Estimation of the inductive current transformer derating for operation with distorted currents

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Abstract. The aim of the paper is to present a new method for estimation of the CT (Current Transformer) rated primary current and / or load of the secondary winding derating levels for transformation of distorted current in relation to the rated values fixed for transformation of sinusoidal current. This ensures the values of the CT composite errors/transformer correction factors as resulting from its IEC 60044-1/IEEE C57.13 accuracy class in condition of distorted currents transformation.

Key words: current transformer, distorted current, derating conditions, composite error, transformer correction factor, accuracy class.

1. Introduction

In low power quality conditions instrument transformers are transforming distorted signals. In these conditions and for transients inductive instrument transformers are characterized by significantly worst metrological properties than at rated frequency of sinusoidal primary signal [1–7]. The increase of transformation error for distorted voltage/current will increase the error of indirect measurements of power and electric energy. Derating of the secondary winding load or/and primary current value will prevent deterioration of the CT (Current Transformer) metrological properties for distorted signals and will ensure that the values of errors of indirect measurements of power and electric energy conforming to the limits resulting from a given CT's accuracy class. Standardization recommendations concerning instrument transformer do not specify requirements for estimation of their accuracy of distorted signals transformation or to calculate derating conditions [8–9]. Therefore, it is necessary to develop appropriate measuring methodology and standardization recommendations of instrument transformers metrological properties estimation for transformation of distorted signals and to estimate their primary current and/or secondary winding load derating levels in such conditions of operation [6, 10]. In publications [11-13] and standard [14] problem of derating of transformers for non-sinusoidal load currents is discussed. Transformers are normally designed and built for utilizing at rated frequency and perfect sinusoidal load current. Supplying non-linear loads by transformer leads to higher losses, early fatigue of insulation, premature defectiveness and reduction of the useful life of the transformer. To prevent these problems, rated capacity of transformers supplying non-linear loads must be reduced [11]. Paper [12] presents a new digital data-acquisition method for measuring derating and reactive power demand of three-phase transformers under full or partial load conditions. Paper [13] describes an improved derating technique based on direct measurements performed at fundamental and harmonic frequencies. Results of measurements of several distribution transformers presented in [13] show the improvement of this method over the one described in IEEE standard C57.110 [14]. Similar steps as presented in [11–14] may be taken for considerations in case of estimation of the inductive current transformer derating conditions for distorted currents.

2. Measuring system

Laboratory studies consisted of the accuracy tests of distorted currents transformation through two window-type CTs with the same low voltage insulation system and accuracy class (1.2 according to IEEE C57.13 [8], 0.5 according to IEC 60044-1 [9]) both designed for secondary winding rated load of 5 VA (power factor 0.8) with rated transformation ratios 300 A/5 A and 100 A/5 A. Measuring circuit was powered by a programmable power supply, which was able to inject additional harmonics into the output voltage. In this mode of operation distorted voltage particular harmonics levels may be set manually by the user or by the value of THD factor. During the tests of the CT's accuracy of transformation in these condition the load of the secondary winding were resistors (power factor 1). The rms value of the voltage proportional to the difference between primary and secondary currents of the tested CT was measured through the current probe, which output voltage was measured by the current sense input of the first module of the digital power meter. The lowest possible range of measured voltage of this device external current sensor input is 25 mV. To measure the difference between the primary and secondary currents the wires were led through the probe in such a way that the flux in its magnetic core was proportional to the difference between instantaneous currents. Used current probe sensitivity is 1 V/A ±1% [6]. Measuring system is presented in Fig. 1.
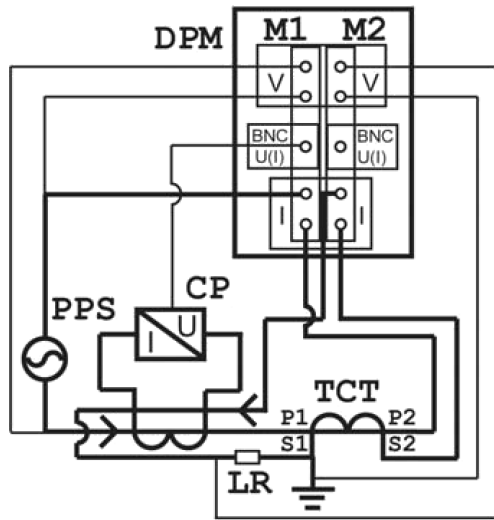
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Fig. 1. Circuit diagram of the measuring system

