A LOW COST ROGOWSKI COIL FOR INSTANTANEOUS CURRENT MEASUREMENTS IN HIGH VOLTAGE ELECTRICAL SYSTEMS

Rafael C. Freitas*, Ernesto Ruppert Filho*, Roberto P. Homrich‡

*State University of Campinas, Electrical and Computer Engineering School
P.O. Box 6101 – CEP 13083-970 - Campinas, SP, Brasil
rafael@dsce.fee.unicamp.br; ruppert@fee.unicamp.br

‡Federal University of Rio Grande do Sul, Electrical Engineering Department
Av. Oswaldo Aranha, 103 - CEP 90035-190 - Porto Alegre, RS, Brasil
homrich@eletro.ufrgs.br

Abstract – **This paper presents the implementation of a transducer known as Rogowski Coil (RC) using low cost electronic components to be used in applications where there is no need to measure large bandwidth current signals like in high power and high voltage electrical energy system. As the instantaneous electric current data shown in an oscilloscope screen or in another type of instrument is a very important and frequent task to monitoring electrical systems it becomes a very attractive transducer. The obtained results show that this RC Transducer has a good accuracy when measuring high-level electrical current.**

Keywords – **Current transducer, electric measurement, instrumentation, rogowski coil.**

I. INTRODUCTION

The visualization of instantaneous electric current data in an oscilloscope screen or another type of instrument is a very important and frequent task to monitoring electrical systems. The electric current measurement can be done by many different ways like direct measurement with an ampermeter, by a shunt resistor and voltmeter, current transformer, Hall sensor or Rogowski Coil.

The Rogowski Coil (RC), based on the Faraday's and on the Lenz's laws, is designed to operate as a transducer addressed to the measuring of transients and high peak current values, mainly in high voltage electrical systems. When the RC is placed around a conductor carrying a time varying electric current, an electromotive force (*emf*) **e** is generated at the RC winding terminals given by the Eq. (1) where **M** is the mutual inductance between the conductor and the RC winding.

$$e = M\frac{di(t)}{dt} \tag{1}$$

This way, the electrical current in the RC is given by Eq. (2).

$$i(t) = \int di(t) = \frac{1}{M}\int e(t)dt \tag{2}$$

Therefore, to get the instantaneous current signal, the coil *emf* must be integrated and multiplied by the inverse of the mutual inductance. This can be done using electronic analog circuit integrator or digital integration of the RC *emf* signal sampled. In this paper the analog method was implemented.

The RC transducer core is a non-magnetic material and the winding is made of insulated conductors. Consequently there are no magnetic losses and no core magnetic saturation or hysteresis in this type of electric device. Besides, there is a very small electrical current flowing in the RC winding due to the high impedance of the electronic integrator connected to it so that the delay of the transducer response is eliminated once the effect of the time constant inherent to resistor-inductor circuits is not present.

Some other papers [1]-[4] show different design ways of Rogowski Coil transducers in order to improve a specific desired characteristic like large bandwidth signal operation or highest accuracy.

The electronic integrator proposed in this paper is made using low cost components found in any electronic devices store, without loss of its necessary accuracy for high level electrical current measurement so it becomes a very attractive transducer in applications where there is no need to measure large bandwidth current signals like in high power and high voltage electrical energy system.

II. THE ELECTRONIC INTEGRATOR DESIGN

The electronic integrator designed for this RC is based on an operational amplifier Texas-TL071 with a feedback network which is responsible for the integration and filtering DC and high frequency components of the measuring current signal i(t), as shown in the Fig (1).

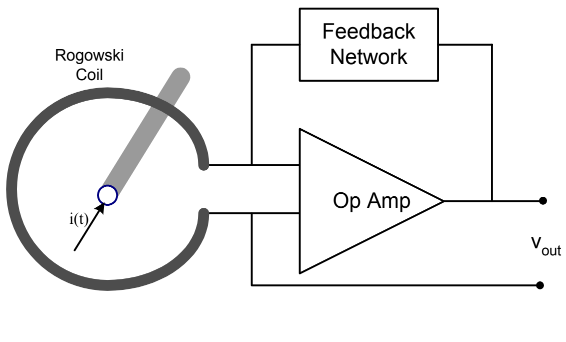

Fig. 1. Complete transducer with Rogowski Coil and the electronic integrator.

According to the range of the current that is going to be measured by the RC transducer, the sensitivity of the electronic integrator must be carefully chosen to provide an output voltage proportional to the electrical current amplitude which is being measured at the frequency of 60 Hz, lying in the linear range of the operational amplifier.

