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BALANCED FRONT-END ELECTRONICS FOR ROGOWSKI COILS

L. Di Rienzo, A. Ferrero and R. Ottoboni
Dipartimento di Elettrotecnica, Politecnico di Milano, Italy

Abstract: The main advantages of the Rogowski coils are the Potential free measurement and the low cost compared to shunt and CT measuring systems.

Usually they are applied for measuring high-amplitude or high frequency currents. The aims of the paper is to investigate a new analog signal processing able to overcome the major limitations of the Rogowski coils in low current and low-frequency range.

Keywords: Measurement of Electrical Quantities

1 INTRODUCTION

A wide range of applications requires low-cost AC current transducer able to match both metrological requirements, such as accuracy, linearity, bandwidth, etc, and application-oriented requirements, such as high level galvanic insulation, compact size, lightweight etc.

Unfortunately, none of the available commercial AC current transducers is able to completely satisfy the above performance.

Resistive shunts are characterised by an excellent bandwidth and linearity but require an external insulation amplifier for the galvanic insulation purpose, that heavily limits the transducer metrological performance.

Hall effect based current transducers feature wide bandwidth, compact size and galvanic insulation but are still limited in their accuracy and linearity performance.

Classical electromagnetic current transformers feature a good compromise between accuracy, long time performance stability and galvanic insulation, but become inadequate when wide band, compact size and lightweight requirements are a must.

As a matter of fact, any choice of available AC current transducers represents a compromise between different tasks, depending on the particular field of application [1].

The recent development in microelectronics technologies pushes to reconsider the Rogowski coil based transducer as an attractive solution able to satisfy both metrological and application-oriented requirements.

It is well known that a Rogowski coil is made by an induction coil of constant section that is assembled around the current conductor. The induced EMF *e(t)* at the terminals of the coil is proportional to the derivative of the current *i(t)* to be measured and to the mutual inductance M of the coil:

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

The current to be measured is obtained by integrating the coil output voltage signal.

Rogowski coils have been widely used for measuring strong pulsed currents in the range of mega amperes in plasma laboratories [2-5]. They are easy to be installed and feature a wide frequency response. The major design problems of Rogowski coils concern the mechanical assembly details. Recent works have shown very interesting solutions in assembling the Rogowski coil, capable to overcome some classical mechanical problems [5-10].

This type of transducer features, from a theoretical point of view, high linearity and accuracy, wide band, high insulation level, compact size and lightweight.

Up to now, problems related to the availability of suitable electronic integrator circuits have limited the use of the Rogowski coil in the field of very large currents and/or very fast electrical transients [5].

The aim of the present paper is to investigate the possibility to employ a Rogowski coil based transducer in low-amplitude current measurements with little repetitive frequency. The goal is represented by the design of a laboratory prototype able to work in the current range from few tens of milliamperes to some amperes in a 50 *Hz* - 10 *kHz* bandwidth and with accuracy better than those of 0.2 class current transformers.

For this purpose, a novel analog signal processing is introduced, based on a total balanced analog circuit, able to minimise the noise in the integration process. In this way, a high value of S/N ratio is achieved, that is mandatory when the amplitude of the current under measurement is in the above specified range.
The paper is especially focused on the adopted electronic design criteria and reports the preliminary experimental results obtained by employing the developed transducer prototype.

2 NOVEL ANALOG PROCESSING ELECTRONICS

The basic problem in the Rogowski coil based transducers concerns the low frequency range of the input current and it is due to the limits of the active integrator behaviour [3], [13]. The integrator design becomes critical when current amplitude and frequency decrease: in these conditions, low- frequency noise, drift and phase response of the integrator represent the major problems.
In this case, the signal at the output terminals of the Rogowski coil needs two analog processing operations:

1. Amplitude amplification: The amplification factor depends on the coil design and on the current amplitude and frequency. When compact size coils (width reduced number of turns) and low amplitude and frequency current are taken into account, the amplification factor may become very high.
2. Integration: The coil delivers a voltage proportional to *di(t)/dt:* this must be integrated over the time to obtain an output signal proportional to *i(t).*

These operations are usually performed by means of a single electronic stage, based on an approximated integrator circuit, as reported in Fig. 1, where resistor R_f must be introduced in order to prevent saturation effects due to the input bias currents of the operational amplifier.

