Equivalent Circuit Parameters of the Current Transformer with Toroidal Core in Conditions of Distorted Signals Transformation

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Abstract— **The subject of the article are the issues regarding the changes of the equivalent and magnetic circuits parameters of the current transformer with toroidal core (made from permalloy NiFe 80) during the transformation of distorted signals. Working mechanism of the windings system and magnetic circuit of transformers in these conditions are being changed as well as their metrological properties. The essence of the problem is that the hysteresis loops of the current transformer core for distorted currents have different shapes than for sinusoidal waveforms. In addition, during the transformation of distorted primary currents there is an increase of active power losses in the transformer core and windings.**

Keywords- current transformer; distorted currents, active power losses; magnestization charakteristic; power quality.

I. INTRODUCTION

To assess the quality of supplied electricity it is necessary to use instrument transformers or other equipment design to measure significant values of voltages and currents. One of the main parameters determining the metrological characteristics of the current transformers is their accuracy class (determined for sinusoidal incremental signals with a frequency of 50 Hz) which limits the error values [1] [2] [3]. In condition of distorted signals transformation, caused by insignificant power quality, conductive disturbances in primary current of the CT cause increase of the power loses in the magnetic core and windings as well as change of the core magnetic properties which results in deterioration of the current transformer metrological properties [4] [5] [6]. This phenomenon is caused by an unfavorable change in the parameters of the CT equivalent circuit and causes increase of the primary signal transformation error and decrease of the current transformer accuracy during estimation of the power quality or working in power system protection circuits [4] [7] [8]. The aim of this study is to determine the change of the electric and magnetic equivalent circuit parameters of the current transformer caused by deterioration of the transferred primary current.

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II. MEASUREMENT METHOD AND OBJECT

During laboratory examinations hysteresis loops of the tested current transformer magnetic core for semi-sinusoidal primary currents, which are magnetization currents distorted only by nonlinearity of the CT magnetic circuit (especially in saturation conditions), as well as for additionally distorted primary currents were determined. Measurements were carried out in accordance with the standards [9] [10] in the measurement system presented in Figure 1

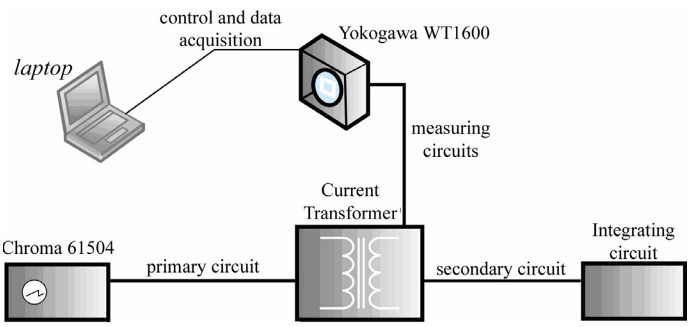

Figure 1. Measuring circuit

AC voltage source model Chroma type 61504 was used for generation of distorted magnetization currents which main frequency was 50 Hz and consisted of additional conductive disturbances with adjustable level. Digital power meter model Yokogawa type WT1600 was applied for measuring of primary current and secondary voltage of the tested current transformer which were used for determine the magnetization characteristic of the toroidal magnetic core. To the secondary side of the transformer (when determining hysteresis loops of the magnetic core) integration circuit is connected to ensure proportionality of the measured secondary voltage to the magnetic flux density in the core. The active power losses in the magnetic core and windings of the current transformer were also determined in both cases for sinusoidal and distorted primary currents. Power loses in the windings of the current transformer were determine in short circuit condition of the secondary winding. The level of active power loses increase in the magnetic core and windings of the CT caused by deterioration of primary current was calculated.

Laboratory studies were made for current transformer which current ratio was 5 A / 5 A [5]. It was an instrument transformer with toroidal core made from permalloy tape (0,2 mm) NiFe 80 which over all cross-section was S_{fe} = 0,0005 m^2. Average magnetic flux path in the core was 0,34 m. Equivalent circuit of the current transformer with one secondary winding for primary currents frequencies to 10 kHz is presented in Figure 2 [2].

