Current sensor based on Rogowski coil

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Abstract. We have built several Rogowski coil current sensors for measuring currents in non sinusoidal systems. In this paper we present the sensor and his behavior. We have built a generator of pulses in order to test it and we compare the results between two types of coils (flexible and Printed Circuit board PCB designed) and the linearity for measuring currents

Key words

Rogowski coil, current sensor, electrical measurements

1. Introduction

Current sensors based in Rogowski coil is an innovative measuring system that offers advantages [1,2,3] with respect to conventional systems based in transformers with magnetic core. Their use has increased very recently in applications in Power Electronics [4], in Relay Protection [5,6] or in Transients [7].

The main characteristics of these sensors are the linearity, the large span and the bandwidth. So these sensors can be used in new applications related with high currents in non-sinusoidal systems.

The measuring principle is known since 1912. The Rogowski coil is a coil distributed uniformly in a non magnetic core that surround the conductor carrying the current to be measured, as indicated in the figure 1.
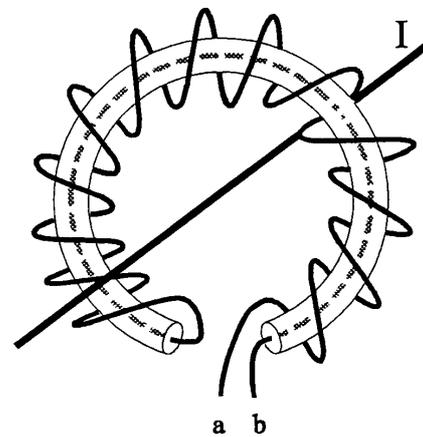
Fig. 1. Model of a Rogowski coil

The construction of a Rogowski coil presents some difficulties because for having some accuracy we need that the turns be equally distributed along the core and the return wire went back concentrically to avoid the external fields produced by external currents near the coil.

The most important characteristics of a Rogowski coil current sensor are::

- Large bandwidth allowing the measure of currents with fast transients as in the power distribution and power electronic circuits.
- Large span because with the same coil is possible to measure between some amps and some hundreds so kiloamperes.
- Good linearity because the coil is supported in a non magnetic material.
- No saturation, so the coil is not damaged by extra currents.
- Galvanic isolation between the primary circuit and the measuring circuit.
- The magnetic coupling between the primary circuit and the measuring circuit is only of several nanohenrys, so no charge effect.

- Rogowski coil is better than conventional transformers in high frequency applications where the magnetic core disturb the linearity and is not useful

The basic disadvantage of the Rogowski coil is that the output is a voltage proportional to the derivative of the current crossing the coil and for obtaining the original signal, the output must be integrated by analog integrators or by digital signal processors (DSP).

Other work has been carried out by some of the authors in order to improve the measurement of high currents with the best accuracy for calibration applications [8,9] but magnetic core is the responsible of low linearity and some problems in high frequency.

2. Rogowski coil

If the electric current varies with the time, a magnetic flux is produced in the coil and applying the Ampere´s law to the circuit of the figure 1, we can obtain a voltage defined by

$$V_{ab} = -\frac{d\phi}{dt} = -\mu_0 \cdot \frac{N}{l} \cdot A \cdot \frac{di}{dt}$$

Where N is the total number of turns, A the area of the turn and l the average length of the toroid. For low frequencies the induced voltage could be of some milivolts if the current is of some tenths of amps, but it could be of some tenths of volts when currents change very fast (eg. 100 A/μs)

We have built a coil of 2045 turns of wire of 0.4 mm of diameter obtaining a coil of 82 cm. The diameter of the toroid is 7,22 mm. The coil is shown in figure 2

Fig. 2. Physical aspect of the Rogowski coil

We have built, as well, several PCB Rogowski coils where the surface and the separation between turns is fixed. Using the two sides of a circuit board is possible to obtain a rigid coil with well defined dimensions and characteristics. In the figure 3 we can see one side of the coil.

This coil has 100 turns with internal radius of 40mm and external radius of 87,37mm an inductance of 25 nH.

Instead of the return wire and for avoiding the noise and disturbances produced by external currents we have built a second coil equal to the first one and both are connected together but in opposition.
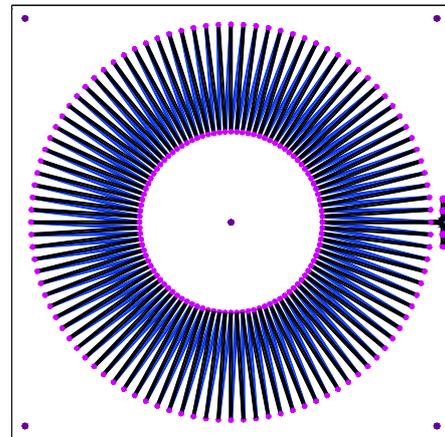
Fig. 3. Detail of PCB Rogowski coil

