Implementation of a Rogowski coil prototype for the measurement of alternating electric current

Implementação de um protótipo de uma bobina de Rogowski para medição de corrente elétrica alternada

Implementación de un prototipo de un Bobina de Rogowski para la medición de corriente alterna

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ABSTRACT
This article aims to present the development of a Rogowski Coil prototype for the measurement of alternating electric current up to 80Arms. For this elaboration, circular hose, ABS filament and enamelled copper conductor was used. In addition, an Arduino and an AD620 instrumentation amplifier were used for data acquisition. The results were satisfactory, because the average percentage of errors corresponded to approximately 1.75%.

Keywords: Rogowski coil, electric current transducer, AC current measurement.

RESUMO
Este artigo tem como objetivo apresentar o desenvolvimento de um protótipo de Bobina de Rogowski para medição de corrente elétrica alternada até 80Arms. Para esta elaboração foi utilizada mangueira circular, filamento ABS e condutor de cobre esmaltado. Além disso, foram utilizados um Arduino e um amplificador de instrumentação AD620 para aquisição de dados. Os resultados foram satisfatórios, pois o percentual médio de erros correspondeu a aproximadamente 1,75%.

Palavras-chave: Bobina de Rogowski, transdutor de corrente elétrica, medição de corrente alternada.

RESUMEN
Este artículo tiene como objetivo presentar el desarrollo de un prototipo de bobina Rogowski para la medición de corriente eléctrica alterna hasta 80Arms. Para esta elaboración se utilizó manguera circular, filamento ABS y conductor de cobre esmaltado. Además, para la adquisición de datos se utilizaron un Arduino y un amplificador de instrumentación AD620. Los resultados fueron satisfactorios, ya que el porcentaje medio de errores correspondió aproximadamente al 1,75%.

Palabras clave: bobina de Rogowski, transductor de corriente eléctrica, medición de corriente CA.

1 INTRODUCTION
The electric energy is essential for the execution of various activities. To have access to her is a fundamental factor in the economic and social development of a country. Coming from other energy sources, electricity arrives to consumers through electrical systems which follow the steps of generation, transmission, distribution and consumption. In the process of making electrical energy available to society without restrictions on reach and capacity, it became necessary to invent the transformer and develop alternating current power stations [1].

An alternative to supply the expansion of the energy matrix is the efficient use of electric energy which occurs through the production of more efficient equipment and/or through the improvement of electrical systems.
In the context presented, the use of energy management equipment is interesting as they allow monitoring the behavior of electrical systems. According to [2], energy management is an important action in the search for the rational and efficient use of natural resources. In addition, it includes technical, economic, political, social and environmental aspects. Observably, the relevance is also noted in the construction of prototypes that enable the development of increasingly efficient technologies [3].

Equipment of this type, that is, energy management equipment, is capable of collecting and storing parameters measured in electrical systems. For this, it is necessary current and voltage sensor of alternating signals, analog-digital converter and microcontroller.

The acquisition of electric current can be obtained by sensors such as resistor shunts, inductive current transformer, Hall effect sensor and the Rogowski coil transducer. The Rogowski coil is a toroid whose primary winding is the conductor in which the electric current will be measured and the secondary is kept open or connected to a high impedance. Furthermore, the core is made of a non-ferromagnetic material [4] and is a non-invasive transducer, since there is no need to open the circuit to do the measurement.

This work is a study on the constitution of Rogowski coil and has as its objective to improve the knowledge about this technology and its operation.

2 ROGOWSKI COIL

The Rogowski coil is a sensor that perpendicularly involves the conductor in which the current to be measured flows. In addition, it requires that its output be connected to an integrator circuit so that the voltage at its terminal results in a value proportional to the electrical current measured [5].

The constitution of a Rogowski Coil is shown in Figure 1 in which the primary conductor, the secondary conductor and the output connected to an integrator circuit are seen.
The advantages of this transducer include linear response, ease of installation and lightness [6]. Furthermore, they do not saturate under high currents and guarantee a good response at high frequencies which allows the measurement of electrical current transients. The non-saturation occurs due to the air core [7].