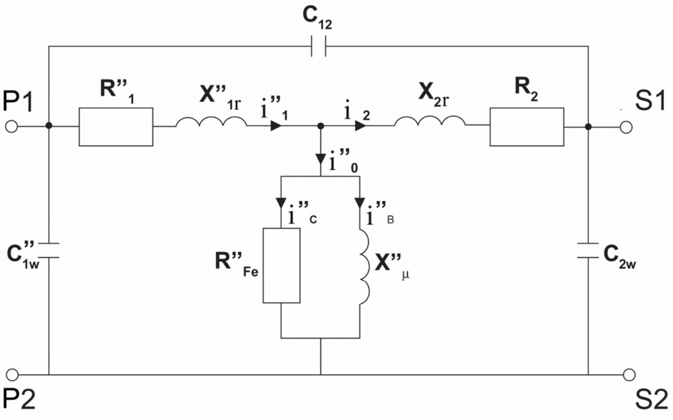

Figure 2. Equivalent circuit of the current transformer with one secondary winding for primary currents frequencies to 10 kHz

On this diagram following designation were used (symbols with two dashes indicate elements converted to the secondary side): i''_1 – current of the primary winding, R''_1 – resistance of the primary winding, X''_{1r} – leakage reactance of the primary winding, i_2 – current of the secondary winding, R_2 – resistances of the secondary winding, X_{2r} – leakage reactance of the secondary winding, i''_C – reactive component of the magnetization current, i''_B – active component of the magnetization current, R''_{Fe} – resistance imagining the active losses in the magnetic core, X''_{μ} – main reactance, C''_{1w} – equivalent capacity of the primary winding, C_{2w} – equivalent capacity of the secondary winding, C_{12} – equivalent capacities between primary and secondary windings.

Used equivalent circuit of the current transformer (fig. 2) in relation to classic equivalent circuit was extended with equivalent capacities of windings (C''_{1w}, C_{2w}) and equivalent capacity between primary and secondary windings (C_{12}) which consideration is required due to range of transferred through tested current transformer distorted primary current higher harmonics [2] [4] [5]. Analysis of laboratory results shows that additional capacities consideration due to the low level of conductive disturbances (8% max of primary current RMS value) in this case is not necessary.

III. Results of the Laboratory Research

The first stage of laboratory tests was to determine the hysteresis loop of the current transformer magnetic core for quasi-sinusoidal magnetic induction that is for an open secondary winding and supply of the current transformer primary winding with sinusoidal voltage of frequency 50 Hz without introducing any additional conducted disturbances.

Figure 3 presents magnetic current I_0 and secondary voltage U_2 curves in condition of magnetic circuit saturation for magnetic flux strength in the current transformer core equal 40 A/m.

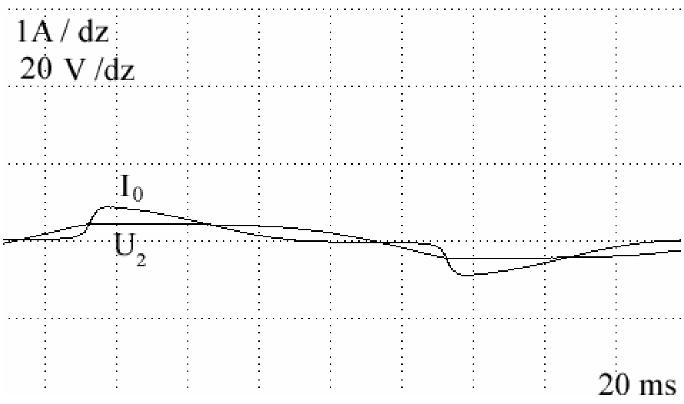

Figure 3. Magnetic current I_0 and secondary voltage U_2 curves in condition of magnetic circuit saturation for magnetic flux strength in the current transformer core equal 40 A/m with no additional conductive disturbances

The shape of the magnetizing current curve shows a high content of harmonics. RMS values of harmonics in the prescribed course of magnetizing current set with a digital power analyzer Yokogawa WT1600 are presented in Figure 4.

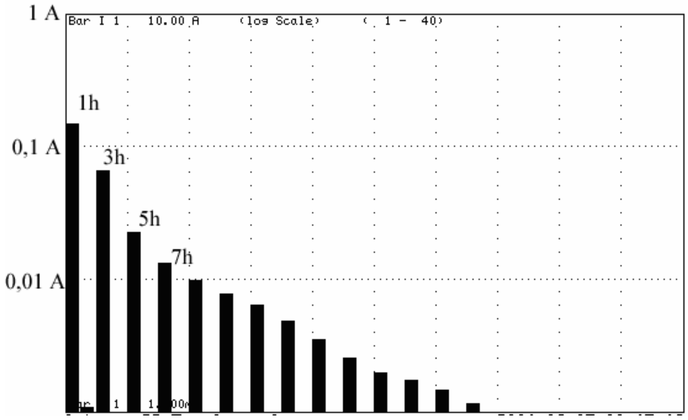

Figure 4. Harmonics of current transformer magnetization current I_0 in condition of magnetic circuit saturation for magnetic flux strength in the current transformer core equal 40 A/m with no additional conductive disturbances

