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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).

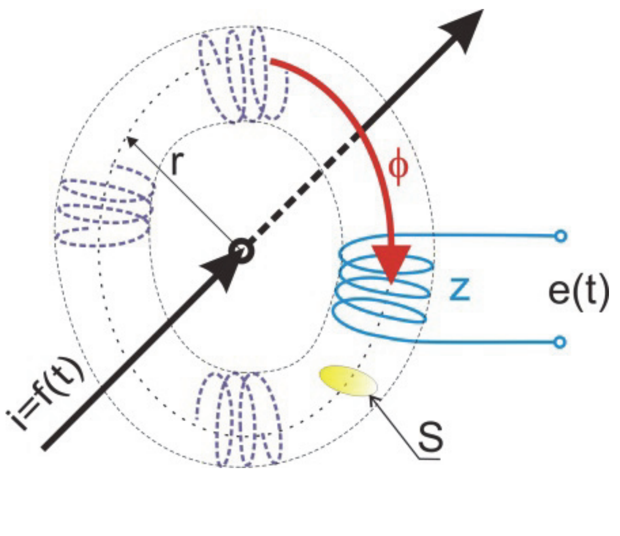

Fig. 1. Rogowski coil scheme

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):

$$e(t) = z\frac{d\phi}{dt} = \frac{\mu_0 \cdot z \cdot S}{2\pi \cdot r}\frac{di}{dt} = M\frac{di}{dt} \tag{1}$$

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.

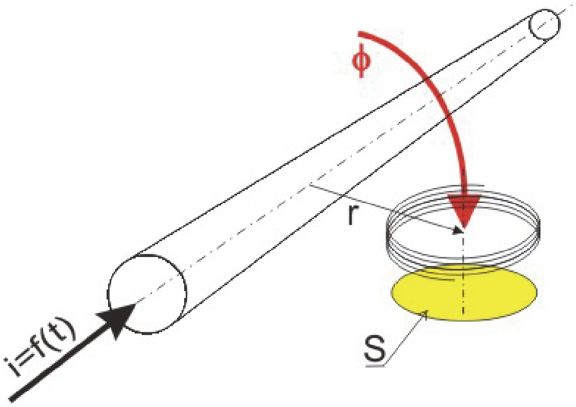

Fig. 2. Proposed measurement scheme with a coil with concentrated winding

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.

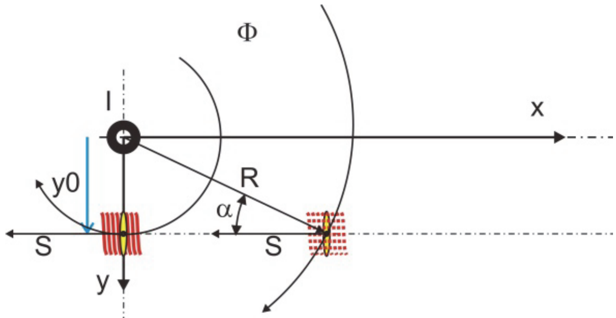

Fig. 3. The coil location with respect to the current circuit with current I

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;
– $x \neq 0$ – 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:

$$e(t) = \frac{\mu_0 * z * S * \sin\alpha}{2 * \pi * R} * \frac{di}{dt}, \tag{2}$$

where:

$$R = \sqrt{X^2 + Y^2} \;; \qquad S' = S * \sin\alpha = S * \frac{Y}{R}$$

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).

$$E_{sk} = S * z * \frac{Y}{Y^2 + X^2} * c * I_{sk}, \tag{3}$$

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_{max}= 14 cm =const.,
– the assumed value E_{max}=1 p.u. induced in the basic coil for the assumed value y_0=2 cm (the coil touches the circuit).