The sensitivity, defined by R_s(mV/A), is a linear relationship between the transducer output voltage and the electrical current, as shown in the Eq. (3),

$$v_{out} = R_S \cdot i \tag{3}$$

The maximum value of di/dt, Eq. (4), with which the integrator can work is defined by the operational amplifier *slew rate* characteristic, defined as dv_{max}/dt.

$$\left.\frac{di}{dt}\right|_{max} = \frac{1}{R_S} \cdot \left.\frac{dv}{dt}\right|_{max} \tag{4}$$

As mentioned before, for a linear operation of the integrator, there is a feedback network that must be designed to filter undesired frequency signals and to guarantee that the electronic circuit will operate as an integrator. So the frequency response curve of the integrator must follow the characteristic curve shown in the Fig. 2.

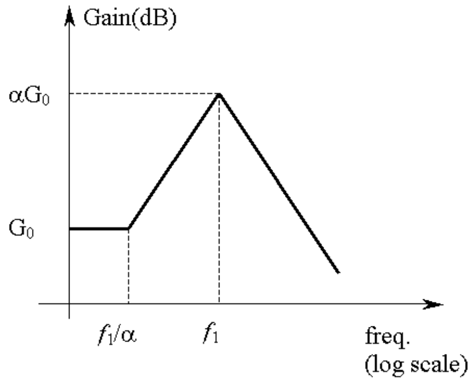

Fig. 2. Frequency response of the integrator.

The central frequency defined as f_1, is the minimum frequency with which the electronic circuit behaves like an integrator. For 60 Hz transducer operation, typical value for f_1 is 1 Hz, below this frequency the gain tends to be constant in order to avoid the operational amplifier saturation and the thermal drift [5].

The factors G_0 and α represent respectively the gain at DC input voltage and the attenuation factor. It is desirable to have α larger than 100.

Another two important parameters in the integrator design are the dumping ζ that must be close to the unity and the time constant T of the circuit given by the resistor-capacitor association in the electronic network. The final transfer function of the electronic integrator is given by the Eq. (5),

$$\frac{v_{out}}{v_{in}} = \frac{G_0(1 + \alpha Ts)}{1 + 2\zeta Ts + T^2 s^2} \tag{5}$$

The proposed electronic circuit for the integrator with its feedback network circuit, the operational amplifier and the symmetrical source are shown in the Fig. 3.

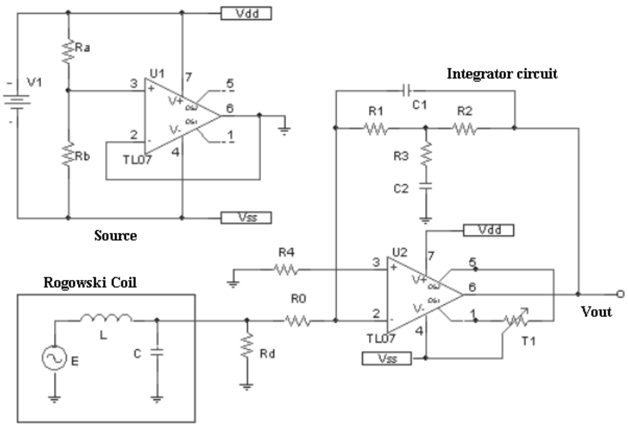

Fig. 3. The RC transducer electronic integrator circuit.

The electronic integrator circuit basically evaluates the output voltage Eq. 6,

$$v_{out} = \frac{1}{C_1 R_0} \int v_{in} dt = R_{sh} \cdot i \tag{6}$$

Where,

$$R_{sh} = \frac{M}{C_1 R_0} \tag{7}$$

In order to implement electronically the equations (5) and (6), the electronic components shown in the Fig. 3 are designed by setting the parameters in equations (8) to (11), as demonstrated in [5].

$$G_0 = \frac{R_1 R_2}{R_0} \tag{8}$$

$$\frac{R_1}{R_3} = \frac{(\alpha - 1)^2}{\alpha - 0.5} \tag{9}$$

$$\alpha = 0.5 \cdot \sqrt{\frac{C_2}{C_1}} \tag{10}$$

$$\zeta = \alpha \cdot \frac{R_3}{R_1} \tag{11}$$

For each desired scale of the transducer, a different value of R_0 must be calculated to adjust the sensitivity. In this work it was used a set of accurate trimpots to get three different scales as shown in Table I.