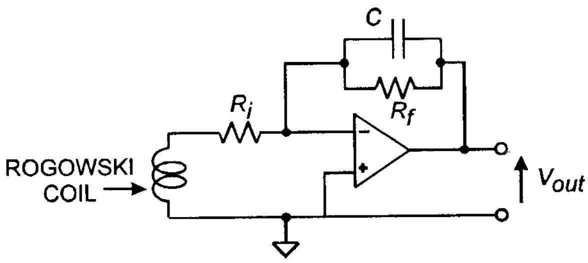


Figure 1. Classical active integrator for Rogowski coil signal process.

In this way, the DC gain of the integrator is fixed by the ratio R_f / R_i.

In this circuit the major problem associated with the integrator design is represented by the frequency of the pole, f_p, of the transfer function. In the circuit of Fig. 1 the pole frequency is proportional to $(R_fC)^{-1}$. In order to avoid significant errors in the integration process, the pole frequency must be, at least, lower than two decades with respect to the lower frequency component, f_{min} of the current under measurement. This means that the DC gain must be two order of magnitude greater than the gain value at the frequency f_{min}.

When high gain level is required at the frequency f_{min} a very high ratio R_f / R_i must be adopted. On the other hand, the increase of R_f value implies a worsening in noise and thermal drift in the integrator performance while the decrease of R_i implies that the coil resistance has to be considered in determining the real integrator transfer function gain.
In order to overcome the above problems related to the use of a single stage integrator, we have reconsidered the possibility to separate the amplification function from the integration one.

The structure of the adopted signal processing electronics is showed in Fig. 2. It is based on the integration of the two output voltage signals collected by the two identical coaxial Rogowski coils that are realised by a pair of twin conductors.
This solution has been already adopted in [11], in order to properly connect the two coils, obtaining a higher signal level and a better SNR. In that paper, however, a different approach has been adopted: the EMFs are not directly summed at the coil level, but they are separately processed by a balanced active signal processing electronics.

The proposed structure is based on two sections. The first section is represented by a couple of ultra-low-noise voltage amplifier, while the second section provides the EMF's integration by means of an analog filter. The adoption of a balanced structure in the analog signal processing assures some further advantages.

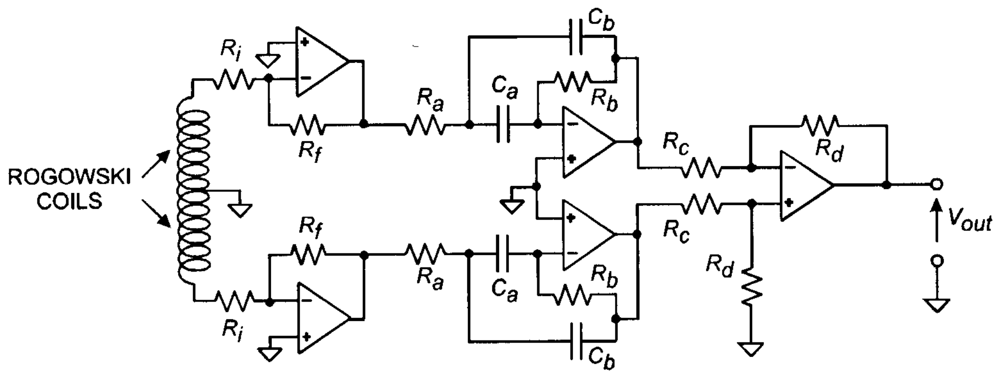


Figure 2. Operating principle of the proposed analog front-end electronics.

- For a given signal amplitude at the transducer output, each branch of the balanced structure collects an input signal whose amplitude is half of that of a single ended structure. This allows to double the current peak factor, thus reducing the saturation problem in the amplification stage [13].
- By selecting single-chip double operational amplifiers for the voltage amplifiers and the integrator implementation, a high matching between the two channels of the balanced structure can be assured, thus reducing offset voltage and drift effects in a wide range of temperature.

