\pi} = \frac{1}{2\pi}\sqrt{\omega_0^2 - 2\beta^2} \tag{9}$$

Resonant boost does not occur for attenuation $\beta \geq \omega_0/\sqrt{2}$. In the analyzed models, the attenuation coefficients are significantly lower than the free resonant pulsation, hence $\omega_r \approx \omega_0$. The model parameters adopted in the simulation are presented in Table 1.

Table 1. Parameter values for Rogowski coils adopted in the simulation tests

Coil	*R* [ohm]	*L* [mH]	*C* [nF]
Rigid	42.9	4.55	1.42
Flexible	38.5	0.824	0.50

4. RESULTS OF MEASUREMENTS

The processing characteristics of both coils were measured at the measurement setup the block diagram of which is presented in Fig. 4. It consists of an NSG4060 generator and a CT 419-5 dedicated module with a current transformer and a shunt, 0.1 Ω, and an Agilent 34401 voltmeter connected to it. Such a system with closed output clamps a, b allows the flow of sinusoidal current of RMS value 2 A in the frequency range from 2 kHz to 150 kHz. With 5 A current the band is limited to 30 kHz.

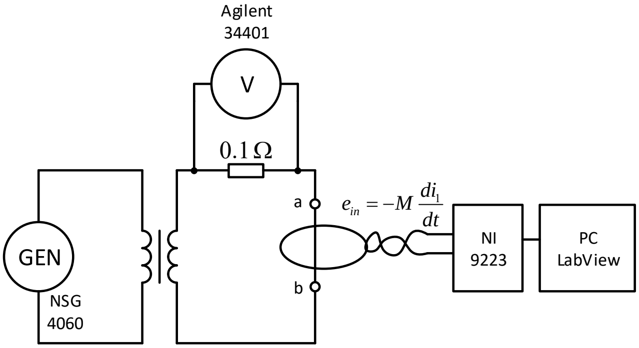

Fig. 4. Measurement setup allowing one to test current transducer characteristics in the frequency range up to 150 kHz

The characteristics of the rigid and flexible coils processing were obtained from the quotient of the RMS value of the currents measured with the transducer and the primary current. Output voltage e_{out} – proportional to current derivative i_1 – was sampled with an NI9223 card and next integrated. The integration operation is a linear transformation

$$G(\omega)=\frac{|e_{\mathrm{out}}|}{|e_{\mathrm{in}}|}=\frac{\left|\int e_{\mathrm{out}}\right|}{\left|\int e_{\mathrm{in}}\right|}=\frac{I_{\mathrm{out}}(\omega)}{I_1(\omega)} \tag{10}$$

where: I_1 – the RMS value of current measured (encompassed) with a measurement coil, while I_{out} – the RMS value of current measured by the measurement system using voltage samples at the transducer output. Figures 5 and 6 show the test results for both transducers in comparison with the values obtained in the simulation test.

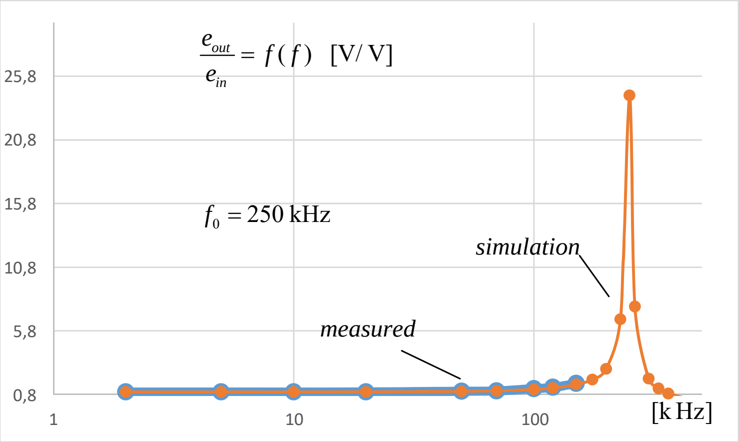

Fig. 5. Characteristic of the amplitude-frequency model of the transducer with a rigid construction

