Coreless coil AC transducer

Today’s circuits of systems for monitoring electrical values as well as circuits of power system automation consume less and less power. This is an inspiration to search for state-of-the-art solutions of AC transducers [1,2,4]. Obviously, classical current transducer not always can be replaced by other solutions, such as Rogowski coil or Hall effect sensors. The paper features the possibility to use a standard air coil as a simple and cheap current-voltage transducer.

key words: current-voltage transducer, Rogowski coil, transformation of deformed courses, AC current monitoring, protection of electrical power systems.

1. INTRODUCTION

The Rogowski coil is known from numerous publications. It has many obvious advantages, yet a few disadvantages, such as a complex production process, high cost and the necessity to use separable coils which are to be installed in already existing current circuits. Besides, in order to produce identical items with the same transformation constant, one has to employ the PCB HDI technology (Printed Circuit Board High Density Interconnect).

![Rogowski coil scheme](image)

Figure 1 features a scheme of a Rogowski coil where the current $i(t)$ passing through the coil window induces electromotive force $e(t)$ (1):

$$e(t) = z \frac{d\phi}{dt} = \frac{\mu_0 \cdot z \cdot S}{2\pi \cdot r} \frac{di}{dt} = M \frac{di}{dt}$$

(1)

The question is whether the Rogowski coil, which embraces the current wire $i(t)$ in a toroidal manner, can be replaced by a standard air coil with concentrated winding (like in Fig. 2) and whether the replacement will allow accurate monitoring of the circuit.

Due to its structure, the Rogowski coil is more resistant to the influence of parasitic streams from neighbouring current circuits than the coil with concentrated winding placed near the circuit with monitored current $i(t)$, while the transformation coefficient is a constant.

2. AIR COIL AS A CURRENT-VOLTAGE TRANSDUCER

Due to the lack of a magnetic circuit, the coil with concentrated winding must take into account the necessity to have proper screening or proper structure in order to minimize the influence of parasitic...
streams generated by neighbouring current circuits. Such an arrangement has a certain advantage: contrary to the Rogowski coil, it is possible to regulate the transformation coefficient fluently.

Fig. 2. Proposed measurement scheme with a coil with concentrated winding

The transformation coefficient of the scheme featured in Figure 2 can be regulated in the two following ways:
- by changing the distance \( r \) between the coil and the current circuit,
- by changing the angle between the coil surface and the stream line.

A coreless coil is especially vulnerable to the influence of parasitic streams, which is a serious disadvantage of this method for monitoring current courses. There are two ways to reduce the results of this unfavourable phenomenon:
- to use different structures of magnetic screens which will strengthen the useful stream and weaken the parasitic stream,
- to use a structure with extra compensation coils.

The tests with the use of the former method showed low effectiveness of parasitic streams elimination. At the same time the circuit was more likely to get saturated when the values of the useful stream were significantly high [3]. The latter method was submitted to the Polish Patent Office [5]. While testing the structures which use an extra compensation coil, it was found out that the influence of the parasitic stream can be compensated almost completely.

Figure 3 presents the location of a measuring coil which monitors the current \( I \) in the current circuit. The coil movement along the axis, as it can be seen in the figure, allows to determine the changes of the EMF (electromotive force) value induced in the function of movement \( x \) for the determined value \( y \) which stands for the distance between the coil axis and the current circuit. The distance \( y \) is determined mainly for security reasons.

The dependency which describes the value of EMF induced in the coil in the function of distances \( x \) and \( y \) will allow to select optimal parameters of the transducer:
- \( y_0 \) – the highest possible value of the useful signal, while a proper security margin is provided;
- \( x_0 \) – determining the value of parasitic EMF induced in the coil.

The value of EMF \( e(t) \) induced in the coil from Fig. 3 is the following:

\[
e(t) = \frac{\mu_0 y^2 x S \sin \alpha}{2 \pi r} \frac{di}{dt} \quad (2)
\]

where:
\[
R = \sqrt{x^2 + y^2} \quad ; \quad S' = S \cdot \sin \alpha = S \cdot \frac{y}{R}
\]

Eventually, the effective value of EMF \( E_{sk} \) induced in the scheme from Fig. 3, depending on the location and the value of current, can be calculated from the dependency (3).

\[
E_{sk} = S \cdot z \cdot \frac{y}{y^2 + x^2} \cdot c \cdot I_{sk} \quad , \quad (3)
\]

where:
\( c \) – constant [V/A m].

The dependency (3) allows to determine both the values of the useful signal (for \( x=0 \)) and those of the parasitic signal induced from the current of the neighbouring circuit located at the distance \( x \) from the coil.

Figure 4 features the results of the simulation scheme from Figure 3.