Used digital power meter enables measure of particular harmonic RMS values to frequency 5000 Hz. In case presented in Figure 4 analysis were limited to frequency 2000 Hz in accordance with standard [11]. It should be noted that there were no presence of higher harmonics above the 40th observed. Exponential distribution of magnetizing current particular harmonic RMS values (on a logarithmic scale - Figure 4) with the spectrum which contains odd harmonics is caused by nonlinear magnetization characteristics of the current transformer core and is characteristic for condition when CT operating point is in a state of its magnetic core saturation. THD_I factor in this condition reaches a value of about 51 % [12] [13].

Figure 5 presents harmonics of current transformer secondary voltage U_2 in condition of its magnetic circuit saturation for magnetic flux strength in the current transformer core equal 40 A/m with no additional conductive disturbances.

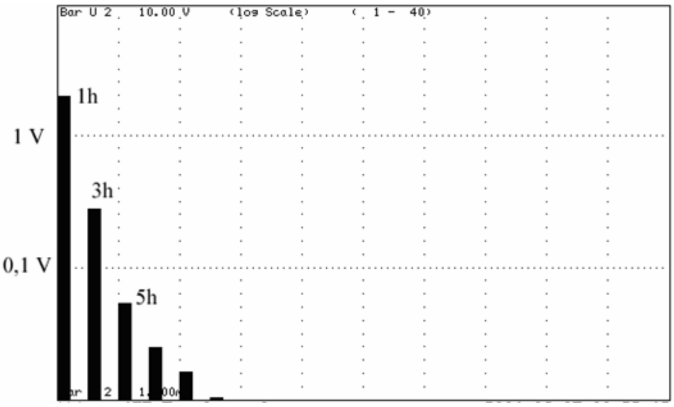

Figure 5. Harmonics of current transformer secondary voltage U_2 in condition of magnetic circuit saturation for magnetic flux strength in the current transformer core equal 40 A/m with no additional conductive disturbances

THD_{U2} factor in tis condition is about 9 %. Graph of secondary voltage particular harmonic RMS values has also an exponential distribution.

Figure 6 shows the hysteresis loop determined for the current transformer core.

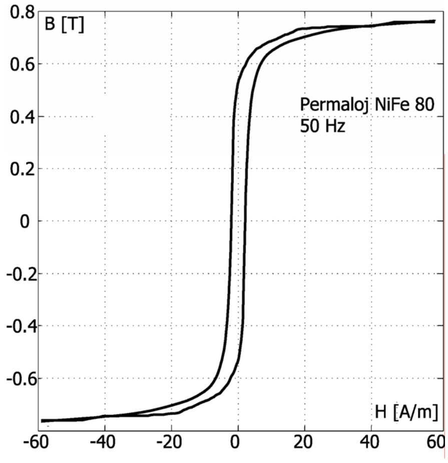

Figure 6. Hysteresis loop of the permalloy NiFe 80 magnetic core determined for primary winding supply voltage frequency 50 Hz with no additional conductive disturbances

Magnetic flux density in saturation of the CT magnetic core is 0,78 T and was reached for magnetic field strength about 36 A/m. Coercive force $H_c = 2{,}5$ A/m. Active power loses in the core is about 0,03 W, while charged reactive power is about 0,1 var. This is a typical characteristic for alloys with high nickel content. The materials of this kind have very high initial and maximum permeability.

Next stage of laboratory studies were measurements made in condition when in the current transformer primary winding supply voltage additional conductive disturbances were generated. The level of these disorders, given from a source, was determined according to the value of the ratio of higher harmonic content. Maximum value of conductive disturbances in this case (in accordance with the standard [11]) was 8%.

Magnetizing current waveforms and secondary voltage in condition of saturation in the magnetic circuit for magnetic field strength 40 A/m is shown in Figure 7.