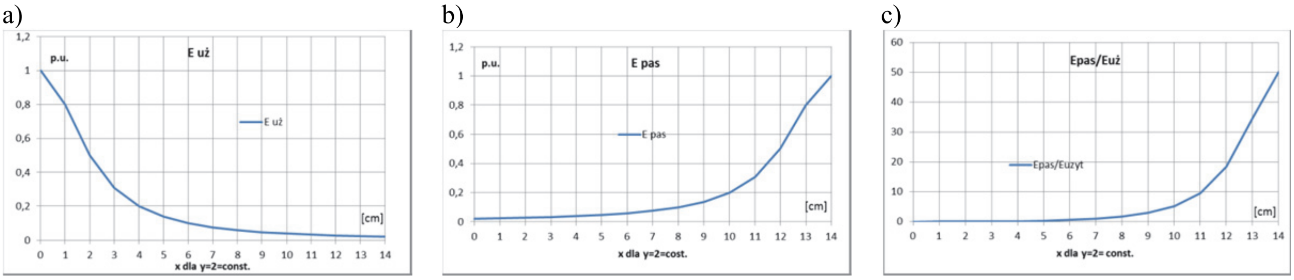

Fig. 4. EMF induced in the circuit coil in the function of distance X at y0=const.=2 cm (a) useful EMF induced in the coil C1 from current I1 (Fig.6), b) parasitic EMF induced in the coil C1 from current I2= I1 (Fig.6), c) relation of the parasitic signal value to the useful signal value (Epas/Euz))

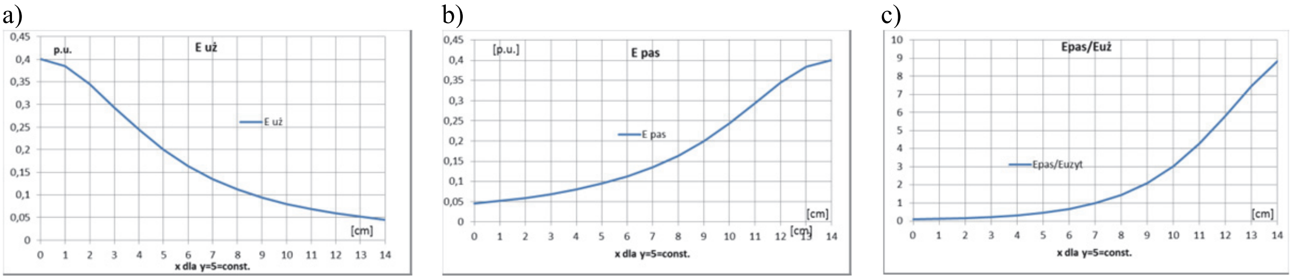

Fig. 5. EMF induced in the circuit coil in the function of distance x at y0=const.= 5 cm

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 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 C1 and the compensation coil Ck12.

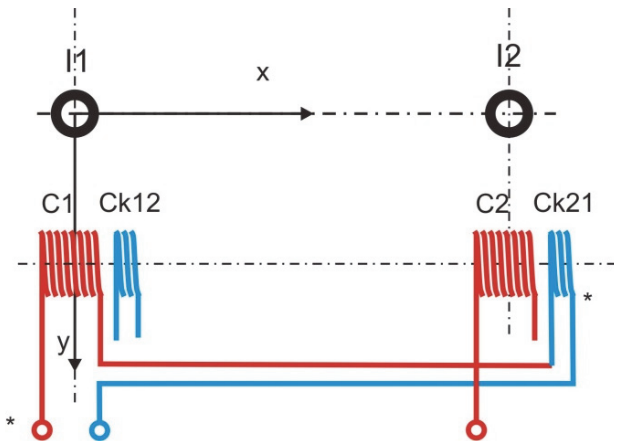

Fig. 6. Compensation of the parasitic signal in a two-circuit arrangement

The 4b diagram makes it possible to calculate the number of coils in the Ck21 compensation coil in such a way as to compensate the influence on the second circuit on the C1 coil.

Thus the useful EMF E_{uz}=1 p.u. is induced in the basic C1 coil placed under the circuit I1 (x=0) at the distance y_0= 2 cm and at the spacing of circuits X_{max} = 14 cm from the circuit I1. While the parasitic EMF E_{pas}=0.02 p.u. is induced from the circuit I2. Therefore the number of coils in the compensation coil Ck21 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 I1 and the parasitic EMF from the current I2 of the neighbouring circuit are both induced in the basic coil C1. 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 Ck21 coil which is located under the circuit with the current I2. 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.

