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The Reference Wideband Inductive Current Transformer

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Abstract: The aim of this paper is to show that the developed inductive current transformer may ensure the required wideband transformation accuracy and it may be applied, as the reference source, in the measuring system for the evaluation of the transformation accuracy of inductive current transformers for harmonics of distorted current. This device ensures 5 A and 1 A RMS secondary currents to provide the opportunity to use the differential measuring setup. Such solutions are characterized by the significantly reduced measurement uncertainty in relation to the comparative measurements made between two current/voltage channels. The problems required to ensure the high wideband transformation accuracy, including the self-generation phenomenon of the low order higher harmonics to the secondary current and a too-low frequency range of operation, were overcome in the design process. The values of its ratio error and the phase displacement of the developed reference wideband inductive current transformer did not exceed ±0.2%/° up to 1 kHz, ±0.4%/° from 1 kHz up to 1.5 kHz and ±0.5%/° from 1.5 kHz up to 3 kHz, as is required to perform the test procedure in accordance with the optional requirements for the inductive current transformers defined in the new edition of the standard IEC 61869-1.

Keywords: current transformer; reference source; wideband accuracy classes; transformation accuracy; distorted current; higher harmonics; current error; phase displacement

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1. Introduction

The second edition of the standard IEC 61869-1, released on 14 June 2023, defines the requirements for optional wideband accuracy classes of the inductive instrument transformers (IT) [1]. They concern the transformation of distorted current and voltage harmonics as well as sinusoidal waveforms of increased frequency. These requirements correspond with those previously presented in the standard IEC 61869-6 for the low power instrument transformers [2]. The wideband accuracy of ITs is essential for the transformation of distorted current/voltage and power measurements, as well as for the evaluation of the power quality for the proper monitoring of the power network. There are five accuracy class extensions for harmonics: WB0 extension level up to the 13th harmonic, WB1 extension for harmonic frequencies up to 3 kHz, WB2 extension for harmonic frequencies up to 20 kHz, WB3 extension for harmonic frequencies up to 150 kHz, and WB4 extension for wide bandwidth applications up to 500 kHz. Therefore, the accuracy class of the wideband IT may be defined, for example, as 0.2-WB1. This means that the voltage transformer (VT) or current transformer (CT) accuracy class for the transformation of sinusoidal voltage or current of frequency 50 Hz/60 Hz is 0.2, while its wideband accuracy class is WB1, ensuring that the ratio error and phase displacement do not exceed ±2%/° up to and including 1 kHz, ±4%/° from 1 kHz up to and including 1.5 kHz, and ±5%/° from 1.5 kHz up to and including 3 kHz. In accordance with the standard IEC 61869-1, the tests on harmonics should be performed with the rated primary signal at the rated frequency plus a percentage of the rated primary signal at each considered harmonic frequency [1]. There are appropriate supplying systems for such tests [3–8]. In the already published standards there are no defined requirements for the reference source. However, it is usually accepted that it

should be ten times more accurate than the tested CT or VT. Therefore, in the case of the reference IT for the 0.2-WB1 class, its ratio error and phase displacement should not exceed ±0.2%/° up to and including 1 kHz, ±0.4%/° from 1 kHz up to and including 1.5 kHz, and ±0.5%/° from 1.5 kHz up to and including 3 kHz.

The articles [7–11] demonstrate the measurement systems to assess the values of voltage error and phase displacement in VTs for the transformation of distorted voltage harmonics. The reference source is the wideband voltage divider [10,12–14]. In the case of the inductive VTs, the step-up voltage transformer must be utilized in order to ensure required for tests rated at primary voltage. This is obligatory due to the nonlinearity of the magnetization characteristics of their magnetic core [7,8]. In the case of the wideband accuracy tests of the inductive CTs, due to the same reason, it is also important to ensure the appropriate values of distorted primary current to properly assess the possible levels of the self-generated low-order higher harmonics [8,15]. Such conditions to test the window type inductive CTs may be obtained in the rated ampere-turns conditions [7,16,17]. In the other case, in the papers [18], the solution is presented that enables the generation of distorted currents with RMS values up to 1000 A and a 10% level of higher harmonics. The step-up current transformer is supplied by the audio amplifier fed by the arbitrary waveform generator [5]. In such cases, the reference source is required. In the typically used measuring setups, the comparative measurements are made between two, e.g., voltage channels of acquisition board, where the voltages between current shunts with secondary currents of the reference transducer and the tested CT are compared. In the case of both CTs and VTs, their wideband accuracy tests are important in order to ensure the required accuracy of distorted current/voltage and power measurements, as well as the evaluation of the power quality [7,8,10,19,20].

