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Calibration of Current Transformers in distorted conditions

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Abstract. In the context of modern power systems, where there are lots of non-linear loads and generators based on switching power electronics, the accurate measurement of voltage and current harmonics is a key task for the knowledge of the actual state of the network. Voltage and current transducers play a crucial role since they are always the first part of the measurement chain. Currently, classical voltage and current instrument transformers are the most installed transducers, but their performance not always is fully characterized in the presence of distorted waveforms. Therefore, in this paper a calibration setup for the accurate characterization of current transformers with distorted waveforms is presented. System implementation and characterization is presented; then it is employed for the evaluation of the performance of a commercial current transformer in distorted conditions.

1. Introduction

Due to the massive and ongoing new expansion of non-linear devices (such as rectifier, distributed generators inverters, switching power devices) the monitoring of distorted voltages and currents is a crucial issue in today's power system ([1]). Proper measurement setups ([2]) are needed to accurately fulfill the new tasks required by this smart grid context, like power quality, synchrophasors, harmonic impedance and system state estimation. The accuracy of these measurement setups is strongly linked to the metrological performance of current and voltage instrument transformers (CTs and VTs) which are essential elements of the measurement chain. Thus, the study of transformers and their behavior with distorted waveform is a crucial issue. Various papers in scientific literature ([3]-[5]) have shown that CTs and VTs have different behaviors when their input is sinusoidal or it is a distorted waveform. This is due to an intrinsic non-linear behavior, which does not allow to use the superposition principle for their characterization. For this reason, they need to be studied by directly applying distorted waveforms. In the light of the above, in this paper a measurement setup for CTs characterization with distorted waveform is presented. To characterize CTs performance in presence of harmonics and, more generally, in presence of distorted signals, the CT ratio and phase errors are evaluated for each tone. In the following, Section 2 shows the implementation of the calibration system, while its performance evaluation is presented in Section 3. Finally, Section 4 presents the results of the characterization of a commercial CT in distorted conditions.

2.Setup for instrument transformer calibration

2.1 Hardware Description

The block diagram of the setup for CTs calibration is shown in Fig.1. Current generation is obtained through the transconductance amplifier (up to three in parallel) Fluke 52120 A (each one up to 120A, up to 10kHz). It is driven by the National Instrument PXI 5421 arbitrary waveform generator (AWG), (± 12 V, 100 MHz maximum sampling rate, 16 bit, onboard memory 256 MB). Current reference value is obtained by means of two calibrated current shunts, LEM NORMA TRIAX Shunt: 30 / 300 A/mV, (0.03 %) and 100 / 100 A/mV (0.15 %), frequency range up to 100 kHz. A versatile comparator ([6]-[9]), which can be employed for the calibration of conventional and non-conventional instrument transformers, is used to compare the outputs of the CT and of the reference shunt. It is based on the National Instruments cDAQ chassis and it is equipped with various input modules (± 7.5 A, ± 75 A, ± 500 mV, ± 10 V): the proper input channels are chosen according to the type of the test and they are synchronously sampled. Comparator sampling clock can be synchronized to the generation sampling clock, exporting a 12.8 MHz signal from the AWG to the comparator. It is worthwhile noting that all the input channels are equipped with antialiasing filter, whose cut-off frequency is automatically set to the half of the chosen sampling frequency. This, in turn, is chosen (up to 50 kHz) higher than the frequency of the maximum spectral component present in the test signal. For window-type CTs, additional primary turns can be used in order to increase the equivalent measured primary current. The amplifier and the comparator are remotely controlled, respectively through IEEE 488.2 and Ethernet, by a PXI controller running the calibration software, developed in LabVIEW.

2.2 CT Testing Procedures

In order characterize the CT performance in presence of distorted signals, an event based state machine has been developed in LabVIEW. A large choice of signal types may be selected, for example sinusoidal (SIN), fundamental plus a harmonic tone (FH1), fundamental with N harmonics (FHN), fundamental with an inter-harmonic (FI1) and so on. All the parameters of the waveforms are fully settable by the user and sweeps on all the parameters are possible, resulting in wide variety of possible waveforms which the CT can be characterized with. CT complex frequency response is determined at every frequency component that is generated. Depending on the sampling method, i.e. synchronous or asynchronous, the phasors of primary and secondary currents are obtained by means of Discrete Fourier Transform (DFT) or Interpolated DFT (IpDFT), respectively. Following the calculation of all complex phasors, ratio and phase errors are evaluated for each frequency component as in (1) and (2):

$$\Delta R_j = \frac{\hat{A}_{1,j}}{\hat{A}_{0,j}} - 1 \quad (1) \qquad \Delta\varphi_j = \hat{\varphi}_{1,j} - \hat{\varphi}_{0,j} \quad (2)$$

where $\hat{A}_{1,j}$ ($\hat{A}_{0,j}$) and $\hat{\varphi}_{1,j}$ ($\hat{\varphi}_{0,j}$) are the estimated amplitude and phase angle of the output of the device under test (reference sensor) at frequency f_j.

