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A comparison of the metrological properties of two-core current transformers

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Abstract

The paper presents a comparative analysis of the two-core Brooks and Brooks &Holtz transformers used in precision measuring systems. The derived relations indicate that the two-core Brooks & Holtz transformer has much better metrological properties. The metrological analysis was verified by the results of tests carried out on standard transformers. The analysis and the results can be used in the design of two-core transformers.

Keywords: current, processing, current transducer.

Porównanie właściwości metrologicznych dwurdzeniowych przekładników prądowych

Streszczenie

W artykule przedstawiono porównanie właściwości metrologicznych przekładników prądowych Brooksa oraz Brooksa i Holtza [3]. W rozdziale 2.1 przedstawiono przekładnik jednordzeniowy, którego błąd opisano za pomocą impedancji jego obwodu zastępczego (rys. 1b). W rozdziale 2.2 pokazano schemat zastępczy przekładnika Brooksa i na tej podstawie wyprowadzono wzór (2) określający błąd przekładnika. Przy założeniu (3) uproszczono wzór (2) do postaci (5), z którego wynika, że błąd przekładnika zależy głównie od impedancji obciążenia. Pokazano również wpływ błędu przekładnika pomocniczego ACIT (6) na błąd przetwarzania przekładnika Brooksa. Ze wzoru (10) wynika, że magnetowód przekładnika pomocniczego powinien być wykonany z materiału ferromagnetycznego o dużej wartości przenikalności początkowej, tj. permaloj, taśma amorficzna. W rozdziale 2.3 pokazano strukturę i analizę przekładnika Brooksa i Holtza. Z analizy wynika, że przekładnik ten powinien charakteryzować się lepszymi parametrami metrologicznymi, niż przekładnik Brooksa i Holtza, ponieważ w równaniu występuje iloczyn błędów przekładnika głównego i pomocniczego. W rozdziale 3 pokazano zastosowane układy pomiarowe do wyznaczania błędów przekładnika Brooksa (rys. 4) oraz Brooksa i Holtza (rys.5), które realizują metodę kompensacyjno-różnicową. W rozdziale 4 przedstawiono wyniki badań dla błędów prądowych i kątowych. Z otrzymanych wyników badań określono klasę przekładnika Brooksa jako 0,5 oraz dla połączenia Brooksa i Holtza 0,05.

Słowa kluczowe: prąd, przetwarzanie, przekładnik prądowy.

1. Introduction

The metrological properties of current transformers can be improved through the use of:

- magnetic cores made of highly permeable ferromagnetic materials, such as permalloy or amorphous tape;
- correction circuits, e.g. ones executing coil correction, the Wilson method, or correction through external means.

A significant improvement (by one or as many as two orders) in the metrological properties of current transformers can be effected through the use of the following solutions:

- a transformer with the supermagnetization of its cores, proposed by Ilioviči M.A. [1,5,6];
- a two-core transformer loaded with single impedance, developed by Brooks H.B. [1];
- a two-core transformer with separated secondary circuits of the main transformer and the auxiliary transformer, loaded with two impedances, built by Brooks H.B. and Holtz F.C. [3].

Since they do not require a core supermagnetizing current source, the two-core Brooks and Brooks & Holtz current transformers are convenient to use. Although the transformers have a similar design (differing in only the way the measuring load is connected), they differ significantly in their metrological properties.

In the Brooks transformer (Fig. 2) the main and auxiliary transformer secondary currents flow through the load impedance and the transformers interact with each other. The higher the power generated in the load, the greater the interaction between the transformers. In the Brooks & Holtz transformer (Fig. 3), the secondary currents flow through two separate equal load impedances. The transformer output quantity is the sum of the voltages across the impedances. Since their secondary circuits have only one common point, the transformers do not load each other. Boyajian A. and Goldstein J. [2, 4] have eliminated this drawback. In their modified Brooks & Holtz transformer the output quantity is current. This was achieved by introducing an additional transformer with a transformation ratio equal to one. In their fundamental paper describing the two-core transformer [3] Brooks and Holtz made an attempt to estimate its error and verified the estimation through experiments using the rather inaccurate wattmeter method proposed by Agniew P.G. from NBS (USA). In their analytical attempt to evaluate the metrological properties of the two-core transformer they used quantities which were difficult to measure, such as the ratio of the magnetic core flows, the difference in the flows and the mutual inductances of the windings, whereby their analysis was confusing and one could not deduce what effect the main transformer and the auxiliary transformer had on the two-core transformer error.