3 ANALOG PROCESSING ELECTRONICS DETAILS

A voltage amplifier represents the first stage in the analog processing electronics. Its design has been oriented to the following requirements.

- High gain: the overall gain of the analog processing electronics is localised in this stage. The gain factor must be selected according to the coil mutual inductance in order to achieve the required transducer sensitivity.
- High input impedance: high input impedance is necessary to prevent load effect on the coil. In this way, the coil resistance does not influence the amplifier performance, thus annihilating the effect due to the thermal drift on the coil resistance.
- Wide band: the amplifier frequency response must cover a range as wide as to avoid amplitude and phase distortion in the signal processing. A DC coupled amplifier represents a mandatory requirement in a low-amplitude current measurement with little repetitive frequency.
- High output voltage dynamic. A limit in the dynamic output voltage behaviour implies a bound in the allowable maximum peak factor for the current under measurement.
- Very low noise. Due to the large amount of the amplification level and bandwidth, the equivalent input noise voltage of the amplifier must be very low, in order to achieve a suitable SNR. The DC coupling of the amplifier requires particular care in the flicker component of noise: the value of this kind of noise is usually much higher than the Johnson noise for the low-frequency range. In order to minimise its effect on the overall analog processing electronics, an amplifier with a low value of the equivalent noise voltage must be selected and it is necessary to properly design the subsequent integration process.

As far as this second aspect is concerned, a classical solution is represented by the analog processing circuit reported in Fig. 3 [13].

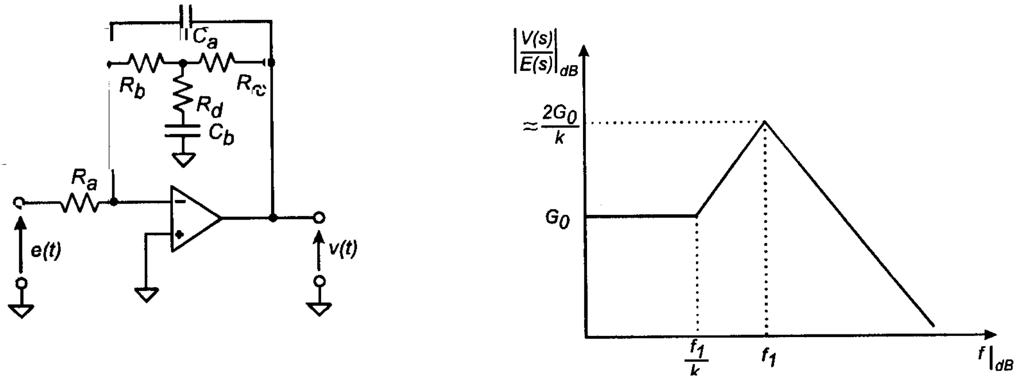
By an appropriate choice of R_b, R_c, C_a and C_b it is possible to place the poles and the zero in such a way that the amplitude transfer function matches that of the integrator for frequency values higher than f_1 (where f_1 represents the poles frequency).

In this case the transfer function assumes the expression:

$$\frac{V_{(s)}}{E_{(s)}} = -G_0 \frac{(1+\frac{Ks}{2pf_1})}{(1+\frac{s}{2pf_1})^2} \tag{2}$$

where V(s) and E(s) are the Laplace transforms of v(t) and e(t), and Go and k are constants, depending on the resistor and capacitor values.

At the frequency values lower than fl, the amplitude frequency response decreases and the DC gain is reduced by a *k/2* factor respect to the classical integrator amplitude response. In this way, the noise



A) B)

Figure 3. Classical improved integrator circuit. A) circuit, B) Bode diagram of the amplitude frequency response.

voltage at the output of the analog processing circuit is also reduced, in the range from DC to f_1 frequency, by a *k/2* factor approximately.

Nevertheless, this noise reduction cannot be sufficient when the SNR requirement becomes very strict, as in the case of low amplitude and frequency current measurements. Moreover, the voltage offset of the previous amplifier stage is still amplified, thus reducing the available amplitude dynamic in the integrator stage.

In the realised prototype, a novel solution for the integration process has been adopted, based on the implementation of the Delyiannis-Friend bandpass filter. This filter, whose structure is reported in Fig. 2, basically consist of an inner differentiator and an output integrator.