The aim of this paper is to determine whether the inductive CT is able to ensure the required wideband accuracy to be applied in the measuring system as the reference source for the evaluation of the inductive CTs' current error and phase displacement at the harmonics of distorted current. The secondary current of the Danisense DC200IF fluxgate-technology-based current transducer was used for comparison with the secondary current of our developed wideband inductive CT [21,22]. Its amplitude error in the frequencies range from 10 Hz to 5 kHz did not exceed ±0.1%, while the phase shift did not exceed ±0.1°. Its rated primary AC current was equal to 200 A, while the current ratio was equal to 1000 A/A. To verify this information provided by the manufacturer, the transducer will be tested in the rated ampere-turns conditions. Then, the device will be used as the reference source for testing our developed inductive CT. It was designed in order to ensure a non-detectable level of self-generation of the low-order higher harmonics and frequencies range of operation from 50 Hz to 5 kHz. The novelty of the paper concerns the verification of the wideband accuracy of the current transducer and its application in the measuring system for the evaluation of the values of current error and phase displacement of the inductive CT. Moreover, the design of the reference wideband inductive CT is discussed and its high accuracy of distorted current transformation is demonstrated and verified. The developed reference wideband inductive CT will provide the opportunity to use the differential measuring setup for testing inductive CTs with these rated values of secondary currents, due to the values of its rated secondary windings, which are equal to 5 A RMS and 1 A RMS. This solution is characterized by the significantly reduced measurement uncertainty in relation to the measurements required to be made between two measuring channels, in which the appropriate signals from the reference source and tested CT were compared.

2. Measuring Systems, Methods, and Reference Inductive CT

The first measuring system presented in Figure 1 was used to validate the accuracy defined by the manufacturer of the Danisense DC200IF current transducer (DS).

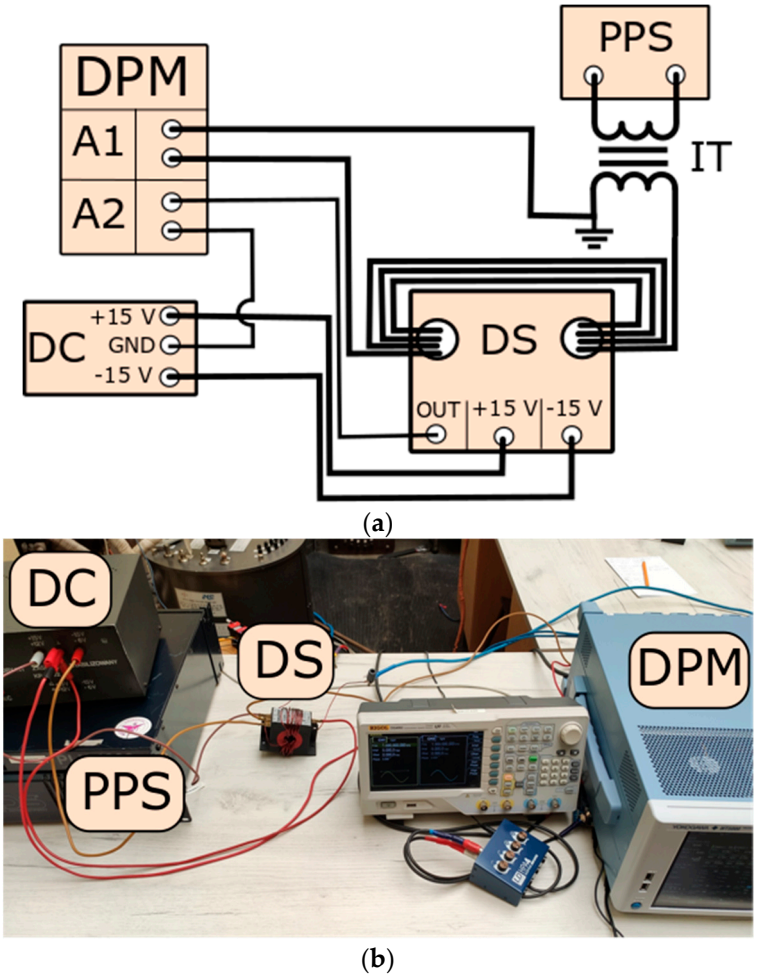


Figure 1. The measuring system used to validate the accuracy defined by the manufacturer of the Danisense DC200IF current transducer: (**a**) electrical schematic, (**b**) photo.

In Figure 1, the following notations are used:

DPM—digital power meter Yokogawa WT5000;
DS—Danisense DC200IF current transducer (the value of rated primary current is equal to 200 A RMS, the value of rated secondary current is equal to 200 mA RMS);
PPS—programmable power supply composed of the audio power amplifier and arbitrary waveform generator;
IT—insulation transformer;
DC—DC power supply for DS (±15 V).

In the rated ampere-turns conditions, the harmonics of primary and secondary currents are compared between two current channels of the WT5000 digital power meter (DPM). The nominal primary current of this particular unit was equal to 200 A RMS. The measuring system was supplied by the programmable power source (PPS), composed of the audio power amplifier and arbitrary waveform generator [7,8,15]. This enabled the possibility of generating the distorted current with programmable levels of harmonics of frequency from 50 Hz to 5 kHz. The phase angle in relation to the main component may be freely adjustable. In the case where the RMS value of the distorted primary current in the additionally made primary winding was set to 5 A RMS and the number of its turns was equal to 40, conditions equivalent to those obtained for 200 A RMS could be ensured. The tested DS required additional DC power supply ±15 V. An insulation transformer was used to separate the measuring system from the power supply in order to prevent any unfavorable feedback of high frequency disturbances and DC component.