As a part of the present research an attempt was made at a comparative metrological analysis of the two-core Brooks and Brooks & Holtz transformers, based on the equivalent circuit diagrams of the transformers, and at verifying its results through measurements using the compensation-finite difference method. If a measuring system carrying out the compensation-finite difference method is unavailable, the metrological properties of the transformers can be assessed by measuring the impedances characterizing their equivalent circuit diagrams.

It should be noted that the above problem is of current interest since two-core transformers continue to be used in precision measuring systems. When the properties of the transformers are determined, it will become possible to better exploit their metrological parameters, or at least to modify the transformers so as to eliminate their drawbacks [2].

It should also be mentioned that Silsbee F.B. from NBS (USA), an outstanding metrologist and specialist in the field of transformers, suggested the idea of an integrated two-core transformer to Brooks and Holtz [3].

2. Current transformer errors

2.1. Standard transformer

As an introduction, the configuration of a standard transformer and its equivalent circuit diagram are shown in Fig. 1.

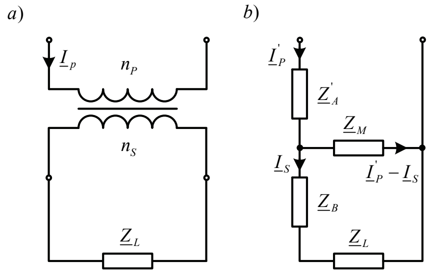

Fig. 1. Configuration of a standard transformer (a) and its equivalent circuit diagram (b)
Rys. 1. Połączenie przekładnika jednordzeniowego (a) i jego schemat zastępczy (b)

The current transformer error is described by the formula

$$\delta \underline{I} = \frac{k_N \underline{I}_S - \underline{I}_P}{\underline{I}_P} = \frac{\underline{I}_S - \underline{I}_P'}{\underline{I}_P'} = -\frac{\underline{Z}_B + \underline{Z}_L}{\underline{Z}_B + \underline{Z}_L + \underline{Z}_M} \tag{1}$$

where: k_N – rated transformation ratio, $\underline{I}_P'$ – primary current reduced to the secondary circuit, $\underline{Z}_B$ – impedance characterizing the secondary winding resistance and leakage ductance, $\underline{Z}_M$ – magnetizing circuit inductance, $\underline{Z}_L$ – load impedance.

2.2. Two-core Brooks transformer

The two-core transformer shown in Fig. 2 was patented (patent no. 169093) by Brooks in the UK in 1920 [1]. The transformer consists of the main transformer (MCIT) with two windings and an auxiliary transformer (ACIT) with three windings.

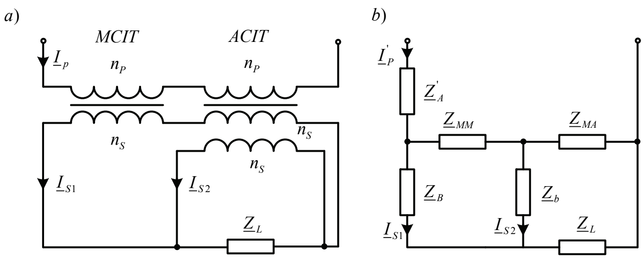

Fig. 2. Two-core Brooks transformer (a) and its equivalent circuit diagram (b)
Rys. 2. Dwurdzeniowy przekładnik Brooksa (a) i jego schemat zastępczy (b)

The secondary winding of the main transformer and one of the windings of the auxiliary transformer are connected in series with load impedance $\underline{Z}_L$. The other secondary winding of the auxiliary transformer is connected with load impedance $\underline{Z}_L$. The auxiliary transformer function is to supply a current close to the main transformer magnetizing current to load $\underline{Z}_L$.