Although the mentioned advantages, the coil is not able to measure direct currents, the secondary winding must be symmetrical, this is sensitive to noise and depends on the distribution of the concatenated flow, so that the relative position of the conductor inside the coil influences on the response.

2.1 ROGOWSKI COIL WORKING PRINCIPLE

The Rogowski coil has working principle based on Ampère’s law and Faraday-Lenz’s law. In short, when a Rogowski coil surrounds a conductor carrying a time-varying electric current, is produced a magnetic field that induces a potential difference between the terminals of coil. The Ampère’s Law is a special case of the Biot-Savart law and declare that line integral of the magnetic field \( \mathbf{H} \) along a closed path is equal to the current involved in that path. This law is represented by Equation (1).

\[
\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 \cdot I 
\]  

(1)

Where:
\( \vec{B} \) is the magnetic field intensity vector (A/m);
\( d\vec{l} \) is the conductor length differential vector (m);
\( \mu_0 \) is the magnetic permeability of free space (H/m);
i is the electric current (A).

The Faraday’s law, in turn, demonstrates that the variation of the magnetic flux generates an electromotive force according to Equation (2). The negative sign is explained by Lenz’s law, which indicates that the induced electromotive force opposes the flux variation that caused it.

\[
\varepsilon = -N \frac{d\phi}{dt}
\]  \hspace{1cm} (2)

Where:

\( \varepsilon \) is the electromotive force (V);
\( N \) is the number of conducting turns;
\( d\phi \) is the magnetic flux differential (Wb);
\( dt \) is the time differential (s).

2.2 RELATIONSHIP BETWEEN VOLTAGE AND ELECTRIC CURRENT

The math behind the phenomenon makes it possible to find the relationship between the voltage on the secondary and the electrical current on the primary.

It should be considered that the coil area has a circular shape and radius \( r_s \), as illustrated in Figure 2.

Figure 2. Radius and position of conductor and coil.

Source: authors, based on [9].
The Biot-Savart law, presented in the equation (3), allows obtaining the magnetic flux for any length $L$ of the primary conductor. For understanding, it is convenient to consider Figure 3.

$$dB(t) = \frac{\mu_0 i(t) \, dl \times \vec{a}_R}{4\pi \, |\vec{R}|^2}$$  

(3)

Where:

$\vec{a}_R$ is the unit vector in the direction of $\vec{R} = \vec{P}_2 - \vec{P}_1$ (m).

Figure 3. Conductor and points in space.

Source: authors, based on [9].

Given that $\vec{R} = -x\vec{i} + y\vec{j}$ and $d\vec{l} = dx\vec{i}$, follows the equation (4) when doing the vector product and integrating of the equation (3).

$$B(t) = \frac{\mu_0 i(t)}{4\pi y} \frac{L}{\sqrt{(L/2)^2 + y^2}}$$  

(4)

From then on, it is possible to calculate the magnetic flux by multiplying the magnetic field $B(t)$ for the area $A$, on where $y = r$ and $A = \pi r_s^2$. As a result, the equation is obtained (5).

$$\phi(t) = \frac{\mu_0 i(t) r_s^2}{4r} \frac{L}{\sqrt{(L/2)^2 + r^2}}$$  

(5)
Where:

\( \phi(t) \) is the magnetic flux (Wb).

Finally, to find the equation (6), that is, the relationship between the voltage in the secondary \( \varepsilon_2(t) \) and the electric current in the primary \( i_1(t) \), it is necessary to perform the current differential in time and multiply by the number of turns \( N \) as shown in the equation (2).

\[
\varepsilon_2(t) = N \frac{\mu_0 r_0^2}{4r} \frac{L}{\sqrt{(L/2)^2 + r^2}} \frac{di_1(t)}{dt}
\]  

(6)

3 PROTOTYPE DEVELOPMENT

The first step taken was the bibliographical study regarding the topic. Followed by the calculation of the number of turns of the coil, coil confection and carrying out tests and electronic treatment.