The value of the current error of the current transducer for hk harmonic is defined by the following formula:

$$\Delta I_{hk} = \frac{k_{DS} \cdot I_{DS2hk} - n \cdot I_{1hk}}{n \cdot I_{1hk}} \cdot 100\% \quad (1)$$

where:

k_{DS}—rated value of current ratio of DS is 1000 A/A;
I_{1hk}—RMS value of the hk harmonic of the distorted primary current of DS;
$_{DS2hk}$—the RMS value of the hk harmonic of the distorted secondary current of DS;
n—number of turns of the additional primary winding made by the 40 wires passed through the window of the transducer.

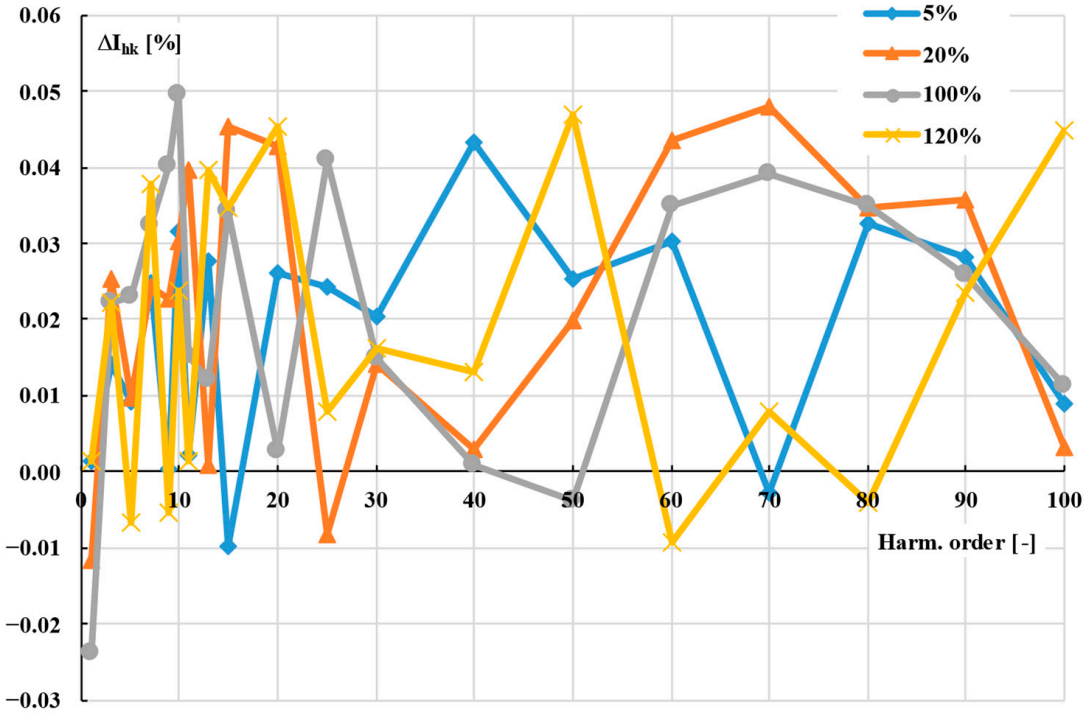
The value of the phase displacement of the current transducer for hk harmonic is defined by the following formula:

$$\delta\varphi_{hk} = \varphi_{DS2hk} - \varphi_{1hk} \quad (2)$$

where:

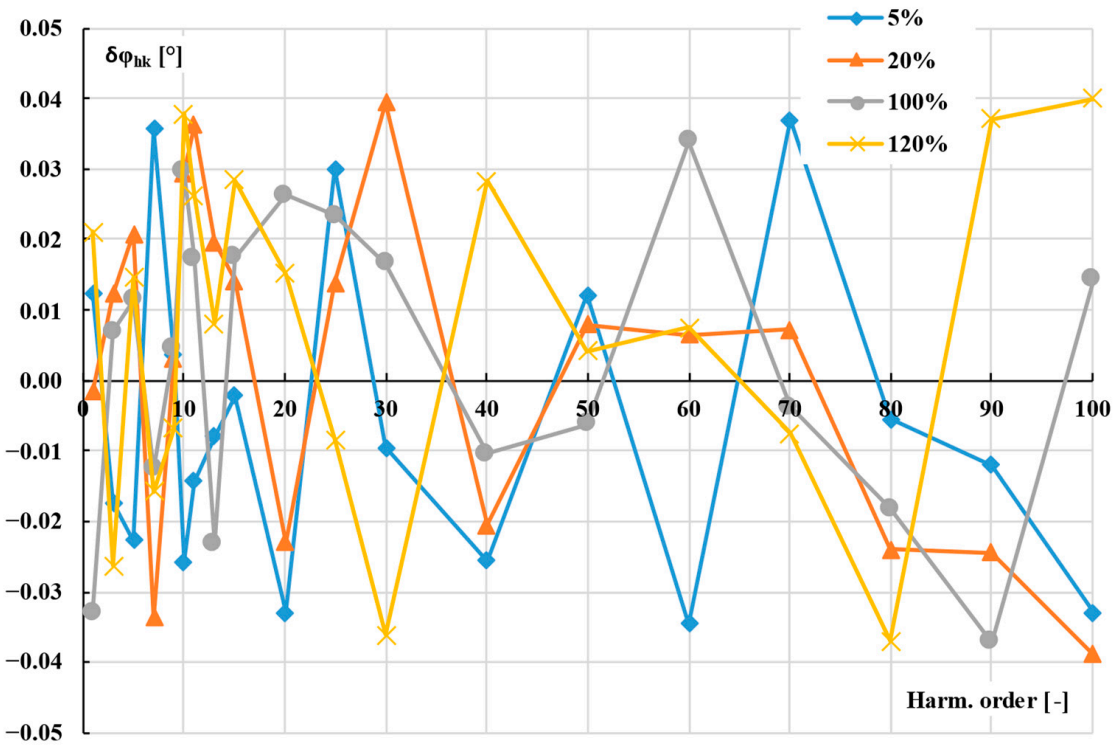
φ_{DS2hk}—phase angle of the hk harmonic of the distorted secondary current of DS in relation to the reference voltage;
φ_{1hk}—phase angle of the hk harmonic of the distorted primary current of DS in relation to the reference voltage.