The following equation defines (similarly as equation (1)) the two-core Brooks current transformer error [9]

$$\delta \underline{I}_B = \frac{\left(\underline{I}_{S1} + \underline{I}_{S2}\right) k_N - \underline{I}_P}{\underline{I}_P} = -\frac{\dfrac{\underline{Z}_B \underline{Z}_b}{\underline{Z}_B + \underline{Z}_b + \underline{Z}_{MM}} + \underline{Z}_L}{\dfrac{\underline{Z}_B \underline{Z}_b}{\underline{Z}_B + \underline{Z}_b + \underline{Z}_{MM}} + \underline{Z}_L + \dfrac{\underline{Z}_b \underline{Z}_{MM}}{\underline{Z}_B + \underline{Z}_b + \underline{Z}_{MM}} + \underline{Z}_{MA}}, \tag{2}$$

where: $\underline{Z}_B$ – impedance characterizing the resistance and leakage reactance of the secondary winding of the main and auxiliary transformers, $\underline{Z}_b$ – impedance characterizing the resistance and leakage reactance of the secondary winding of the auxiliary transformer, $\underline{Z}_{MM}$ – impedance of the magnetizing circuit of the main transformer (*MCIT*), $\underline{Z}_{MA}$ – impedance of the magnetizing circuit (*ACIT*).

Considering that

$$\underline{Z}_B, \underline{Z}_b << \underline{Z}_{MM}, \tag{3}$$

the equation describing the Brooks transformer has the form

$$\delta \underline{I}_B \approx -\frac{\dfrac{\underline{Z}_B \underline{Z}_b}{\underline{Z}_{MM}} + \underline{Z}_L}{\dfrac{\underline{Z}_B \underline{Z}_b}{\underline{Z}_{MM}} + \underline{Z}_L + \underline{Z}_b + \underline{Z}_{MA}}. \tag{4}$$

If, in accordance with expression (3), the minor terms are omitted, the two-core Brooks transformer error is expressed by the equation

$$\delta \underline{I}_B \approx -\frac{\underline{Z}_L}{\underline{Z}_L + \underline{Z}_b + \underline{Z}_{MA}}, \tag{5}$$

which indicates that the transformer error does not depend on the main transformer error, slightly depends on impedance $\underline{Z}_b$ and considerably depends on load impedance $\underline{Z}_L$.

The Brooks transformer error can be expressed by the auxiliary transformer error described by the formula

$$\delta \underline{I}_A = -\frac{\underline{Z}_L + \underline{Z}_b}{\underline{Z}_L + \underline{Z}_b + \underline{Z}_{MA}}. \tag{6}$$

If one adds and subtracts impedance $\underline{Z}_b$ to/from the numerator of relation (5), one gets

$$\delta \underline{I}_B \approx -\frac{\underline{Z}_L + \underline{Z}_b}{\underline{Z}_L + \underline{Z}_b + \underline{Z}_{MA}} - \left(-\frac{\underline{Z}_b}{\underline{Z}_L + \underline{Z}_b + \underline{Z}_{MA}}\right). \tag{7}$$

The first term represents the error of the auxiliary transformer loaded with impedance $\underline{Z}_L$

$$\delta \underline{I}_A \left(\underline{Z}_L \neq 0\right) = -\frac{\underline{Z}_L + \underline{Z}_b}{\underline{Z}_L + \underline{Z}_b + \underline{Z}_{MA}} \tag{8}$$

The second term represents the auxiliary transformer error when load impedance $\underline{Z}_L$=0

$$\delta \underline{I}_A \left(\underline{Z}_L = 0\right) = -\frac{\underline{Z}_b}{\underline{Z}_L + \underline{Z}_b + \underline{Z}_{MA}} \approx -\frac{\underline{Z}_b}{\underline{Z}_b + \underline{Z}_{MA}} \tag{9}$$

Ultimately the following relation describing the two-core Brooks transformer error was obtained

$$\delta \underline{I}_B \approx \delta \underline{I}_A \left(\underline{Z}_L \neq 0\right) - \delta \underline{I}_A \left(\underline{Z}_L = 0\right) \tag{10}$$

According to the above relation, the two-core transformer error depends significantly on the auxiliary transformer errors and the lower it is, the lower is the impedance $\underline{Z}_L$ loaded with. In order to ensure the lowest possible errors, the auxiliary transformer magnetic core should be made of a ferromagnetic material (permalloy or amorphous tape) characterized by the highest possible initial permeability. Since the error was derived under the above simplifications, one should not draw the conclusions that the error of the two-core Brooks transformer is equal to zero when load $\underline{Z}_L$ =0, and that it does not depend on the main transformer parameters.