The simulation was conducted with the following assumptions:
- distance between two neighbouring circuits \( X_{\text{max}} = 14 \text{ cm} = \text{const.} \),
- the assumed value \( E_{\text{max}} = 1 \text{ p.u.} \) induced in the basic coil for the assumed value \( y_0 = 2 \text{ cm} \) (the coil touches the circuit).
Fig. 4. EMF induced in the circuit coil in the function of distance $X$ at $y_0=\text{const.}=2\,\text{cm}$ (a) useful EMF induced in the coil $C_1$ from current $I_1$ (Fig.6), b) parasitic EMF induced in the coil $C_1$ from current $I_2=I_1$ (Fig.6), c) relation of the parasitic signal value to the useful signal value ($E_{\text{pas}}/E_{\text{uz}}$)

Fig. 5. EMF induced in the circuit coil in the function of distance $x$ at $y_0=\text{const.}=5\,\text{cm}$

Figure 5 features the results of the simulation of the scheme from Figure 3 for a higher value of the distance $Y$ between the transducer and the circuit ($Y=5\,\text{cm}$).

Moving the transducer by 3 cm in relation to its former location reduces the value of the useful signal from 1.0 p.u. to 0.4 p.u. While the value of the parasitic signal increases from 0.02 p.u. to 0.04 p.u. Figure 6 presents the operating principle of a transducer in a two-circuit arrangement. A sample compensated transducer uses two coils: the basic coil $C_1$ and the compensation coil $C_{k12}$.

The 4b diagram makes it possible to calculate the number of coils in the $C_{k21}$ compensation coil in such a way as to compensate the influence on the second circuit on the $C_1$ coil.

Thus the useful EMF $E_{\text{uz}}=1$ p.u. is induced in the basic $C_1$ coil placed under the circuit $I_1$ ($x=0$) at the distance $y_0=2\,\text{cm}$ and at the spacing of circuits $X_{\text{max}}=14\,\text{cm}$ from the circuit $I_1$. While the parasitic EMF $E_{\text{pas}}=0.02$ p.u. is induced from the circuit $I_2$. Therefore the number of coils in the compensation coil $C_{k21}$ should be 0.02 of the number of coils in the basic coil. However, these advantageous conditions lead to worse security as the coils are located close to the current circuits. If such a transducer is moved away from the circuit, the security is improved but, at the same time, the value of the useful signal is reduced and that of the parasitic signal increases.

The useful EMF from the current $I_1$ and the parasitic EMF from the current $I_2$ of the neighbouring circuit are both induced in the basic coil $C_1$. Knowing the distance $X$ between the circuits, it is possible to use the dependency (3) to calculate the value of this parasitic EMF and then deduct it from the value of the useful EMF. For this purpose one needs to use the compensation signal of the $C_{k21}$ coil which is located under the circuit with the current $I_2$. The compensation coil can be made in the same way as the basic one. The only difference is that its number of coils is much smaller and can be determined for the given distance between the circuits. It would be advantageous to employ in such transducers the coils printed with the use of the PCB HDI technology (Printed Circuit Board High Density Interconnect).
Obviously, such a solution is suitable mainly for bus systems. Figure 7 presents a current monitoring system in a three-phase bus bar arrangement. Each compensated transducer has two compensation coils. The basic coils are marked with one-digit numbers which correspond to the numbers of circuits T with monitored current. The compensation coils are marked with two-digit numbers where the first digit stands for the current circuit which induces the EMF in the coil, while the second digit informs to which measuring system P the coil should be connected.

Figure 8 features measuring circuits which take into account the influence of the remaining neighbouring phases on the measuring coil of the given circuit. For example, if the stream $\Phi_2$ of the circuit $T_2$ induces parasitic voltage in the basic coil $C_1$ of the circuit $T_1$, then the compensation coil $C_{21}$, placed under the circuit $T_2$, subtracts the same value taking into account the phase shift in the courses of the $T_2$ circuit.

![Fig. 7. Transducers compensated in a three-phase arrangement](image)

![Fig. 8. Connections of compensation coils of compensated transducers in a three-phase arrangement](image)
The measuring (monitoring) blocks $P$ of each phase have the following supplied: the total of the useful EMF of the given phase and the subtraction result of the parasitic EMFs of the remaining phases (Fig. 8).

In symmetrically arranged bus systems (like in Fig. 7, 8) compensation coils ($C_{12}=C_{21}=C_{23}=C_{32}$) are identical. While compensation coils placed under outermost buses are respectively the same ($C_{13}=C_{31}$). Thus the three-phase current measuring system with such a compensated transducer would comprise the following:

- 3 identical basic coils $C_1$, $C_2$, $C_3$ ,
- 2 identical compensation coils ($C_{13}$ and $C_{31}$),
- 4 identical compensation coils ($C_{12}$, $C_{21}$, $C_{23}$, $C_{32}$).