3.1 CALCULATION OF THE NUMBER OF COIL TURNS

It was idealized the creation of a coil with a maximum current value equal to 80 Arms. The Table 1 presents the parameters defined for later calculation of the number of turns \( N \). It is important to emphasize that the value of \( r_s \) was determined by the chosen core: a hose with \( 2\pi r_s = 28 \text{ cm long} \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon )</td>
<td>60 mV p</td>
</tr>
<tr>
<td>( f )</td>
<td>60 Hz</td>
</tr>
<tr>
<td>( L )</td>
<td>1 m</td>
</tr>
<tr>
<td>( r )</td>
<td>0.045 m</td>
</tr>
<tr>
<td>( \mu_0 )</td>
<td>( 4\pi 10^{-7} \text{NA}^{-2} )</td>
</tr>
<tr>
<td>( r_s )</td>
<td>0.00810 m</td>
</tr>
</tbody>
</table>

Source: based on our own research.

In this way, a value of \( N \) equal to 1542 turns was obtained, according to equation (7).
\[ N = \frac{2r \epsilon_p}{\mu_0 r_s^2 \pi f I_p} \sqrt{\left(\frac{L}{2}\right)^2 + r^2} \frac{L}{L} \]  

(7)

This equation was obtained from (6) considering the primary current as 
\[ i_1(t) = I_p \sin(\omega t) \] and \( \omega = 2\pi f \).

3.2 COIL IMPLEMENTATION

The secondary of the Rogowski coil is composed of turns around a core of nonferromagnetic material. For the development of the prototype was used:

- ABS filament (Acrylonitrile Butadiene Styrene) for three-dimensional printing;
- Enameled copper wire 33 AWG (American Wire Gauge) for winding;
- Flexible polyethylene tube for core.

The preference for using a hose is justified by the format and material, since it has a circular shape, resistance and flexibility. This last characteristic collaborates in the development of a non-invasive coil, that is, an instrument in which there is no need to open the circuit to do out the measurement.

The ABS filament was used to print 2 pieces that make it possible to open the coil for insertion into the primary non-invasively.

3.3 BENCH OF TESTS

To carry out tests in the laboratory, a bench was set up with the items below:

- 01 Variable autotransformer – 0 to 240V, 50/60Hz, 1200W and output: 0 to 240V.
- 01 STECK Differential Circuit Breaker – 2P, 230V and sensitivity: 30mA.
- 11 Lamps – 220V and 60W.
- 01 Multimeter Pliers POLITERM – max 1000A and 600V.
- 01 SINGLENT SDS1102CN digital oscilloscope.

The bench of tests was assembled according to the scheme in Figure 4.
3.4 CONFECTION OF INTEGRATOR CIRCUIT AND SIGNAL AMPLIFICATION

The Rogowski coil output is connected to an integrator circuit, which transforms the amplitude and phase of the coil output. This step is suitable because the transducer output is proportional to the primary derivative. Therefore, the integrator recovers the original current signal.

Furthermore, the Rogowski coil induces a low amplitude signal at its output. And, it is necessary to use an instrumentation amplifier. The AD620 is an electronic module that enables signal amplification in a range of 1.5 to 1000 times, high precision, low noise level, operating voltage of 3V - 12V DC, trimpot for input signal amplification adjustment and trimpot for zero point adjustment. In addition, it reads input signals from 100µV - 300 mV. The Figure 5 shows the schematic of the AD620 module.
Aware of this, a study and tests were carried out on the use of the integrator circuit at the coil output. At first, a circuit was built on a protoboard active integrator with the LM741 IC, but without good results. Subsequently, the same circuit was done with the AD620 instrumentation amplifier, however, the output was quite noisy as the primary electric current increased.

As the studies continued, another possibility was found. In this case, a passive integrator circuit was inserted in both coil terminals (Vin1 e Vin2) as shown in the Figure 6. Also, the outputs (Vout1 e Vout2) are the differential inputs to an instrumentation amplifier. The result of this simulation without the amplification step can be seen in the Figure 7.