2.3. Two-core Brooks & Holtz transformer

Brooks and Holtz presented their two-core transformer design in 1922 [3]. This transformer has a similar structure as the Brooks transformer discussed in the preceding section, the only difference being that the secondary currents of the main and auxiliary transformers flow through separate loads $\underline{Z}_L$ of the same magnitude, as shown in Fig. 3.

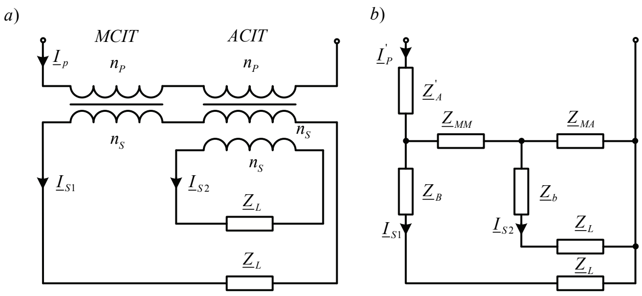

Fig. 3. Two-core Holtz & Brooks transformer (a) and its equivalent circuit diagram (b)
Rys. 3. Dwurdzeniowy przekładnik Brooksa I Holtza (a) i jego schemat zastępczy (b)

According to the equivalent circuit diagram, the errors of the transformers are expressed by the formulas

- for the Brooks & Holtz transformer

$$\delta \underline{I}_{BH} = \frac{\left(\underline{I}_{S1} + \underline{I}_{S2}\right)k_N - \underline{I}_P}{\underline{I}_P} = \frac{\underline{I}_{S1} + \underline{I}_{S2} - \dfrac{\underline{I}_P}{k_N}}{\dfrac{\underline{I}_P}{k_N}} = \frac{\underline{I}_{S1} + \underline{I}_{S2} - \underline{I}_P^{'}}{\underline{I}_P^{'}} \quad (11)$$

- for a transformer with output current $\underline{I}_{S1}$, formed from the main transformer and the auxiliary transformer

$$\delta \underline{I}_M = \frac{\underline{I}_{S1}k_N - \underline{I}_P}{\underline{I}_P} = \frac{\underline{I}_{S1} - \underline{I}_P^{'}}{\underline{I}_P^{'}} \quad (12)$$

- a transformer with output current $\underline{I}_{S2}$, formed from the auxiliary transformer

$$\delta \underline{I}_A = \frac{\underline{I}_{S2}k_N - \left(\underline{I}_P - \underline{I}_{S1}k_N\right)}{\underline{I}_P - \underline{I}_{S1}k_N} = \frac{\underline{I}_{S2} - \left(\underline{I}_P^{'} - \underline{I}_{S1}\right)}{\underline{I}_P^{'} - \underline{I}_{S1}} \quad (13)$$

The Brooks & Holtz transformer is described by the system of equations

$$\begin{aligned} \underline{I}_{S1}\left(\underline{Z}_B + \underline{Z}_L\right) &= \left(\underline{I}_P^{'} - \underline{I}_{S1}\right)\underline{Z}_{MM} + \left(\underline{I}_P^{'} - \underline{I}_{S1} - \underline{I}_{S2}\right)\underline{Z}_{MA} \\ \underline{I}_{S2}\left(\underline{Z}_b + \underline{Z}_L\right) &= \left(\underline{I}_P^{'} - \underline{I}_{S1} - \underline{I}_{S2}\right)\underline{Z}_{MA} \end{aligned} \quad (14)$$

The determined secondary currents $\underline{I}_{S1}$ and $\underline{I}_{S2}$ are described by the relations

$$\underline{I}_{S1} = \underline{I}_P^{'} \frac{\left(\underline{Z}_b + \underline{Z}_L\right)\left(\underline{Z}_{MM} + \underline{Z}_{MA}\right) + \underline{Z}_{MM}\underline{Z}_{MA}}{\left(\underline{Z}_B + \underline{Z}_L + \underline{Z}_{MM} + \underline{Z}_{MA}\right)\left(\underline{Z}_b + \underline{Z}_L + \underline{Z}_{MA}\right) - \underline{Z}_{MA}^2} \quad (15)$$

$$\underline{I}_{S2} = \underline{I}_P^{'} \frac{\left(\underline{Z}_B + \underline{Z}_L\right)\underline{Z}_{MA}}{\left(\underline{Z}_B + \underline{Z}_L + \underline{Z}_{MM} + \underline{Z}_{MA}\right)\left(\underline{Z}_b + \underline{Z}_L + \underline{Z}_{MA}\right) - \underline{Z}_{MA}^2} \quad (16)$$