3.Evaluation of system accuracy

For an accurate characterization of the CT, all the systematic errors introduced by the various system components have to be measured and compensated following a proper procedure. In particular, the setup systematic errors are evaluated following procedures similar to those used for CT characterization (i.e. SIN, FH1, etc.). Looking at the block diagram in Fig. 1 it is clear that:

$$\bar{G}_{CT,j} = \frac{\bar{V}_{1,j}}{\bar{V}_{0,j}} \frac{\bar{G}_{1,j}}{\bar{G}_{0,j}} \frac{\bar{G}_{S_R,j}}{\bar{G}_{S_{CT},j}} \quad (3)$$

where the subscript j refers to the frequency f_j, $\bar{G}_{CT,j}$ is the complex gain of the CT under test, $\bar{V}_{1,j}$ and $\bar{V}_{0,j}$ are the estimated phasors of the samples of channel 1 and 0, respectively, of the comparator, $\bar{G}_{1,j}$ and $\bar{G}_{0,j}$ are the complex gains of channel 0 and 1 of the comparator, $\bar{G}_{S_R,j}$ and $\bar{G}_{S_{CT},j}$ are the complex gains of the reference shunt and of the shunt at the CT output. These quantities are measured in different steps. In the first step the systematic complex ratio (i.e. the ratio between $\bar{G}_{1,j}$ and $\bar{G}_{0,j}$) introduced by the two channels of data acquisition system is evaluated. In the second step, using the reference shunt, the shunt at CT output is calibrated, that is the ratio between $\bar{G}_{S_R,j}$ and $\bar{G}_{S_{CT},j}$ is measured, using a configuration for the measuring system like that shown in Fig. 2.

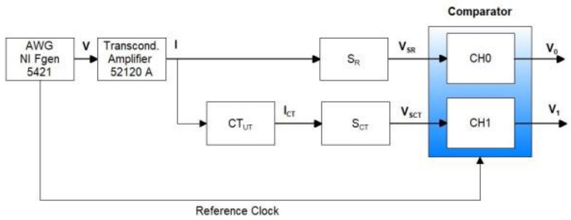

Fig. 1: Block diagram of the setup for CT calibration

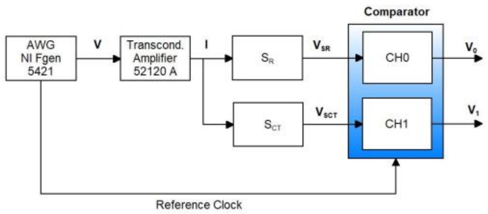

Fig. 2: Block diagram of the setup for comparator calibration

For sake of brevity, here only the results of the measurement of the systematic complex ratio introduced by two acquisition (those with ± 500 mV input range) is reported. A FH1 test is performed using fixed fundamental frequency (50 Hz), amplitude (about 260 mV) and phase (0 rad) and a harmonic tone with variable frequency (from 2^{nd} to 200^{th} order) and variable amplitude (10 % and 30 % of fundamental tone). Ratio and phase errors vs harmonic order are shown in Fig. 3 and Fig. 4, respectively. From Fig. 3 and Fig. 4 it results that the digitizer, after the compensation of systematic deviations, introduces maximum standard uncertainties on fundamental and harmonic ratio errors of 0.1 µV/V and 1 µV/V, respectively, and maximum standard uncertainties on fundamental and harmonic phase errors of 1 µrad and 3 µrad, respectively, up to 10 kHz.