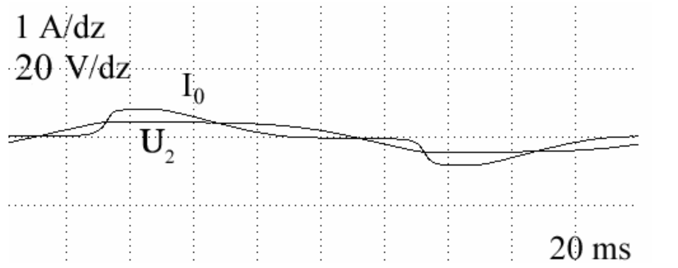

Figure 7. Magnetic current I_0 and secondary voltage U_2 curves in condition of magnetic circuit saturation for magnetic flux strength in the current transformer core equal 40 A/m for primary winding supply voltage THD_{U1} = 8%

High value of conductive disturbances content cause visible in Figure 7 smoothing of the current curve I_0 peak value.

THD_I factor determined for magnetizing current is about 54% while THD_{U2} factor of secondary voltage is about 11%.

Magnetization current particular harmonic RMS values for curve presented in Figure 7 are shown in Figure 8.

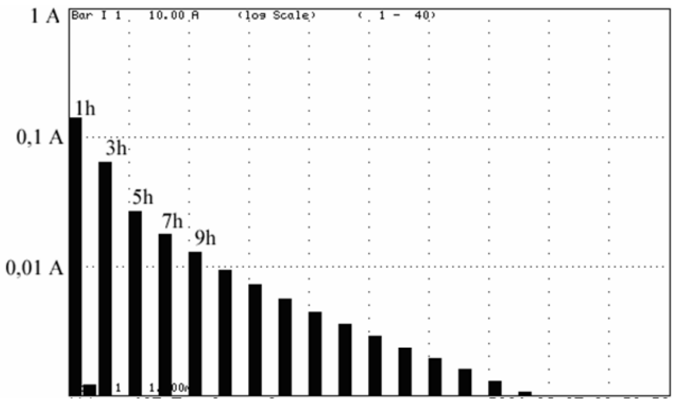

Figure 8. Harmonics of current transformer magnetization current I_0 in condition of magnetic circuit saturation for magnetic flux strength in the current transformer core equal 40 A/m for primary winding supply voltage THD_{U1} = 8%

Magnetization current particular harmonic RMS values in condition when the value of primary winding supply voltage total harmonic distortion factor is 8% increased for about 3%. Occurrence of additional 29th and 31st harmonic in Figure 8 is also noticeable.

Figure 9 shows the results of measuring the RMS value of CT secondary voltage harmonic in saturation conditions of the magnetic circuit when the magnetic field strength in the core of the transformer is 40 A/m and the primary winding supply voltage THD_{U1} is equal 8%.

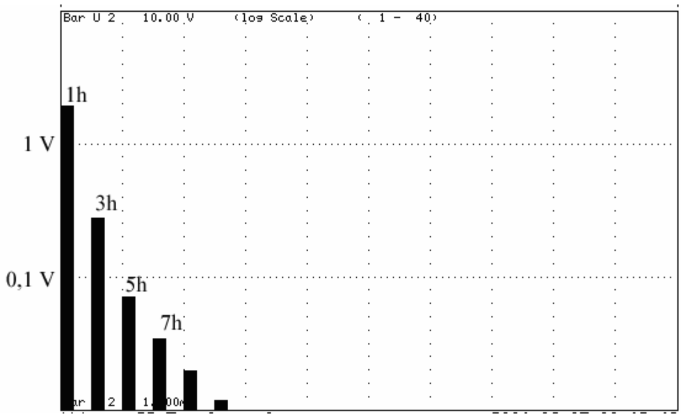

Figure 9. Harmonics of current transformer secondary voltage U_2 in condition of magnetic circuit saturation for magnetic flux strength in the current transformer core equal 40 A/m for primary winding supply voltage THD_{U1} = 8%

Both the course of the secondary voltage and magnetizing current show an increase in particular harmonic RMS values.

The result of the magnetizing current distortion increase is the change of the current transformer toroidal core hysteresis loop shape (Fig. 10.) observed in relation to estimated characteristic without additional conductive disturbances in the current(fig. 6).