In Fig. 1 the following notations are used: TCT – Tested Current Transformer, LR – Load Resistor, DPM – Digital Power Meter, M1/M2 – first/second DPM module, V/I – voltage/current inputs of first/second DPM modules, BNC U(I) – current sense input of first DPM module, CP – Current Probe, PPS – Programmable AC Power Supply.

During the measurements (Fig. 1) the wire with 5 A rms (tested CT's with 5 A secondary rms current) supplying current is led through the window of tested CT as many times to give a proper number of amp-turns equal its rated primary current. If rated primary current rms value of tested window CT is 300 A and its secondary current rms value is 5 A, than the wire with 5 A supplying current must be led by the window of this CT 60 times. If tested CT is not a window CT, than additional window CT (previously tested in presented in Fig. 1 measuring circuit) must be used in the measuring system presented in Fig. 2, as a reference CT.
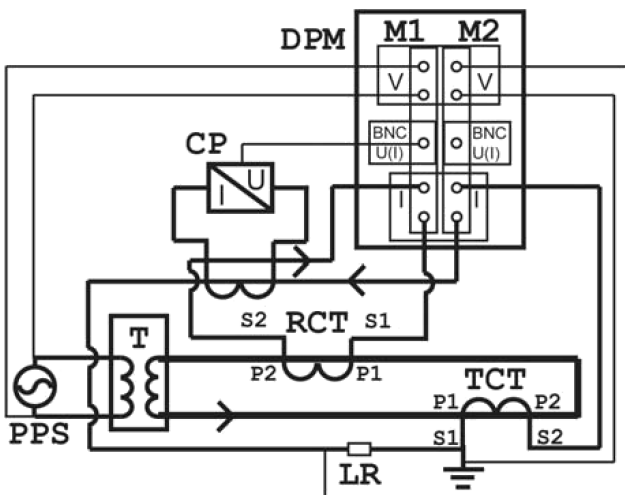

Fig. 2. Circuit diagram of the measuring system with a reference CT

In Fig. 2 the following additional notations in relation to Fig. 1 are used: T – supplying Transformer, RCT – Reference Current Transformer.

To determined in measuring system 2 (Fig. 2) values of composite error/transformer correction factor additional error resulting from the use of reference CT must be added.

The use of a transformer in the supply circuit ensures proper for test values of the rms primary current in accordance with standards [8–9]. Not without significance is the influence of the transformer on the waveform of the test signal. Therefore, THD_U levels of the tested CT primary winding supply voltage are set to ensure proper for tests THD_I levels of the primary current (distortion of the secondary current of the reference current transformer is measured by the ICM module of the digital power meter).

3. Measuring procedure

The evaluation of a tested CT's metrological properties for transformation of distorted currents is made on the basis of composite error defined in the IEC 60044-1 standard for current transformers [6–7, 9]:

$$\varepsilon_c = \frac{100}{I_p} \sqrt{\frac{1}{T} \int_0^T (K_n i_s - i_p)^2 dt}, \tag{1}$$

K_n – rated current ratio of tested CT; i_p, i_s – instantaneous values of primary and secondary currents; I_p – rms value of primary current; T – period.

For steady-state conditions the composite error is the rms value of the difference between the instantaneous values of the primary current, and the instantaneous values of the actual secondary current multiplied by the rated transformation ratio. The numeric value of the composite error will never be less than the vector sum of the current error and the phase displacement. Consequently, the composite error always indicates the highest possible value of current error or phase displacement. In accordance with IEC standard 60044-1 [9], the composite error is determined for protection CTs and the limiting values of this error for measuring CTs are not defined by this IEC standard but they may be calculated from formula (1) for limiting values of current error and phase displacement defined in this standard. Calculated limiting values of composite error for measuring CTs are presented in Table 1.

