Calibration of high voltage transducers for power quality measurements

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Abstract: - Transmission and distribution networks are increasingly affected by sensitive loads, considering the increase of power electronics based equipment and devices. For keeping under control power quality parameters, for instance, harmonics, sags, swells, flicker, reliable measurements performed at high voltage level are necessary. This kind of measurement is performed using high voltage transducers. Considering present technical standards on this subject, for instance IEC 61000 series [1] and ANSI/IEEE Standards, one can find that calibration procedures for transducers, are not yet defined in those standards. This paper proposes calibration procedures and an experimental setup for generation of the required high voltage waveforms, and shows an example of calibration performed in a real high voltage transducer.

Key-Words: - high voltage transducers, capacitive voltage dividers, power quality measurements, harmonics, IEC 61000 series, high voltage

1 Introduction

The increase of sensitive loads in electrical networks, and increase in the harmonic content in voltage and in electrical current, is a reality today [2, 3, 4, 5, 6, 7]. Most of the sensitive loads, producing distorted current and at the same time, more prone to be affected by those harmonics, are connected to the low voltage network. However, as a matter of fact, harmonics are reflected to the power system high voltage side through power transformer, spreading its effects. In some situations high power distorting loads, for instance, high power arc furnaces, in the range of hundreds MVA, are fed directly by the high voltage network, imposing to perform measurements of the power quality parameters at high voltage level. Also, others types of power quality phenomena, like voltage sags and swells, may be caused by faults in the high voltage network, affecting both high and low voltage level [8]. The increase of the distributed generation, using power electronics based equipment like power inverters, connected with the transmission and subtransmission grid at high voltage levels, imposes the measurements to be performed at this high voltage level, to assure conformity with regulatory and technical standards [1]. Hence, this research presents some studies on possible experimental setup for such calibrations, in real high voltage transducers.

2 Test Setup

The conventional high voltage laboratory, in general, is equipped only with high voltage sources for generating power frequency (60Hz or 50Hz) and impulse (atmospheric and switching) high voltage waveforms, used in dielectric tests of high voltage equipment insulation [9]. For calibration of high voltage transducers used in measurements of power quality disturbances, additional waveforms are necessary, for instance, voltage harmonics, sags (or dips), swells, etc. In this way, in this research, the following test circuit components were defined, for implementing the calibration circuit:

- arbitrary waveform voltage source for generating sinusoidal waveforms, with low harmonic distortion, considering harmonic frequencies up to the 50th order (3000Hz), and generation of composite waveforms (fundamental frequency + harmonics), with enough power capacity for the calibration tests. In this research, a conventional commercial programmable power quality generator was used for this purpose.
- a step-up high voltage test transformer, fed at the low voltage side by the arbitrary waveform voltage source, to produce in the high voltage side, the waveforms generated by the source (considering composite waveforms and harmonics), with enough power required by the calibration tests. The option of to generate high voltage waveforms in the way described above, was motivated by absence, or by the non availability, of high voltage sources for the

waveforms required by the research in the calibration tests, mainly considering high voltage levels found in transmission systems, in the hundreds of kV range. The expected load for the test transformer, during the calibration tests, is supposed to be of capacitive nature, mainly capacitive voltage dividers (CVD) and capacitive voltage transformers. The capacitive voltage transformer (CVT) is a transducer commonly found in transmission and distribution substations. A CVT, in general, presents a high capacitance (thousands of pF), arising, from this fact, a technical difficulty for the test circuit implementation, becoming in this way a very heavy load for the high voltage test transformer.

- Capacitive voltage dividers, composed by 500pF modules, voltage 50kV.
- Power quality analyzer for the transducers' calibrations. In this research, a class A [10] commercial power quality analyzer was used.

The test transformer used in this circuit is a 300kV, 70kVA step-up transformer.

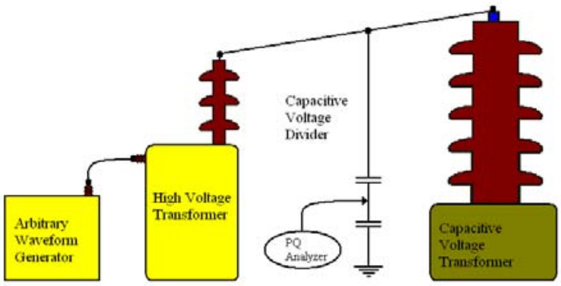

Fig. 1 – Test setup for the calibration of a capacitive voltage transformer, with voltage source (arbitrary waveform generator), high voltage transformer, capacitive voltage divider (adopted as Reference Transducer) and test object (CVT).