According to formula (11) the two-core Brooks & Holtz transformer error is defined by the equation

$$\delta \underline{I}_{BH} = \frac{\underline{I}_{S1} + \underline{I}_{S2}}{\underline{I}_P^{'}} - 1 \quad (17)$$

After relations (15) and (16) were substituted into the above equation the following formula was obtained

$$\delta \underline{I}_{BH} = -\frac{\left(\underline{Z}_B + \underline{Z}_L\right)\left(\underline{Z}_b + \underline{Z}_L\right)}{\left(\underline{Z}_B + \underline{Z}_L + \underline{Z}_{MM} + \underline{Z}_{MA}\right)\left(\underline{Z}_b + \underline{Z}_L + \underline{Z}_{MA}\right) - \underline{Z}_{MA}^2} \quad (18)$$

The denominator in the above formula was rearranged whereby the following expression was obtained

$$\left(\underline{Z}_B + \underline{Z}_L + \underline{Z}_{MM}\right)\left(\underline{Z}_b + \underline{Z}_L + \underline{Z}_{MA}\right) + \left(\underline{Z}_b + \underline{Z}_L\right)\underline{Z}_{MA} \quad (19)$$

Since the first summand is much larger than the second one, formula (18) was written in the form

$$\delta \underline{I}_{BH} < -\frac{\underline{Z}_B + \underline{Z}_L}{\underline{Z}_B + \underline{Z}_L + \underline{Z}_{MM}} \frac{\underline{Z}_b + \underline{Z}_L}{\underline{Z}_B + \underline{Z}_L + \underline{Z}_{MA}} \quad (20)$$

The first factor defines the main transformer error which, as expressed through the equivalent circuit impedance, is described by the relation

$$\delta \underline{I}_M \approx -\frac{\underline{Z}_B + \underline{Z}_L}{\underline{Z}_B + \underline{Z}_L + \underline{Z}_{MM}} \quad (21)$$

The auxiliary transformer error is defined by equation (6).

Thus the two-core Brooks & Holtz transformer error is expressed by the equation

$$\delta \underline{I}_{BH} \approx -\delta \underline{I}_M \delta \underline{I}_A \quad (22)$$

from which it follows that the error depends on the product of the main transformer error and the auxiliary transformer error and it is significantly lower than the Brooks transformer error expressed by formula (10). The auxiliary transformer error assumes relatively high values since this transformer operates at very small excitation current ($\underline{I}_{S1}k_N$-$\underline{I}_P$). In order to reduce the auxiliary transformer error, one should use a magnetic core (e.g. made from permalloy or amorphous tape) characterized by very high initial permeability.

3. Determination of the metrological properties of two-core transformers

The main transformer and the auxiliary one have ϕ100xϕ50x25mm toroidal magnetic cores made of cold-rolled transformer plate characterized by relative permeability $\mu_r = 22 \cdot 10^3$ and unit magnetic core losses $P^{'} = 0,065$ W/kg for $B = 0.4$ Vs/m^2 and $f = 50$ Hz.

The windings on the magnetic cores consist of a hundred ϕ=0.7 mm coil wire turns each. The main transformer has two windings while the auxiliary transformer has three windings.

The metrological properties of the two-core transformers with transformation ratios k_N=1 A/A were determined in compensation-finite difference systems.

3.1. Brooks transformer

The two-core Brooks transformer was tested in the system shown in Fig. 4, in which the secondary current was compared with the primary current by means of an admittance current divider [7,8].

Since the reference value in this system is primary current $\underline{I}_p$, the current difference comparison error is defined by the admittance current divider parameters (*r*, *IVD*, *G* i *C*).