Table 1
Calculated limiting values of the composite error for measuring CTs (IEC 60044-1 classes from 0.1 to 1)

Acc. Class	Percentage values of composite error calculated for percentage values of rated primary current			
	5%	20%	100%	120%
0.1	±0.45	±0.2	±0.15	±0.15
0.2	±0.9	±0.4	±0.3	±0.3
0.5	±2.7	±1.3	±0.9	±0.9
1	±5.4	±2.6	±1.8	±1.8

In IEEE C57.13 standard accuracy classes for revenue metering are based on the requirement that the transformer correction factor (*TCF* – equivalent of composite error in IEC standard) of the CT shall be within the specified limits (Table 2) when the power factor (lagging) of the metered load

has any value from 0.6 to 1.0 for the specified standard burden at 10% and at 100% of rated primary current [8].

Table 2
Standard accuracy class for metering service and corresponding limits of transformer correction factor [0.6 to 1.0 power factor]

Acc. Class	Limits of transformer correction factor for percentage values of rated primary current			
	10%		100%	
0.3	0.994	1.006	0.997	1.003
0.6	0.988	1.012	0.994	1.006
1.2	0.976	1.024	0.988	1.012

TCF at 0.6 power factor (lagging) of the metered load for current transformers is as follows:

$$TCF = RCF - \beta/2600, \qquad (2)$$

where *RCF* – ratio correction factor, *β* – phase angle (in minutes).

4. Results of the measurements

In Table 3 the results of composite error measurements of tested CT 300 A/5 A and primary current distortion from 10% to 40% are presented.

Table 3
The results of the composite error measurements for the tested CT 300 A/5 A and secondary winding active load power equal 4 W

CT 300 A/5 A, class 0.5 (4 W)					
I_1 [A]	THD$_{I1}$ [%]	0	20	30	40
0.25		2.8	2.8	2.8	2.8
1	ε [%]	1.4	1.4	1.4	1.4
5		1	1	1.1	1.2
6		1	1.1	1.2	1.4

The measurements presented in Table 3, in accordance with standard [9], were made for 5%, 20%, 100% and 120% of rated primary current (Table 1). During the tests active load power of the secondary winding was 4 W, due to the fact that tested CT is designed for rated apparent power of the secondary winding equal 5 VA for power factor equal 0.8. Analysis show that for primary currents rms values equal 300 A and 360 A measured composite error values are greater than the calculated limiting values presented in Table 1 (±0.9%). Measured values of transformer correction factor are greater than the limiting values ±1.2% for 1.2 accuracy class only when THD$_I$ level reaches 40% (Table 3), but for primary current equal 360 A rms no accuracy tests are required by the IEEE C57.13 standard [8]. In condition when secondary winding active load power of tested CT 300 A/5 A is increased to 5 W measured values of transformer correction factor for rated primary current are greater than the limiting value for 1.2 accuracy class starting from THD$_I$ level equal 20%. For primary current THD$_I$ level equal 40% measured transformer correction factor reaches 2% [6]. Determined increase of composite errors / transformer correction factors for primary currents rms values equal 300 A and 360 A (Table 3) with the increase of the THD$_I$ level will result in increase of

the errors of power and electrical energy measurements in low power quality conditions in indirect circuit with the usage of this tested CT.

In Table 4 the results of composite error measurements of CT 100 A/5 A for same test conditions are presented.