Regarding the components for the circuit, was defined 0.1μF capacitor and to meet the integration criteria, the resistance must be greater than 26.52kΩ (obtained according to equation 8). The use of 100kΩ resistors was defined.
It is important to highlight that the output voltage for being linear, can be used without integration in applications that only require the measurement of electric current. However, for power measurement applications it is essential to use this circuit due to the phase difference between current and voltage.

3.5 DEVELOPMENT OF A DASHBOARD AS AN INTERFACE FOR DATA ACQUIRED BY AN ARDUINO

The arduino is a data input and output control board which makes it possible to develop electronic and robotic projects more easily. It is a microcontroller board based on the ATmega328P with 14 digital inputs/outputs, 6 analog inputs, a 16MHz crystal oscillator and USB connection. The Figure 8 shows an Arduino board.

The PLX-DAQ (Parallax Data Acquisition Tool), in turn, is a tool that allows send data from the microcontroller directly to Microsoft Excel. This benefits data analysis and charting creation. The arduino device and PLX-DAQ rely on UART serial communication.

A dashboard was developed to quantify the value of the electric current carried by the primary conductor measured by the Rogowski transducer. For this, a code was implemented in the Arduino IDE, whose function is, with the help of the PLX-DAQ tool, to collect 500 data samples directly in Microsoft Excel. From then on, the Dashboard presents graphs and information, such as the maximum and minimum points of the wave.

\[ R \gg \frac{1}{2\pi fC} \gg \frac{1}{2\pi 60.0.1\times10^{-6}} \gg 26.52k\Omega \]  

(8)
The main advantage of using the Dashboard is to verify the behavior of the AC current. However, in addition to displaying the wave graphs and RMS value, it also has a page for calculating the number of turns N.

To implement out this methodology, the gain of the instrumentation amplifier was adjusted, so as not to exceed the 5V limit of the Arduino, in addition applied an offset to the wave, given the need to read with positive values. This adjustment is shown in Figure 9 and was made by adjusting the trimpot of AD620. It is important to inform that this offset was digitally “removed” in the Arduino IDE programming to represent the waveform with greater fidelity. The Figure 10 represents the assembled circuit to obtain data by Arduino.

4 RESULTS AND DISCUSSIONS

The theory related to the Rogowski coil is fundamental to analyze and discuss the collected experimental data.
4.1 COIL PROTOTYPES

A lot of coils were implemented during this work, but without success due to problems such as conductor breakage. The last coil prepared and used, has a number of turns and electrical resistance according to the Table 2 and the Figure 11 shows the Rogowski prototypes made.

Table 2. Parameters for calculating N.

<table>
<thead>
<tr>
<th>N (Turns)</th>
<th>Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1525</td>
<td>17.1</td>
</tr>
</tbody>
</table>

Source: based on our own research.

Figure 11. Coil 80Arms.

Source: authors.

4.2 COIL OUTPUT WITHOUT SIGNAL PROCESSING

The first test made on the coil after checked continuity, was verification the output directly on the oscilloscope. In this analysis, the presence of noise was observed, which was expected, since they are subject to the influence of external magnetic fields. In the Figure 12, it is possible to observe that in addition to modifying the wave, the noise increased the amplitude of the signal in relation to the expected theoretical voltage.
In addition, the behavior of the coil was verified according to the position of the primary in your inside, so that as the primary conductor approaches the connector of the Rogowski core, where there is no copper winding, there was a reduction in f.e.m. induced. This situation can be seen in Figures 13 and 14 and was predicted, because as pointed out by the theory, the relative position of the primary conductor interferes with the concatenated flow.
4.3 COIL OUTPUT AFTER INTEGRATION AND AMPLIFICATION

In view of the results obtained in the first test, the coil response was then verified after passing through a low-pass filter on a protoboard. In this analysis, a good result was obtained due to the attenuation of the highest frequencies. In the same way, the passive integrator circuit was mounted on a protoboard, which performed better response when compared with the output of the filter and therefore, this circuit was used, made according to Figure 6. The integrator board was also elaborated as shown in the Figure 15.