The current error of the two-core transformer is defined by the relation [7]

$$\delta \underline{I}_B = \frac{\underline{I}_S k_N - \underline{I}_P}{\underline{I}_P} = rG + j\omega rC \quad (23)$$

The current error is expressed by the term

$$\delta I_B = rG \tag{24}$$

and the phase displacement is equal to

$$\gamma_B = \omega r C \tag{25}$$

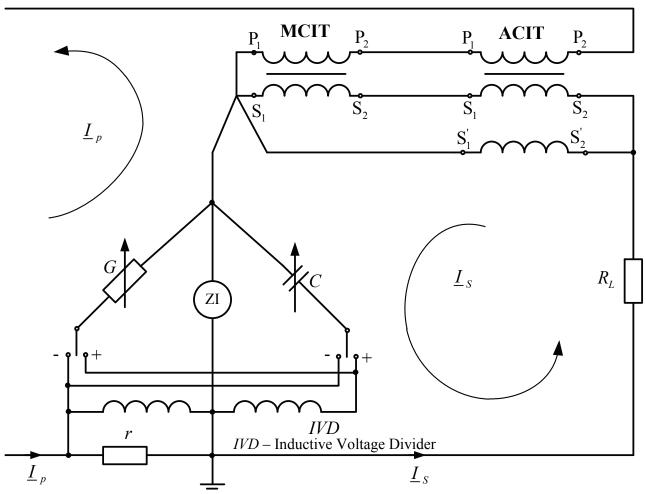

Fig. 4. Current compensation-finite difference system for testing Brooks transformer

Rys. 4. Układ kompensacyjno-różnicowy do badania przekładnika Brooksa

The inaccuracy of the transformer current measurement error is [8]

$$\Delta(\delta I_B) = \delta(\Delta I_k)\delta I_B \tag{26}$$

and that of the phase measurement error is

$$\Delta\gamma_B = \delta(\Delta I_k)\gamma_B \tag{27}$$

where $\delta(\Delta I_k)$ – admittance current divider error below 1%.

3.2. Brooks & Holtz transformer

The Brooks & Holtz transformer was tested in the system shown in Fig. 5, in which the secondary current and the primary current were compared indirectly, i.e. through voltage drops across resistors R_N and R_{N1}, R_{N2}.

The error of the tested transformer is defined by the general formula

$$\delta \underline{I} = \frac{\underline{I}_S k_N - \underline{I}_P}{\underline{I}_P} = \frac{\underline{I}_S - \underline{I}_P}{\underline{I}_P} = \frac{\Delta \underline{I}}{\underline{I}_P} \tag{28}$$

where transformation ratio $k_N = 1$.

Since indirect comparison is performed in the system, formula (28) assumes the form

$$\delta \underline{I}_{BH} = \frac{\underline{I}_{S1} + \underline{I}_{S2} - \underline{I}_P}{\underline{I}_P} = \frac{\frac{\underline{U}_{N1}}{R_{N1}} + \frac{\underline{U}_{N2}}{R_{N2}} - \frac{\underline{U}_P}{R_N}}{\frac{\underline{U}_P}{R_N}} = \frac{\frac{\Delta \underline{U}_N}{R_{N1}}}{\frac{\underline{U}_P}{R_N}} = \frac{\Delta \underline{U}_N}{\underline{U}_P} \tag{29}$$

where $R_{N1} = R_{N2} = R_N$.

The voltage difference characterizing the error of the transformer with transformation ratio k_N=1 is described by the relation

$$\Delta \underline{U}_N = \underline{I}_{S1} R_{N1} - \underline{I}_{S2} R_{N2} - \underline{I}_p R_N \tag{30}$$

$$\Delta \underline{U}_N = \underline{I}_{S1} R_{N1} - \underline{I}_{S2} R_{N2} - \underline{I}_p R_N \tag{30}$$

When the main and auxiliary transformer error (δI_{MA}) and the auxiliary transformer error (δI_A) are taken into account in expression (30), one obtains

$$\begin{aligned} \underline{I}_{S1} &= \frac{\underline{I}_p}{k_N}\left(1 + \delta \underline{I}_{MA}\right), \\ \underline{I}_{S2} &= \frac{\underline{I}_p - \underline{I}_{S1}}{k_N}\left(1 + \delta \underline{I}_A\right), \end{aligned} \tag{31}$$

and after transformations

$$\Delta \underline{U} = \underline{I}_p\left(1 + \delta \underline{I}_{MA}\right) R_{N1} - \underline{I}_p \delta \underline{I}_M \left(1 + \delta \underline{I}_A\right) R_{N2} - \underline{I}_p R_N \tag{32}$$

Since the resistance values R_N, R_{N1}, R_{N2} are equal to each other, the equation for the transformer voltage drop is as follows

$$\Delta \underline{U} = -\underline{I}_P R_N \delta \underline{I}_{BH} \tag{33}$$

where $\delta \underline{I}_{BH} = -\delta \underline{I}_{MA} \delta \underline{I}_A$.