TABLE I
Scales of the Transducer

Scale (A)	Sensitivity (mV/A)
20	100
200	10
2000	1

Off-set adjust is achieved throughout the trimpot T_1 and the resistor R_4 which is connected to the operational amplifier non inverter input in order to give a better off-set adjust to the integrator and its value is given by the Eq. (12) [6].

$$R_4 = \frac{R_0(R_1 + R_2)}{R_0 + (R_1 + R_2)} \quad (12)$$

A coaxial cable with an impedance $Z_0 = 50\ \Omega$ was used to connect the RC to the integrator circuit. In order to avoid wave reflections from the coil to the integrator, the resistor $R_d = 50\ \Omega$ was used in the connection point to match the impedances.

Finally, the symmetrical source circuit requires a 9-volt battery or even an external DC source to feed the integrator circuit.

III. THE ELECTROMAGNETIC DESIGN

Once the electronic integrator is designed, the maximum input voltage level for measuring scale is known and then it is necessary to design the coil that will produce the correct *emf* level when placed around a conductor carrying a time varying electrical current.

Therefore, the electromagnetic design of the RC transducer is focused on the coil design in order to calculate the dimensions of the toroidal coil and the correct number of turns [7].

From the Biot-Savart's law, shown in the Eq. (13), it is possible to calculate the vector density of magnetic flux $\boldsymbol{B}$ in any point of the space produced by the electric current circulating in the conductor [8].

$$d\boldsymbol{B} = \frac{\mu_0 i d\boldsymbol{l} \times \boldsymbol{a}_R}{4\pi |R|^2} \quad (13)$$

Placing the coil around the conductor carrying the current i(t) which is to be measured, the magnetic flux ϕ is calculated using the B_z component of the vector $\boldsymbol{B}$ calculated at the point (x = 0,y = r, z = 0) and the Eq. (14) as shown in the Fig. 4.

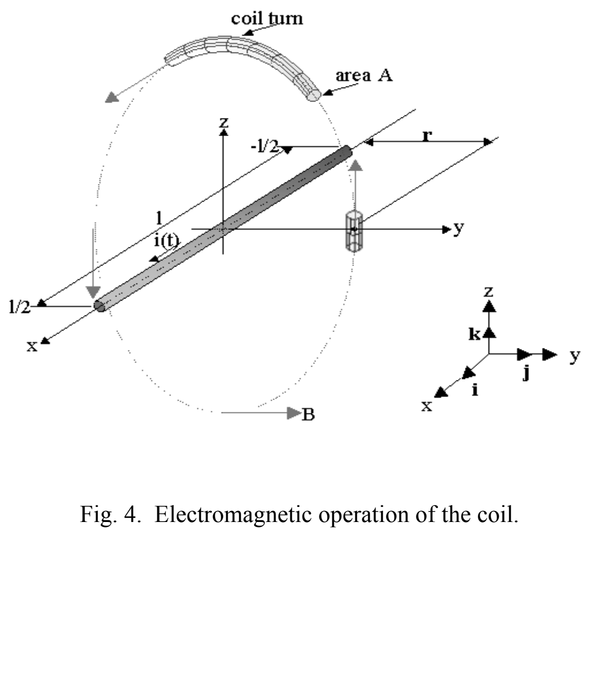

Fig. 4. Electromagnetic operation of the coil.

$$\phi = B_Z A = \frac{\mu_0 i(t)}{4\pi r}\left(\frac{1}{\sqrt{(l/2)^2 + r^2}}\right)A \quad (14)$$

Considering the N turns of the coil, the *emf* e(t) induced by the flux ϕ(t) produced by the current i(t) will be:

$$e(t) = N\frac{d\phi(t)}{dt} = \frac{\mu_0 NA}{4\pi r}\left(\frac{1}{\sqrt{(l/2)^2 + r^2}}\right)\frac{di(t)}{dt} \quad (15)$$

For a sinusoidal current with frequency f in the form shown in the Eq. (16), the rms value of the *emf* induced will be given by Eq. (17):

$$i(t) = I_{max}\sin(2\pi f\, t) \quad (16)$$

$$E_{rms} = \frac{\mu_0 NAf\, I_{rms}\sqrt{2}}{2r}\left(\frac{1}{\sqrt{(l/2)^2 + r^2}}\right) \quad (17)$$

Finally, the number of turns N of the RC can be calculated by the Eq. (18) and then it is possible to calculate the mutual inductance as shown in the Eq. (19).

$$N = \frac{2rE_{rms}}{\mu_0 Af\, I_{rms}\sqrt{2}}\sqrt{(l/2)^2 + r^2} \quad (18)$$

$$M = \frac{N\phi}{i} \quad (19)$$

The coil can be wounded with one or multiple layers of turns on a non ferromagnetic toroidal core and it usually has a central return turn, also called compensation turn or return loop which is placed on the medium radius r_c of the main spiral winding as shown in the Fig. 5. Due to the fact of the winding to presents the toroidal form, the inclusion of the compensation turn in the core repels the possible external magnetic field interference from conductors other than the enclosed target conductor [9].