Table 4
The results of the composite error measurements for the tested CT 100 A/5 A and secondary winding active load power equal 4 W

CT 100 A/5 A, class 0.5 (4 W)					
I_1 [A]	THD$_{I1}$ [%]	0	20	30	40
0.25		1.2	1.4	1.5	1.5
1	ε [%]	1.0	1.0	1.1	1.1
5		0.6	0.7	0.7	0.8
6		1.2	2.2	X	X

Analysis of results presented in Table 4 shows that for primary currents rms values to 100 A (rated primary current) and THD$_I$ levels to 40% measured values of composite error / transformer correction factors are not greater than the limiting values presented respectively in Tables 1 and 2. When distorted primary current reaches 120 A rms composite error values are greater than the limiting values presented in Table 1. THD$_I$ level above 25% causes saturation of the tested CT's magnetic core and composite error values are greater than 100% (proper operation of tested CT in such conditions is impossible). On the basis of results presented in Table 4 in tested conditions for currents from 10% to 100% of rated primary current and THD$_I$ levels to 40% transformer correction factors determined for this CT are not greater than the limiting values set by the IEEE C57.13 standard [8]. Tested CT 100 A/5 A, when used in indirect measuring circuit for power and electrical energy measurements in low power quality conditions such as tested, for 5% to 100% of rated primary current will not introduce additional errors than resulting from its accuracy class determined for sinusoidal primary current [8].

In Table 5 the results of composite error measurements of tested CT 300 A/5 A after derating of the secondary winding active load power to 3.75 W are presented.

Table 5
The results of the composite error measurements for the tested CT 300 A/5 A and secondary winding active load power equal 3.75 W

CT 300 A/5 A, class 0.5 (3.75 W)					
I_1 [A]	THD$_{I1}$ [%]	0	20	30	40
0.25		2.8	2.8	2.8	2.8
1	ε [%]	1.4	1.4	1.4	1.4
5		0.9	0.9	1	1
6		1	1	1	1

Tested CT load resistor value was reduced from 0.8 Ω to 0.75 Ω in order to achieve acceptable in relation to the limiting values presented in table 1 measurement errors in the presents of harmonics distortion. Now tested CT 300 A/5 A, when used in indirect measuring circuit for power and electrical energy measurements from 5% to 120% of rated primary

current will not introduce higher errors than resulting from its accuracy class.

In Table 6 the results of composite error measurements of tested CT 100 A/5 A after derating of the secondary winding active load power to 3.2 W are presented.

Table 6
The results of the composite error measurements for the tested CT 100 A/5 A and secondary winding active load power equal 3.2 W

CT 100 A/5 A, class 0.5 (3.2 W)					
I_1 [A]	THD$_{I1}$ [%]	0	20	30	40
0.25		1.2	1.2	1.2	1.2
1	ε [%]	1	1	1	1
5		0.5	0.5	0.5	0.5
6		0.8	0.8	0.9	1

After derating of the tested CT 100 A/5 A secondary winding active load power to 3.2 W determined values of composite errors for primary current equal 120 A are not greater than the limiting values in accordance with the standard [9] and Table 1.

5. Conclusions

Presented method for evaluating the accuracy of distorted currents transformation through inductive current transformers enables estimation if tested CT in a given low power quality conditions will introduce additional errors than resulting from its accuracy class during electrical power and energy measurements.

In proposed measuring system CT's accuracy of transformation for sinusoidal and distorted primary currents may be tested. For a given percentage value of rated primary current and given THD$_I$ level composite errors / transformer correction factors are measured. This enable the possibility to calculate additional error introduced by tested CT during transformation of distorted current in relation to operation conditions, where sinusoidal current is transformed. On the basis of these measurements derating levels of primary current or/and load of the secondary winding may be calculated. This will ensure in condition of distorted currents transformation through the CT values of composite errors/transformer correction factors as resulting from the IEC 60044-1/IEEE C57.13 accuracy classes.

In case of tested CTs with low voltage insulation system designed for transformation of relatively small primary currents, when distorted primary signal contain higher harmonics, which frequencies are close to the main primary signal frequency, no increase of composite error/transformer correction factor caused by deterioration of CT's metrological properties for primary signal higher frequency components were measured.

Moreover, obtained results of the laboratory studies show that some constructions of the inductive CTs are characterized by significantly higher metrological properties of distorted current transformation, in the same measuring conditions,

than other. Derating levels of these CTs to ensure values of composite errors/transformer correction factors as resulting from the IEC 60044-1/IEEE C57.13 accuracy classes are relatively smaller.

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