In Figure 2, the results of the accuracy tests of the current transducer are presented. In part (a), the values of the current error are shown, while in part (b) the values of phase displacement are presented.



(**a**)

Figure 2. *Cont.*



(**b**)

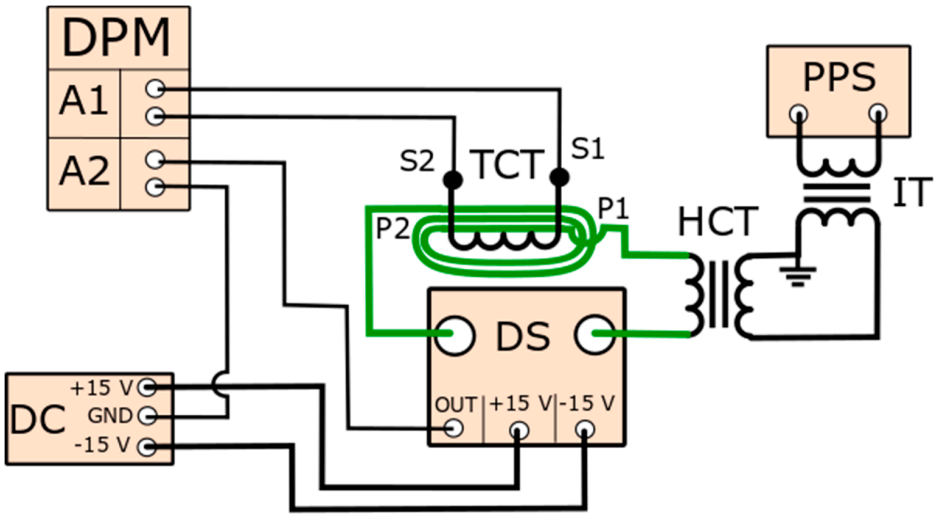
Figure 2. The results of the accuracy test of the current transducer: the values of (**a**) current error and (**b**) phase displacement.

In Figure 2, the following notations are used:

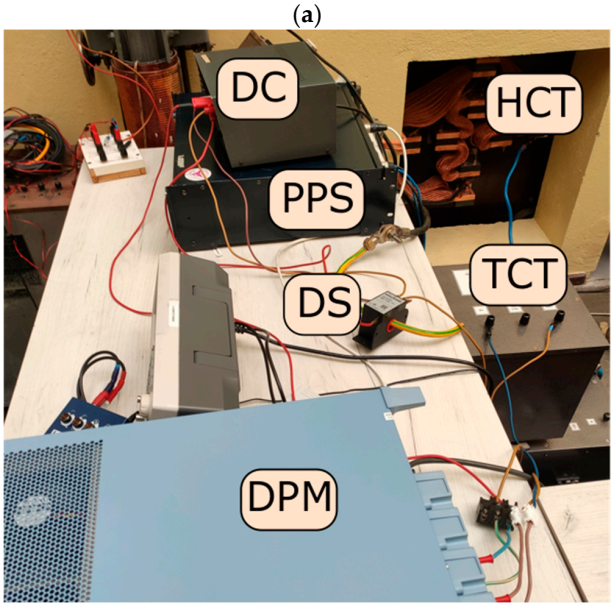
ΔI_{hk}—value of the current error for hk harmonic;
$\delta\varphi_{hk}$—value of the phase displacement for hk harmonic.

From Figure 2, it can be seen that the accuracy defined by the manufacturer of the tested current transducer in the frequencies range from 50 Hz to 5 kHz is confirmed. The visible fluctuations of the determined values of current error and phase displacement result from the measurement uncertainty of the WT5000 DPM. The nominal primary current of the used DS was equal to 200 A RMS. The rated primary current of the developed wideband inductive CT was equal to 300 A RMS. Therefore, during the tests, the primary current of the DS could be set to 5%, 20%, 100%, and 120% of the 100 A RMS primary current and the wire with the primary current would be passed through the window of TCT three times. In the measurement system presented above, the measurements were performed in the ampere turns conditions of DS equivalent to the 100 A RMS primary current, since the RMS value of the current in the additional primary winding was equal to 2.5 A and 40 turns were used. The wideband accuracy tests for DS were performed for 5%, 20%, 100%, and 120% of the 2.5 A RMS primary current in the additional primary winding for the main frequency equal to 50 Hz and the 5% level of a single higher harmonic in the range of frequencies from 100 Hz (2nd) to 5 kHz (100th). Various phase angles of higher harmonics in relation to the main harmonic were tested with no detected influence on the results.