### 3. MODEL TESTS

The transformation of deformed courses in the presented transducer is similar to that in the Rogowski coil. The EMF of the coil is a derivative of current while higher harmonics of k-th orders are transformed with the transformation coefficient which is $k$ times bigger than that for the basic harmonic [4]. A coreless coil of an SM-3 contactor with the number of coils $z=6500$ was used as the basic coil.

The tests were conducted in the arrangement from Fig. 10. The distance between the C coil and the current circuit was set at $Y=\text{const.}$ Then the flow of AC current with a constant RMS value was forced. The harmonics in the current were measured by means of a Fluke 43 analyzer, while the harmonics in the EMF induced in the C coil – by means of a selective nanovoltmeter. The measurement results are presented in Table 1 (for $y=15$ cm) and Table 2 (for $y=10$ cm).

#### Table 1.

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<th>$k$</th>
<th>$I_k$</th>
<th>$E_k$</th>
<th>$n_k=E_k/I_k$</th>
<th>$n_k/n_1$</th>
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<tbody>
<tr>
<td>-</td>
<td>$A$</td>
<td>mV</td>
<td>mV/A</td>
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<td>7</td>
<td>1.6</td>
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#### Table 2.

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<th>$k$</th>
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<th>$E_k$</th>
<th>$n_k=E_k/I_k$</th>
<th>$n_k/n_1$</th>
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</thead>
<tbody>
<tr>
<td>-</td>
<td>$A$</td>
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<td>mV/A</td>
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<td>-</td>
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<td>1.1</td>
<td>15.5</td>
<td>14.09</td>
<td>7.3</td>
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The measurement results confirm the effect of the k-times amplification of the k-th harmonic of current with respect to the value of the transformation coefficient for the basic harmonic. In the next stage the following dependency was determined: the changes in the basic harmonic transformation coefficient $n_1$ as a function of the distance $Y$ between the coil and the current circuit. The results were presented in Table 3.
Fig. 11. Sample distribution of harmonics measured in the current with the RMS value $I=20\,A$ with respect to the value of the basic harmonic and the measured EMF value of the coil.

Table 3.

Results of measurements of EMF $E_1$ (1st harmonic) induced in the coil at $I_{sk}=19.21\,A$, in the function of the distance $y$ from the current circuit ($n_1$ – transformation constant for the basic harmonic, $E_1$ – RMS value of the basic harmonic in the EMF induced in the coil)

<table>
<thead>
<tr>
<th>$I_{sk}=$ const</th>
<th>$E_1$</th>
<th>$y$</th>
<th>$n_1$</th>
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<tbody>
<tr>
<td>$A$</td>
<td>mV</td>
<td>cm</td>
<td>mV/A</td>
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<td>80.0</td>
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<td>43.0</td>
<td>9</td>
<td>2.24</td>
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<td>19.21</td>
<td>36.0</td>
<td>10</td>
<td>1.87</td>
</tr>
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Figure 12 features a diagram of changes of the quantity $E_1$ and the value of the transformation coefficient $n_1$ of the 1st harmonic of current in the function of the distance $y$ between the coil and the current circuit.

Contrary to Rogowski coils, the presented structure enables fluent regulation of the transformation coefficient $n_1$.

This feature makes the transducer suitable to be used in residual current protection. Figure 13 features the principle of residual protection of a current circuit with the use of such a transducer. The current $I_{DO}$ flowing into the protected object $O$ and the current $I_{OD}$ flowing from this object produce streams $\phi_{DO}$ and $\phi_{OD}$ respectively. According to the dependency 1 there are two EMFs with opposite phases that are induced in the measuring coil $C$. The coil movement towards one or another current circuit allows to obtain complete compensation of both electromotive forces. Disturbing the balance due to a leakage in the protected zone will produce an EMF $e$ which will excite the measuring element $P$.

Fig. 12 Diagram of measured values $E_1$ and $n_1$ in the function of the distance $y$. Dashed curved line of EMF $E_1$ is determined theoretically according to the dependency 3.
4. CONCLUSIONS

1. One of the basic advantages of the transducer is the possibility to regulate fluently the value of the transformation coefficient and easy installation of the device with no necessity to switch off current circuits.

2. These transducers are mainly dedicated to bus bars with a constant value of distance between current circuits.

3. Compensation coils in the transducers allow to eliminate completely the influence of parasitic streams coming from neighbouring current circuits.

4. A coreless transducer in the form of an air coil can be a valuable supplement to the group of current transducers which are used in the systems for monitoring and protection of electrical power systems.

References


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