A measuring system to test current transformers at high frequencies for power quality analysis

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Abstract: The increase of distorted loads and non-conventional generation has led to limit the harmonic distortion in power networks. However, current instrument transformers (CT) are usually designed and tested only at power frequency. This paper describes a measuring system to test the behavior of CTs used in power networks when the waveform is not sinusoidal. Preliminary results are shown applying a distorted waveform to a commercial CT.

Keywords: Current transformer, instrument transformer, distortion, power network, smart grids.

1. INTRODUCTION

The development of smart grids and the increase of using of non-linear loads and non-conventional generation as wind farms have led regulation authorities to limit the amount of harmonic distortion in power networks [1, 2, 3, 4]. Regulations require the measurement of the harmonic content, which is usually done though instrument transformers that reduce the high voltage and high current to low values compatible with the meters, 100 V and 5 A for most cases [5, 6]. In case of current transformers (CT), general standards only oblige to test them at power frequency [7, 8]. In this case, the errors at higher frequencies are not known. Even, if additional requirements for harmonic response would be added to the standards [9], they will apply to new CTs, but there are a large number of CTs in service that must be verified. As they were fabricated earlier, their errors would be high at higher frequencies than 50 Hz or 60 Hz.

Different regulations have different harmonic content limits for consumers. One of the most used is IEEE 519 [1]. Tables I shows the maximum values according to the harmonic order, for systems from 120 V to 69 kV. Short-circuit current I_{sc} is the maximum current under short-circuit and I_L is the maximum demand current. For generators, limits of I_{sc}/I_L<20 are applied. These tables show limits only for odd harmonics. Even harmonics are limited to 25% of the odd harmonic limits above.

Table I. Limits of harmonic content for systems from 120 V to 69 kV [1].

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
$< 20^c$	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

For networks voltages from 69 kV to 161 kV, Table II shows the corresponding limits. The limit values of these tables go from 0.15% up to 15% for individual components.

Table II. Limits of harmonic content for systems from 69 kV to 161 kV [1].

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)						
I_{sc}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
$< 20^c$	2.0	1.0	0.75	0.3	0.15	2.5
$20 < 50$	3.5	1.75	1.25	0.5	0.25	4.0
$50 < 100$	5.0	2.25	2.0	0.75	0.35	6.0
$100 < 1000$	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0

The lowest limit applies to the highest order harmonic in high voltage networks with small short circuit current (Table II). It is required that the uncertainty of the measurement system be four times less than the measured value, which means 0.04%. For even harmonics the limit values are lower, then the measurement uncertainty must be also lower. These small uncertainty values require a high precision measuring system. Besides, the CT under test must have very low distortion in order to avoid the generation of harmonics by itself due to non-linearity of the core.

Many papers have proposed measuring systems for testing the behavior of CTs at frequencies higher than power frequency, but most of them were based on the frequency response [10] or tests in conditions far from real ones. If the excitation of the core is different than under real operation, differences between tests and field operation would appear because the core has non-linear behavior. Using these techniques it is not possible to know those differences, so that the use of them alone is not useful.

This paper proposes to complement simplest testing techniques with tests under real operation conditions, that is, tests with currents of nominal values with distortions similar to those existing in power networks. For that, a high current programmable distorted generator was developed to test commercial CTs using a standard harmonic meter [11, 12].

2. HIGH CURRENT DISTORTED SOURCE

The high current source is formed by a programmable generator followed by a high power amplifier that drives a step-down power transformer. This last one provides currents up to 1000 A to the CT under test.

2.1 Programmable generator.

Technical specifications of several middle-range commercial generators of arbitrary waveforms were analyzed for this use [13,14]. Despite their capacity to generate complex waveforms, they were not versatile to generate harmonics of arbitrary amplitude and phase. The general limitation is the amount of harmonics they can manage as well as the configuration of amplitudes and phases in an arbitrary way. For this, multi-function cards capable of generating arbitrary waveforms were selected. They are based on the reproduction of a numeric vector previously loaded into an internal FIFO memory. Furthermore, this type of cards has analog and digital inputs and outputs that allow to control some process of the generator. The card USB-6211 [15] was chosen. It has 4 digital inputs, 4 digital outputs, 16 analog inputs (or 8 in differential mode) and 2 analog outputs. All analog converters have 16 bits, 250 kS/s per channel and 4095 samples of internal memory per channel. This set of technical specifications fulfils the requirements of the project.

The voltage waveforms generated by this card are amplified by a power amplifier, which is described in the next paragraph.