The high capacitance of the Capacitive Voltage Transformer (CVT), and associated low impedance, may become a problem for the voltage source (an arbitrary waveform generator) to feed the test setup, considering its rating of 5kVA. For instance, a 4,000pF CVT, for use in a 230kV power system, is a 27kVA load at rated voltage, above the rating of the arbitrary waveform generator with rated power of 5kVA.

2.1 Electric Model of Test Circuit

Fig. 2 shows the electrical equivalent model of the test setup shown in Fig. 1

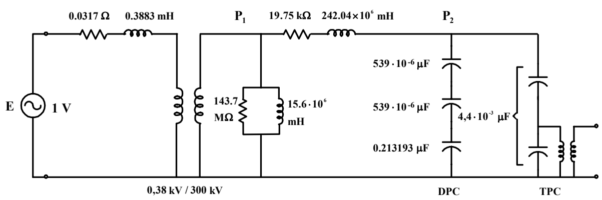

Fig. 2 – Electric model of the test setup shown on Fig. 11, with voltage source (arbitrary waveform generator), high voltage transformer, capacitive voltage divider (adopted as Reference Transducer) and test object (CVT).

The test transformer used in this circuit is a 300kV, 70kVA step-up transformer, where the equivalent circuit, again, was obtained by means of no-load and impedance voltage tests.

3 Test Setup Implementation

Considering the typical configuration of high voltage labs and typical power sources for generation of power quality disturbance waveforms, there aren't commercially available test equipment to generate the required waveforms at high voltage level, and with the required power rating for the calibration of high voltage transducers with high capacitance. In this research a number of alternatives to the test circuit shown in Fig. 1 were studied, in which passive reactive compensation were applied, at low voltage side of the test setup.

3.1 Generation of High Voltage at Harmonic Frequencies

In this section, by means of modelling and computer simulation using ATP – Alternative Transients Program [11] variants of the test setup were studied, aiming the generation of high voltage at harmonic frequencies. For this purpose a series resonating circuit was used, by applying series association of a capacitance and power source, shown in Fig. 3 as *series capacitance*.

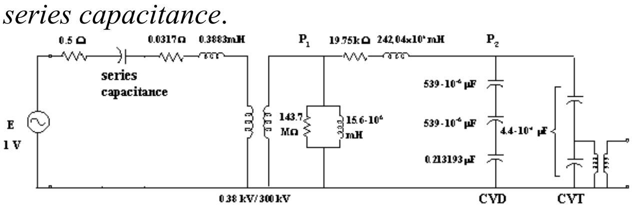

Fig. 3 – Series resonating test setup, with series association of a 0.5Ω damping resistance and a series capacitance, at low voltage side of the test setup.

By changing the series capacitance value, circuit tuning can be obtained, aiming high values of test voltage at the shunt association of the capacitive voltage divider – CVD and capacitive voltage transformer – CVT, with concomitant low values of electrical current fed by the voltage source (the arbitrary waveform generator).

Computer simulation studies were performed, using Alternative Transients Program – ATP, considering a hypothetical voltage source (amplitude 1V) applied at the circuit's input.

In the sequence, computer simulation results are shown, for tuned circuit at frequency of 1500 Hz (25^{th} harmonic).

Also, some additional results are shown, as output current at voltage source, voltage at step-up transformer low voltage winding, voltage at 0.5 Ω resistance, voltage at series capacitance, considering that too high values of voltage and current can be achieved in the series resonating condition.

3.1.1 Generation of Sinusoidal High Voltage at 1500 Hz (25th Harmonic)

Figs. 4 through 8 show computer simulation of test circuit shown in Fig. 3, for 14.7μF series capacitance.

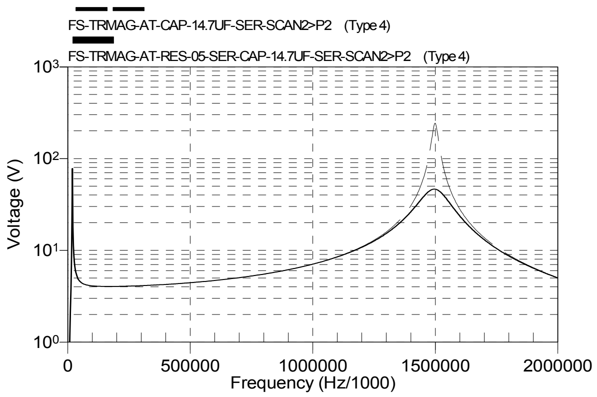

Fig. 4 – Test setup frequency response, with reactive compensation for 1500Hz, with 14.7μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Test voltage applied at shunt association of CVD and CVT, at high voltage side.