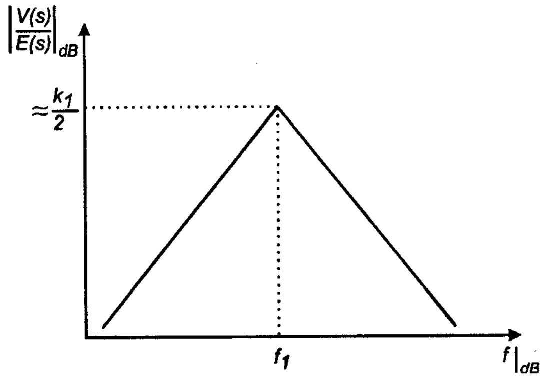


Figure 4. Bode diagram of the amplitude frequency response of the proposed integrator

By an appropriate choice in the resistor and capacitor values, the resulting transfer function is given by the following equation, where k_1 is a constant.

$$\frac{V(s)}{E(s)} = -\frac{k_1 s}{\left(1+\frac{s}{2p\ f_1}\right)^2} \tag{3}$$

The filter amplitude response is showed in Fig. 4.

By comparing Fig. 3 B and Fig. 4, the effective reduction in the flicker noise amplification in the range from DC to the first pole frequency attained by this solution appears quite clearly. Besides, since this kind of integrator is not D.C. coupled, the output voltage offset of the signal amplifier stage does no longer represent a problem, thus simplifying the design of the amplifier.

4 DEVELOPED PROTOTYPE AND EXPERIMENTAL RESULTS

A prototype of a Rogowski-coil-based transducer has been developed. The balanced pick-up coils have been obtained wounding a pair of twin conductors on a rigid toroidal core. No particular care has been adopted in its design, since our attention is focused on the electronics.

The Rogowski coil parameters are the following: 50 mm outside diameter, 36 mm inside diameter, 22 mm thickness, 280 turns for each coil.
Under these conditions, the resulting theoretical mutual induction *M* is about 0.4 µH [6].

In each branch, the amplification stage is based on a low noise operational amplifier (Burr Brown INA103), connected in a non-inverting configuration, whit gain factor equal to 501.
As it was previously discussed, the noise performance of the operational amplifier represents a focal point. In this case, the employed device features an equivalent noise voltage equal to $2nV/\sqrt{H_z}$ *at 10* Hz and *1* $nV/\sqrt{H_z}$ *at 1 kHz,* while the input noise current is $2pA/\sqrt{H_z}$ at *1 kHz.* The output voltage range is $\pm 21\,V$, allowing the correct processing of a high crest factor current. The bandwidth goes from DC to 150 *kHz,* thus assuring a phase error lower than 0.3 *mrad* at 50 *Hz* and a non-linearity in the phase response lower than *1 mrad* at 23 *kHz.*

As far as the integrator stage is concerned, the pole frequency is set to 0.05 Hz, which corresponds to a phase shift of about 1 *mrad,* referred to the phase response of an ideal integrator, at 50 *Hz.*
At the same frequency, the amplification factor is about 0.5.

Due to the very high value required for the resistor R_b (470 *M**W**,* Fig. 2), a CMOS operational amplifier with high DC gain and a very low input bias current (less than 1 *pA)* is employed in this stage. Nevertheless, in order to better control the effect of the bias current and voltage of this operational amplifier on the overall electronics performance, single-chip, double operational amplifiers have been selected for the implementation of the integrators: this assures a high matching between the two channels of the balanced structure, especially for the offset voltages, in a wide range of temperature.
These operational amplifiers feature an equivalent noise voltage equal to 40 $nV/\sqrt{H_z}$ *at* 10 Hz and 12 $nV/\sqrt{H_z}$ *at 1 kHz,* while the input noise current is 20 $pA/\sqrt{H_z}$ at 1 *0* Hz and 0.4 $pA/\sqrt{H_z}$ at *1 kHz.*

In the analog signal processing of Fig. 2, a differential to single ended converter is then employed, based on the classical differential amplifier configuration. Due to the relative high level of the signals processed by this stage, it does not give a significant contribution to the overall noise voltage.
The maximum total expected rms noise voltage at the output of the analog signal processing circuit is about 0.05 *mV,* over a bandwidth of 100 *kHz (0.04 mV* for the amplifier and 0.02 *MV* for the integrator). Under the above design criteria and considering a *1 A, 50* Hz current, the resulting signal at the output of the transducer has an amplitude of 60 *mV.* this means a SNR of about 50 dB.

