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Understanding the contribution of the noise to the error in LPITs

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SUMMARY

Electronic Low-Power Instrument Transformers (LPITs) are being more and more popular in the transport and distribution networks due to their improved characteristics when comparing with conventional (linearity, no saturation, extended frequency range, digital interface…). These new devices present a different behaviour against the noise compared with the conventional. With small signals, the main contribution to the error in electronic LPITs is the electronic noise added to the measured signal in the analogue to digital conversion. This noise presents a normal distribution with mean zero and can be enough to characterize the electronic LPITs.

This paper analyses and characterizes the electronic noise present in a particular optical current transformer technology (based on a passive 3x3 interferometer) and explains the influence of this noise in the error for different applications. The aim is to provide a general view of the capabilities of the LPITs and introduce new factors when evaluating their accuracy depending on the application.

KEYWORDS

Optical Current Transformers, OCT, LPIT, metering, protection, accuracy, error, noise, digital substation.

1. Introduction

Instrument Transformers (IT) are a key element in the energy transport and distribution networks. They are used to provide the needed electrical magnitudes for the protection, metering and monitoring of the grid. The main standard that these devices must comply with is the IEC 61869 series. Some parts of this series are still being developed and replaces the previous standard series IEC 60044. The IEC 61869-1 [1] describes the general requirements for instrument transformers while IEC 61869-2 [2] focuses in general requirements for current instrument transformers. As this paper is focused on Optical Current Transformers (OCT) the applicable parts of the standard series are IEC 61869-6 [3] and IEC 61869-8. Part 6 covers general requirements for all Low-Power Instrument Transformers (LPIT) and part 8 will cover specific requirements for electronic current transformers (still under development). As the OCTs include both the optical passive primary converter and the associated Merging Unit (MU) they are considered electronic instrument transformers, even when the measurement in the sensor is fully passive. Finally, the IEC 61869-9 [4] must be also considered as it defines the digital interface for the electronic LPITs and Stand Alone Merging Units (SAMU) and also contains some accuracy definitions.

This paper analyses the differences between the error behiaviour in electronic LPITs (more concretely in Optical Current Transformers) compared with the conventional instrument transformers. One of the most important difference between the two type of devices is the source of the error.

A conventional current instrument transformer’s accuracy is mainly affected by core material, the current level (percentage of the nominal current) and the burden connected in the secondary. During the manufacturing process the number of turns in the secondary must be adjusted (mainly) according to the losses due to the core magnetization flux, resulting on a lower number of turns. Figure 1 shows this compensation and the error of a conventional current transformer for different burden values (class 0.2).

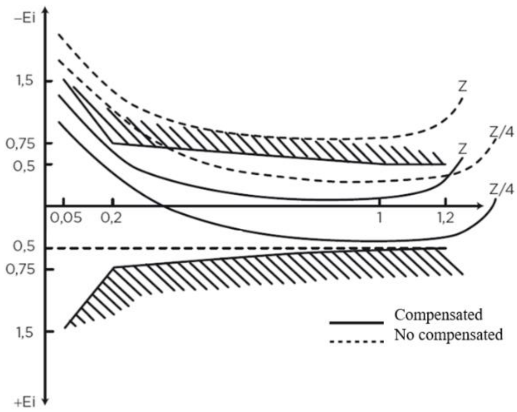

Figure 1

On the other hand the error in the Optical Current Transformers (and in most of the electronic LPITs) is caused by the electronic noise added in the current calcullation process (from ligth to the digital values).

This article will not cover other differences between the technologies such as the saturation, step response or frequency range.

2. Optical Current Transformer

Optical Current Transformers use the Faraday effect to measure the current flowing through a conductor. The Faraday effect causes a polarization rotation in the light beam that is proportional to the magnetic field. As the magnetic field is also proportional to the current flowing through a conductor, the OCT converts this rotation into a current value.

Among the different topologies for the current measurement with optical transformers, the device used in this paper implements a 3x3 passive Sagnac interferometer (presented in [5]). As shown in Figure 2 this interferometer is manufactured using a 3x3 optical coupler and special sensing fibre loops that surrounds the primary. This topology generates a 9-pulse output (for each single light pulse sent from the MU) with redundant information of the current that allows the MU to accurately calculate the current regardless of the link between the both devices (OCT and MU). This device also features unlimited dynamic range with no saturation.