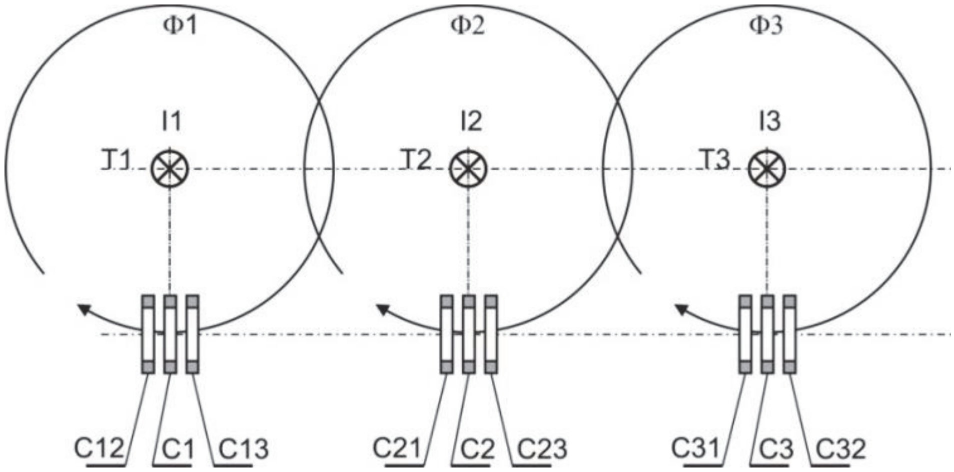

Fig. 7. Transducers compensated in a three-phase arrangement

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 Φ2 of the circuit T2 induces parasitic voltage in the basic coil C1 of the circuit T1, then the compensation coil C21, placed under the circuit T2, subtracts the same value taking into account the phase shift in the courses of the T2 circuit.

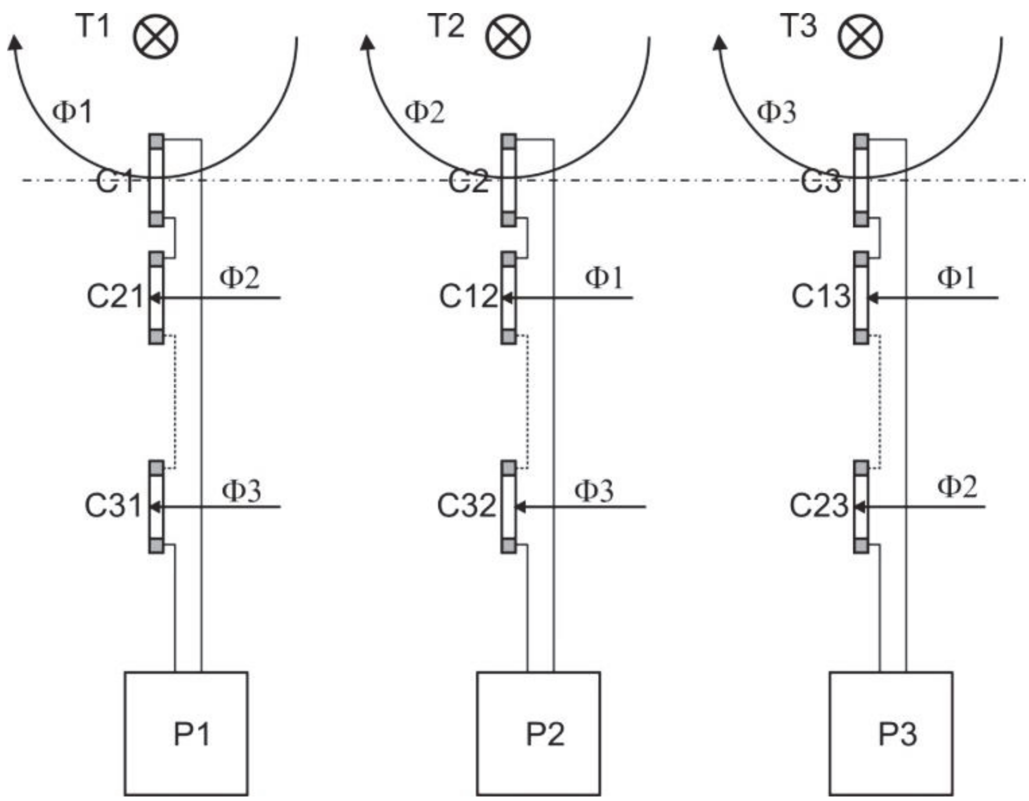

Fig. 8. Connections of compensation coils of compensated transducers in a three-phase arrangement

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 (C12=C21=C23=C32) are identical. While compensation coils placed under outermost buses are respectively the same (C13 = C31). Thus the three-phase current measuring system with such a compensated transducer would comprise the following:

- 3 identical basic coils C1, C2, C3 ,
- 2 identical compensation coils (C13 and C31),
- 4 identical compensation coils (C12, C21, C23, C32).