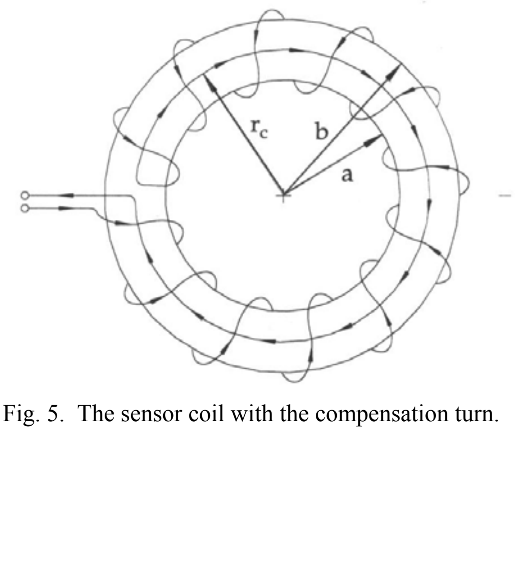

Fig. 5. The sensor coil with the compensation turn.

IV. THE ROGOWSKI COIL PROTOTYPE

A RC transducer prototype was implemented in this work using low cost parts and electronic components as mentioned before.

The coil of the transducer was wounded on a PVC flexible tube using varnish-isolated copper conductor. Care must be taken to wind the turns at a regular distance between them in order to involve uniformly the magnetic flux lines.

The electronic circuit was assembled on a printed circuit board specially designed, which was placed inside a shielded box to minimize the effect of electromagnetic interference [9]-[10].

The passive components of the electronic integrator are high precision resistors of metal film with 1% of tolerance, the capacitor C_1 is a high stability silvered mica capacitor which shows any change with temperature variation and very low leakage current and C_2 is a tantalum capacitor, both 1% of tolerance.

The calculated values of the electronic components of the circuit shown in the Fig. 3 are described in Table II. The different values of R_0 and R_4 resistors are due to the three scales of the RC transducer described in Table I.

TABLE II
Electronic passive components

R_0 = 374kΩ; 37,4 kΩ; 3,74 kΩ	R_4 = 220kΩ; 39 kΩ; 3,5 kΩ
R_1 and R_2 = 470 kΩ	C_1 = 2,2 nF
R_3 = 3,5 kΩ	C_2 = 100 μF

The final view of the designed RC transducer prototype with the coil and the integrator is shown in the Fig. 6.

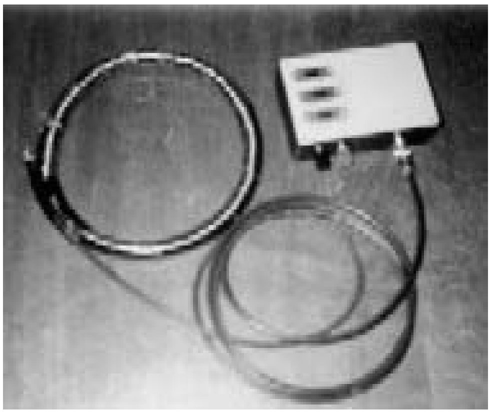

Fig. 6. View of the Rogowski Coil and the Integrator.

The estimated cost for this RC transducer was about US$ 30 and a similar commercial model can be purchased by US$ 466.

V. SIMULATION AND RESULTS

A computational simulation of the integrator circuit frequency response was performed on PSPICE software. The Fig. 7 shows the bandwidth and gain in dB of the integrator, as can be seen in the simulation curve is in very agreement to the one in Fig. 2. The circuit has a fixed gain for frequencies below 1 Hz and behaves as an integrator for frequencies above 1 Hz. At the industrial frequency of 60 Hz the gain was calculated to adjust the sensitivities of the integrator and at high frequencies the signal is very attenuated.

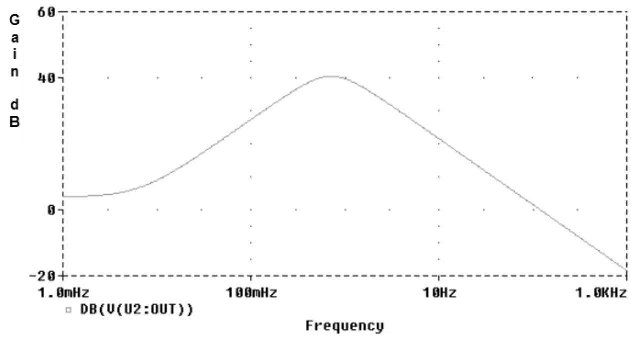

Fig. 7. Integrator frequency response.