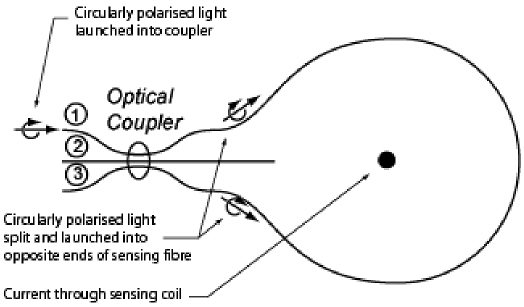

Figure 2

The sensitivity of the OCT depends on the effective Verdet constant of the sensor (in this case a HiBi optical fibre [6]) which has dependance with several parameters:

- Temperature of the sensing fibre (T).
- Laser wavelength (λ).
- Polarization state of the light beam (ϑ).

$$I_{Measured} = k_{(T,\lambda,\vartheta)} \cdot I_P$$

The calculated value by the OCT includes an additive component $I_N(t)$. This component is a noise signal added by the MU in the different analog and digital processes carried out to calculate the current.

$$I_{Measured}=k_{(T,\lambda,\vartheta)} \cdot I_P+I_N(t)$$

This noise is a random signal with a normal (Gaussian) distribution and a zero mean value. The noise is independent of the measured magnitude and must be considered a characteristic of the LPIT.

3. Noise analysis

The traditional method to measure the accuracy of the current instrument transformers is the use of a measuring bridge to determine the ratio error of the device under test. In this method a current source and a callibrated reference is used appart from the bridge. When adapting this method to the electronic LPITs with digital output, the bridge requires a digital interface, in order to compare the analog output from the callibrated reference with the digital output of the MU as shown in Figure 3.

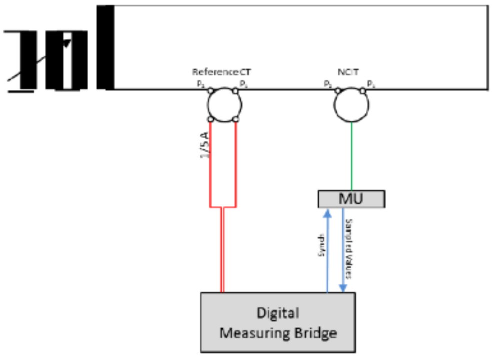

Figure 3

This test calculates the error of the LPIT to check the accuracy of the device according to the next equation:

$$Ratio\ Error = \frac{I_{Measured} - I_P}{I_P} = \frac{k(T,\lambda,\vartheta) \cdot I_P + I_N(t) - I_P}{I_P}$$

As explained in the introduction, the main source of the error in optical LPITs when measuring low currents is not related with the calibration or the burden (there are no secondaries) but with the electronic noise. This noise level is constant, so if we consider a device without error due to the callibration ($k(T,\lambda,\vartheta) = 1$) the error equation can be simplified to:

$$Ratio\ Error = \frac{I_N(t)}{I_P}$$

This means that the *Ratio Error* will follow the same distribution as the electronic noise (normal distribution with zero mean), and that the higher the current tested the smaller the error. Taking this into account, we find that the performance of the optical LPIT can be defined by the electronic noise level of the system. For this, it is not necessary to use current flowing through the primary circuit, as we can characterize the electronic noise by analysing the output of the system in the absence of current.

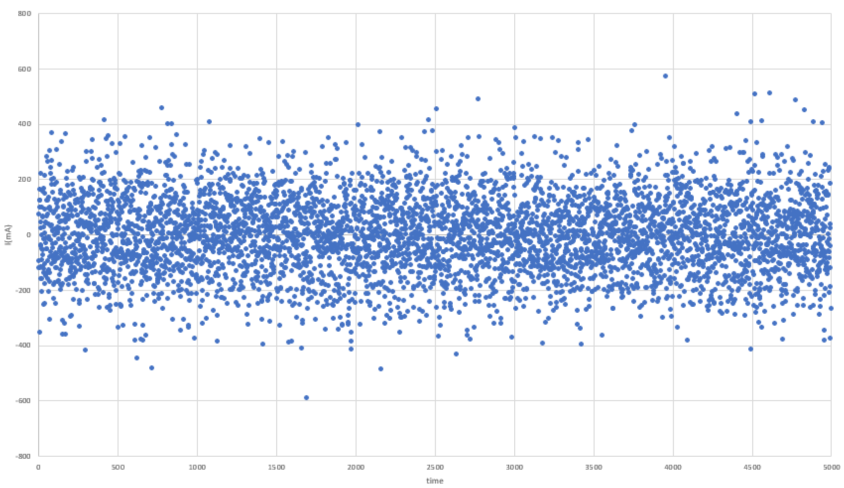

Figure 4

Figure 4 shows the output of an optical LPIT with no current in the primary, using the sample values digital frame F4000S1I4U4 (this notation is explained in [4] and means a sampling frequency of 4kHz, 1 set of measurements per ethernet frame and 4 currents and 4 voltages in each set). The MU used in the test implements an oversampling to measure the current, it samples at a frequency of 192 kHz and then filters (to avoid antialiasing) and down-samples to get the desired frequency rate.