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.

Fig. 9. Coil used in model tests

The tests were conducted in the arrangement from Fig. 10. The distance between the C coil and the current circuit was set at Y=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).

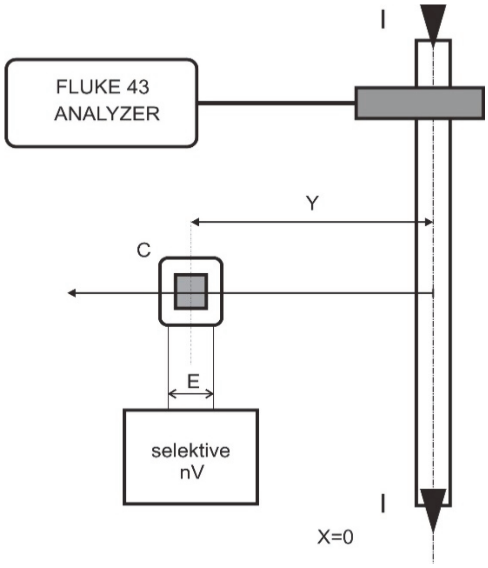

Fig. 10. Measuring system for recording the characteristics of the transformation of higher harmonics of current

Table 1.
Measurement results for current I_{sk}=101.6 A, *y*=15 cm

k	Ik	Ek	n_k=Ek/Ik	n_k/ n_1
-	A	mV	mV/A	
-	101.6			
1	100.8	100,0	0.99	1
3	4.2	11.8	2.81	2.81
5	1.3	6.5	5.0	5.05
7	1.6	11.5	7.18	7.25

Table 2.
Measurement results for Isk=48.9 A, y=10 cm (Ik, Ek – RMS values of k-th harmonics of current and EMF respectively, n1, nk – transformation coefficients of the 1st and k-th harmonic respectively)

k	Ik	Ek	n_k=Ek/Ik	n_k/ n_1
-	A	mV	mV/A	
-	48.9			
1	48.6	94.0	1.93	1
3	2.5	13.5	5.4	2.80
5	1.1	11.5	10.45	5.41
7	1.1	15.5	14.09	7.3

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 n1 as a function of the distance Y between the coil and the current circuit. The results were presented in Table 3.

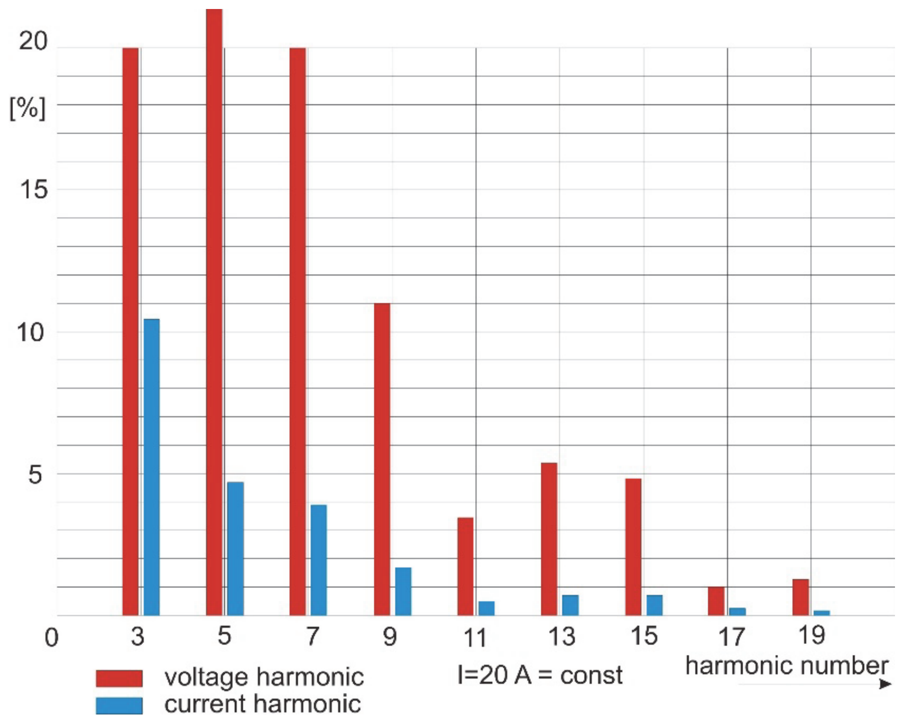

Fig. 11. Sample distribution of harmonics measured in the current with the RMS value I=20 A with respect to the value of the basic harmonic and the measured EMF value of the coil

