Michał KACZMAREK, Ryszard NOWICZ

Technical University of Lodz, Institute of Electrical Power Engineering

Comparison of wide frequency metrological properties of inductive current transformers

***Abstract**. This paper presents the comparison of 50 Hz to 20 kHz frequency metrological properties of inductive current transformers (CTs) with a toroidal cores made of Ni80Fe20 permalloy and nanocrystalline tape Finmet. The essence of the problem is that for frequencies higher than 50 Hz metrological parameters of CTs are deteriorated. Determination of the CT errors characteristics with the change of the primary current frequency enables possibility to assess their accuracy during the transformation of sinusoidal conductive disturbances or currents of frequencies above 50 Hz.*

***Streszczenie.** W artykule przedstawiono porównanie właściwości metrologicznych indukcyjnych przekładników prądowych z rdzeniami toroidalnymi wykonanymi z permaloju Ni80Fe20 i taśmy nanokrystalicznej Finmet przeprowadzone w zakresie częstotliwości transformowanych sinusoidalnych prądów pierwotnych od 50 Hz do 20 kHz. (**Porównanie szerokopasmowych właściwości metrologicznych indukcyjnych przekładników prądowych**).*

Keywords: Current transformer (CT), transfer factor, phase displacement, transformation of above 50 Hz frequency sinusoidal currents.
Słowa kluczowe: Przekładnik prądowy, współczynnik transferu, przesunięcie fazowe, transformacja prądów o częstotliwościach powyżej 50 Hz.

Introduction

Problem of the inductive current transformers usage for transformation with a given accuracy class of above 50 Hz frequency sinusoidal currents is the aim of many papers [1 - 10]. The essence of the problem is that with the increase of the transformed signal frequency metrological parameters of instrument transformers are deteriorated and their accuracy of transformation decreases [5 - 10]. The level of this deterioration depends from CT electrical and magnetic circuits parameters, primary signal frequency and also from its operation conditions like the RMS value of primary current and load of the secondary winding [6 - 10].

Measuring circuit

Laboratory studies consisted of two CTs with the same low voltage insulation system and rated transformation ratio (5 A / 5 A) as well as identical geometric dimensions of toroidal magnetic cores (cross section $s_{fe} \approx 0.0005\ m^2$, the average flux path in the core l = 0.34 m). The numbers of turns in the windings were only changed (with a fixed transformation ratio) and material of the magnetic core. Both tested CTs have toroidal cores: first is made of permalloy Ni80Fe20 (180 / 180) turns, second is made of nanocrystalline tape Finmet (120 / 120) turns. Measuring circuit is presented in Figure 1.

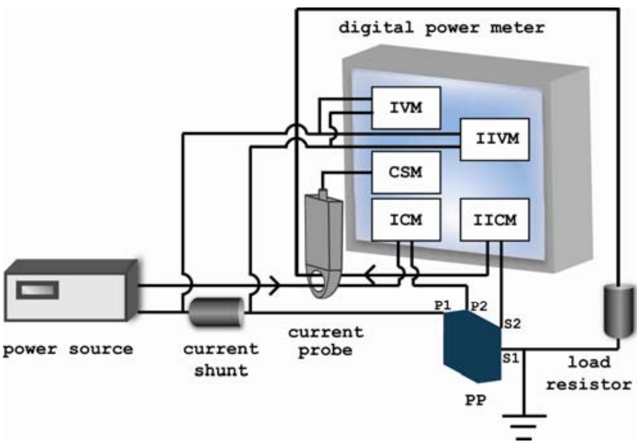

Fig.1. Block diagram of the measuring system [11]

In figure 1 the following notations are use:
IVM – voltage input of the first digital power meter module,
ICM – current input of the first digital power meter module,
CSM – current sense input of the first digital power meter module designed to connect current probes - low voltage measurements,
IIVM – voltage input of the sec. digital power meter module,
IICM – current input of the sec. digital power meter module.

During laboratory studies the source of sinusoidal currents 5A (RMS) in frequency range from 50 Hz to 20 kHz was generator PO 28. Since the commonly used instrument transformer load boxes are compensated for $\cos\varphi$ = 0,8 only for a frequency of 50 Hz during the tests of the CTs accuracy of transformation of above 50 Hz frequency sinusoidal currents CTs secondary windings were shorten.

The RMS value of the voltage proportional to the difference between primary and secondary currents of the tested CTs was measured through the current probe model Fluke i30s, which output voltage was measured by the current sense input of the first module of the digital power meter model WT1600. The lowest possible range of measured voltage of the WT1600 external current sensor input may be 25 mV. To measure the difference between the primary and secondary currents the wires were led by the probe in such a way that the flux in its magnetic core was proportional to the difference between instantaneous currents. When calculating the RMS value of the difference current from the measured RMS value of the current probe output voltage an additional voltage arising from the phase shift between measured currents was considered [9 - 11].