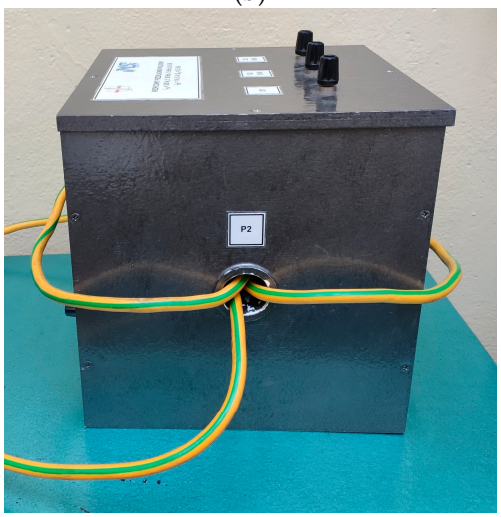
In Figure 3, the measuring system used to test the wideband accuracy of CTs and the developed reference wideband inductive CT are presented.



(**a**)



(**b**)



(**c**)

Figure 3. The measuring system used to test the wideband accuracy of the developed reference wideband inductive CT: (**a**) electrical schematic, (**b**) photo, and (**c**) photo of developed CT.

In Figure 3a,b, the following additional notations are used:

TCT—tested wideband reference inductive CT (the value of rated primary current is equal to 300 A RMS, the values of rated secondary currents from two secondary windings are equal to 5 A RMS and 1 A RMS);
HCT—step-up current transformer [18].

The nominal primary current of the DS used was equal to 200 A RMS. The rated primary current of the developed wideband inductive CT was equal to 300 A RMS. Therefore, during the tests, the wire with the primary current was passed through the window of its magnetic core three times. In the measurement system presented above, the measurements were performed in the rated ampere turns conditions of TCT since the primary current RMS value was equal to 100 A and three turns were used [7,8,17]. The value of the current error of the hk distorted current harmonic transformation by the tested inductive CT was evaluated on the basis of the current measurement in two modules of the DPM. The RMS values of the harmonics in the secondary current of the TCT and the reference current transducer DS, as well as their mutual phase angles, were simultaneously measured.

The value of the current error of the tested reference wideband inductive current transformer for hk harmonic is defined by the formula:

$$\Delta I_{hk} = \frac{k_{TCT} \cdot I_{TCT2hk} - k_{DS} \cdot I_{DS2hk}}{k_{DS} \cdot I_{DS2hk}} \cdot 100\% \quad (3)$$

where:

k_{TCT}—rated value of current ratio of TCT (60 if secondary current is equal to 5 A or 300 if secondary current is equal to 1 A);
I_{TCT2hk}—RMS value of the hk harmonic of the distorted secondary current of TCT.

The value of the phase displacement of the tested reference wideband inductive current transformer for hk harmonic is defined by the following formula:

$$\delta\varphi_{hk} = \varphi_{TCT2hk} - \varphi_{DS2hk} \quad (4)$$

where:

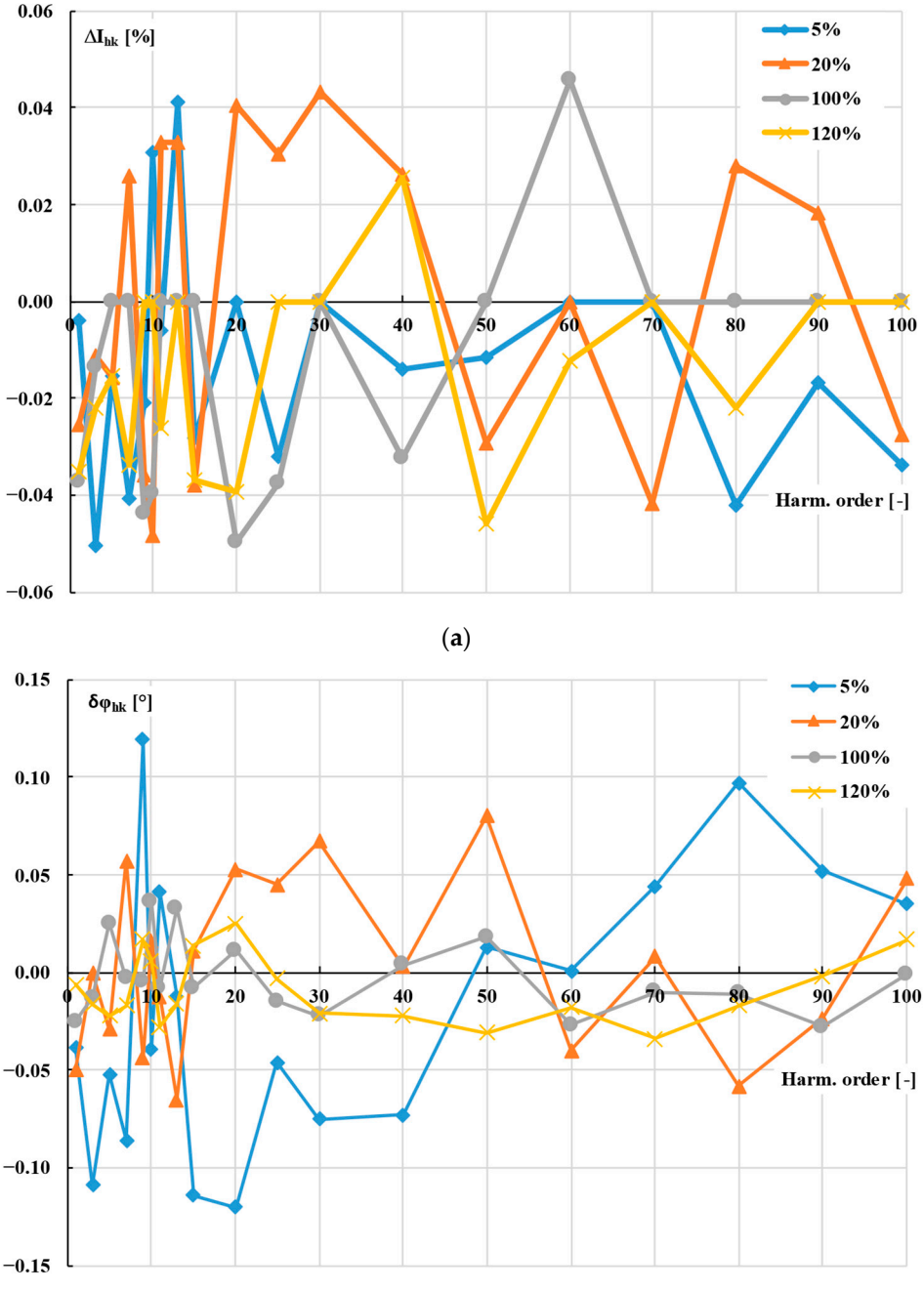
φ_{TCT2hk}—phase angle of the hk harmonic of the distorted secondary current of TCT in relation to the reference voltage.

The wideband accuracy tests were performed for 5%, 20%, 100%, and 120% of the rated primary current RMS value equal to 300 A with the main frequency equal to 50 Hz and a 5% level of a single higher harmonic in the range of frequencies from 100 Hz (2nd) to 5 kHz (100th). Various phase angles of higher harmonics in relation to the main harmonic were tested, with no detected influence on the results. The accuracy of the TCT as the reference wideband inductive CT was determined with the appropriate secondary winding being loaded only with the current shunt of the measuring current channel of DPM (the conditions close to the short circuit of the secondary winding: 6.5 mΩ ± 10% + approx. 0.3 μH). The unused secondary winding was left open.

In Figure 4, the results of the accuracy evaluation of the TCT for the secondary current rated RMS value equal to 1 A are presented.

The result from Figure 4 indicates that the maximum detected values of current error did not exceed ±0.05% and the value of phase displacement did not exceed ±0.15° for the secondary current rated RMS value equal to 1 A. Therefore, the reference wideband inductive CT meets the requirements for the 0.2-WB1 class because its ratio error and phase displacement did not exceed ±0.2%/° up to and including 1 kHz, ±0.4%/° from 1 kHz up to and including 1.5 kHz, and ±0.5%/° from 1.5 kHz up to and including 3 kHz. The visible fluctuations of the determined values of current error and phase displacement results from the doubled measurement uncertainty of the WT5000 DPM caused by the usage of two measuring channels. Moreover, if the primary current was decreased for 5% and 20% of the rated primary current of TCT equal to 300 A RMS, the measurement uncertainty of

phase displacement determined for the transformation of the hk harmonic of the distorted primary current increased. This is due to the fact that the measurement conditions make it more difficult to determine the phase angle of higher harmonics as the signal to noise ratio decreases.



(**a**)

(**b**)

Figure 4. The results of the accuracy evaluation of the TCT for the secondary current rated RMS value equal to 1 A: (**a**) current error and (**b**) phase displacement determined for transformation of the hk harmonic of distorted primary current.

In Figure 5, the results of the accuracy evaluation of the TCT for the secondary current rated RMS value equal to 5 A are presented.