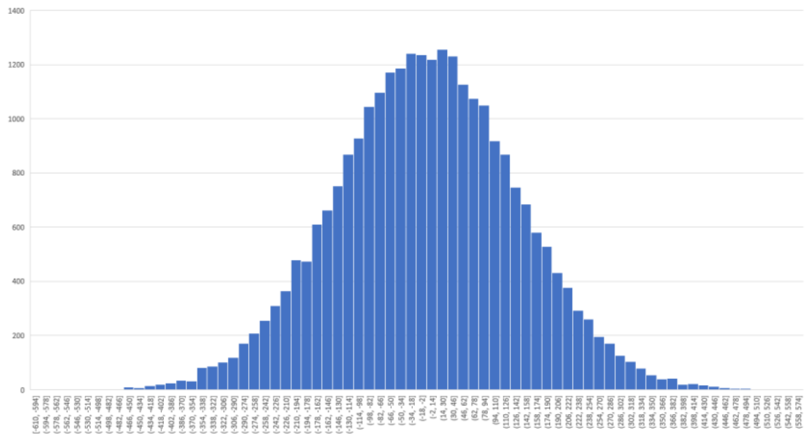

Figure 5

This result confirms that the noise presents a normal distribution with zero mean (Figure 5 presents the histogram of the noise). The noise of the optical CT can be characterized by the following parameters:

RMS	139,6 mA
Mean	-1,85 mA
Sigma	139,6 mA
Min. value	572 mA
Max. value	-595 mA

Table 1

In the device under test according to [3] we can calculate the spectral density of the *"white noise in the form of a number with unit of equivalent primary current per square root of frequency"*. As the digital frame is F4000S1I4U4 the bandwidth of the signal is 2000 Hz, thus the spectral density can be calculated as $PSD = 0.139A/\sqrt{2000Hz} = \mathbf{3,3mA/\sqrt{Hz}}$. Supposing the nominal current of the OCT under test is 400A we can also express it as $\mathbf{-101dB/\sqrt{Hz}}$. This value is useful not only to compare optical devices from different manufactures but also to compare different electronic LPITs technologies between them.

When integrating the noise over the time, the value of the instantaneous noise gets closer to the mean (theoretically zero), this result is logical as *Sigma* = *RMS*. Figure 6 shows different running averages using different number of samples. The original values have been sampled at 4 kHz, so we have decided to use groups of samples multiple of 80 (1 signal cycle at 50Hz). The graph shows how the larger the number of samples the lower the noise, confirming the zero-mean characteristic of the electronic noise.

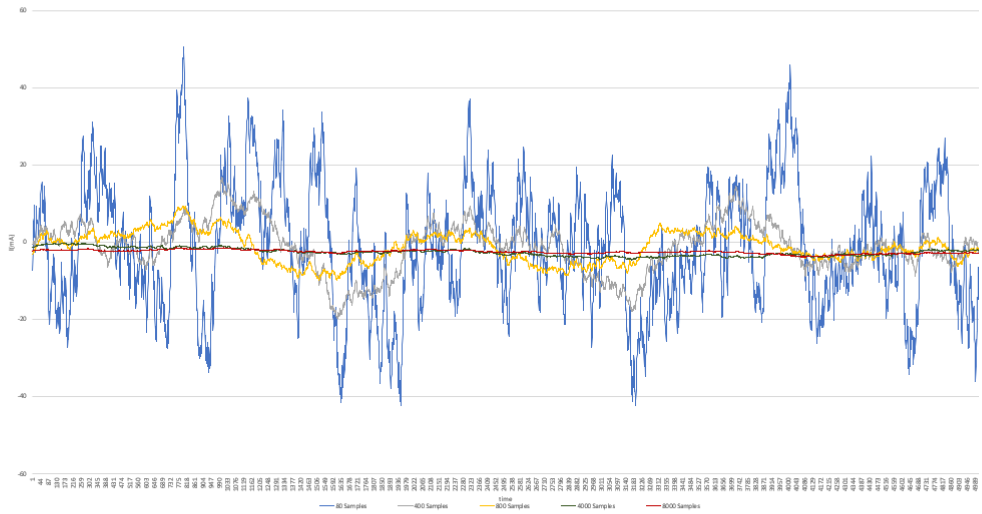

Figure 6

To know the maximum value of the measured error we can consider the value *3*Sigma*, what means the 99.7% of the measurements are under this value. In the following equation we can observe that the integration time (T) is a parameter that has an important weight in the result when we want to calculate the accuracy class of the LPITs at low currents. This result is valid independently of the type of output the LPIT uses (digital or analogue).