Developed measuring system also allow measurement of the phase displacement between primary and secondary current of the CT based on the designated power factor $\cos\varphi$ and calculated phase shift between the voltage drop on shunt (in the primary circuit) and the CT secondary current. The first module of the digital power meter, by the measurement of the power factor $\cos\varphi$ for current and voltage of the current shunt, enables determining of the phase shift between these two values. This phase shift should be included in the calculation of transfer factor when the shunt is not strictly non-inductive for a specified frequency range of testing primary currents [9 - 11].

Accuracy of developed measuring circuit

The accuracy of measurements of presented in the paper transfer factor characteristics with the change of the primary sinusoidal current frequency calculated from RMS value of the differences between primary and secondary currents of the tested CTs depends mainly on the accuracy of current measurements by the current probe model Fluke i30s. According to the specifications supplement of the current probe Fluke i30s current measurement accuracy may be calculated from the formula [12]:

(1) $$\Delta I = \pm 6\%\ I_r \pm 2\ \text{mA}$$

where: ΔI – accuracy of differential current measurement [A], I_r – measured RMS value of current [A].

This means that the accuracy of current probe fluke i30s for e.g. 5 mA AC RMS measured current is 30% of reading, for 30 mA AC RMS is 13% of reading and for 1 A AC RMS is □5% of reading.

The accuracy of measurements of the phase displacement may be calculated from the equation [13]:

(2) $$\Delta\varphi = \pm[|\varphi - \{\cos^{-1}(\lambda/1.0002)\}| + \sin^{-1}[(S \cdot (0{,}1 + 0{,}3 \cdot f(kHz))\%/100)]\ \text{deg} \pm 1\ \text{digit}$$

where: φ –phase displacement [deg], λ –power factor [-], S – measured apparent power, f – frequency.

The 0.3 coefficient before f in equation (3) may be equal 0.05 for 5 A input module of WT1600 / WT1800, which will improve accuracy of measurements about 6 times.

For measured phase displacement smaller than 10 degrees equation (2) may be simplified to:

(3) $$\Delta\varphi = \pm\sin^{-1}(S \cdot (0{,}15 + 0{,}3 \cdot f(kHz))\%/100)^\circ$$

To ensure best accuracy of measurements of the phase displacement the measurements should be made for lowest value of measured apparent power but in the same time resistance value of current shunts should be properly selected to achieve measurable referents voltage in the primary circuit.

The usage of e.g. (40 – 20) mΩ shunts for frequencies of primary current from 50 Hz to 2 kHz will ensure measurement accuracy of about 10' for primary current of frequency 2 kHz, the usage of (20 – 10) mΩ shunts for frequencies from 2 kHz to 6 kHz will ensure measurement accuracy of about 15' for primary current of frequency 6 kHz and the usage of 10 mΩ shunt for frequencies of primary current higher than 5 kHz will ensure measurement accuracy of about 30' for 10 kHz frequency and 50' for 20 kHz frequency of the primary current.

It is possible to obtain higher measurements accuracy for lower frequencies of primary current when using smaller value of the current shunt e.g. 10 mΩ for 2 kHz will ensure measurement accuracy of about 5' but in this condition it is more complex to read measured maximum value of the phase displacement due to some distortion of the primary current and changes of the WT1600 reading.

It should be noted then measurement of tested CT phase displacement requires measurements of two phase displacements: one in the first module of the WT1600 - between voltage drop on the current shunt and primary current and second phase displacement between this voltage drop and secondary current. The uncertainty of both measurements of the phase displacement with the assumption of uniform distribution of errors of WT1600 will be not worst than accuracy of measurements of phase displacement by one module of WT1600.

Results of laboratory studies

When analyzing the measurement results it was assumed that for the increased frequencies of the sinusoidal signals similar errors limits for given accuracy class as for 50 Hz currents are used [8 - 11], [14].

To determine the accuracy of transformation of tested CTs for sinusoidal currents of frequencies above 50 Hz (conductive disturbances) transfer factors were calculated from the equation [6], [9 - 10]:

(4) $$T_I = \frac{I_2}{I_1} \cdot 100\%$$

where: I_2 – RMS value of the transformed current (CT secondary current) [A], I_1 – RMS value of the CT primary current [A].

Figure 2 shows transfer factor characteristics with the change of the primary sinusoidal current frequency determined for tested CTs in condition of shorten secondary windings and rated primary current RMS value of 5 A for the primary winding supply voltage frequency change from 50 Hz to 20 kHz.