2.2. Power amplifier.

The power required by the test mainly depends on the stray inductance of the high current circuit. Large areas of the current loop led to high inductances and high apparent power. For calibrating a 1000-A CT the power requirement is 10 kVA with a power factor of 0.7. For a 150-A CT, these values are 1.7 kVA, power factor 0.75. As a relevant component of the apparent power is the reactive part, it could be compensated using a capacitor bank. However, some care is needed because the compensation depends on the frequency. If it is calculated for the fundamental component, it will not fit for the higher ones. This compensation bank has a continuous control to adjust the required reactive power, as well as a reactive power meter that measures the reactive power at each harmonic component.

The main component of the power amplifier is a commercial audio amplifier with high nominal power of 50 kW. It was designed for battery operation, but we substitute that source for an hexa-phase rectifier system with very low internal impedance. Filters to eliminate high frequency pulses generated by the amplifier were studied for avoiding interferences in the measuring system.

The amplifier output, up to 220 V, drives a high current power transformer for supply the nominal current of the under test CT. Different transformers are used, one up to 400 A and other from 400 A up to 1000 A.

3. HARMONIC MEASUREMENT SYSTEM

The measurement system is composed by a standard harmonic meter and current transducers.

3.1 Harmonic measurement standard meter.

Recently, a standard system for measuring power quality parameters was developed [11, 12]. It also can measure voltage ratios of distorted waveforms, as required by this work. It is based on two multimeter Agilent 3458A [16]. The nominal voltage is 0.8 V, so the 1 V range is used. Both multimeters are used as synchronized digitizers in master/slave mode. The digitized signals are processed by a computer through a software developed for this purpose, based on the Pogliano algorithm [17]. Additionally to the computation of power parameters, the software can calculate the relationship between the two voltage signals at the input of the multimeters, in phase and quadrature for the fundamental frequency and the harmonic content.

The uncertainty of this system measuring voltage ratios is 3μV/V of the fundamental component, enough for this work.

Adding two current-to-voltage transducers it is possible to measure the behavior of CTs at power frequency and their harmonics, in phase and quadrature. One transducer measures the input current and the other, the output current.

3.2 Current to voltage transducers.

For low current CTs, resistor shunts were used as current-to-voltage transducer, but this is not possible for currents higher than 10 A. For larger currents, the power dissipated in the resistors is very high at 0.8 V. In this case, Rogowski transducers were used. They have three ranges, 1 mV/A, 10 mV/A and 100 mV/A. These transducers were tested at 20 A and different frequencies. Table III shows a summary of the results. The variation of the transducer constant is 0.2% when changing the range, and 0.4% when changing the frequency. For this last one, the variation curve is the same for all ranges, so it will be automatically compensated because the CT calibration system computes the ratio between the outputs of both transducers.

Table III. Behavior of Rogowski coil at different frequencies.

Range (mV/A)	Frequency (Hz)	Output voltage (V)
100	50	2,007
100	1000	2.008
100	5000	2,000
10	50	0,2011
10	1000	0,2012
10	5000	0,2004
1	50	0,02012
1	1000	0,02013
1	5000	0,02004

4. PRELIMINARY TEST RESULTS

The error definition stated by standards is

$$\varepsilon = \frac{kI_S - I_P}{I_P} \qquad (1)$$

were k is the rated ratio, and subscripts p and s indicate primary and secondary currents, respectively [7, 8]. We extrapolate this definition to the harmonic content,

$$\varepsilon_n = \frac{kI_{Sn} - I_{Pn}}{I_{P1}} \qquad (2)$$

being I_S and I_P the secondary and primary currents at each harmonic order. The subscript n indicates the index of the harmonic. As this is a fractional error definition, the uncertainty of the error increases at low current values. For this, the definition has in the denominator the fundamental component of the current.

Different test were done on commercial CTs. One consists in the superposition of the fundamental component with several harmonics component at the same time in a CT of 10 A/5 A ratio, class 0.2, 10 VA. It was loaded with its nominal burden. Table IV shows the errors with a current waveform that has up to the 21th component. The fundamental amplitude was 8 A and 1 A for each harmonic amplitude.

Table IV. Errors of a class 0.2 CT with distorted waveform.

Harmonic component order	ε (ppm)	δ (µrad)
1	-311	589
3	-155	-380
5	-148	-201
7	-100	-137
9	-81	-102
11	-69	-78
13	-64	-59
15	-51	-24
21	-46	-1

Up to the tested order, the CT reproduces the input waveform adequately according to its class. Extension to the 50th order and other commercial CTs used in high voltage substations will be shown at the conference.

5. CONCLUSIONS

A system for calibrating CTs with distorted waveforms was described. The system comprises a distorted current generator and a measuring system. The generator has an arbitrary waveform generator, a power amplifier, filters, high current step-down transformers and reactive power compensators. The measuring system is based on two multimeter 3458A and current-to-voltage transducers. More details and tests will be presented at the conference.

6. ACKNOWLEDGMENT

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