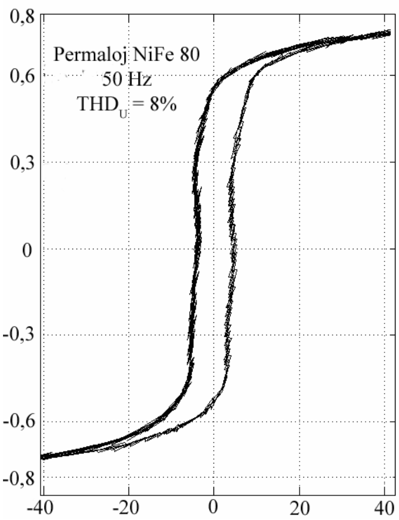

Figure 10. Hysteresis loop of the permalloy NiFe 80 magnetic core determined for primary winding supply voltage frequency 50 Hz and primary winding supply voltage THD_{U1} = 8%

The hysteresis loop determined for the CT magnetic core for an increased level of conducted disturbances in its power supply (THD_{U1} = 8%) is characterized by fluctuations observed in its linear (nominal conditions) part. The increase of histeresis loop width caused by the increase of the active power losses in the CT magnetic core is also noticeable. Coercive force (fig. 10) is now about 4 A/m.

Active power loses and charged reactive power in the core of the current transformer as well as the RMS value of the secondary voltage U_2 were measured for the conditions corresponding to the magnetizing currents shown in Figures 3 and 7 and were determined in the measurement system presented in Figure 1. On these basis the values of reactive component I_C and active component I_B of the magnetizing current as well as parameters R_{Fe} and X_μ of the equivalent circuit from Figure 2 were calculated. It was assumed that in idle state conditions of the current transformer active power loses on resistance R_1 and charged reactive power of leakage reactance X_1 are negligible.

TABLE I. PARAMETERS OF THE CURRENT TRANSFORMER EQUIVALENT CIRCUIT DETERMINED FOR OPEN SECONDARY CIRCUIT AND GIVEN THD_{U1}

THD_{U1} [%]	**Measured values**				**Calculated values**			
	I_0 [A]	***U_2 [V]***	***P [W]***	***Q [var]***	***I_B [A]***	***I_C [A]***	***R_{Fe} [Ω]***	***X_μ [Ω]***
0%	0,029	4,63	0,030	0,11	0,023	0,006	833	208
8%	0,032	4,63	0,044	0,12	0,026	0,007	900	185

The increase of the magnetizing current distortion causes for the same value of the saturation magnetic flux density an increase of the magnetizing current RMS value which results in increase of the active power loses in the magnetic core and increase of the R_{Fe} parameter value. Charged reactive power due to the increase of the magnetizing current reactive component also increases while main reactance X_μ in this condition decreases.

Last stage of the laboratory studies was parameters X_{1r}, X_{2r} and R_1, R_2 calculation. The values were determined on the basis of active and reactive power measurements in CT short circuit conditions. It was assumed that in this condition active power loses on resistance R_{Fe} and charged reactive power by main reactance X_μ are negligible.

TABLE II. PARAMETERS OF THE CURRENT TRANSFORMER EQUIVALENT CIRCUIT DETERMINED FOR SHORT CIRCUIT CONDITION AND GIVEN THD_{U1}

THD_{U1} [%]	**Measured values**				**Calculated values**	
	I_1 [A]	***U_1 [V]***	***P [W]***	***Q [var]***	***R_1 ,R_2 [Ω]***	***X_{1r}, X_{2r} [mΩ]***
0%	5,00	2,59	13,01	0,16	0,26	3,21
8%	5,00	2,64	13,51	0,17	0,27	3,41

Results presented in table II shows that distortion of the current transformer primary current cause for the same RMS value of the primary current (5 A) increase of the supply voltage RMS value. This leads to the active power loses increase in the windings of the current transformer and cause increase of the R_1 and R_2 parameters of the equivalent circuit. Leakage reactance of the current transformer windings X_{1r} and X_{2r} for tested current transformer construction are very small and particularly identical. A slight increase of their value with the increase of the primary current distortion is noticeable.

IV. CONCLUSIONS

- Unfavorable change in the parameters of the current transformer equivalent circuit caused by the primary current distortion leads to the deterioration of the CT metrological characteristic [4] [5] [14] [15].

- The increase of current transformer magnetizing current distortion leads to a deterioration of its magnetic core hysteresis loop and cause the change of its magnetic circuit properties.
- The increase of the total harmonic distortion level (THD_{U1}) of current transformer primary winding supply voltage, which is equal an increase of the magnetization current distortion, causes increase of the active power loses in the CT magnetic core and may lead to the decrease of the magnetic circuit main coupling reactance.
- Increase of the current transformer primary current distortion causes a slight increase of the windings resistance and may lead to the increase of their leakage reactance.

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