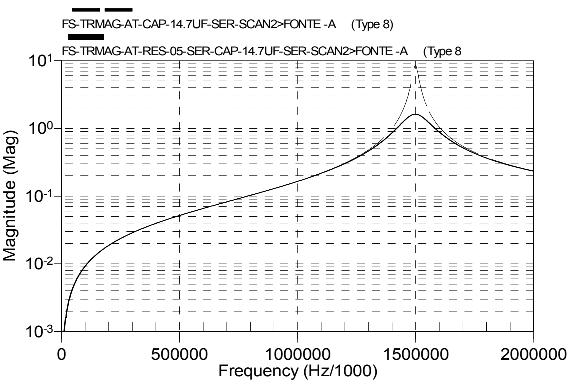

Fig. 5 – Test setup frequency response, with reactive compensation for 1500Hz, with 14.7μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Electrical current fed by the voltage source (the arbitrary waveform generator).

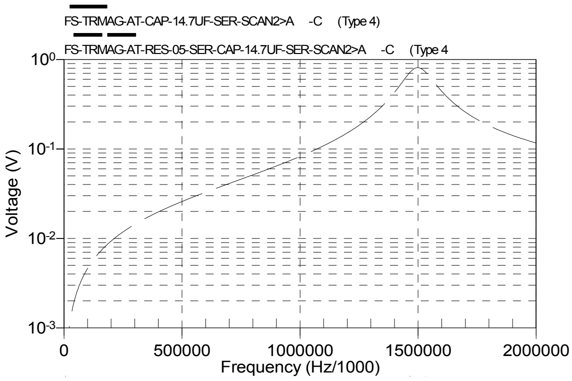

Fig. 6 – Test setup frequency response, with reactive compensation for 1500Hz, with 14.7μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Voltage at 0.5 Ω damping resistance.

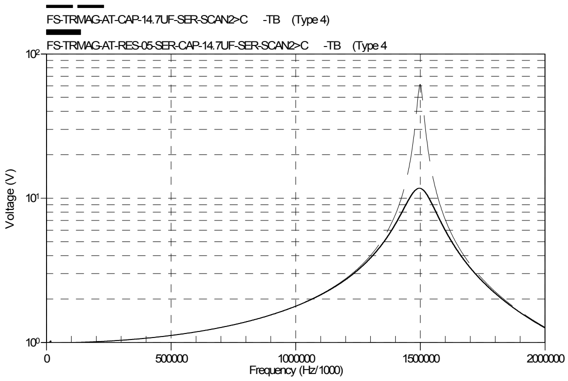

Fig. 7 – Test setup frequency response, with reactive compensation for 1500Hz, with 14.7μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Voltage at series capacitance.

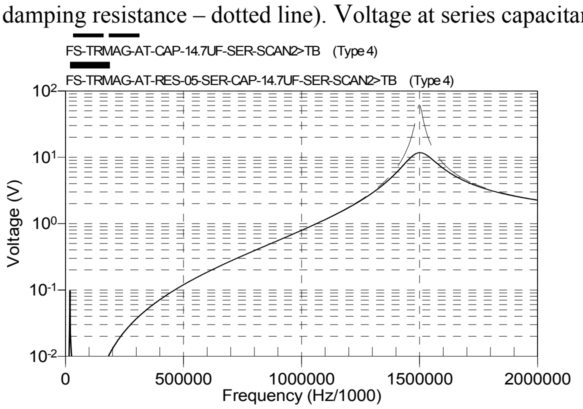

Fig. 8 – Test setup frequency response, with reactive compensation for 1500Hz, with 14.7μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Voltage at step-up transformer low voltage winding.

3.1.2 Generation of High Voltage at 2100 Hz (35th Harmonic)

In the next figures, computer simulation results are shown, for tuned circuit at frequency of 2100 Hz (35th harmonic). Again, some additional results are shown, as voltage source output current, voltage at step-up transformer low voltage winding, voltage at 0.5 Ω resistance, voltage at series capacitance, taking into account that those electrical voltage and current can reach too high values in the series resonating condition.

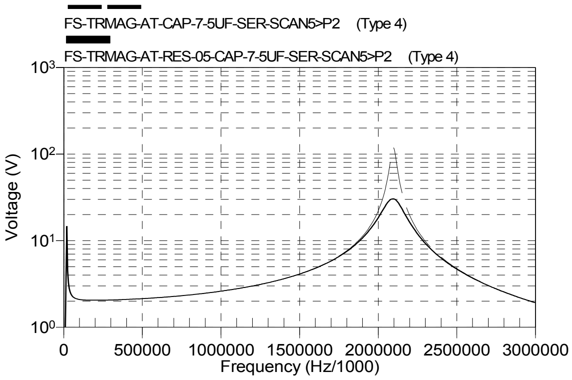

Fig. 9 – Test setup frequency response, with reactive compensation for 2100Hz, with 7.5 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Test voltage applied at shunt association of CVD and CVT, at high voltage side.