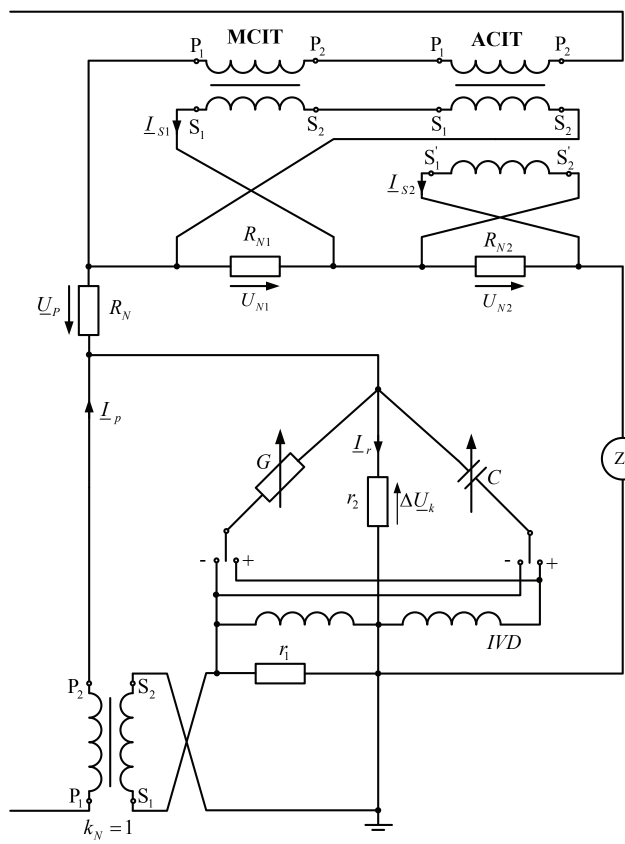

Fig. 5. Current compensation-finite difference system for testing Brooks & Holtz transformer

Rys. 5. Układ kompensacyjno-różnicowy do badania przekładnika Brooksa I Holtza

When expression (33) was substituted into formula (29), the following relation was obtained

$$\delta \underline{I} = \delta \underline{I}_{BH} \tag{34}$$

The above relation indicates that the Brooks & Holtz transformer error is proportional to the product of the main and auxiliary transformer error $\delta \underline{I}_M$ and the auxiliary transformer error $\delta \underline{I}_A$.

The voltage $\Delta\underline{U}_N$ is balanced with the voltage $\Delta\underline{U}_k$ obtained from a voltage divider formed from resistors r_1, r_2, conductance G, capacitor C and inductive voltage divider *IVD*. If the transformation ratio of the transformer exciting current in resistor r_1 is assumed to be $k_{In} = 1$, one gets

$$\Delta\underline{U}_k = \underline{I}_P r_1 \left(\frac{r_2}{\frac{1}{G}+r_2} + \frac{r_2}{\frac{1}{j\omega C}+r_2} \right) \approx\sim \underline{I}_P r_1 r_2 \left(G + j\omega C\right) \quad (35)$$

since the conditions $1/G >> r_2$ and $1/(j\omega C) >> r_2$ are satisfied here.

From relations (28), (29) and (35) the following expression for the tested transformer error (for settings G and C) was derived

$$\delta\underline{I}_{BH} = \frac{r_1 r_2}{R_N}\left(G + j\omega C\right) \quad (36)$$

Hence the transformer current error is

$$\delta I_{BH} = \frac{r_1 r_2}{R_N} G \quad (37)$$

and the phase displacement is

$$\gamma_{BH} = \omega \frac{r_1 r_2}{R_N} C \quad (38)$$

Using the above relations and [8] the inaccuracy of transformer error determination was expressed as

$$\Delta\left(\delta\underline{I}_{BH}\right) = \delta R_{N1} - \delta R_N + \delta\underline{I}_{BH}\left[\delta\left(\Delta\underline{U}_k\right)\right] \quad (39)$$

where $\delta(\Delta\underline{U}_k)$ – error of the voltage $\Delta\underline{U}_k$ setting.