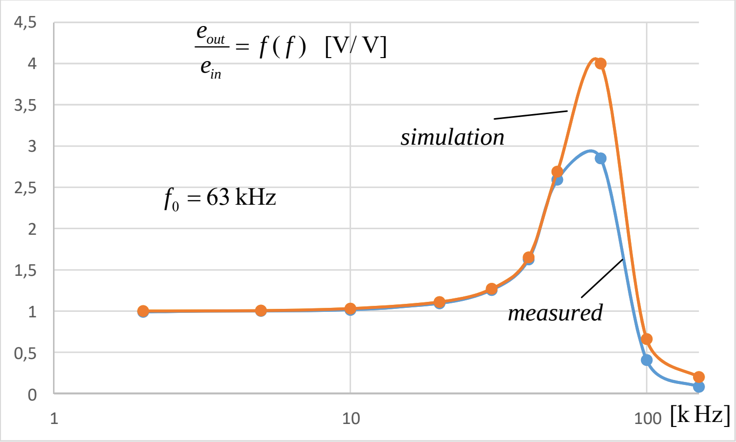

Fig. 6. Amplitude-frequency characteristic of the Rogowski coil (flexible)

It seems that the presented transducer model and the adopted parameters were correct. The value of the resonant frequency for the transducer with rigid construction can be determined from both the simulation and measurements. The difference in the values of the maxima of these characteristics results from the increase in resistance in the actual system, which is manifested with the growth of the attenuation coefficient β. Constant *RLC* was adopted in the models.

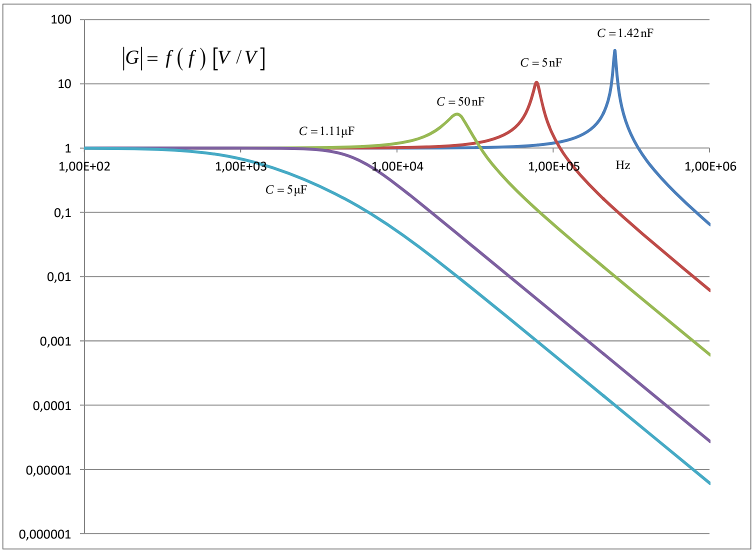

Fig. 7. Dependence of the frequency characteristic of the flexible coil on capacity

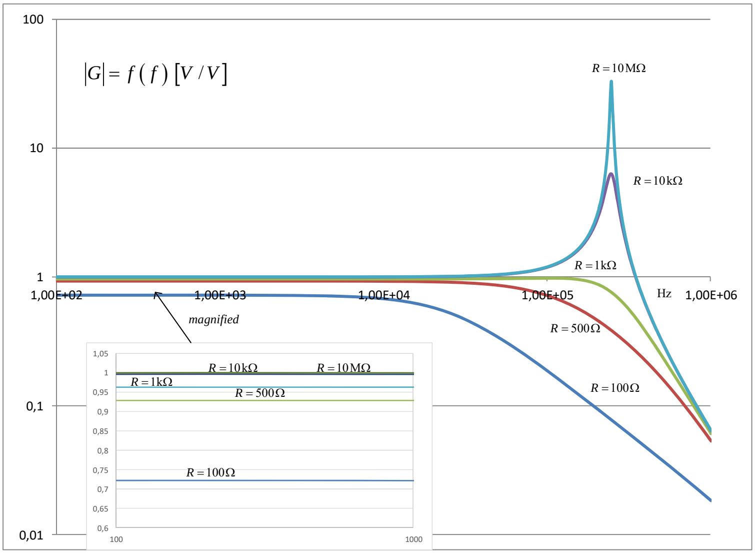

Fig. 8. Dependence of the frequency characteristic of the flexible coil on the input resistance of the measurement system