Table 3.
Results of measurements of EMF E1 (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)

I_{sk}= const	E_1	*y*	n_1
A	mV	cm	mV/A
19.21	100.0	5	5.20
19.21	80.0	6	4.16
19.21	62.0	7	3.23
19.21	51.0	8	2.65
19.21	43.0	9	2.24
19.21	36.0	10	1.87

Figure 12 features a diagram of changes of the quantity E_1 and the value of the transformation coefficient n1 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 ϕ_{DO} and ϕ_{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.

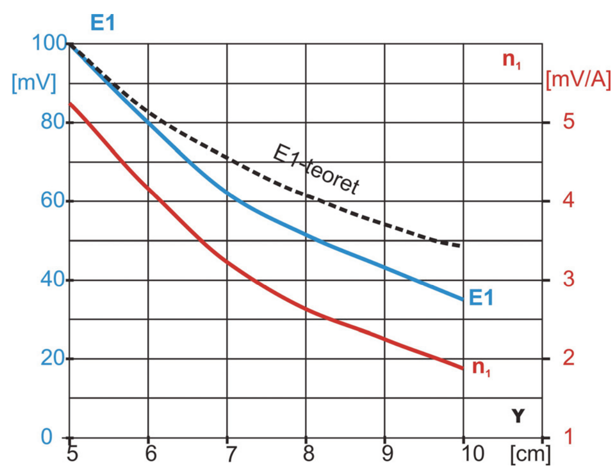

Fig. 12 Diagram of measured values E1 and n1 in the function of the distance y. Dashed curved line of EMF E1 is determined theoretically according to the dependency 3

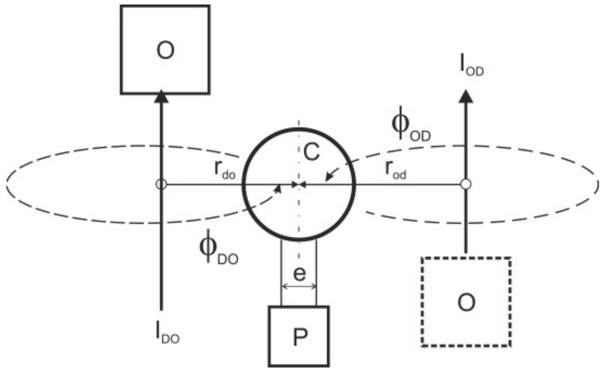

Fig. 13. Principle of residual current protection of one current circuit

Figure 14 features a principle of bus bars system protection against earth-fault current.

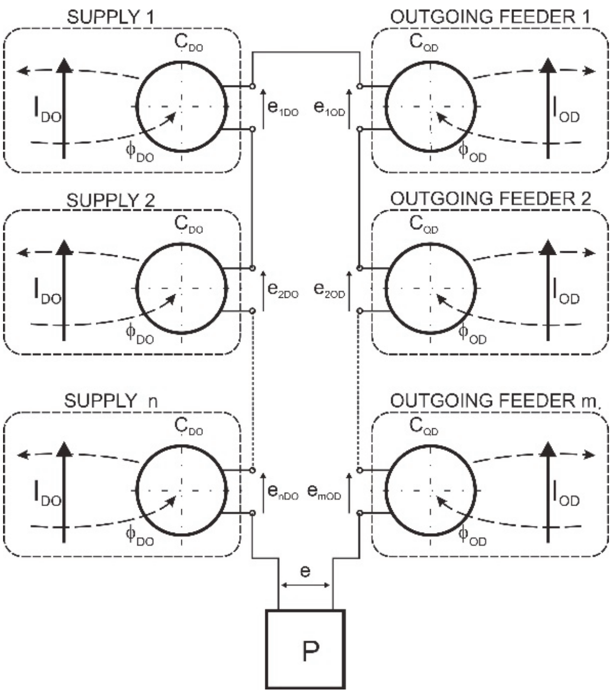

Fig. 14. Principle of protection against earth-fault current of one current circuit in a bus bar system

The addition of all in- and out-flowing currents is conducted in the addition system of EMFs induced in particular coils of ingoing and outgoing feeders of the same phase.

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.

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