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Nonlinearity of Magnetic Core in Evaluation of Current and Phase Errors of Transformation of Higher Harmonics of Distorted Current by Inductive Current Transformers

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ABSTRACT The novelty of the paper contributes to the increase of the reliability of the methods used for evaluation of the inductive CTs accuracy of transformation of the distorted current. The results of performed analyses shows that the values of current and phase errors of transformation of the low order higher harmonics by inductive CT depends significantly from the phase angle between transformed higher harmonics of the distorted primary current and the self-generated higher harmonics of the secondary current. Moreover, higher harmonics of the distorted primary current may increase the peak value of the magnetic flux density in the magnetic core. Then the impact of the self-generated low order harmonics resulting from the nonlinearity of the magnetic core on values of current and phase errors of transformation of the higher harmonics of the distorted primary current is increased. Proposed evaluation procedure enables determination of the maximum values of current and phase errors of transformation of the higher harmonics of the distorted primary current. It is essential to determine the accuracy class. In such approach the impact of the secondary current's distortion caused by the nonlinearity of the magnetic core and the influence of the harmonic distortion on the peak value of the magnetic flux density are considered. Therefore, transformation accuracy of tested CT is ensured for specified range and type of the load of the secondary winding, rms values of primary current and its distortion.

INDEX TERMS Inductive current transformer, nonlinearity of magnetic core, transformation accuracy, distorted current, power quality, composite error, current and phase errors at harmonics.

I. INTRODUCTION

Distortion of current in the power network causes the needed for control of the level of higher harmonics to ensure required power quality [1]–[3]. Mainly used inductive current transformers (CT) are able to provide wideband operation with their accuracy class determined for sinusoidal current of frequency 50 Hz [4]–[9]. Therefore, the measurement error of non-sinusoidal electrical power and energy is not increased [10]. However, due to the nonlinearity of their magnetic core several issues must be considered during determination of their accuracy of transformation of higher harmonics. The rms values of generated higher harmonics, as well as magnetic permeability and losses in the magnetic core are dependent from the magnetic flux density. Its value in the magnetic core results from the rms value of primary current and load of the secondary winding as well as the rms values of higher harmonics in the primary current. Therefore, the highest wideband accuracy is provided if the rms values of the self-generated higher harmonics for required load of the secondary winding and rms value of the primary currents as well as its distortion are negligible. All mentioned external factors conditioning the rms values of the self-generated higher harmonics by the inductive CT into the secondary current must be considered to ensure effective compensation. None of the methods proposed in the papers [11]–[15] provides this. The nonlinear mathematical models can be used to compensate the measured value [16]. Unfortunately the cost of the numerical computations is not specified. Transformation accuracy of the low-power CTs (non-conventional

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instrument CT) is by principle of their operation independent from this phenomenon [3], [7], [17]–[22]. In the case of inductive voltage transformer it should be noticed that the fundamental component is considerably larger than all other harmonics. Therefore they influence on magnetic flux density in the magnetic core may be assumed to be negligible [23].

The novelty of the paper concerns analysis of the dependence of the peak value of the magnetic flux density in the magnetic core from the rms values and the phase angles of the higher harmonics in the primary current. Their influence on transformation accuracy of the distorted current is explained and considered. The lowest and the highest values of the magnetic flux density in the magnetic core of tested CT caused by the primary current's higher harmonics for its maximum distortion defined in the standard IEC 61000-3-12 are considered [24]. Simultaneously, its impact on the secondary current distortion caused by the nonlinearity of the magnetic core is investigated. Presented solutions and methods in papers [5]–[15], [23], [25]–[29] do not cover these issues. Therefore, in the evaluation of the transformation accuracy of the low order higher harmonic it is required to consider their different phase angle in relation to the main harmonic of the distorted primary current. Moreover, the possible increase of the self-generated higher harmonics into the CT's secondary current must be considered. Proposed evaluation procedure of the inductive CTs wideband accuracy enables determination of the maximum values of current and phase errors of transformation of the higher harmonics with consideration of mentioned nonlinear effects. Therefore, it is the same approach as used in the standards IEEE\IEC to define accuracy class for transformation of sinusoidal current [30], [31].

II. THE MEASURNING CIRCUIT AND THE OBJECT OF THE RESEARCH

The object of the research are two inductive CTs, the 50 Hz type unit designed for transformation of sinusoidal current and the wideband unit, both with current ratio equal to 5 A \ 5 A and rated secondary winding apparent power equal to 10 VA. However, during the tests resistive loads are used not to additionally increase the secondary voltage and the magnetic flux density for transformation of the higher harmonics of the distorted primary current. Selected objects of the research have the primary and the secondary currents ratio equal to 1 in order not to require reference current transformer, as it could be expected to affect the results of the research [32]. In the measuring circuit presented in Fig.1 the differential connection is made in accordance with the standard IEC 61869-2 [30]. However, it is used to determine the composite error of the protective CTs. The same method may be applied to the measuring CTs. The 1 Ω current shunt is used to measure the differential current in the connection made between the primary and the secondary circuits of the tested CT. The digital power meter with DFT enables determination of the rms values and the phase angles of its higher harmonics.

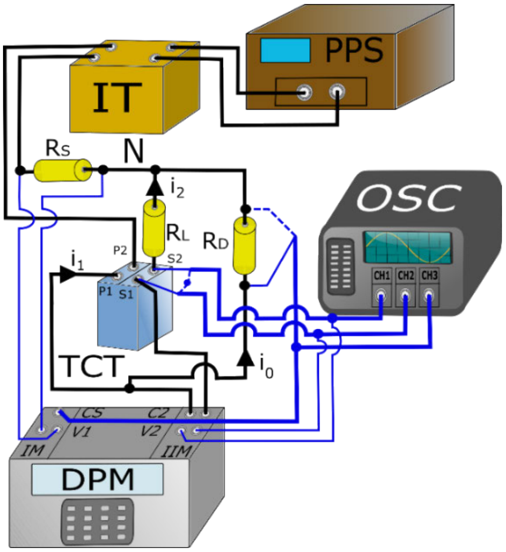

FIGURE 1. The measuring circuit to determine the values of current and phase errors at harmonics and waveforms of the excitation current and the secondary voltage of tested inductive CT.

In Figure 1 the following notations are used: *IT* - insulation transformer, *PPS* - programmable power source, *TCT* - tested current transformer, *DPM* - digital power meter, R_D - 1 Ω current shunt for measurements of the differential current, R_S - 0.1 Ω current shunt for measurements of the primary current, R_L - load resistor of tested CT's secondary winding, osc – oscilloscope, $i_{0\backslash 1\backslash 2}$ - instantaneous value of the excitation \primary \secondary current.

The measuring circuit is supplied by the programmable power voltage source through the insulating transformer [33]. If required for testes rms value of the primary current exceeds 20 A application of the inductive high current testing transformer for supplying of the measuring circuit with distorted current is required [34]. The oscilloscope is used to determine the waveforms of the excitation current measured by the R_D resistor and the secondary voltage measured by the differential connection of two voltage probes. The digital power meter is used to measure simultaneously the voltages from R_D(1 Ω) and R_S (0.1 Ω) current shunts. The rms value of the *hk* harmonic of the primary current of the tested CT is determined from the formula:

$$I_{1hk} = 10 \cdot U_{RShk} \tag{1}$$

U_{RShk} - the rms value of the *hk* harmonic of voltage from R_S current shunt.

The percentage value of the *hk* harmonic of the composite error in relation to its rms value in distorted primary current is determined from the equation:

$$\varepsilon_{\%Ihk} = \frac{U_{RDhk}}{I_{1hk}} \cdot 100\% \tag{2}$$

U_{RDhk} - the rms value of the *hk* harmonic of voltage of 1 Ω current shunt.

The rms value of the *hk* harmonic of the secondary current is determined from the relationship:

$$I_{2kh} = \sqrt{\left(\frac{U_{\mathrm{RS}hk}}{R_s}\right)^2 + \left(\frac{U_{RDhk}}{R_D}\right)^2 - 2\frac{U_{\mathrm{RS}hk}}{R_s} \cdot \frac{U_{RDhk}}{R_D} \cdot \cos_{hk}} \tag{3}$$

φ_{hk} - phase angle between *hk* harmonic of voltages from resistors R_S and R_D.