The real behaviour of the realized prototype has been experimentally evaluated. The results of the first experimental tests are reported.
The rms value of the output noise is equal to 36 *µV,* while the output signal at the transducers output is equal to 65 *mV,* for a *1 A, 50* Hz current.
The measured value for the input-output time delay is constant on the specified frequency range and shorter than 3 *µs*, that is equivalent to the phase error of a class 0.1 current transformer.

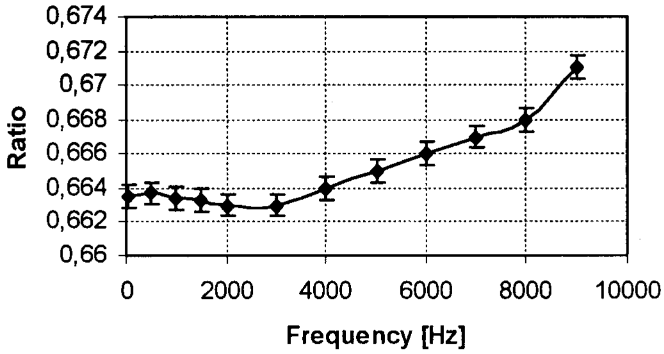


Figure 5. Transducer uncertainty in the amplitude frequency response, evaluated by comparison with a reference shunt. The error bars represent the evaluated uncertainty in the measurement process

The amplitude frequency response of the transducer has been evaluated by comparison with a reference non-inductive shunt.

Fig. 5 shows the plot of the ratio between the transducer output voltage and the shunt one versus frequency, in a frequency range from 50 *Hz* to 9000 Hz and for 1 A sinusoidal input current. The accuracy in a 50 *Hz - 4* kHz bandwidth is better than those of 0.2 class current transformers. For frequency values higher than 4000 *Hz,* a distortion in the transducer output signal is present, thus decreasing the transducers accuracy.

This distortion is due to a slew rate limitation of the operational amplifiers employed in the integration stage: the maximum value of their output currents (less than 10 mA) are not able to correctly charging and discharging the feedback capacitances C_b , that presents a high value (10 *µF*). As a matter of fact, the full power bandwidth of the transducers decreases as the frequency increases. Although this condition does not represent a real limitation in many applications, where the signal is pratically confined to its low frequency components, this problem can be overcome by employing operational amplifiers with higher output current. Devices with 80 mA output current and low noise (9 nvlj-H-z) have been recently introduced and are therefore available. Another solution can be represented by cascading a buffer to the operational amplifier, thus improving the output current drive, at the cost of a worse noise characteristic.

5 CONCLUSIONS

A novel balanced front-end electronics was proposed that is able to extend the application of the Rogowski coils to currents in the industrial frequency range. The guidelines followed for the design were discussed. A lab prototype of a transducer has been developed and the new analog signal processing technique has been experimentally evaluated and some preliminary experimental results were reported in the paper. These results show that the goal of applying the Rogowski coil principle in the measurement of current with amplitude range from few tens of milliamperes to some amperes is achieved. A very high SNR is obtained, that assures good accuracy even in the low amplitude current measurements. Some problems in the transducers bandwidth were stressed: the view rate of the employed operational amplifiers limits the full power bandwidth of the assembled prototype. Even though this limitation does not represent a problem in many application, it can be overcome by choosing devices with better view rate performances.

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AUTHORS: Univ. Prof. Dr. P. Roberto OTTOBONI, Ass. Prof. Dr. Gabriele D'ANTONA and Mr. Luca DI RIENZO, Department of Electrical Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy, Phone lnt. ++39 02 2399 3727, Fax lnt. ++39 02 2399 3703
E-mail: ottoboni@bottani.etec.polimi.it