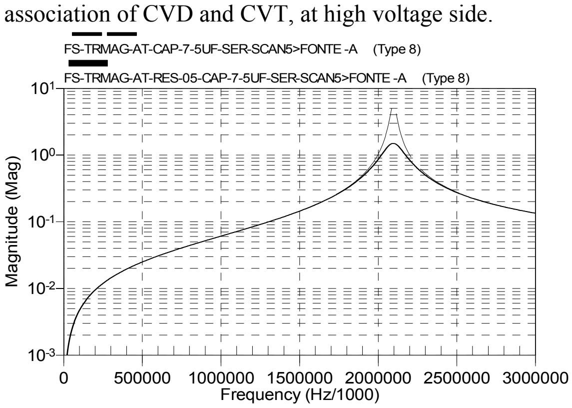

Fig. 10 – Test setup frequency response, with reactive compensation for 2100Hz, with 7.5 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Electrical current fed by the voltage source (the arbitrary waveform generator).

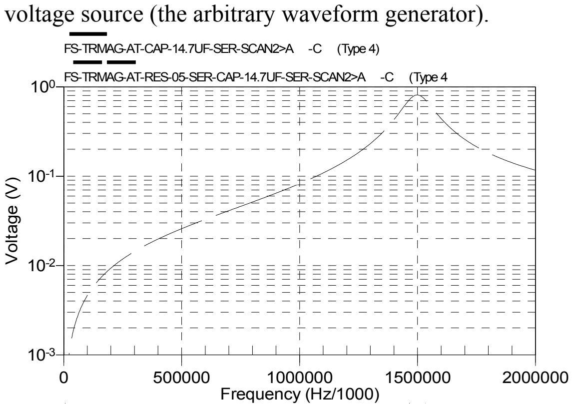

Fig. 11 – Test setup frequency response, with reactive compensation for 2100Hz, with 7.5 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Voltage at 0.5 Ω damping resistance.

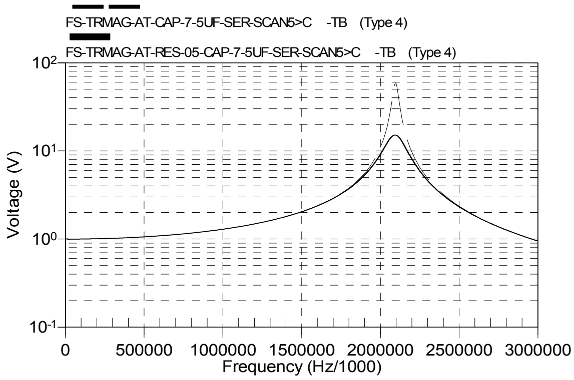

Fig. 12 – Test setup frequency response, with reactive compensation for 2100Hz, with 7.5 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Voltage at series capacitance.

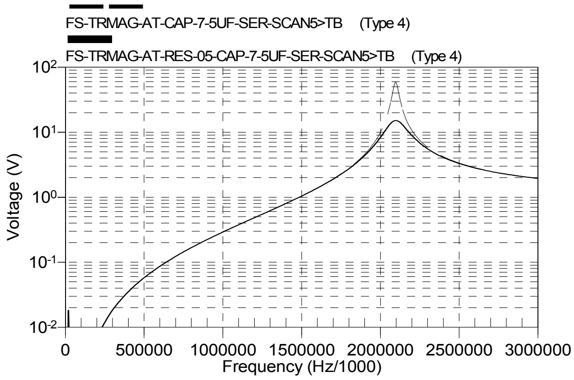

Fig. 13 – Test setup frequency response, with reactive compensation for 2100Hz, with 7.5 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Voltage at step-up transformer low voltage winding.

3.1.3 Generation of High Voltage at 3000 Hz (50th Harmonic)

Additionally, the next figures show similar results for the generation of high voltage at 3000 Hz. Again, some additional results are shown, as voltage source output current, voltage at step-up transformer low voltage winding, voltage at 0.5 Ω resistance, voltage at series capacitance, taking into account that those electrical voltage and current can reach too high values in the series resonating condition.