The percentage value of the current error of transformation of the *hk* higher harmonic of the distorted current by the tested CT if its secondary to primary currents ratio is equal to 1 is determined from the equation:

$$\Delta I_{kh} = \frac{I_{2hk} - I_{1hk}}{I_{1hk}} \cdot 100\% \tag{4}$$

Determined *hk* values of the composite and the current errors allow to calculate the phase error of transformation of higher harmonic of the distorted current by the tested CT:

$$\delta_{Ihk} = \arcsin\left(\frac{\sqrt{\varepsilon^2_{\%Ihk} - \Delta I^2_{hk}}}{100\%}\right) \tag{5}$$

The phase angle between *hk* harmonic of voltages from resistors $\mathrm{R_S}$ and $\mathrm{R_D}$ is between 0° and 180° the phase error is positive, in the other case the phase error is negative [5].

In accordance with the information provided by manufacturer tolerance of resistance of used current shunts is equal to ±1% for 0.1 Ω and ±0.01% for 1 Ω. Their inductance is below 0.08 μH. Therefore, calculated from equations (6) and (7) measurement errors of 50 Hz frequency main component of distorted current and its phase caused by current shunts are equal to respectively: ±1% \ ±0.02° and ±0.01% \±0.01°.

$$\Delta U_{Rhk} = \Delta U_{RDC} + \frac{\mathrm{Z}_{hk} - R}{R} \cdot 100\% \tag{6}$$

$$\delta_{Rhk} = \tan^{-1}\left(\frac{2 \cdot \pi \cdot \mathrm{f}_{hk} \cdot L}{R}\right) \tag{7}$$

ΔU_{RDC}– the DC tolerance of used current shunt, $\mathrm{Z_{hk}}$ – the impedance of current shunt for higher harmonic of *hk* frequency, $\mathrm{f_{hk}}$– 5 kHz as the limiting frequency of the measurements, R - the value of the DC resistance of current shunt equal to $\mathrm{R_S}$ or $\mathrm{R_D}$, L - the value of the inductance of the current shunts equal to 0.08 μH.

In accordance with equation (6) and (7) the uncertainty of measurements caused by used current shunts at given frequencies (rms value\phase angle) is equal to:

→ 1 Ω from 50 Hz to 5 kHz: ± 0.02%\± 0.02°

→ 0.1 Ω 50 Hz: ± 1.00%\± 0.015°; 5 kHz: ± 1.05% \±1.5°

Accuracy of measurement of the rms value and the value of the phase angle of harmonics of voltage by used digital power meter provided by manufacturer:

→ 50 Hz: ± 0.2%\± 0.2°; 5 kHz: ± 0.75% \±1.5°

The combined uncertainties of determination of the values of current and phase errors at harmonics by developed measuring system resulting from the accuracy of used current shunts and digital power meter are equal to (current error\phase error):

→ 50 Hz: ± 0.01%\± 0.01°

→ 5 kHz: ± 0.05% \± 0.02°

These are maximum values determined for the uniform distribution of the standard uncertainties with the coverage factor 2 and the level of confidence of about 95%. They were calculated for the distorted current *hk* harmonic values equal to: 0.025 A, 0.1 A, 0.5 A and 0.6 A, values of phase angle between *hk* harmonic of voltages from resistors $\mathrm{R_S}$ and $\mathrm{R_D}$ equal from 0° to 360° analysed in 10° steps and values of the composite error at harmonic equal to: 0.1% and 1%. The standard uncertainty type A is negligible since it is significantly lower than 0.1 of uncertainty type B, as results from averaging from 256 series of measurements.

III. DEPENDENCE OF THE PEAK VALUE OF THE MAGNETIC FLUX DENSITY IN THE MAGNETIC CORE FROM PRIMARY CURRENT HARMONICS

This paragraph contains analysis of the influence of the rms values and the phase angles of the higher harmonics of the distorted primary current on instantaneous values of the magnetic flux density obtained in the magnetic core of the tested CT in accordance with equation:

$$B(t) = \frac{1}{z_2 \cdot s_{Fe}} \cdot \int [u_{core} \cdot dt] \tag{8}$$

B(t) - instantaneous value of the magnetic flux density; $\mathrm{z_2}$ – numbers of turns of the secondary winding; $\mathrm{s_{Fe}}$ - cross-section of the magnetic core, $\mathrm{u_{core}}$ - instantaneous value of the voltage of the magnetic core.

$$u_{core} = u_2 + R_2 i_2 \tag{9}$$

During the measurements presented in the paper curves of the instantaneous value of the excitation current and the secondary voltage were determined with the oscilloscope. The samples were collected to the file to perform the needed integration of the secondary voltage. The resistance of the secondary winding is equal to 0.101 Ω. The value of the leakage inductance of the evenly winded in the single layer secondary winding on the toroidal core is negligible.

The tests of the impact of the primary current harmonics on the peak value of the magnetic flux density in the magnetic core were performed for three cases. The maximum ($\mathrm{B_{max}}$) and the minimum ($\mathrm{B_{min}}$) peak values were achieved and for the case when the distorted supply voltage of the primary winding was composed of the main frequency harmonic and the one higher harmonic. In order to obtain the $\mathrm{B_{max}}$ and the $\mathrm{B_{min}}$ conditions the percentage values of voltage harmonics for phase angles from 0° to 360° in relation to the main harmonic were change in a range from 0 to the values permissible by the standard IEC 61000-3-12 in the power network for the highest total harmonic distortion of the current equal

TABLE 1. The cases B_{max} and B_{min} percentage values (and phases) of the harmonics of the secondary voltage and the rms values (and phases) of the harmonics of the magnetic flux density in the magnetic core.

Harm. order [-]	Case B_{MAX}		Case B_{MIN}	
	Harm. value [%] of U_{2h1} (phase) [°]	FFT(B_{max}) [T] (phase) [°]	Harm. value [%] of U_{2h1} (phase) [°]	FFT(B_{min}) [T] (phase) [°]
0	-	0.022 [0]	-	-
1	-	0.346 [180]	-	0.306 [180]
2	8 [180]	0.013 [0]	-	-
3	41 [0]	0.047 [180]	41 [180]	0.041 [0]
4	4 [180]	0.003 [0]	-	-
5	24 [0]	0.016 [180]	24 [180]	0.014 [0]
6	2.7 [180]	0.001 [0]	-	-
7	15 [0]	0.007 [180]	15 [180]	0.006 [0]
8	2 [180]	0	-	-
9	12 [0]	0.004 [180]	12 [180]	0.004 [0]
10	1.6 [180]	0	-	-
11	10 [0]	0.003 [180]	10 [180]	0.002 [0]
12	1.3 [180]	0	-	-
13	8 [0]	0	8 [180]	0

to 47% [24]. In the case B_{max} the distorted primary current supplied to tested inductive CTs is composed of the primary component of frequency equal to 50 Hz and all higher harmonics of order from 2nd to 13th. The percentage values of obtained higher harmonics of CT's secondary voltage (Fig.1) are presented in Table 1 as percentages of rms value of its main component.

U_{2h1} – the rms value of the main component of the distorted secondary voltage, FFT(B) – the results of the Fast Fourier Transformation obtained for the instantaneous values of the magnetic flux density.

The rms value of the main component of the distorted primary current is equal to 5 A as the rms value of the rated sinusoidal current. The rms value of the main harmonic of the magnetic flux density obtained for the rated primary current of the tested CT is equal to 0.346 T as obtained for transformation of sinusoidal current. Constant component equal to 0.022 T in the waveform of the distorted magnetic flux density is caused by presents of the even higher harmonics in the distorted primary current.

In Fig.2 obtained from the measuring circuit presented in Fig.1 waveforms of the secondary voltage ($u_{2\ dist.}$) and the magnetic flux density ($B(t)_{dist}$) are compared with the waveforms of the secondary voltage (u_{50Hz}) and the magnetic flux density ($B(t)_{50Hz}$) for sinusoidal primary current. The instantaneous value of the voltage of the magnetic core (u_{core}) is computed from equation (9) for distorted secondary voltage.