The calibration of the transducer was made comparing its output voltage with a Tektronics Hall Sensor connected in the same line current. The final results shown in the Fig. 8 and the dotted line square detail in Fig. 9 were obtained measuring the electric current in a RL load connected to a PWM inverter operating at 60 Hz. The channel 1 of the oscilloscope shows the current measured by a Hall sensor at 0.1 mV/A and the channel 2 shows the current measured by the Rogowski Coil Transducer of this work at 1 mV/A.

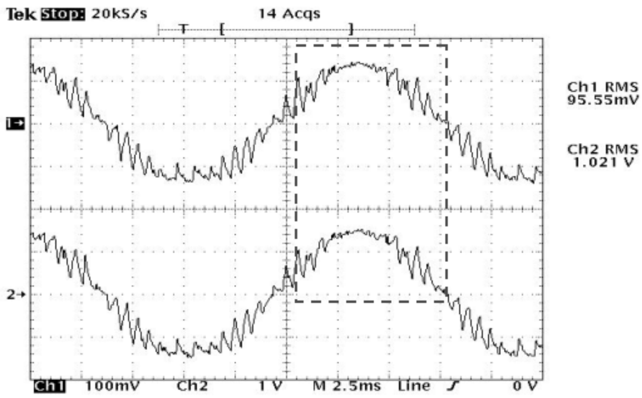

Fig. 8. Comparison between a Tektronics Hall Sensor and the RC Transducer.

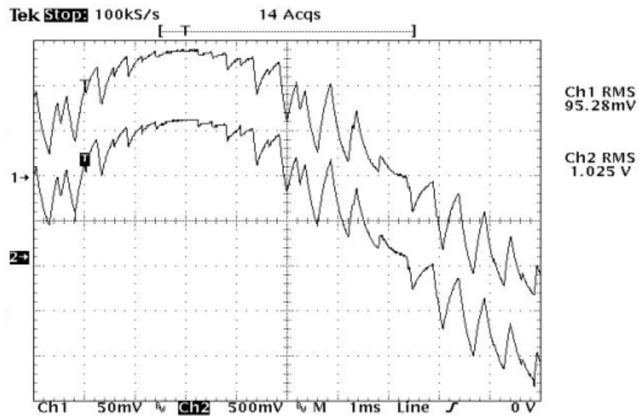

Fig. 9. Detail of figure 8.

The curves of figures 8 and 9 show the accuracy of the RC transducer and the accuracy in the reproduction of the electric current waveforms.

Regarding to the EMI from neighbor conductors, a test was performed as shown in Fig. 10. In this case the voltage signal at the integrator output stayed about 1% of the electrical current circulating in the conductor placed outside of the Rogowski coil, showing the good accuracy of the transducer even under EMI.

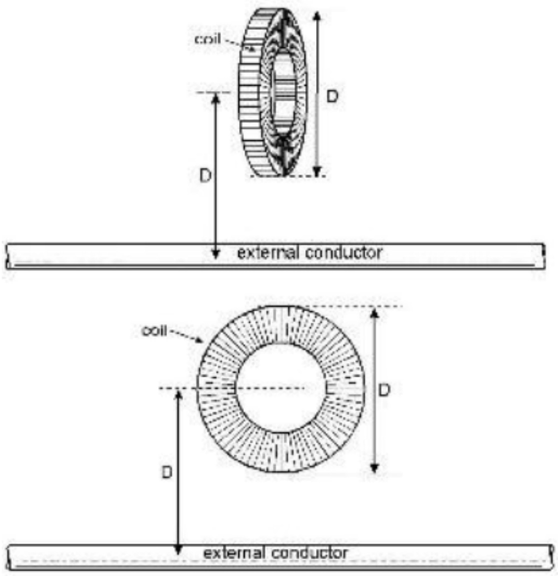

Fig. 10. EMI interference test.

VI. CONCLUSION

In this paper it was presented the design, construction and test of a low cost Rogowski Coil addressed to instantaneous current measurements on high voltage electrical systems.

This kind of transducer has many advantages regarding to others current transducers as it can measure large currents without saturation, it is a non invasive transducer, it provides an isolated measurement at ground potential, it can measure AC signals superimposed to large DC, it has compact size and it is easy to clip-around and use [11].

The obtained results show that the RC transducer made of low cost coil and electronic integrator presents a good accuracy when measuring electric currents and it is a very useful equipment to be used in industrial environments whenever sinusoidal or quasi-sinusoidal currents have to be measured for control or system monitoring purposes and when it is necessary to see electric current waveforms.

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