Frequency analysis of DC tolerant current transformers

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Abstract. This article deals with wide frequency range behaviour of DC tolerant current transformers that are usually used in modern static energy meters. In this application current transformers must comply with European and International Standards in their accuracy and DC tolerance. Therefore, the linear DC tolerant current transformers and double core current transformers are used in this field. More details about the problems of these particular types of transformers can be found in our previous works. Although these transformers are designed mainly for power distribution network frequency (50/60 Hz), it can be interesting to understand their behaviour in wider frequency range. Based on this knowledge the new generations of energy meters with measuring quality of electric energy will be produced. This solution brings better measurement of consumption of nonlinear loads or measurement of non-sinusoidal voltage and current sources such as solar cells or fuel cells. The determination of actual power consumption in such energy meters is done using particular harmonics component of current and voltage. We measured the phase and ratio errors that are the most important parameters of current transformers, to characterize several samples of current transformers of both types.

1. Introduction
This paper deals with wide frequency range behaviour of current transformers (CT) that are used in energy meters. In present day, the static energy meters replace the traditionally used Ferraris energy meters. The static energy meters are based on digitalization of voltage and current waveforms. Then the energy is computed in microcontroller.

This principle allows, due to high performance of today’s microcontrollers, getting more information of voltage and current distortion. Moreover it allows measuring power of higher harmonics components in distorted (non-harmonic) power networks, which is the typical case today. In this application the phase shift between voltage and current is crucial. The knowledge of phase shift between corresponding harmonics allows designing new generation of energy meters where actual power consumption will be computed from particular harmonics and it allows measurement of deformation power [1].

For analysis of higher harmonic components of measured current it is necessary to know about behavior of CT in wider frequency range.

CTs used in static energy meters must comply with European and International Standards e.g. EN 62053-21, EN 50470-3 etc. These standards define several requirements and among them the accuracy and DC immunity that are affected mainly by CT in energy meter. Moreover, another requirement that
is not defined in Standards is the price of current sensor and whole device that is important for manufacturers and their customers.

According to these requirements two main types of CT are used: single core linear CT and double core CT. Linear CT consists of the core made from amorphous or nanocrystalline material with very linear and narrow B-H loop and high saturation magnetic field strength $H_s$. This arrangement brings non-zero but almost constant phase error that can be easily compensated.

Double core CT consists of two parallel or concentric ring cores that are together wound by the secondary coil. High permeability core ensures very low ratio and phase error and low permeability core with high saturating magnetic field strength ensures high DC immunity. This design is cheaper than linear CT; therefore manufacturers are interested in it. On the other side double core CT introduces some problems under special condition e.g. measurement of consumption of non resistive (reactive) load together with a load that is powered through a diode. Generally, when the DC magnetic flux appears in the core the phase error rapidly increases because of the high permeability core saturation. For purely active load (with $\cos \phi$ close to 1) this is not such a big problem thanks to the flat maximum of cosine function. For reactive load, even small phase error causes large error of power measurement. More about these problems can be found in our previous works [2], [3] and in [4].

As stated above some additional functions can be implemented in the energy meters to increase their functionality – e.g. monitoring of energy quality, spectrum analysis etc. For this is necessary to understand the measurement errors of CT in wider frequency range than the nominal 50/60 Hz [5].

2. Theoretical Analysis of Errors

Commonly used equations are derived from simplified model of current transformer (Figure 1) and they define amplitude and phase error.

$$\varepsilon_1 = \frac{R}{\omega L} \sin \delta$$  
$$\varphi_1 = \arctan \left( \frac{R}{\omega L} \cos \delta \right)$$

where $\delta$ represents the core losses angle, $R = R_{cw} + R_b$ is a sum of winding resistance and burden resistance, $L$ is main inductance and $\omega = 2\pi f$, where $f$ is frequency of current.

From the equations above can be seen that both errors decrease with increasing frequency ($\omega$).

The amplitude error (ratio error) is very low even for low frequencies (tenths of percentage) and therefore it is not so important to measure its dependency on frequency.

Moreover, the change of the phase error can cause large measurement error especially at measurement with low power factor (PF), see [2], [3], [4].

These errors apply only to an ideal current transformer. There are other properties of CT that modify this dependence and it is very difficult to calculate the error while taking all these properties into account.

3. Real Measurements of the Errors

We arranged the experimental measurement setup that consists of generator Agilent 33120, amplifier Krohn-Hite KH75 and precision power meter ZES Zimmer LMG500 (see block diagram on Fig. 2).
The generator and power meter were controlled by PC via GPIB. The frequency varied from 50 Hz up to 5 kHz and the waveforms of primary and secondary currents were sampled. Primary current was measured on built-in shunt resistor in LMG500. The secondary current was measured on burden resistor specified for the CT by manufacturer and the current sensor input of LMG500 was used for sampling.

Since some measurements have been done with non sinusoidal current, the phase error in this case was defined as a phase shift of 1st harmonic – see equation (3). The LMG500 power analyzer uses simultaneous sampling of all channels so the FFT analysis of both waveforms provides the magnitudes and consistent relative phases of particular harmonics. The phase error was calculated from these results.

\[ \phi_e = \phi_{I_{\text{sec harm}}} - \phi_{I_{\text{prim harm}}} \] (3)

Estimation of uncertainty of phase error calculation is not easy and it exceeds the scope of this paper. In our first measurement we compare the phase error of CT at 50 Hz with specification from manufacturers and it fits well.