The peak value of distorted secondary voltage equal to 0.81 V is higher than sinusoidal equal to 0.7 V due to the additional higher harmonics. Moreover, waveform of distorted

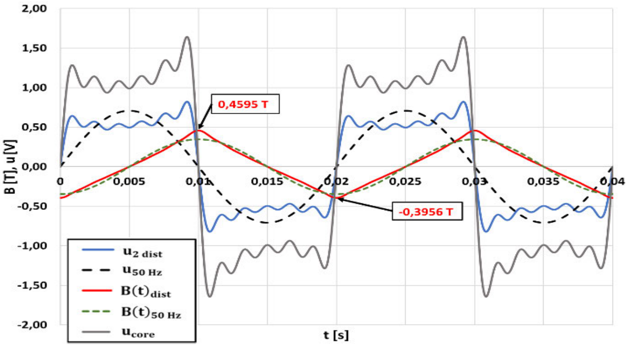

FIGURE 2. Waveforms for the case B_{max}.

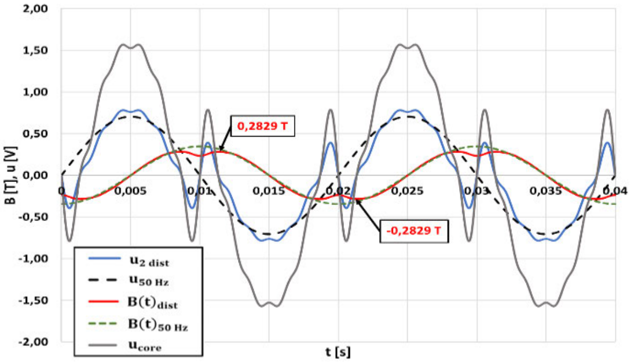

FIGURE 3. Waveforms for the case B_{min}.

secondary voltage is close in shape to rectangular. These conditions causes increase of the peak value of magnetic flux density in relation to sinusoidal secondary voltage from 0.35 T to 0.46 T. Presence of the even harmonics in distorted secondary voltage causes that the waveform of the magnetic flux density becomes asymmetrically displaced towards positive values. In condition when the rms value of distorted primary current is equal to the rms value of the sinusoidal primary current 5 A the value of peak magnetic flux density is equal to 0.40 T.

In the case B_{min} the distorted primary current of tested inductive CTs is composed of primary component of frequency equal to 50 Hz and the odd higher harmonics of order from 3rd to 13th. To achieve the minimum peak value of the magnetic flux density in the magnetic core (B_{max}) in relation to sinusoidal primary current the phase angles of odd harmonic in relation to the main harmonic of distorted secondary voltage are equal to 180°.

The minimum value of the magnetic flux density in the case B_{min} is equal to 0.28 T and it is lower than obtained for the sinusoidal primary current (0.35 T). The peak value of the distorted secondary voltage is higher than the sinusoidal secondary voltage but the peak value of the magnetic flux density results from the phase angles of the odd harmonic in relation to the main harmonic of the distorted secondary voltage that are equal to 180°.

In Fig.4 the waveforms are presented for the case when the distorted primary current is composed of the main frequency harmonic and 11^{th} higher harmonic equal to 10% of its value.

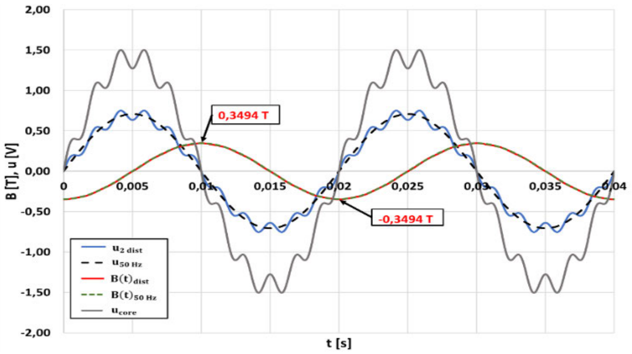

FIGURE 4. Waveforms for the case when distorted primary current is composed of main frequency harmonic and 11th higher harmonic.

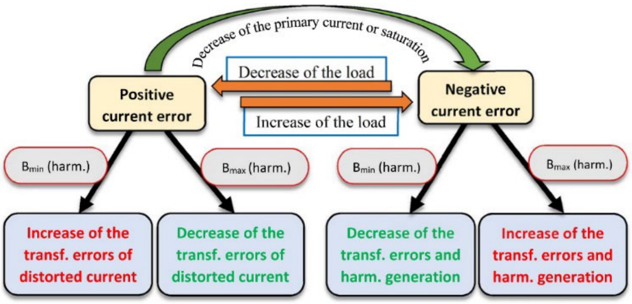

FIGURE 5. The flowchart of the influence of higher harmonics on transformation accuracy of distorted current by inductive CT.

In this case the increase of the peak value of the magnetic flux density caused by higher harmonic equal to 10% of the main harmonic of distorted primary current is equal to 0.003 T. The value of its main component is equal to 0.346 T and the value of the 3rd harmonic is equal to 0.005 T (this component is caused by distortion of the primary current by the nonlinearity of the magnetic core). Further increase of the frequency of higher harmonic in distorted primary current causes decrease of its influence on obtained magnetic flux density in the magnetic core.

IV. FLOWCHART OF THE PROPOSED EVALUATION PROCEDURE

The influence of rms values and phase angles of the higher harmonics on transformation accuracy of the distorted current by inductive CTs results from the change of the magnetic flux density in the magnetic core of the inductive CT (Fig.5).

In the condition B_{max} the magnetic flux is increased in relation to the sinusoidal conditions. This results from both its shape and increase of its rms value due to the higher harmonics. Therefore, for high value of the load of the secondary winding and high rms value of the primary current it may cause increase of the transformation errors and even saturation of the magnetic core. Moreover, the rms values of the self-generated low order higher harmonics into the secondary current also increases. The decrease of the magnetic flux density in the case B_{min} will have the opposite result. If in the CT the turns correction is made, the current error of the distorted current transformation by inductive CTs for the low value of the load of the secondary winding is positive. Further decrease of the magnetic flux density in the case B_{min} will cause the increase of its value as it will become more positive. The increase of the magnetic flux density in the case B_{max} will have the opposite result.

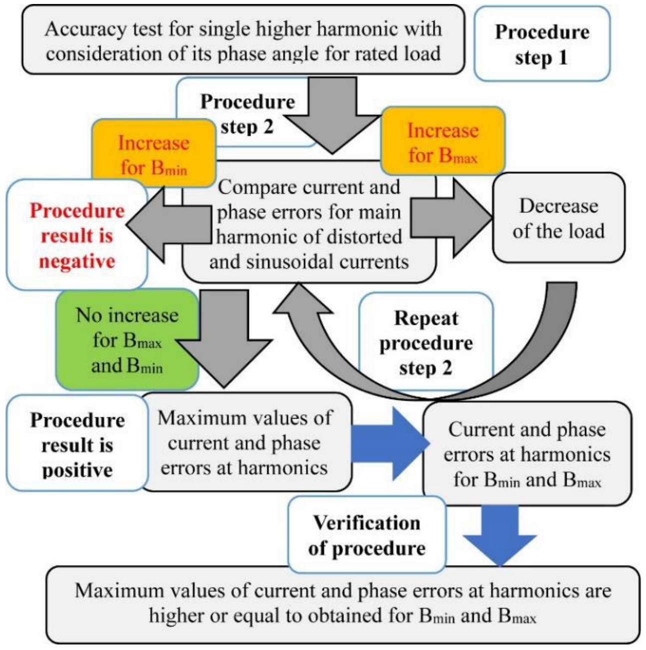

FIGURE 6. The flowchart of the proposed procedure to determine the maximum values of current and phase errors at harmonics for transformation of distorted current by the tested inductive CT.

The flowchart of the proposed procedure to determine the maximum values of current and phase errors at harmonics for transformation of the distorted current by the tested inductive CT for its specified value and type of load of the secondary winding is presented in Fig.6.