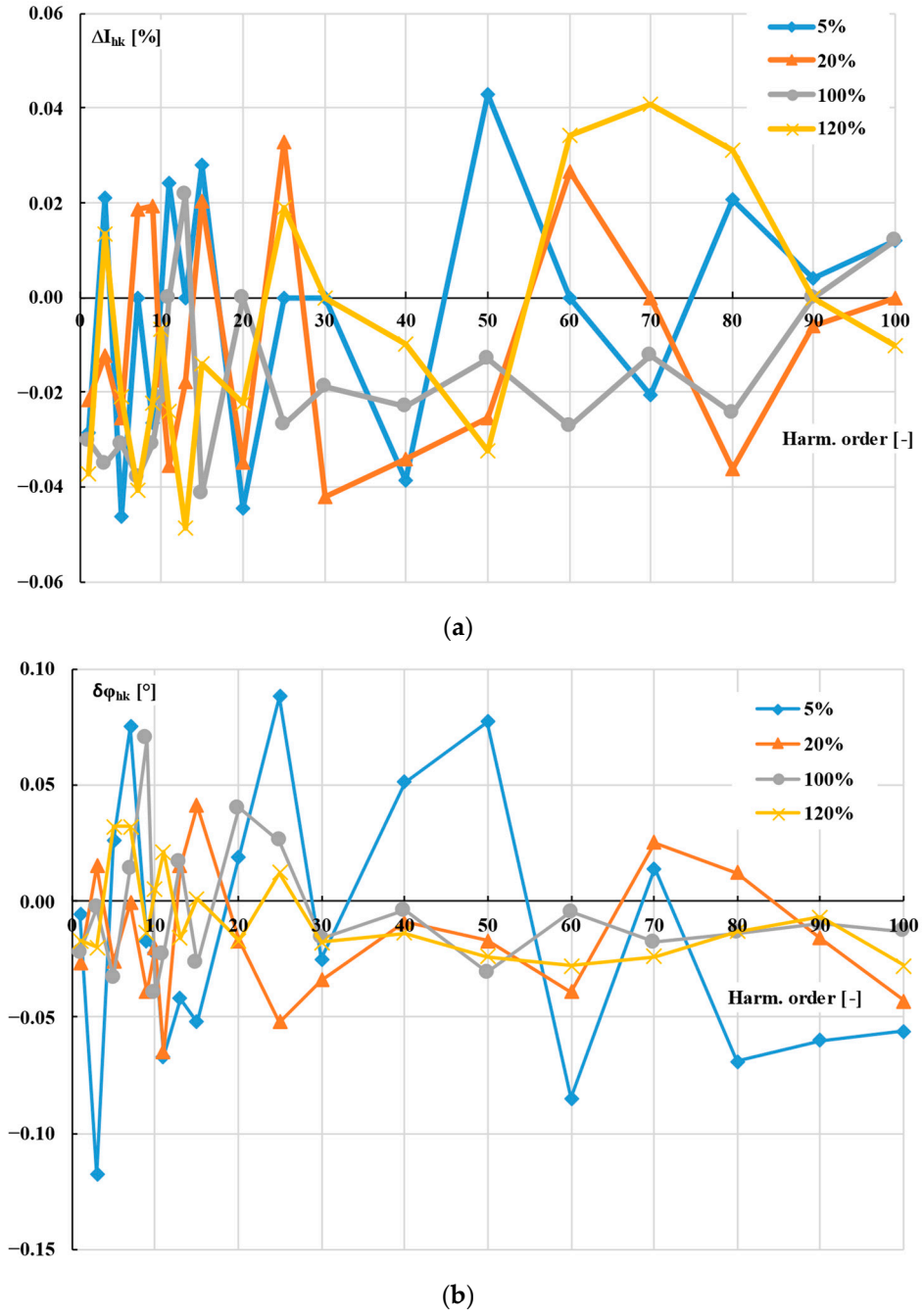


Figure 5. The results of the accuracy evaluation of the TCT for the secondary current rated RMS value equal to 5 A: (**a**) current error and (**b**) phase displacement determined for the transformation of the hk harmonics of distorted primary current.

The result from Figure 5 indicates that the maximum detected values of current error also did not exceed ±0.05% and the value of phase displacement did not exceed ±0.15° for the secondary current rated RMS value equal to 5 A. Therefore, the reference wideband inductive CT also met the requirements for the 0.2-WB1 class for the secondary winding because the ratio error and phase displacement did not exceed ±0.2%/° up to and including 1 kHz, ±0.4%/° from 1 kHz up to and including 1.5 kHz, and ±0.5%/° from 1.5 kHz up to and including 3 kHz. The visible fluctuations in the determined values of current error and phase displacement in this case also resulted from the doubled measurement uncertainty of the WT5000 DPM caused by the usage of two measuring channels. In the case when the secondary current rated RMS value was equal to 5 A, the measurement uncertainty of the

phase displacement, as well as the current error determined for the transformation of the hk harmonic of distorted primary current, was not dependent from the percentage value of the rated primary current used during the tests. This is due to the fact that the signal to noise ratio was sufficiently favorable in all these cases.