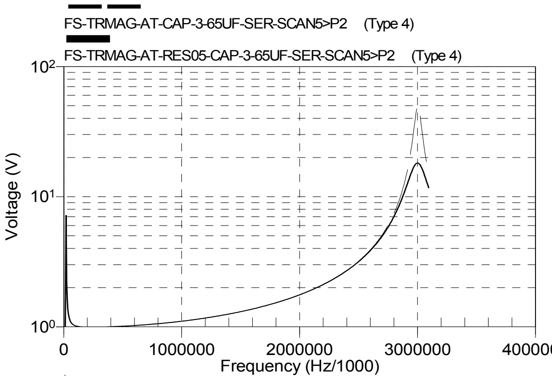

Fig. 14 – Test setup frequency response, with reactive compensation for 3000Hz, with 3.65 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Test voltage applied at shunt association of CVD and CVT, at high voltage side.

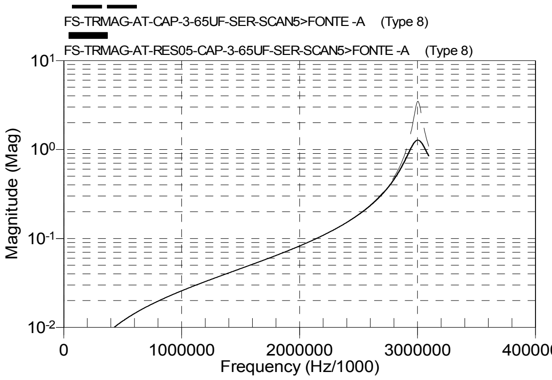

Fig. 15 – Test setup frequency response, with reactive compensation for 3000Hz, with 3.65 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Electrical current fed by the voltage source (the arbitrary waveform generator).

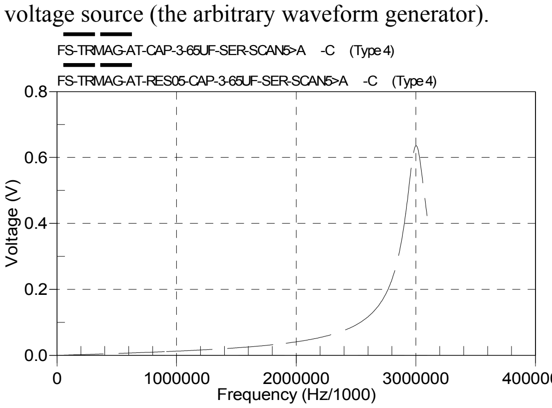

Fig. 16 – Test setup frequency response, with reactive compensation for 3000Hz, with 3.65 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Voltage at 0.5 Ω damping resistance.

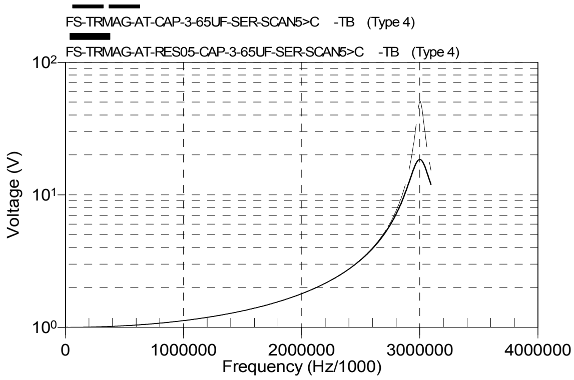

Fig. 17 – Test setup frequency response, with reactive compensation for 3000Hz, with 3.65 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Voltage at series capacitance.

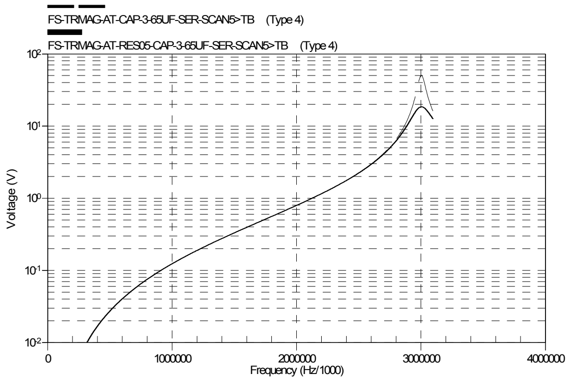

Fig. 18 – Test setup frequency response, with reactive compensation for 3000Hz, with 3.65 μF series capacitance (with 0.5Ω damping resistance – continuous line and without 0.5Ω damping resistance – dotted line). Voltage at step-up transformer low voltage winding.

3.2 Generation of Composite High Voltage Waveforms (60 Hz + Harmonic Frequency)

Fig. 19 shows the electric model of the test setup for the calibration of a 145kV CVT, capacitance 4,400pF, with reactive compensation provided by the shunt capacitance and shunt inductance. This reactive compensation is intended for to obtain low current at 60Hz and, simultaneously, high values of harmonic voltages applied to the CVT. The dimensioning of shunt capacitance and inductance was performed using ATP program computer simulation. A more detailed study on the behavior of this test circuit can be found in [12].