In accordance with presented above flowchart first the values of current and phase errors at harmonics for transformation of the distorted current with single higher harmonic are determined. During this evaluation in the step 1 of the proposed procedure the influence of the phase angle of the higher harmonic in the transformed primary current in relation to its main component is considered. This is required due to determine the maximum values of current and phase errors at harmonics for transformation of higher harmonic of the distorted current. The change of the values of current and phase errors results from the different phase angle for summation of higher harmonic in transformed primary current with higher harmonic already present in the secondary current due its self-distortion by the inductive CT. This phenomenon is discussed in "5. Generation of the lower order harmonics and their influence on the values of current and phase error of transformation of higher harmonics of distorted current". In the step 2 of the procedure current and phase errors are determined for transformation of sinusoidal current and the main harmonic of distorted current in the conditions B_{min} and B_{max}. The tests are made for required operation range of rms values of the primary current and load of the secondary winding of a given CT. The step 2 of the procedure is used to determine increase of the current and phase errors of transformation of distorted current caused by the conditions B_{min} and B_{max}. Increase of the magnetic flux density caused by higher harmonics may be decreased by derating of the load of the secondary winding [27]. Than the step 2 of the procedure is repeated for the reduced load of the secondary winding. Procedure result is positive if the B_{max} conditions does not cause increase of the current and phase error of transformation of the main harmonic of the distorted current with rated or decreased load of the secondary winding. Simultaneously, the B_{min} conditions may not cause increase of the current and phase error for 25% of load of the secondary winding. Therefore, maximum values of the current and phase errors at harmonics for transformation of distorted current by the tested inductive CT for its specified load of the secondary winding may be determined. Procedure result is negative if derating of the load of the secondary winding has no expected effect. It means that the tested CT is no able to obtaining the condition of no significant increase of the values of current and phase errors of transformation of the main harmonic of distorted current in the conditions B_{max} and B_{min} in relation to values measured for sinusoidal current. This results from the fact that for such inductive CT maximum values may not be determined by the procedure since the magnetisation characteristic of its magnetic core is strongly nonlinear. Obviously it may not be used for accurate transformation of the distorted current due to high self-distortion of its secondary current. During verification of the procedure the values of current and phase errors at harmonics are determined in the conditions B_{max} and B_{min}. This evaluation in contrast to values determined in step 1 of the proposed procedure the influence of the phase angle of higher harmonic in transformed primary current in relation to its main component is not considered. This is due to the fact that if phase angle of any harmonic is changed the maximum B_{max} or the minimum B_{min} values of the magnetic flux density for the limiting rms values of the higher harmonics in accordance with the standard IEC 61000-3-12 are not obtained. Procedure verification is positive if simultaneously determined values of current and phase errors of order 1st to 13th harmonics are lower than determined for the each higher harmonic separately in the step 1.

V. GENERATION OF THE LOWER ORDER HARMONICS AND THEIR INFLUENCE ON THE VALUES OF CURRENT AND PHASE ERROR OF TRANSFORMATION OF HIGHER HARMONICS OF DISTORTED CURRENT

In this section the results of accuracy tests of both inductive CTs during transformation of the distorted currents composed of the main harmonic of frequency 50 Hz and the one single harmonic of order from 3rd to 100th are presented. First, the analyses of the higher harmonics content of their secondary current during transformation of sinusoidal primary current are made. This is important to estimate the level of the self-distortion of their secondary current. It is caused by the nonlinearity of the magnetization characteristic of the magnetic core and depends from the load of the secondary winding and the rms value of the primary current. Measured rms values of the higher harmonics of the secondary current during transformation of the sinusoidal current by the tested CT designed for transformation of the sinusoidal current are presented in Fig. 7.

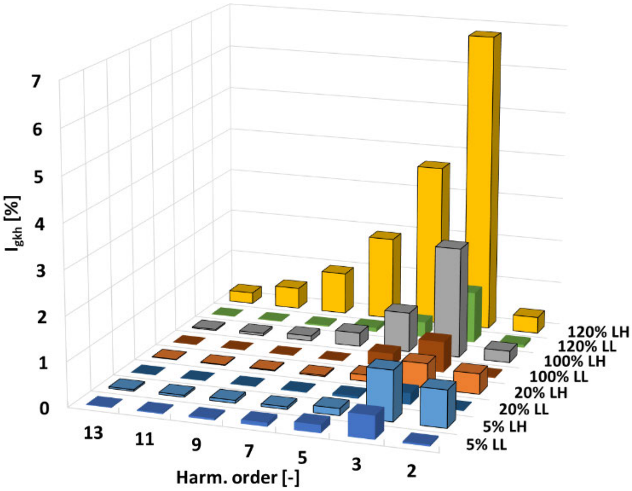

FIGURE 7. The rms values of higher harmonics in the secondary current of 50 Hz type tested CT for transformation of the sinusoidal current.

In Fig.7. the following notations are used: LL – 25% of rated load, LH – rated load, I_{ghk} – the percentage value of higher harmonic in relation to rms value of main harmonic of distorted secondary current.

The test were made for values of primary currents equal to 5%, 20%, 100% and 120% of the rated value equal to 5 A and two values of the load of the secondary winding. In the case of the rated load of tested CT, values of generated higher harmonics in secondary current are higher than for 25% of rated load. Moreover, the number of the higher harmonics in the secondary current increases. This is due to the increase of the magnetic flux density causing the movement of CT's operating point on the magnetization characteristic from point $B_1(H_1)$ nearer to its knee into the nonlinear region in point $B_2(H_2)$ as presented in Fig.8.

The value of the magnetic flux density in the core as results from equation (9) increases with load of the secondary winding and value of the primary current. Therefore, the highest value of the magnetic flux density is obtained for rated load of the inductive CT and 120% of its rated primary current (150% or 200% if applicable). Higher harmonics in distorted primary current causes the change of the magnetizing curve of the magnetic core from black line to red line [7], [25]. Therefore, for the same magnetic field strength H_2 higher magnetic flux density B_3 is obtained. Moreover, as presented in Fig. 9 for the case B_{max}, there is an increase of the self-generation of the higher harmonics into the secondary current by tested 50 Hz type inductive CT. This is due to the increase of the magnetic flux density causing by the change of the magnetization characteristic and the movement of CT's operating point from

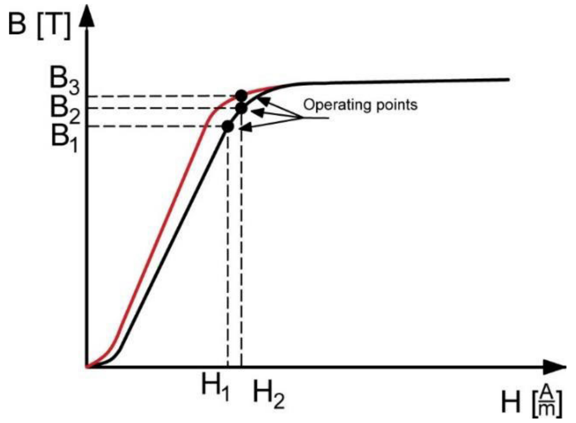

FIGURE 8. **The operating points of the inductive CT on its magnetization curve of the magnetic core.**

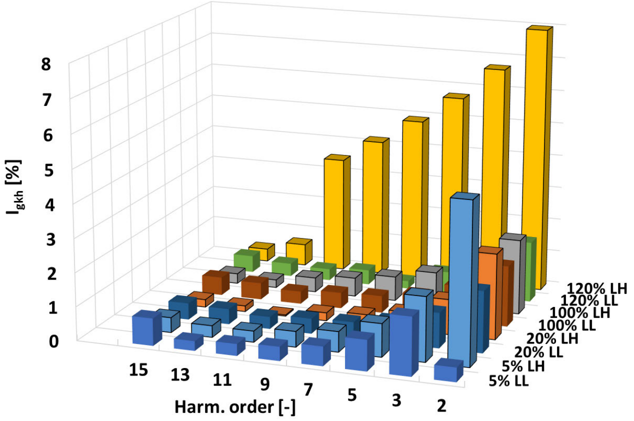

FIGURE 9. **The rms values of higher harmonics in the secondary current of 50 Hz type tested CT for transformation of the distorted current in the case B_{max}.**

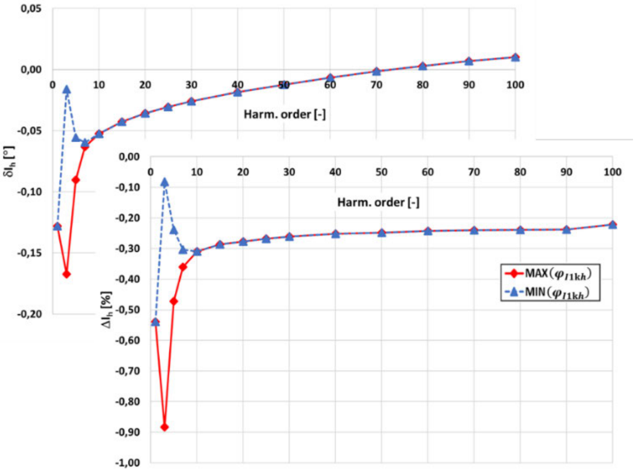

FIGURE 10. **The influence of the self-generated by wideband CT higher harmonics on current and phase errors of transformation of higher harmonics of distorted primary current for rated rms value and load.**

point $B_2(H_2)$ deeper into its nonlinear region in point $B_3(H_2)$ as presented in Fig.8.