3. Model for the Rogowski coil

The behavior of a Rogowski coil can be simulated by a simple model, shown in the figure 4.
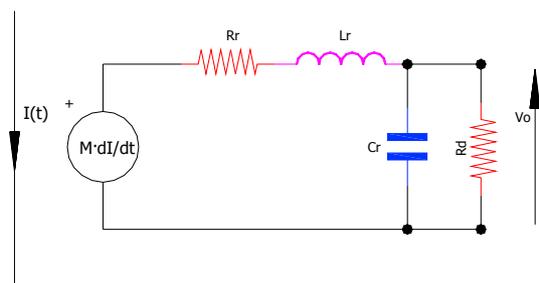
Fig. 4. Simplified model of the Rogowski coil

R_r is the intrinsic resistance of the coil, L_r is the distributed inductance of the coil and C_r is the stray capacitance. R_d is the resistance connected to the end of the coil for a correct measurement.

The transfer function of the circuit of the figure 3 is

$$\frac{V_o(s)}{I(s)} = \frac{M \cdot s}{T_b^2 \cdot s^2 + 2 \cdot \xi \cdot T_b \cdot s + 1} \quad (1)$$

where

- $T_b = \sqrt{\dfrac{R_d}{R_r + R_d}} \sqrt{L_r \cdot C_r}$

- $\xi = \dfrac{1}{2} \sqrt{\dfrac{R_d}{R_r + R_d}} \cdot \left(R_r \cdot \sqrt{\dfrac{C_r}{L_r}} + \dfrac{1}{R_d} \cdot \sqrt{\dfrac{L_r}{C_r}} \right)$

- $M = \mu_0 \cdot \dfrac{N}{l} \cdot A$

Typical values for M could be between 20 and 100 nVs/A, for L_r between 20 μH and 150 μH. For the stray capacitance the values could be between 30 pF and 60 pF.

For our flexible coil, the electric characteristics are :

Resistance 6.2 Ω
Inductance 220 μH
Capacitance 45 pF
Coefficient M 0.1283 μVs/A

Those values for the coil permit us to measure with a bandwidth between 2 and 6 MHz. Values higher than the corresponding for the current transformers with magnetic core.

In figure 5 we can see the output voltage obtained by one of the prototypes of the coil as a response to an input current surge of type of rise time of 500ns, (the resistance R_d was not connected in this case neither the integrator)
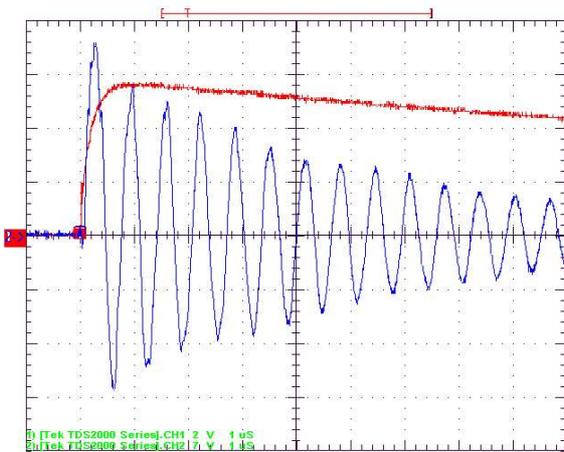
Fig. 5. Output voltage of the Rogowski coil (oscillatory) and current input (in dark)

The output voltage obtained in the coil is in accordance with the transfer function given by (1), and considering that $R_d \rightarrow \infty$. The oscillation frequency and the decay factor depend on R_r, L_r y C_r.

4. Integrator circuit

For obtaining the original current wave shape we need to integrate the signal in the output of the Rogowski coil. We can use integrator stages based on operational amplifiers (OA) with the appropriate bandwidth for the frequency of the current to be measured and a low noise level, because to a frequency of 50 Hz the output voltage of a Rogowski coil is of the order of several μV/A

The characteristic of an analog integrator is that the gain raises when the frequency diminish, so the random noise of low frequency and the noise coming from the offset must be attenuated by a filter so the characteristic gain-frequency for the integrator that we have built is shown in figure 6.
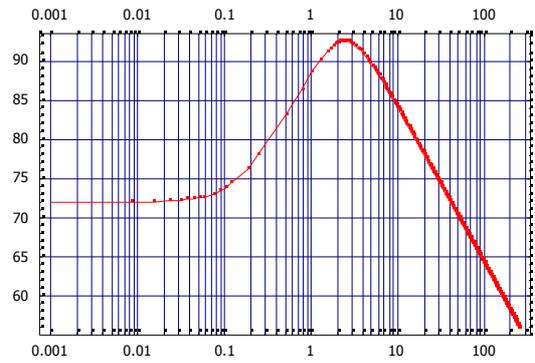
Fig. 6. Relationship between gain (dB)-frequency (Hz) for the analog integrator

Another way to built an integrator is using a digital signal processor (DSP). In that case the DSP convert the signal from analog to digital, then filter it and later convert it again from digital to analog with the advantage of the flexibility to use different kinds of filters.