$$Max\ Ratio\ Error = \frac{3 \times PSD \cdot \sqrt{\frac{1}{T}}}{I_P}$$

The part 9 of the IEC 61869 standard [4] introduces this concept in the 7.2.6 chapter when mentions:

> *"For protection classes, accuracy tests shall be performed over one period of power frequency signal; e.g. 20 ms for a 50 Hz system.*
> *For measuring classes, accuracy tests may be performed over several power frequency cycles, or several measurements may be averaged. If the comparison is not over one period of power frequency signal, the details of the test arrangement and timing and/or bandwidth of test system shall be provided in the accuracy test report."*

4. Optical LPITs for different applications.

The optical LPITs must cover all the applications where conventional current transformers are used. These applications are mainly protection, metering, and grid monitoring. Each of these applications imply different requirements in terms of accuracy and time integration. For protection, accuracy requirements for low currents are not very demanding, but the measurement must be done very fast (1 cycle). On the other hand, metering applications require high accuracy (0.2% at nominal current) even in low currents (0.75% at 1% of nominal current for 0,2s accuracy class), but period of integration for the measurements are usually larger than 60 seconds. Grid monitoring requires certain accuracy level in the measurement of harmonics.

As previously explained, the optical current transformer under test does not have any saturation point and presents a constant electronic noise characterized by its PSD. This means that for a given device, we can calculate the nominal current for which the device can comply with a certain accuracy class as a function of the integration time, using the spectral density of the electronic noise.

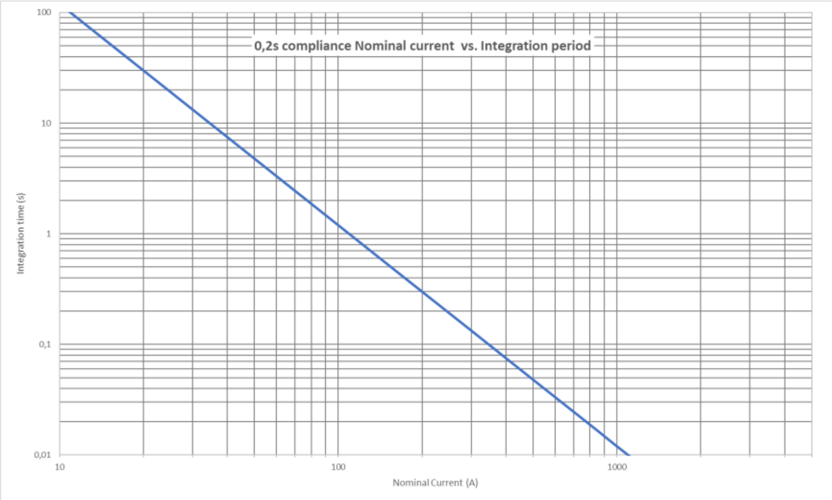

Figure 7

Figure 7 shows the relation between stated nominal current and integration time for the analysed optical CT to comply an accuracy class 0,2s. The worst case is the lower value of the current, in this case it is the 0,75% at 1% of the nominal current. If we take an integration period of 60 seconds (a coherent value for the power meters energy integration time), the chosen LPIT complies with 0,2s accuracy class for nominal currents lower than 20A.

On the other hand, if we choose an integration period of 1 cycle (20ms at 50Hz) the same device would comply accuracy class 0,2s for nominal currents from 800A.

This effect can also be analysed calculating the contribution of the noise to the measurement as a function of the integration period. Next table shows these values for the LPIT under test.

	Protection	Protection	Control	Metering
	Peak value	1 period	10 periods	50 periods
Noise contribution	420mA	22mA	7mA	3,1mA

5. Conclusions.

The most important parameter to compare accuracy of different electronic LPITs is the noise spectral density, and it should be mandatory for the manufactures to inform this value.

The definition of the accuracy class in an electronic LPIT requires the definition of the integration period used in the accuracy test. This integration period must be in accordance with the application requirements.

This definition, which considers the integration period in the accuracy test, is clearly explained in [4], but it should be extended to the general requirements of the IEC 61869 series and the preferred number of periods should be set for each application.

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