Due to the explained self-distortion of the inductive CT's secondary current the low order higher harmonic of distorted primary current transformed by CT adds up with the same frequency self-generated harmonic. The maximum and minimum values of current and phase errors determined with consideration of the influence of self-generated by the wideband CT higher harmonics are presented in Fig.10.

The values of current and phase errors at harmonics were determined for transformation of the distorted primary current of main frequency 50 Hz with single higher harmonics of frequency from 100 Hz to 5 kHz. The measurements are made for the rated rms value of the primary current and the rated load of the secondary winding. It results from Fig.7 that significant is only the impact of higher harmonics of frequencies below 650 Hz self-generated by wideband type CT. To obtain MAX\ MIN characteristics the phase angle of primary current's higher harmonic in relation to the main harmonic is changed for each frequency from 0° to 360° in the 10° steps. The decrease of the values of current and phase errors along with the frequency of transformed lower order higher harmonic (starting from 5th) results from the increase with frequency of the reactance of the magnetic core and therefore decrease of the excitation current. This is obtained due to the high quality magnetic core that ensures high permeability and low power losses in the magnetic core in the frequency range up to 5 kHz. The main aspect in which the results presented in the Fig.9 were analysed is the influence of self-generated by the wideband type CT low order higher harmonics on its transformation accuracy of higher harmonics of distorted primary currents. In the case when low order higher harmonic in transformed distorted current is in phase with generated harmonic, negative current error is decreased and it obtains positive value. While when their phases are opposite negative current error is increased. Moreover, if transformed low order higher harmonic is 90° shifted in phase in relation to generated harmonic, negative phase error is decreased and it obtains positive value. While when their phases are shifted by 270° negative phase error is increased. The dependence of the values of current and phase errors of transformation of 3rd higher harmonic from its phase angle in relation to main harmonic of distorted primary current is presented in Fig.10. It result from self-generation of the same frequency harmonic in the secondary current caused by nonlinearity of the tested wideband type inductive CT.

In Fig.11. the following notations are used: Composite \ Current\Phase error 100%\20% – maximum (solid line) and minimum (dashed line) values of composite\current\ phase error determined for 3rd higher harmonic if primary current is equal to 100%\20% of rated rms value.

The course of the changes of current and phase errors of transformation of higher harmonic by inductive CTs is sinusoidal. Amplitude and Y axis offset of such waveform depends on CT operating conditions that determine values of current and phase errors without the influence of self-generated by the tested CT harmonic in the secondary current. The results confirming such influence for 20% of rms value of primary current and rated load are presented in Fig.12.

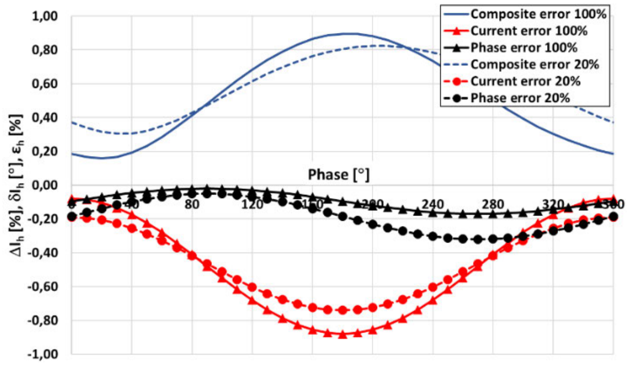

FIGURE 11. The dependence of the values of current and phase errors of transformation of 3rd higher harmonic by the wideband type inductive CT from its phase angle in relation to main harmonic of the distorted primary current.

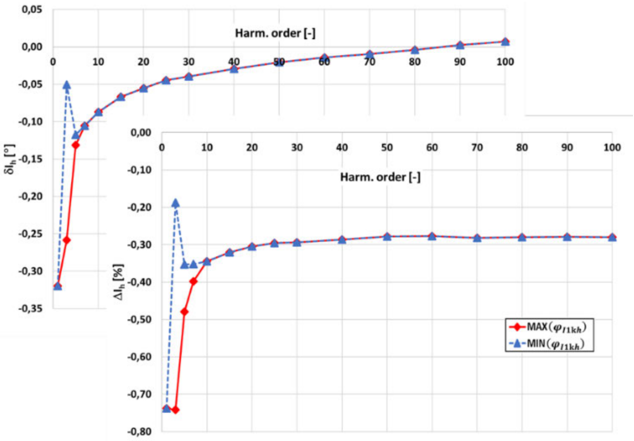

FIGURE 12. The influence of self-generated by the wideband CT higher harmonics on current and phase errors of transformation of higher harmonics of distorted primary current for 20% of rated rms value and rated load (the notations are used same as in Fig.10).

The maximum values of phase and current errors determined for transformation of low order higher harmonics by the tested wideband type CT as presented in Fig. 12 have lower values than for rated rms value of primary current and same load (Fig.10). This results from lower distortion of the secondary current caused by nonlinearity of the magnetic core. The magnetization characteristic of the tested CT's magnetic core becomes more nonlinear with increase of the rms value of the primary current towards its saturation. However, CT's nonlinearity due to the magnetic core is still present.

VI. ESTIMATION OF THE INFLUENCE OF THE CHANGE OF THE MAGNETIC FLUX DENSITY CAUSED BY DISTORTION ON THE SELF-GENERATION OF HIGHER HARMONICS INTO THE SECONDARY CURRENT OF CT

The measuring circuit presented in Fig.13 is used first for verification of determined by the digital power meter values of current and phase errors of transformation of the main harmonic of distorted current with current comparator. It is designed to tests accuracy of inductive CTs for transformation of sinusoidal current. Therefore, it is equipped with the 50 Hz bandpass filter.

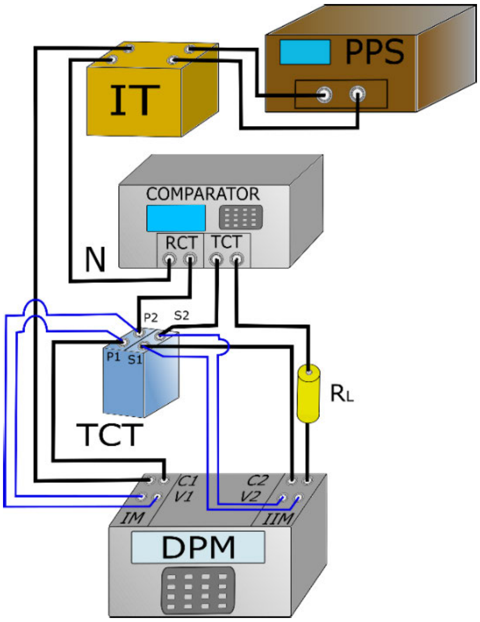

FIGURE 13. The measuring circuit for verification of determined values of current and phase errors of transformation of main harmonic of distorted current with current comparator.

Usage of the current comparator required disconnection of the differential wire due to forced ground in the terminal of the reference CT on the input (*RCT*). The digital power meter is used in this measuring circuit for control of the rms values of harmonics in distorted primary and secondary currents and voltages on primary and secondary windings of the tested CT.

Estimation of the influence of the change of the magnetic flux density caused by higher harmonics on self-generation of higher harmonics into the secondary current of the CT is made from the change in the values of current and phase errors of transformation of main harmonic of distorted current.