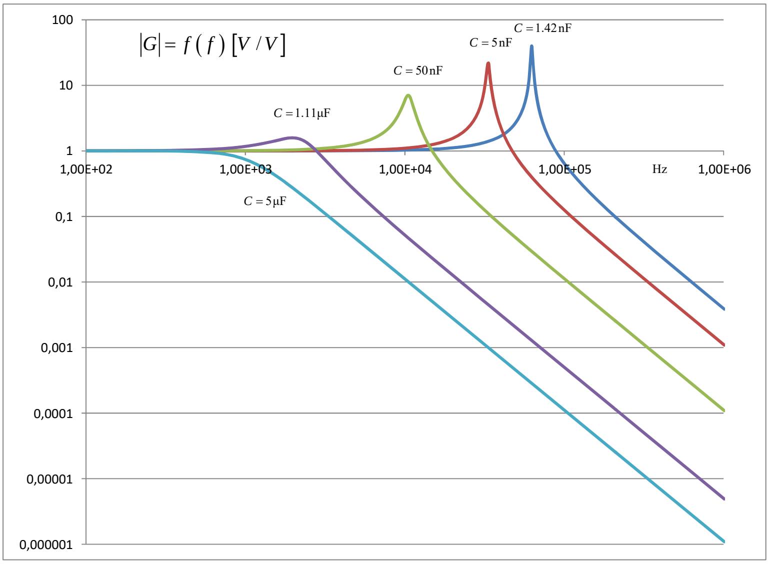

Fig. 9. Dependence of the frequency characteristic of the rigid coil on capacity

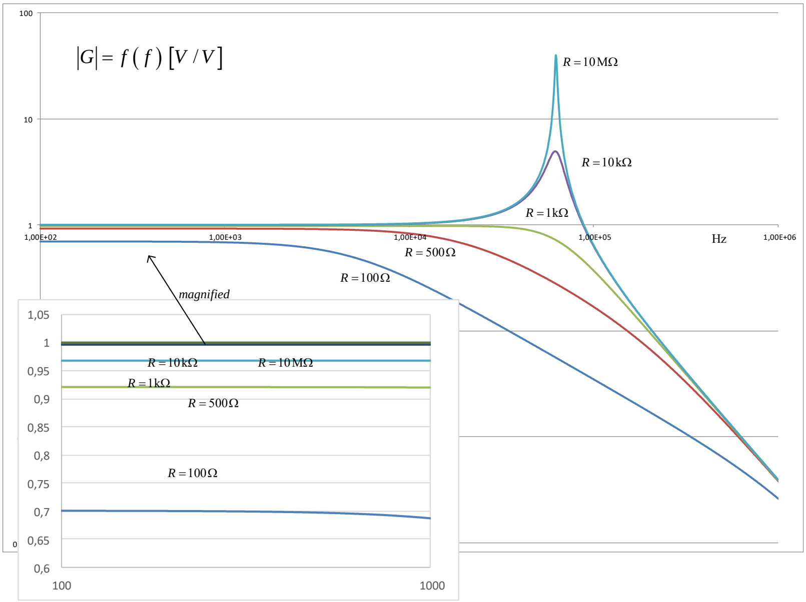

Fig. 10. Dependence of the frequency characteristic of the rigid coil
on the input resistance of the measurement system

The resonant frequency of the transducer with a flexible construction was determined using the simulation because it occurs beyond the capacity of the measured signal generator. The performed simulation showed that by adding capacity to a current transducer, one narrows the measurement band (Figs. 7, 9), while by adding a resistor one attenuates the maximum at resonant frequency (Figs. 8, 10). The characteristic can be corrected by loading the coil with a resistor. The most beneficial solution is the selection of a resistor ensuring that there will be no resonant boost $\beta = \omega_0 / \sqrt{2}$.

5. CONCLUSIONS

An inductive sensor transforms current into a voltage signal induced in a circuit which is galvanically insulated from the current circuit. Such a signal is precisely proportionate to the current derivative and the coefficient of proportionality is constant for random values of currents. The differential dependence of the signal on current results in the fact that it is necessary to conduct the integration or averaging operation and take into consideration the initial condition so as to reproduce the current. The inductive sensor with a uniform magnetic circuit and rigid construction cannot be installed in a current circuit without breaking it, whereas this is possible in a flexible construction. The conducted research and the simulation results show that if a designed inductive current transducer was to operate in the frequency range of up to 150 kHz without the necessity to introduce corrections for each harmonic, it would have to meet the condition of the low substitution capacity value of the whole measurement system. This means that for the purpose of achieving precise measurements of a current deformed by higher harmonics, the resonant frequency of the measurement system must be one order higher (1.5 MHz) than the border frequency (150 kHz).

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