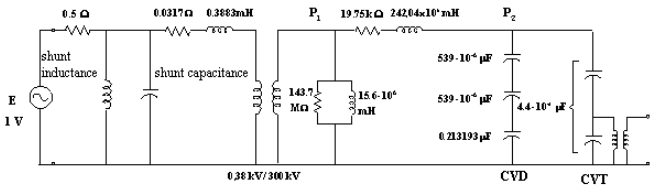

Fig. 19 – Electric model of the test setup, for calibration of a 230kV CVT. At left, is shown the shunt capacitance and inductance, and the 0.5Ω resistance for reactive compensation.

In this test setup, shunt inductance and capacitance values are tuned for each harmonic frequency. For instance, for calibration of CVT at 300Hz (5th harmonic), a 1.5mH inductance and a 650μF capacitance were used. The 0.5 Ω resistance smooths the frequency response curve, simplifying the tuning of the shunt capacitance and inductance values for reactive compensation. Table 1 shows values of reactive compensation for other harmonic frequencies, considering a 4,400pF - 145kV capacitive voltage transformer.

Table 1 – Reactive compensation for each harmonic frequency, for 4,400pF CVT

CVT Capacitance (pF)	Frequency (Hz)	Shunt inductance (mH)	Shunt capacitance (μF)
4,400	120	0.35	15,000
	180	1.2	2,300
	300	1.2	650
	660	1.4	117

Figs. 20 and 21 shows the frequency response of the test setup (without the 0.5Ω series resistance), with reactive compensation for 300Hz, for test transformer voltage (high voltage side) and voltage source output current, respectively.
Similarly as in the series resonating circuit shown above, care should be taken for to keep low voltage and current values in the test setup components. Results of studies on this subject are shown in [12].

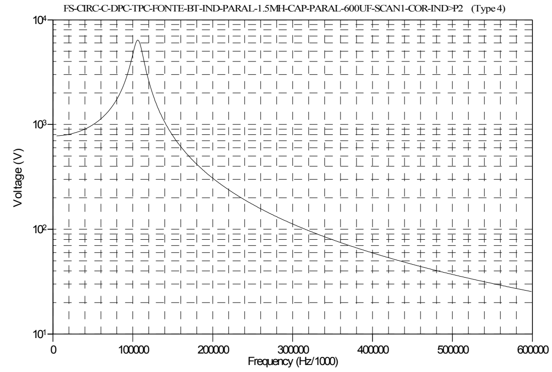

Fig. 20 – Test setup frequency response, with reactive compensation for 300Hz, without the 0.5Ω series resistance. Test transformer output voltage (high voltage side).

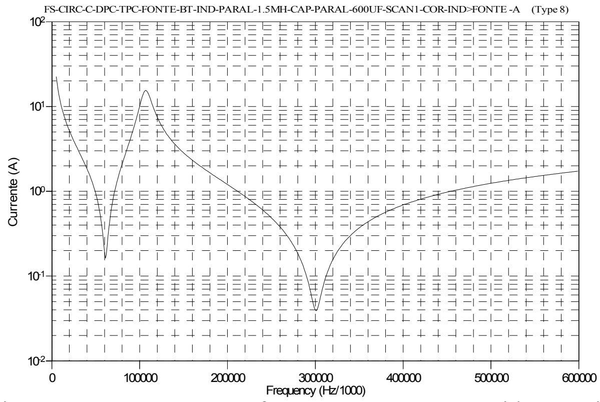

Fig. 21 – Test setup frequency response, with reactive compensation for 300Hz, without the 0.5Ω series resistance. Voltage source (arbitrary waveform generator) output current.

4 Accuracy Requirements for Measurement of Harmonics

Table 2, extracted from IEC Standard 61000-4-7 - 2º edition 2002 08 (Test and measurement techniques – General guide on harmonics and interharmonics measurements and interpretation, for power supply systems and equipment connected thereto), shows accuracy requirements for power quality analyzers for measurement of current, voltage and power, considering spectral components up to 9kHz, superposed to fundamental component (50Hz or 60Hz).