In Table 2 determined by current comparator values of current and phase errors of transformation of the main harmonic of distorted current by the 50 Hz type inductive CT designed for transformation of sinusoidal current are presented. The results concern cases B_{max}, B_{min} and transformation of distorted current with single higher harmonic (50 Hz + hk).

In both tables the highest values of current and phase errors for each tested case are bolded.

First important conclusion from the results presented in the table above is that the increase of the magnetic flux density in the case B_{max} causes significant increase of the values of current and phase errors of transformation of main harmonic of distorted current. In conditions of rated load of the secondary winding and main harmonic of distorted current equal to 120% of rated primary current significant decrease of transformation accuracy of the main harmonic of distorted current is detected. Therefore, the self-generation of

TABLE 2. Current and phase errors of transformation of the main harmonic of the distorted current by the 50 Hz type inductive CT for tested cases B_{max}, B_{min} and with single higher harmonic.

Secondary winding load: 10 W / 2.5 W						
[%] of I_1	ΔI [%]			δφ[°]		
	B_{max}	B_{min}	50 Hz + hk	B_{max}	B_{min}	50 Hz + hk
5%	-0.69/ 0.06	**-0.75/ 0.07**	-0.68/ 0.05	0.84/ 0.48	**1.10/ 0.51**	0.82/ 0.50
20%	-0.45/ 0.23	**-0.59/ 0.25**	-0.46/ 0.23	0.60/ 0.30	**0.60/ 0.30**	0.59/ 0.30
100%	**-0.49/** 0.32	-0.45/ **0.33**	-0.48/ 0.33	**0.34/** 0.15	0.33/ **0.15**	0.33/ 0.15
120%	***-0.73*****/** 0.33	-0.47/ **0.35**	-0.47/ 0.33	***1.75*****/** 0.14	0.24/ **0.14**	0.61/ 0.14

TABLE 3. Current and phase errors of transformation of the main harmonic of the distorted current by the wideband type inductive CT for tested cases B_{max}, B_{min} and with single higher harmonic.

Secondary winding load: 10 W / 2.5 W						
[%] of I_1	ΔI [%]			δφ[°]		
	B_{max}	B_{min}	50 Hz + hk	B_{max}	B_{min}	50 Hz + hk
5%	-0.85/ -0.38	**-0.95/ -0.44**	-0.84/ -0.40	0.54/ 0.26	**0.65/ 0.38**	0.53/ 0.25
20%	-0.64/ -0.26	**-0.70/ -0.29**	-0.65/ -0.28	0.38/ 0.19	**0.45/ 0.20**	0.40/ 0.20
100%	**-0.53/** -0.23	-0.53/ **-0.25**	-0.53/ -0.22	**0.20/** 0.11	0.19/ **0.12**	0.20/ 0.11
120%	**-0.55/** -0.23	-0.50/ **-0.25**	-0.55/ -0.21	**0.20/** 0.12	0.19/ **0.12**	0.19/ 0.11

higher harmonics into the secondary current of tested CT is also increased. Therefore, derating of the secondary winding rated load to 8 W is required to ensure highest accuracy of wideband transformation and lowest values of current\phase errors at harmonics. Then in conditions of rated load of the secondary winding and main harmonic of distorted current equal to 120% of rated primary current no increase of the values of current and phase errors of transformation of main harmonic of distorted current is detected.

The decrease of the rms value of the main harmonic of distorted current in the case B_{min} in relation to other two cases (B_{max} and *sin 50 Hz + h.*) causes increase of the values of current and phase errors of its transformation. This occurs in all cases except conditions for the rated load of the secondary winding and the main harmonic of distorted current equal to 100% and 120% of the rated primary current. Therefore, only if high value of the magnetic flux density in the magnetic core is obtained it leads to decrease of the values of current and phase errors of transformation of the main harmonic of the distorted current. This results then from the CT operation beyond the linear region of its magnetization characteristic (Fig.8). The decrease of the rms value of main harmonic of distorted current cause decrease of the magnetic flux density in the magnetic core. In result the CT operates closer to the linear region of its magnetization characteristic. In Table 3 determined by the current comparator values of current and phase errors of transformation of main harmonic of distorted current by the wideband type inductive CT for tested cases B_{max}, B_{min} and the distorted current with single higher harmonic are presented.

In the case B_{max} tested the wideband CT is not beyond the linear region of its magnetization characteristic for any of the rms values of the primary current. Therefore, there is no increase of the values of current and phase errors of the main harmonics transformation. However, similar increase of the positive value of these errors as for previously tested the 50 Hz type inductive CT is detected in the case B_{min} for 25% of rated load of its secondary winding.

In the case when sinusoidal voltage with single higher harmonic is transformed by both tested CTs the values of current and phase errors are not increased by changes of the magnetic flux density caused by higher harmonics.

VII. THE SUMMARY OF THE RESULTS FROM THE WIDEBAND TRANSFORMATION ACCURACY TESTS OF CTs

Proposed evaluation procedure enables determination of the highest values of current and phase errors for transformation of the higher harmonics of the distorted primary current with the limited permissible distortion. In Fig.14 the final complete set of the results fully specifying the wideband transformation accuracy of the 50 Hz type inductive CT is presented.

In Fig.14. the following notations are used: 5%, 20%, 100%, 120% and LH (dashed line) or LL (solid line) – a given percentage of rated primary current and a given percentage of rated load of the secondary winding of tested CT.

From the results presented in Fig.14 the accuracy class of transformation of sinusoidal current of frequency equal to 50 Hz may be determined as well as wideband accuracy of transformation of higher harmonics of distorted primary current. The accuracy class for sinusoidal current is 0.5, taking into consideration defined limits for current and phase errors in the standard IEC 61869-2: (I_1 = 5%: ±1.5%, ±1.5°), (I_1 = 20%: ±0.75%, ±0.75°), (I_1 = 100%\120%: ±0.5%, ±0.5°). It can be clearly seen that if same limits are used for evaluation of the wideband accuracy class the problem for low frequency higher harmonics lays first in accuracy of transformation of the 3rd harmonic (I_1 = 100%\120%: ΔI_h = ±1.0%\1.2% for rated load). Further derating of the load of the secondary winding of the 50 Hz type inductive CT than previously adopted value equal to 8 W will only increase the frequency band of its operation in 0.5 accuracy class to 11th harmonic. This results from the fact that for the secondary winding load equal to 2 W the value of current error of transformation of 15th higher harmonic is now equal

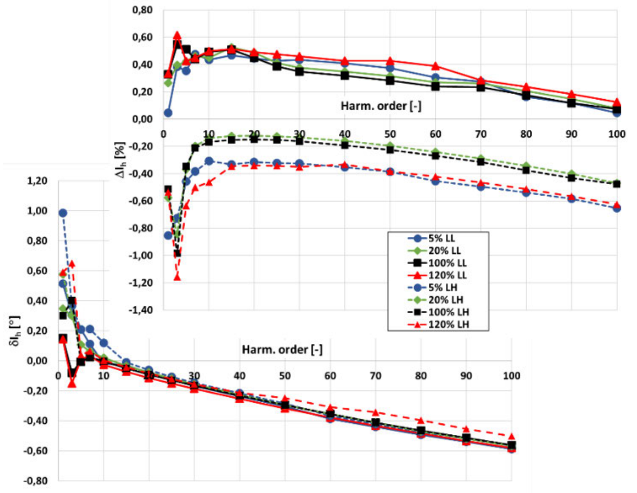

FIGURE 14. The final complete set of the results fully specifying the wideband transformation accuracy of the 50 Hz type inductive CT.