With the use of the instrumentation amplifier after the integration step, a significant gain without wave deformation was applied to the circuit, considering the maximum measurement for the coil.

The worry with the current limit to be measured by the Rogowski coil became necessary, especially, when using the instrumentation amplifier and arduino uno, which has limited voltage value on the analog ports. For this, the voltage of the variac was raised until the current in the circuit reached a value close to the desired, and then adjusted the gain on the AD620. The Figures 16 to 19 show the output of the coil after signal integration and amplification.
It is possible to verify a signal in which the noise has been noticeably reduced, the frequency circles in 60Hz, and occurs the increase in amplitude $V_{\text{rms}}$ with the increase in electric current.

4.4 AC CURRENT MEASUREMENT WITH THE ARDUINO

The last test done was the measurement of AC current by Arduino. This methodology consists of collecting 500 samples for graphic representation of the
alternating wave. In addition, every 50 samples, the RMS value of the signal is calculated, so that result in a 10-point graph for RMS current.

Using the PLX-DAQ to send the data read from the Arduino to a Microsoft Excel spreadsheet, it was possible to obtain with the use of the MAX(), MIN() and AVERAGE() functions, the maximum peak, minimum peak, and wave offset values, respectively.

The Dashboard developed with two buttons on the homescreen for choosing between the options: calculation of the number of turns and visualization of the measured AC current. If the first option is chosen, it is necessary to inform the coil parameters as presented in Figure 20. However, if the user chooses the second option, it is necessary to collect the samples and then go to the graphics tab. For this, it is essential to inform the port and the communication speed of the Arduino. These steps are shown in Figure 21.

![Figure 20. Calculation of the number of turns by Dashboard.](Source: based on our own research.)

![Figure 21. Sample collection by Arduino.](Source: based on our own research.)

Done that, the results for two measurements are presented. In the first, the ammeter indicated current equal to 51.7 Arms. In the second, the meter indicated
39.8 Arms. That said, the Figures 22 and 23 indicates the variation of AC waves and the Table 3, the values obtained.
This methodology allowed to check that both measurements had an RMS value close to the measured value, wherein the errors were equal to 2% considering the current of 51.7Arms and 1.5% for current of 39.8Arms. In addition, it is seen that both measurements had a low positive offset of the signal.

In the second graph, that is, “RMS current” it is possible to see the variation of the RMS signal in time. Although this variation is not so accentuated and oscillate around the RMS value, this demystifies the idea that the value of the power grid is always constant.

<table>
<thead>
<tr>
<th>Values</th>
<th>Metering 1 (A)</th>
<th>Metering 2 (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>73.79</td>
<td>59.74</td>
</tr>
<tr>
<td>Minimum</td>
<td>-73.19</td>
<td>-56.18</td>
</tr>
<tr>
<td>Average</td>
<td>0.56</td>
<td>1.39</td>
</tr>
<tr>
<td>RMS</td>
<td>50.65</td>
<td>39.20</td>
</tr>
</tbody>
</table>

Source: based on our own research.
5 CONCLUSION

The Rogowski coil is a device for measuring alternating electric current and current transients. This device is considered a transducer and consists of a winding helical, which around of a loaded conductor, induces an electromotive force at its terminals. In addition, it has a core of non-ferromagnetic material.

The output signal of coil needs to be subjected to electronic treatment, such as amplification and integration, with the objective of transform the f.e.m. induced in a value proportional to the measured electric current.

In the present work, a prototype of a Rogowski coil was developed, in which the signal integration occurred by a passive integrator, and the output amplification by the use of the AD620 instrumentation amplifier. For the user interface, a Dashboard with Microsoft Excel was created. By analyzing of the results of this methodology, it was verified good results, because the values obtained were close to measured current with error corresponding to 1.75%.

Also, in this work, it was possible to verify the linearity of this alternating current meter and how susceptible your output is to outside interference. Although the coil has simple geometry, it has complex concepts and points to be followed to get good measurements.
REFERENCES