Table 2 – Accuracy requirements for current, voltage and power measurements

Class	Measurement	Conditions	Maximum error
I	Voltage	$U_m \geq 1\%\ U_{nom}$ $U_m < 1\%\ U_{nom}$	$\pm 5\%\ U_m$ $\pm 0{,}05\%\ U_{nom}$
	Current	$I_m \geq 3\%\ I_{nom}$ $I_m < 3\%\ I_{nom}$	$\pm 5\%\ I_m$ $\pm 0{,}15\%\ I_{nom}$
	Power	$P_m \geq 150$ W $P_m < 150$ W	$\pm 1\%\ P_{nom}$ $\pm 1{,}5$ W
II	Voltage	$U_m \geq 3\%\ U_{nom}$ $U_m < 3\%\ U_{nom}$	$\pm 5\%\ U_m$ $\pm 0{,}15\%\ U_{nom}$
	Current	$I_m \geq 10\ \%\ I_{nom}$ $I_m < 10\ \%\ I_{nom}$	$\pm 5\%\ I_m$ $\pm 0{,}5\%\ I_{nom}$

I_{nom}: Nominal current range of the measurement instrument

U_{nom}: Nominal voltage range of the measurement instrument

U_m and I_m : Measured values

NOTE 1 Class I instruments are recommended where precise measurements are necessary, such as for verifying compliance with standards, resolving disputes, etc. Any two instruments that comply with the requirements of Class I, when connected to the same signals, produce matching results within the specified accuracy (or indicate an overload condition).

NOTE 2 Class I instruments are recommended for emission measurements, Class II is recommended for general surveys, but can also be used for emission measurements if the values are such that, even allowing for the increased uncertainty, it is clear that the limits are not exceeded. In practice, this means that the measured values should be lower than 90% of the allowed limits.

NOTE 3 Additionally, for Class I instruments, the phase shift between individual channels should be smaller than $n \times 1°$.

Table 2 considers two classes of measuring instruments. Particularly, class I instruments are used where more accurate measurements are required, for instance, measurements of harmonic emission. Defining U_m as measured harmonic voltage and U_{nom} as rated voltage range of measuring instrument, for the commercial instrument used in this research U_{nom} value is 600V.

The harmonic content present in transmission and distribution networks is regulated by national regulatory documents or international Standards. For instance, Table 3 shows upper limits for harmonic voltages, adopted in Brazilian transmission networks, expressed as percentage of fundamental voltage, at 60Hz.

Considering measurement of power quality parameters in high voltage networks over 69kV, using voltage transducers (for example a capacitive voltage transformer – CVT), one can find that typical secondary output voltage range from 115/√3 and 115V. Considering the upper limit of Table 3, for harmonic order of 3, 5 and 7 (in this case 2%), hypothetically the secondary output voltage of CVT should be 2% X 115V = 2,3V.

Reporting to Table 3, and considering U_{nom} = 600V for the commercial power quality analyzer used in this research, measuring a 2.3V value corresponds to 0.4% of U_{nom}. This way, considering Table 2, such measurement should present an upper limit error of ±0.05% of U_{nom} = 600V, that means, upper limit error of 0.3V. So, for measurement of harmonic voltages near limit values present in Table 3, for harmonic order 3, 5 and 7, maximum acceptable error in this case is 0,3V÷2,3V x 100% = 13%.

Considering same boundary conditions, estimate maximum error for measurement of upper order voltage harmonics, with values near limits shown in Table 3, are shown in Table 4.

Table 3 – Harmonic voltage upper limits, and total harmonic distortion (THD), expressed as percentage of fundamental voltage

V <69kV				V ≥ 69kV			
odd		even		odd		even	
Harmonic order	Value (%)	Harmonic order	Value (%)	Harmonic order	Value (%)	Harmonic order	Value (%)
3, 5, 7	5%			3, 5, 7	2%		
		2, 4, 6				2, 4, 6	1%
9, 11, 13	3%			9, 11, 13	1.5%		
		≥8	1%			≥8	0.5%
15 up to 25	2%			15 up to 25	1%		
≥27	1%			≥27	0.5%		
THD = 6%				THD = 3%			

Table 4 – Comparison between harmonic voltage limits (Brazilian specification) and maximum error (IEC61000-4-7) considering V≥69kV networks

Harmonic order		Limit (Brazilian standard)	Maximum error
odd	even		
3, 5 and 7		2%	13%
	2,4 e 6	1%	26%
9,11 and 13		1,5%	17%
	≥ 8	0,5%	52%
15 up to 25		1%	26%
≥ 27		0,5%	52%

5 Calibration of a 145 kV/4,400 pF CVT for Harmonic Frequencies.

Calibration of a 145kV/4,400 pF capacitive voltage transformer – CVT was performed, using the test circuit shown on Fig. 19, by comparing the output of the CVT with the output of the capacitive voltage divider – CVD, adopted as Reference Divider. The test voltages used in the calibration procedures were generated by the arbitrary waveform generator and applied to the test circuit of Fig. 19. According to the study detailed in [12], the shunt capacitance and inductance shown in Fig. 19 combines with the inductance of the step-up transformer and the capacitance of the CVT, resulting in a tuned circuit for the required harmonic frequencies, in this way generating high voltage at 60 Hz + harmonic frequencies, together with low values of output current at the waveform generator for the calibration tests. Figs. 22 and 23 show the calibration test setup at the lab.