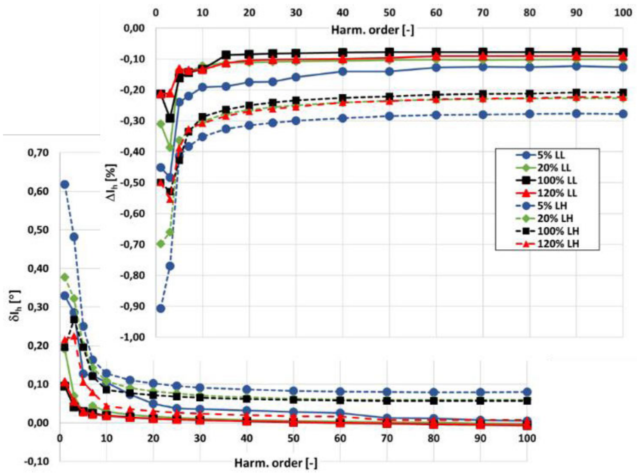

FIGURE 15. The final complete set of results fully specifying the wideband transformation accuracy of the wideband type inductive CT (used notations are as in Fig.13).

to ±0.48%. Therefore, further derating of the load will result in increase of the positive current error for 25% of rated load and even for higher harmonic of lower order. Moreover, as results from determined values of current error starting from 70th higher harmonic the accepted limit value of the current error equal to ±0.5% is exceeded for rated load of the tested CT secondary winding.

In Fig.15 the final complete set of the results fully specifying the wideband transformation accuracy of the wideband type inductive CT is presented.

In the case of the inductive CT described by the manufacturer as wideband type, it can be confirmed from results presented in Fig.15 that its accuracy class is 0.5 for transformation of the sinusoidal current of frequency equal to 50 Hz. Moreover, as results from determined wideband transformation accuracy the value of current error exceeds accepted in this considerations limiting value of current error equal to ±0.5% only for 3rd higher harmonic. This concerns only rated load of the secondary winding of the tested wideband type CT and condition when its primary current in equal to 120% of its rated value. Example calculations are presented for 10th harmonic and this wideband type CT at 100% of its rated primary current and rated load of its secondary winding from measured quantities:

- the rms value of the *hk* harmonic (U_{RShk}) in voltage of current shunt R_S (0.1 Ω) equal to 0.0501 V,
- the rms value of the *hk* harmonic (U_{RDhk}) in voltage of current shunt R_D (1 Ω) equal to 0.0017 V,
- the phase angle (ϕ_{kh}) between *hk* harmonic of voltages U_{1h} and U_{RDhk} equal to 17.4°.

According to equation (3) the rms value of the 10th harmonic of the secondary current of tested CT is equal to 0.4994 A. The percentage value of the composite error in relation to its rms value in distorted primary current is determined from the equation (2) and is equal to 0.333%. Then, the value of the current error according to equation (4) is equal to 0.032% and the value of the phase errors determined from equation (5) is equal to 0.052 °.

VIII. VERIFICATION OF THE EFFECTIVENESS OF THE PROCEDURE TO DETERMINE THE MAXIMUM VALUES OF CURRENT AND PHASE ERRORS AT HARMONICS

Presented in this paragraph values of current and phase errors of transformation of the harmonics of the distorted primary current in the range of frequencies from 100 Hz to 5 kHz are determined in the measuring circuit from Fig.1. The measurements are made for the conditions when the maximum (B_{max}) and the minimum (B_{min}) peak values were achieved in tested CT's magnetic core. The values of current and phase errors at harmonics from 1st to 13th and *hk* higher harmonics up to order 100th are simultaneously determined. These results presented in Fig.16 are compared with the values of current and phase errors at harmonics obtained for transformation of distorted current composed of the main frequency harmonic and one higher harmonic (50Hz+hk) in step 1 of the proposed procedure. In this conditions the influence of the phase angle of higher harmonic in transformed primary current in relation to its main component is considered. The values of current and phase errors at *hk* higher harmonics up to order 100th are determined severally.

In Fig.16. the following notations are used: CE (solid line)\PE (dashed line) - values of current \ phase error determined in conditions B_{max}, B_{min} and (50 Hz+hk).

Increase of the magnetic flux density in the case B_{max} causes the increase of the self-generation of the low order higher harmonics into the secondary current by the tested 50 Hz type CT in relation to results obtained for transformation of distorted primary current with single higher harmonic (50Hz+hk). Performed derating of the load of the secondary winding to 8 W causes that the valaues of current\phase errors become equal to obtained for the case B_{min} and lower than in case (50Hz+hk). Therefore, the maximum values of current and phase errors at harmonics for transformation of

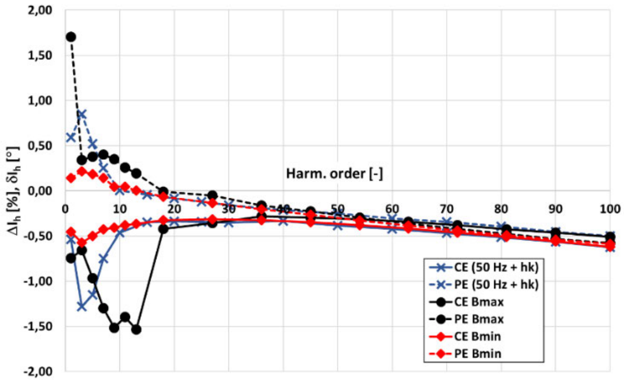

FIGURE 16. The values of current and phase errors at harmonics determined for the 50 Hz type CT and 120% of the rated primary current and the rated load in the conditions Bmax, Bmin and (50Hz+hk).

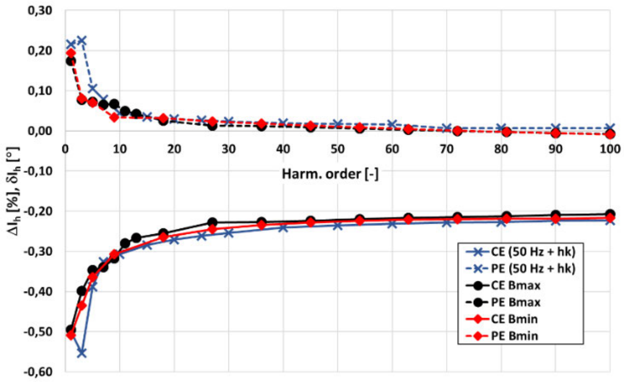

FIGURE 17. The values of current and phase errors at harmonics determined for the wideband type CT and 120% of the rated primary current with the rated load in the conditions Bmax, Bmin and (50Hz+hk) (the notations are used as in Fig.16).

the distorted current by the tested 50 Hz type CT are determined in accordance with proposed procedure. Such transformation accuracy of tested CT is ensured for its secondary winding load from 2 W to 8 W and the primary current rms value from 5% to 120% with the highest distortion acceptable in accordance with the standard IEC 61000-3-12.

In Fig.17 the values of current and phase errors of harmonics transformation by wideband type CT for 120% of rms value of primary current and rated load determined in the conditions B_{max}, B_{min} and (50 Hz+hk) are presented.

The wideband type inductive CT is characterized by low distortion of the secondary current in relation to the 50 Hz type inductive CT made by the same manufacturer. Moreover, transformation accuracy of the higher harmonics in the frequencies range from 100 Hz to 5 kHz is also significantly higher. The limiting value of current error equal to ±0.5% only for 3^{rd} higher harmonic is exceeded. The values of current and phase errors obtained for the cases B_{max} and B_{min} are lower than determined in case (50Hz+hk). The change of the magnetic flux density cause no change in determined values of current and phase errors. This results from the fact that the operating point of the CT is still in the linear region of the magnetization characteristic of its magnetic core (Fig.8).

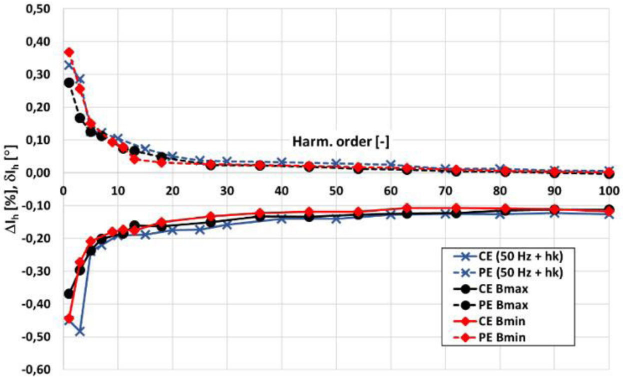

FIGURE 18. The values of current and phase errors at harmonics determined for the wideband type CT and 5% of the rated primary current with 25% of the rated load in the conditions Bmax, Bmin and (50Hz+hk) (the notations are used as in Fig.16).

In Fig.18 values of current and phase errors of harmonics transformation by the wideband type CT for 5% of rms value of primary current and 25% of rated load are presented.