3. Discussion

The general context in the field and the motivation of this work is that the second edition of the standard IEC 61869-1, released in 14 June 2023, defines the requirements for the optional wideband accuracy classes of the inductive instrument transformers (IT). They concern the transformation of distorted current and voltage harmonics, as well as sinusoidal waveforms of increased frequency. Therefore, the inductive CTs may be tested for optional accuracy classes. In the design of the reference wideband inductive CT, the application for the magnetic core of the magnetic material with increased magnetic permeability to decrease the excitation current required for the operation of inductive CT is critical [23–29]. Therefore, the self-generation phenomenon of the low order higher harmonics caused by the nonlinearity of the magnetization characteristic will also not be significant and self-distortion of the secondary current will not be detectable [7,8,30]. In this case, the magnetic core coaxially composed of the nanocrystalline material (50%) and permalloy (50%) was used [28,31]. The method and the measuring system used for the evaluation of the self-generated low order higher harmonic by the inductive CTs are presented in the paper [8]. The presented results of the wideband accuracy tests of the developed inductive current transformer confirm its applicability as a reference source in the measuring systems for the evaluation of the inductive current transformers' compliance with the optional requirements of the WB1 extension for harmonic frequencies up to 3 kHz defined in the standard IEC 61869-1 edition 2 [1]. This will provide the opportunity to use the differential measuring setup characterized by significantly reduced measurement uncertainty in relation to comparative measurements made between two current channels of DPM or the current comparator where the secondary current of reference and tested CTs are evaluated [7]. In this case, the developed reference wideband inductive CT enabled the possibility of measuring the differential current between them and directly determining the composite error for the rated secondary current of tested inductive CTs equal to 1 A or 5 A. Research has been performed in a number of research centers on characterizing the metrological and operational properties of inductive CTs for the transformation of distorted currents [8,32–35]. Measurements and results of analyses indicate that the accuracy of inductive CTs depends on the phenomenon of self-generation of higher harmonics to the secondary current caused by the nonlinearity of the magnetization characteristics of the magnetic core. The results and analyses presented in [30] relate to the metrological characteristics determined for the transformation of distorted currents by a corrected inductive CT. The vectorial diagrams presented in the paper indicate the factors determining the values of current error and phase displacement of a given harmonic transformation for distorted current. Many studies have also addressed the compensation techniques of inductive CTs transformation errors [36–39]. However, due to the phenomenon of self-generation of higher harmonics, the proposed solutions may not be effective. Therefore, accurate wideband inductive CTs should be designed and manufactured, as such a possibility is presented in this paper in order to ensure the wideband transformation accuracy as required by the WB1 optional accuracy class defined in the new edition of the standard IEC 61869-1. The proposed CT is not able to reduce the effect from higher harmonics. It ensures the secondary current without the significant impact of the self-generation phenomenon of the low order higher harmonics resulting from the nonlinearity of the magnetic core's magnetization characteristic—the secondary current is not detectably self-distorted by this CT, as it is in other inductive CTs, and therefore they may not be used as a reference CT. This also means that it is not producing significant/detectable RMS values of the low order higher harmonics, as in the case of the typical inductive CT (mainly 3rd, 5th, and 7th higher harmonics are produced and therefore the transformation accuracy of such an inductive

CT is significantly deteriorated in the frequencies range from up to 500 Hz). The aim of this paper is not to introduce a new measuring method. Many references are provided in order to show that the used measuring method is generally accepted by the scientific community. The developed CT is tested in accordance with the idea of comparing its secondary current with the output current of the reference source, e.g., the high accuracy transducer using the A/D converters and computation methods (in this case, the digital power meter was used; however, other scientist use, e.g., an acquisition board).

4. Conclusions

The results and analysis presented in this paper demonstrated that the developed inductive current transformer may be used as a reference source in the measuring systems for the evaluation of the inductive current transformers compliance with the wideband optional requirements of the WB1 class defined in the standard IEC 61869-1 edition 2 for the transformation of distorted current higher harmonics. The advantage of this approach in relation to the usage of the current transducers or the electronics current transformers is that it enables the possibility of using differential current measuring system. This is due to the fact that its rated secondary current is equal to 5 A or 1 A, as in the case of typical, standardized inductive current transformers that ought to be tested. The Danisense DC200IF fluxgate-technology-based current transducer was used for comparison with our developed wideband reference inductive current transformer. It was confirmed that our solution ensured the required accuracy to perform the tests of distorted current harmonics transformation of current transformers for the 0.2-WB1 class. This results from the values of its ratio error and phase displacement, not exceeding $\pm 0.2\%/^{\circ}$ up to and including 1 kHz, $\pm 0.4\%/^{\circ}$ from 1 kHz up to and including 1.5 kHz, and $\pm 0.5\%/^{\circ}$ from 1.5 kHz up to and including 3 kHz. The unit was designed with the utilization of the magnetic core coaxially composed of the nanocrystalline material (50%) and permalloy (50%). Moreover, the windings were spread uniformly over the surface of the magnetic core. The solution was the application for the magnetic core of the magnetic material with the increased magnetic permeability to decrease the excitation current required for the transformation of the primary current, as well as the proper selection of this inductive CT operating point on the magnetization characteristics. This approach ensured the secondary current without a significant impact of the self-generation phenomenon of the low order higher harmonics resulting from the nonlinearity of the magnetic core's magnetization characteristic. The further novelty of this paper concerns the verification of the current transducer harmonics transformation accuracy and its application in the measuring system. Moreover, the required assumptions for the development of the reference wideband inductive current transformer are discussed and its high accuracy of distorted current transformation is confirmed. In the case of both CTs and VTs, their wideband accuracy tests are important in order to ensure the required accuracy of distorted current/voltage and power measurements, as well as the evaluation of the power quality.

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Conflicts of Interest: The authors declare no conflict of interest.

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