We measured two different types of CT in our tests. Dual core CT and precise linear CT from different manufacturers (see Table 1 for the parameters).

**Table 1. Specification of used current transformers.**

| Manufacturer    | Vacuumshmelze 4626X131 | Magnetec MB-361-01 | Taehwatrans TD120L | Oswell DCT103 |
|-----------------|-------------------------|---------------------|--------------------|---------------|
| Design          | linear                  | linear              | linear             | dual core     |
| Current range   | 100 A                   | 100 A               | 510 A              | 100 A         |
| DC tolerance    | 100 A                   | 100 A               | 120 A              | 100 A         |
| Turns ratio     | 1:2500                  | 1:2500              | 1:2500             | 1:2500        |
| Phase error     | 3.3 deg                 | 5.1 deg             | 3.3 deg            | < 0.33 deg    |
| Burden          | 7.5 Ω                   | 7.5 Ω               | 1 Ω (7.5 Ω)       | 12.5 Ω        |

**Figure 2.** Block diagram of measurement setup ($R_n$ – internal sensing resistance of LMG500 power meter, D – Schottky diode for half-wave rectified current measurement)

**Figure 3.** Errors of 4626X131 ($I_{\text{prim}} = 10$ A, $L = 3.2$ H, $R_{Cu} = 54.1$ Ω, $R_b = 7.5$ Ω, $\delta = 0.4^\circ$)

**Figure 4.** Errors of MB-361-01 ($I_{\text{prim}} = 10$ A, $L = 2.0$ H, $R_{Cu} = 47.8$ Ω, $R_b = 7.5$ Ω, $\delta = 0.4^\circ$)
Figure 3 shows the frequency dependency of phase displacement and ratio error of three samples of linear CT VAC 4626X131. Results well correspond with theoretically computed values that are depicted by black dashed line. Similar measurement was done for next three samples of CT MB-361-01 (Figure 4) and for TD120L (Figure 5). Despite of recommended burden we used the 7.5 Ω even for the TD120L due to the same sensitivity and higher output voltage.

Perceptible variation at higher frequency (>2 kHz) is caused by parasitic properties of CT (stray field and core losses, capacitances etc.), which are strongly dependent on position of primary conductor with respect to the CT. This frequency is very close to resonant frequency (around 1.5 kHz). Some types of phase displacement of same sample above resonant frequency can be seen in detail in Figure 6.

4. Measurement with Non-sinusoidal Current

It is important to measure the phase displacement even for non-sinusoidal current. Half-wave rectified current is an important type of primary current because it is a frequent case of DC load seen today in applications of energy meters. A Schottky diode (with very low forward voltage drop and thus very low power loss) has been inserted in primary circuit for this measurement.

As expected the phase displacement remain unchanged for all linear CT due to the constant permeability in wide range of magnetic field strength. The DC component of measured current moves the operating point along the B-H loop. The only differences were at higher frequencies due to resonant effects (see above).

On the other hand there was significant change for double core CT as can be seen in Figure 7 (cp. red and green lines). This change is due to the saturation of high permeability core by DC component of primary current. Thus magnetic flux flows through low permeability core with significant and non-constant phase displacement (about 3 deg).

**Figure 5.** Errors of TD120L ($I_{prim} = 10$ A, $L = 2.7$ H, $R_{Cu} = 55.9$ Ω, $R_b = 7.5$ Ω, $\delta = 0.4^\circ$)

**Figure 6.** Detail of phase displacement curves for several position of primary turns

**Figure 7.** Errors of DCT103 ($L = 135.5$ H, $R_{Cu} = 117$ Ω, $R_b = 12.5$ Ω, $\delta = 0.4^\circ$)

**Figure 8.** Comparison of phase displacement and ratio error of different current transformers
The measurement with half-wave rectified primary current has been performed for two amplitudes of primary current. In contrast to linear CT (constant permeability of core in wide range of DC magnetizing) the phase displacement of dual core CT varies with amplitude changing. It is due to the low quality of low permeability core (in order to be cheaper than the linear CTs) and causes variation of phase displacement with changing DC magnetization of CT. The results of measurement for varying amplitude of primary current can be also seen in Figure 7 (see blue and green lines).

5. Conclusion
In present day the manufacturers of static energy meters would like to implement new features to their products in order to get advantage against their competitors. Some of these features can be measuring of energy quality or analysis of power of higher harmonics. These features allow using the energy meters in Smart Grids which is required by Directive of the European Parliament and Council Directive 2009/72/EC.

It is very important to select proper current sensor for the current measurement in energy meter or other device that can measure also non-sinusoidal current. Cheap double core CT can be used in these devices, but the problems with non-constant phase displacement have to be considered. Especially in application with non-resistive loads such CT should be replaced with high-quality linear CT.

Current transformers for energy meters are specially designed for the single frequency but they can be used even in wider frequency range after phase displacement correction as was shown in the text above. The frequency dependency of the errors of a current transformer can be very well predicted according to the basic parameters – inductance $L$ and resistance of winding $R_{Cu}$ as was shown in figures 3, 4 and 5. Fig. 8 compares the results for all tested linear types CT.

References
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