5. Experimental results

We have tested two coils one flexible coil and another PCB type in order to verify the linearity in a large range of currents.

As shown in figure 7 we can see that for both sensors the output is very linear from several amps to 750 amps. In both cases the error in linearity is lower than 0.8%.

The only difference between the two coils is the coefficient that gives the proportionality between current and voltage because of the electronic circuits.
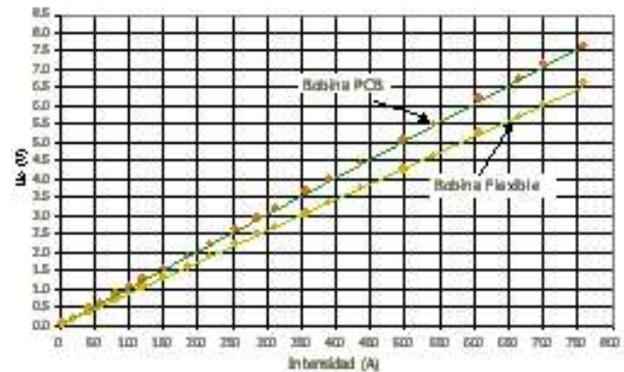
Fig. 7. Results of the linearity for both coils

With respect to the ability to detect fast transients the two kind of coils work well with the surge but due to the fact that the PCB has a lower value of the inductance is expected that higher bandwidth will be obtained.

In figures 8 and 9 we show the behaviour of the coils with a surge pulse.
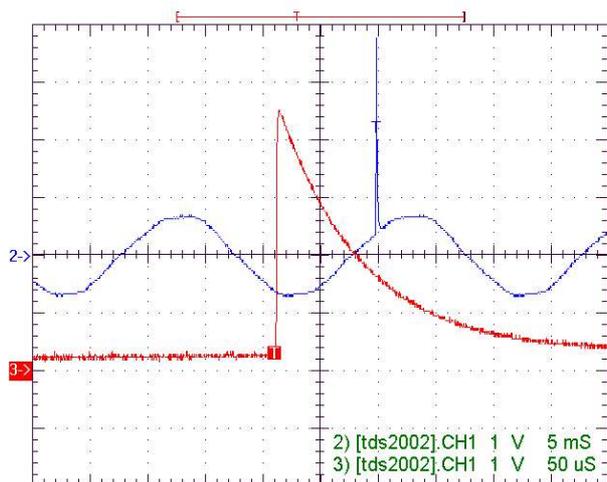
Fig. 8. Sinusoidal signal with a surge pulse detected with our Rogowski coil (1V and 5 ms and 50μs)

6. Conclusion

We have designed and built a Rogowski coil with the electronic integrator able to measure electric currents with transients as shown in figure 6. We have tested the coils in order to improve their behavior and linearity.

The idea is to use the coil for protection and measurement in power generation or in distribution. In particular for measuring the disturbances produced in power electric distribution or in power plants [10,11,12].

Another possibility that we are considering is the use of the coil for the fast detection of failures in distribution systems

In a future work we are considering the improvement of the knowledge of the errors produced by other currents flowing near the sensor.
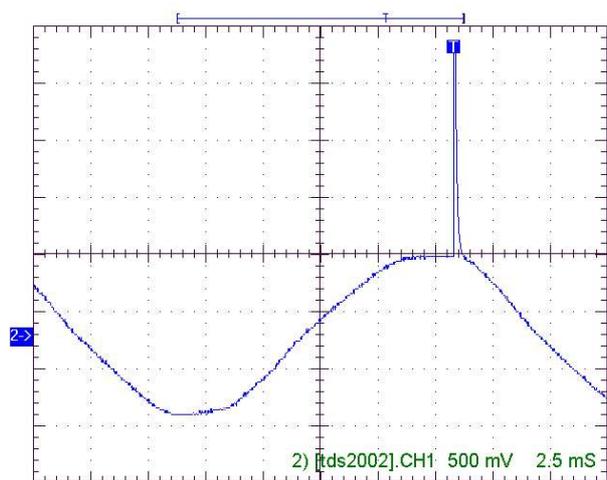
Fig. 9. Sinusoidal signal with a surge pulse detected with our Rogowski coil (500 mV and 2.5 ms)

We have tried to present in the paper a comparative between different coils that we are building, for selecting the best coil with more accuracy for future applications. The work continues with studies of the position of the external conductors and internal conductors carryìng currents with respect to the coil.

Two more fields of work are open, the first one the simulation with finite element method of the rogowski coil for improving the design of more performant coils and the second theknowledge in the laboratory for reduce the effects of other conductors in the vicinity in the measurements.

Acknowledgement

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