Fig. 22 – Calibration test setup at the lab – step-up transformer (at right), CVT (center), CVD (at left) and 1mH inductances used for reactive compensation (front).

Fig. 23 - Calibration test setup at the lab – Power quality analyzer at left and arbitrary waveform generator, at right.

Figs 24 and 25 shows details of components used for the test setup reactive compensation, for obtaining calibration waveforms voltages considering harmonic frequencies.

Fig. 24 – Capacitances used for reactive compensation, μF range, 380V.

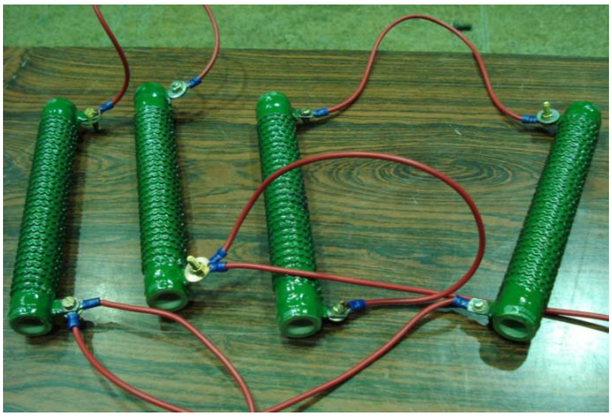

Fig. 25 – Resistances used for reactive compensation, 0.5Ω, 200W.

6 Calibration Results

Results of the calibration test for the 145 kV/4,400 pF CVT are shown in Table 5.

In this Table 5, measured values of sinusoidal voltage at the high voltage side of step-up transformer (3rd column), measured with the capacitive voltage divider (CVD – adopted as Reference) are presented. Additionally, values measured by the capacitive voltage transformer (CVT, 4th column), and the percentual deviation (5th column), for each harmonic frequency, are shown.

Table 5 – Calibration test results for the 145 kV/4,400 pF CVT

Harmonic number	Frequency Hz	CVD (V)	CVT (V)	Percentual deviation
1	**60**	24034.81	24289.17	1.06%
3	**180**	1435.76	1490.79	3.83%
5	**300**	530.20	582.52	9.87%
7	**420**	188.06	236.96	26.00%
9	**540**	60.42	92.91	53.77%
10	**600**	31.72	49.42	55.79%
11	**660**	16.62	27.44	65.15%
12	**720**	8.31	14.28	71.94%
13	**780**	0.76	1.29	70.33%
14	**840**	3.78	12.12	221.05%
15	**900**	4.53	7.27	60.53%

7 Conclusion

In Table 5, a dependence of the percentual deviation between measured values by CVD and CVT for each frequency is observed. Using Table 5 values, Table 6 shows calculated values of a correction factor for each harmonic frequency. In this way, correct values of the output voltage of CVT are obtained, by multiplying by corresponding correction factors for each harmonic frequency.

Table 6 – Correction factor of the secondary voltage of CVT according to frequency

Harmonic number	Frequency Hz	Correction factor
1	60	0.99
3	180	0.96
5	300	0.91
7	420	0.79
9	540	0.65
10	600	0.64
11	660	0.61
12	720	0.58
13	780	0.59
14	840	0.31
15	900	0.62

Fig. 26 shows a calibration curve, according to frequency, considering the correction factors shown in Table 6.

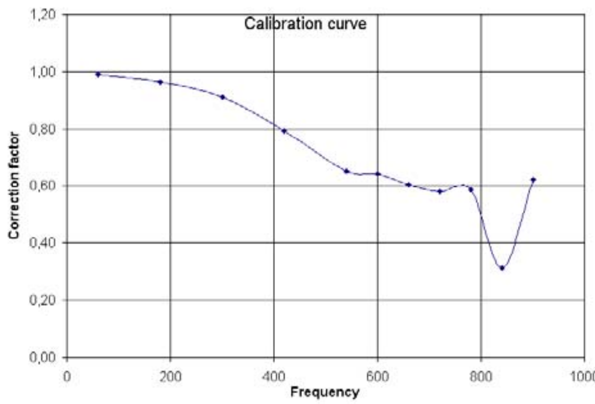

Fig. 26 – CVT calibration curve according to harmonic frequency.

In the development of the test setup, the difficulty in obtaining high voltage values at circuit's output was observed, for higher frequencies and for high capacitance loads (like CVTs). The solution adopted was to use resistances, capacitances and inductances for reactive compensation. With reactive compensation, it was possible to keep under acceptable low values, the voltage source output current considering 60Hz and other higher order harmonic current components

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