In the case of the wideband inductive CT small distortion of secondary current is detected also for 5% of rms value of primary current and 25% of rated load. The values of current and phase errors obtained for cases B_{max} and B_{min} are still lower than determined in case (50Hz+hk).

In the case of both tested CTs proposed procedure was verified to be effective and ensures determination of the maximum values of current and phase errors of transformation of the harmonics of the distorted current.

IX. CONCLUSION

The results of presented analysis shows that in the evaluation of the wideband accuracy of the inductive CTs the impact of the primary current harmonics on the peak value of the magnetic flux density in the magnetic core and their phase angles in relation to the self-generated higher harmonics into the secondary current must be considered. The dependence of the values of current and phase errors of transformation of higher harmonic by the inductive CT from its phase angle in relation to main harmonic of distorted primary current is sinusoidal. Therefore, every 90° the value of current or phase error is decreased or increased. Obtained differences between determined values of current and phase errors at harmonics may be simultaneously caused by the change of the magnetizing curve of the magnetic core. The same magnetic field strength in the magnetic core for distorted primary current may cause higher value of the magnetic flux density is the magnetic core. Therefore, there may be also an increase of the self-generation of the higher harmonics into the secondary current of the inductive CT. However, such deterioration of their accuracy may be limited by derating of the load of the secondary winding. Moreover, this impact of the higher harmonics may be detected from the increase of the values of current and phase errors of transformation of the main harmonic of the distorted current in relation to the sinusoidal conditions. In accordance with the developed procedure it is possible to determine the maximum values of current and phase errors for a given operating conditions of the tested inductive CT. It combines both the influence of secondary current distortion caused by nonlinearity of the magnetic core and the impact of the harmonic distortion on the peak value of the magnetic flux density. The wideband transformation accuracy of tested CTs is ensured for specified range and type of the load of the secondary winding, rms values of the primary current and its level of distortion. The limiting value of the higher harmonics content in the primary current is defined by the maximum considered increase of the magnetic flux density in the magnetic core. Therefore, it is possible to assign to the inductive CT its accuracy class for transformation of distorted current with specified limited rms values of a given frequency higher harmonics.

LIST OF SYMBOLS AND ACRONYMS

ΔI_{hk}	the percentage value of current error determined at hk harmonic of the distorted primary current;
ΔU_{Rdc}	the tolerance of resistance of the current shunt;
δI_{hk}	the value of phase error determined at hk harmonic of the distorted primary current,
ε_{Ihk}	the percentage value of the composite error determined for transformation of hk harmonic of the distorted current;
ϕ_{hk}	the phase angle between *hk* harmonic of voltages from resistors R_S and R_D;
B	the instantaneous values of the magnetic flux density,
$B(t)_{dist}$	the instantaneous values of the magnetic flux density obtained for the instantaneous values of the distorted secondary voltage (u dist.);
$B(t)_{50\ Hz}$	the instantaneous values of the magnetic flux density obtained for the instantaneous values of the sinusoidal secondary voltage (u_{50Hz}) of tested CT if its rms value is equal to the rms value of the distorted secondary voltage ($u_{2dist.}$);
B_{max}	the maximum value of the magnetic flux density in the magnetic core that is obtained for the rms values of the higher harmonics in the distorted primary current equal to the highest limits for harmonic currents produced by equipment connected to public low-voltage systems in accordance with the standard IEC 61000-3-12;
B_{min}	the minimum value of the magnetic flux density in the magnetic core that is obtained for the rms values of the odd higher harmonics in the distorted primary current equal to the highest limits for harmonic currents produced by equipment connected to public low-voltage systems in accordance with the standard IEC 61000-3-12;
CE B_{MAX}	the values of current errors at harmonics determined for conditions when the rms values of the higher harmonics in distorted primary current are equal to the limits for harmonic currents produced by equipment connected to public low-voltage systems and the magnetic flux density in the magnetic core of tested CT is equal to B_{max};
CE B_{MIN}	the values of current errors at harmonics determined for conditions when the rms values of the odd higher harmonics in distorted primary current are equal to the limits for harmonic currents produced by equipment connected to public low-voltage systems and the magnetic flux density in the magnetic core of tested CT is equal to B_{min};
CE (50Hz+hk)	the values of current errors at harmonics determined for transformation of the distorted primary current composed of the main frequency harmonic (50 Hz) and the one higher harmonic of frequency for 100 Hz to 5 kHz;
CT	the current transformer;
DPM	the digital power meter;
EMC	the electromagnetic compatibility;
f_{hk}	the frequency of *hk* harmonic;
$FFT(B_{max})$	the results of the Fast Fourier Transformation obtained for the instantaneous values of the magnetic flux density if its maximum value is equal to B_{max};
$FFT(B_{min})$	the results of the Fast Fourier Transformation obtained for the instantaneous values of the magnetic flux density if its maximum value is equal to B_{min};
I_{1kh}	the rms value of *hk* harmonic of the distorted primary current;
I_{2kh}	the rms value of the *hk* harmonic of the secondary current of tested CT;
I_{ghk} [%]	the percentage value of higher harmonic in relation to the rms value of the main harmonic of distorted secondary current;
IT	insulation transformer;
L	the value of the inductance of the current shunts equal to 0.08 μH;

MAX(φ_{I1hk})	the maximum values of phase and current errors obtained for a given phase angle ϕ_{I1hk} between *hk* higher harmonic and main harmonic of the primary current;
MIN(φ_{I1hk})	the minimum values of phase and current errors obtained for a given phase angle ϕ_{I1hk} between *hk* higher harmonic and main harmonic of the primary current;
MV	Medium Voltage;
PE BMAX	the values of phase errors at harmonics determined for the conditions when the rms values of the higher harmonics in distorted primary current are equal to the limits for harmonic currents produced by equipment connected to public low-voltage systems and the magnetic flux density in the magnetic core of tested CT is equal to Bmax;
PE BMIN	the values of current errors at harmonics determined for the conditions when the rms values of the odd higher harmonics in distorted primary current are equal to the limits for harmonic currents produced by equipment connected to public low-voltage systems and the magnetic flux density in the magnetic core of tested CT is equal to Bmin.
PE (50Hz +hk)	the values of phase errors at harmonics determined for transformation of the distorted primary current of the main frequency 50 Hz and the one higher harmonic of frequency from 100 Hz to 5 kHz;
PPS	the programmable power source;
R	the value of the DC resistance equal to 10 Ω for current shunt $\mathrm{R_D}$ or 0.1 Ω for current shunt $\mathrm{R_S}$;
RCT	the reference current transformer;
$\mathrm{R_D}$	the 10 Ω current shunt for measurements of the excitation current;
$\mathrm{R_L}$	the load resistor of different values connected in the secondary winding of tested CT;
$\mathrm{R_S}$	the 0.1 Ω current shunt for measurements of the primary current;
$\mathrm{s_{Fe}}$	the cross-section area of the magnetic core;
TCT	the tested current transformer;
$\mathrm{u_2}$	the instantaneous values of the secondary voltage;
$\mathrm{u_{2dist.}}$	the instantaneous values of the distorted secondary voltage of tested CT;
$\mathrm{u_{50Hz}}$	the instantaneous values of the sinusoidal secondary voltage of tested CT if its rms value is equal to the rms value of the distorted secondary voltage (u dist.);
$\mathrm{u_{core}}$	the instantaneous values of the voltage of the magnetic core of tested CT;
$\mathrm{U_{2h1}}$	the rms value of the main component of the distorted secondary voltage;
$\mathrm{U_{RDhk}}$	the rms value of *hk* harmonic of voltage of $\mathrm{R_D}$ current shunt;
$\mathrm{U_{RShk}}$	the rms value of *hk* harmonic of voltage from $\mathrm{R_S}$ current shunt;
X% LH	the results for the *X*% of the rated rms value of the primary current with the rated load of the secondary winding of tested CT;
X% LL	the results for the *X*% of the rated rms value of the primary current with the 25% of the rated load of the secondary winding of tested CT;
$\mathrm{z_2}$	the numbers of turns of the secondary winding;
$\mathrm{Z_{hk}}$	the value of the impedance of the current shunts for *hk* harmonic of the distorted current.

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