4.Characterization of a Current Transformer

The realized system has been used to characterize the behaviour of a commercial, window type 500 / 5 A / A CT, with rated ratio of 100, accuracy class of 0.5, rated burden of 2.5 VA, operating frequency 50/60 Hz. For the case at hand, 25 additional turns have been realized on the primary side and the 30 A reference shunt has been used. This was made in order to assimilate the CT performance obtained with 25 turns and 20 A, to those obtainable with just one turn and 500 A. The 25 cables were wounded in a compact group and the diameter of each turn was very large with respect to the CT window area diameter, thus obtaining very similar magnetic effects to those of a 500 A current flowing in a straight single cable perpendicular to the CT core section. The CT output current has been directly acquired with the comparator: its current terminals have an input impedance of about 12 mΩ, which corresponds to a burden of about 12 %. Waveforms with a fundamental component (50 Hz, 20 A, zero phase angle) and a harmonic tone with two amplitudes (1 % and 5 %), fourteen frequencies (from 2^{nd} to 15^{th} order) and 21 phase angles (from -180 degrees to 180 degrees) have been used. For each test, sampling frequency of 10 kHz has been chosen, 10000 points have been acquired and ten iterations have been performed.

Fundamental and harmonic ratio and phase errors have been evaluated. For sake of brevity, here only the results relative to the tests with third harmonic are reported. Fig. 5 shows ratio error deviations (i.e. the mean value of the ratio errors has been subtracted) of fundamental component and third harmonic versus third harmonic angle, when third harmonic amplitude is 1 % and 5 %. Fig. 6 shows instead phase errors, referring to the same test conditions.

The maximum peak-to-peak value of ratio error deviation shown at fundamental component is about 46 µV/V, while that at third harmonic is about 2 %. The maximum peak-to-peak values of phase error at fundamental component is about 100 µrad, while that at third harmonic is about 20 mrad. The expanded uncertainties (level of confidence 95 %), conservatively evaluated, on ratio errors are 10 µV/V at fundamental and 92 µV/V at third harmonic, while the expanded uncertainties (level of confidence 95 %) on phase errors are 7 µrad at fundamental and 74 µrad at third harmonic.

5.Conclusion

In this paper, a measurement system for the accurate characterization of Current Transformers in distorted conditions has been presented. The system has been employed to characterize a commercial CT, showing that when it is supplied with a distorted waveform, its ratio and phase errors at harmonic frequencies depend on the characteristics of the input waveform, that are amplitude, phase and order of the harmonic content. Therefore, an accurate characterization the performance of a CT should be performed with proper distorted waveforms.

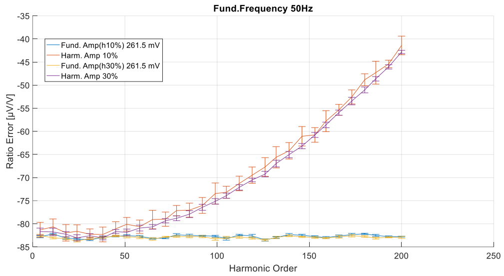

Fig. 3: Systematic ratio error of two channels (± 500 mV) of the comparator

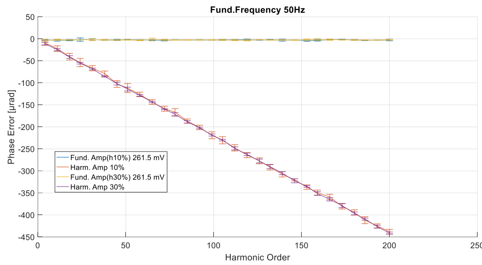

Fig. 4: Systematic phase error of two channels (± 500 mV) of the comparator

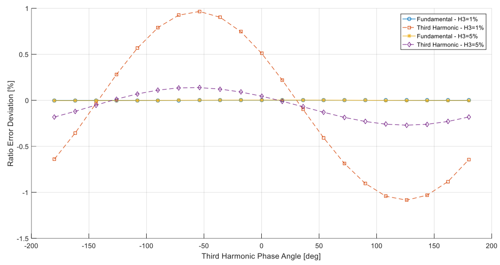

Fig. 5 Ratio error deviation of fundamental and third harmonic components vs. third harmonic phase angle

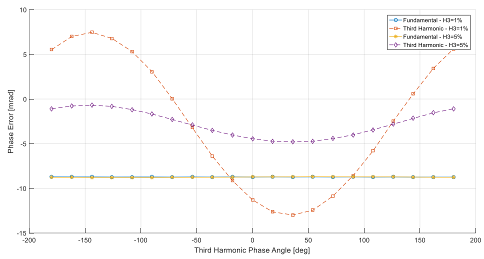

Fig. 6 Phase error of fundamental and third harmonic components vs. third harmonic phase angle

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