Selection of measuring tools

Resistors for which the resistance difference between resistor R_N and resistor R_{N1} does not exceed 0.001% and the resistance difference between resistor R_N and R_{N2} is below 0.005% were selected from the available set of normal resistors. The errors of the resistors were measured with use of a Hewlett Packard 34420A instrument which measured resistance with an accuracy of $\pm(0.0070\ \%\ R_x + 0.0002\ \%\ R_z)$.

The time constants of resistors R_N, R_{N1}, R_{N2} do not exceed $\tau = 0.1 \cdot 10^{-6}$, which at a frequency of 50 Hz corresponds to the phase displacement $\gamma_{rad} = 34.1 \cdot 10^{-6}$ rad, $\gamma_{min} = 0.1$ min.

If one compares the formulas for the transformer measurement error inaccuracy it appears that the inaccuracy for the Brooks transformer is significantly lower than that for the Brooks & Holtz transformer. This is due to the fact that the former transformer was tested in the system using the direct method (without physical standards) while the latter in the system realizing the indirect method.

The measurements were performed matching the metrological properties of standard resistors R_N, R_{N1}, R_{N2} and those of the voltage and current elements so that measurement uncertainty affected the third decimal place of the measured result.

4. Test results

The results of the tests carried out in the measuring systems described in Section 3 for three values of standard resistors R_N, R_{N1}, R_{N2} equal to 1 Ω, 0.1 Ω, 0 Ω (for system reasons, only the Brooks transformer was tested for the last value) are presented in Fig. 6.

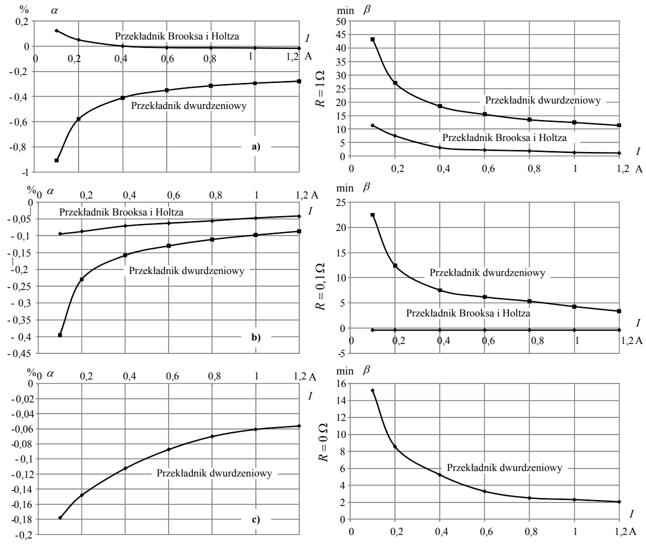

Fig. 6. Modulus α and argument β error for Brooks & Holtz transformer and Brooks transformer under loading with resistors R=1 Ω a), R=0.1 Ω b) and R=0 Ω c)

Rys. 6. Błędy modułu α i argumentu β przekładnika Brooksa I Holtza oraz przekładnika Brooksa przy obciążeniu rezystorami R=1 Ω a), R=0,1 Ω b) i R=0 Ω c)

5. Conclusions

The measurement results show that the current transformers under resistive load $R = 1$ Ω meet the following accuracy requirements:

- class 0.05 – Brooks & Holtz,
- class 0.5 – Brooks.

When the transformers are loaded with resistance $R = 0.1$ Ω, they meet the following requirements:

- class 0.05 – Brooks & Holtz,
- class 0.2 – Brooks.

It should be noted that the two-core Brooks transformer not loaded (short-circuited - R=0 Ω) has the same properties as the Brooks & Holtz transformer loaded with resistor $R = 0.1$ Ω or $R = 1$ Ω.

This means that the Brooks & Holtz transformer is characterized by much better metrological parameters than the Brooks transformer, which is due to the fact that the difference in main winding amp-turns in the Brooks & Holtz transformer induces a current in the secondary winding of the auxiliary transformer, whereas in the two-core Brooks transformer there occurs an adverse interaction of the transformer secondary currents.

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otrzymano / received: 25.05.2014
przyjęto do druku / accepted: 01.07.2014 *artykuł recenzowany / revised paper*