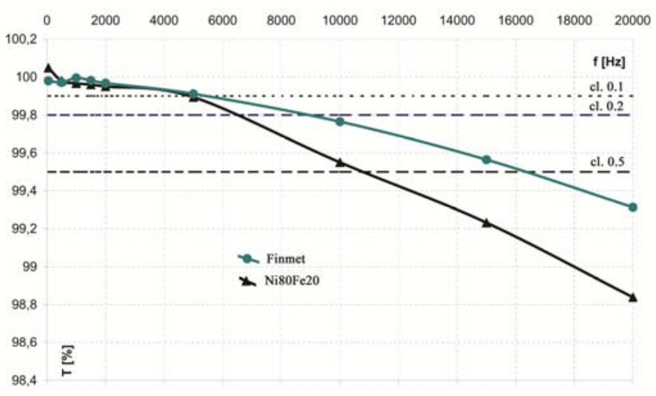

Fig.2. Transfer factor characteristics with the change of the primary sinusoidal current frequency determined for tested CTs

Analysis of results from figure 2 shows, that in this test conditions the highest values of transfer factors are calculated for CT with nanocrystalline magnetic core made from Finmet tape. For rated current 5 A and shorten secondary winding this CT is characterized by transfer factor which do not exceed the limit values set for accuracy class 0,5 in the range of primary current frequencies from 50 Hz to 16 kHz, class 0,2 in the range of frequencies from 50 Hz to 9 kHz and class 0,1 in the range of frequencies from 50 Hz to 5 kHz.

After consideration of the calculated uncertainty of measurements the range of frequencies in which tested CT is characterized by accuracy which do not exceed class 0,1 was limited to about 3 kHz, class 0,2 to about 5 kHz and class 0,5 to about 14 kHz.

Figure 3 shows results of measurements of the tested CTs phase displacements in condition of shorten secondary windings and rated primary current RMS value of 5 A for the primary winding supply voltage frequency change from 50 Hz to 20 kHz (same test conditions as for results presented in figure 2).

Tested CT with magnetic core made from Finmet tape, in condition of shorten secondary winding, is characterized also by the lowest phase displacement. Results from figure 3 shows, that this CT has phase displacement which do not exceed the limits set for accuracy class 0,5 for frequencies range from 50 Hz to 20 kHz, class 0,2 from 50 Hz to 10 kHz and class 0,1 to frequency of the primary current lower than 6 kHz.

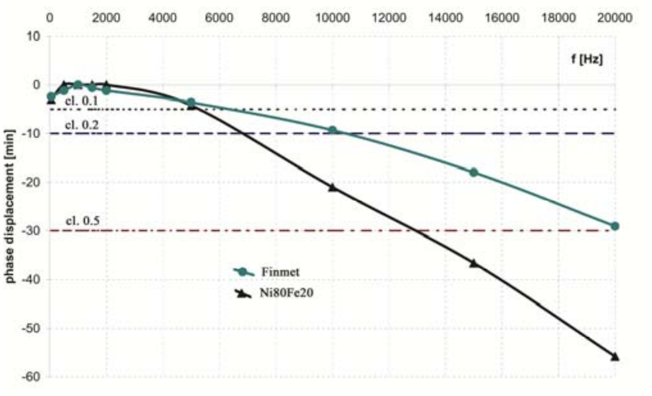

Fig.3. Phase displacement characteristics with the change of the primary sinusoidal current frequency determined for tested CTs

After consideration of calculated uncertainly of phase displacement measurements tested CT (Finmet) is characterized by phase displacement, which do not exceed the accuracy class 0,5 for limited frequencies range of primary currents from 50 Hz to about 8 kHz, class 0,2 to about 4 kHz and class 0,1 to about 2 kHz.

Analyzing the results from both figures 2 and 3 it can be concluded that the CT with toroidal core made of nanocrystalline tape provides a transformation of current RMS value of 5 A with shorten secondary winding (including uncertainties) in the frequency range from 50 Hz to 8 kHz in Class 0.5, 50 Hz to 4 kHz in the class 0.2 and class 0.1 in the frequency range up to 2 kHz.

Conclusions

After analysis of measurements results presented in the paper it was found that:

- developed measurement method gives an opportunity to test the CT accuracy for sinusoidal currents of frequencies 50 Hz and higher. This enables their usage in measurement systems for above 50 Hz frequency sinusoidal currents transformation,
- determine of the CTs phase displacements and transfer factors characteristics with the change of the primary sinusoidal current frequency enables assignation of its accuracy for the transformation of sinusoidal currents or conductive disturbances (with reliable approximation) of frequencies above 50 Hz,
- in case of both tested CTs the increase of the primary current frequency cause deterioration of their metrological properties. CT with the magnetic core made from nanocrystalline (Finmet) tape, in the tested frequency range and conditions, is characterized (as expected) by significantly higher metrological properties, than CT with the toroidal magnetic core made from permalloy Ni80Fe20.

The project was funded by the Polish National Science Centre

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***Authors**: prof. dr hab. inż. Ryszard Nowicz, dr inż. Michał Kaczmarek, michal.kaczmarek@p.lodz.pl, Politechnika Łódzka, WEEliA, Instytut Elektroenergetyki, Zakład Przekładników i Kompatybilności Elektromagnetycznej, ul. Stefanowskiego 18 / 22, 90 - 924 Łódź.*