Harmonic Measurement and Power Electronics

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Abstract— **This paper establishes the challenge of harmonic measurement in Electric Power Systems given the huge growth of Power Electronics-based equipment. An analysis of the international normative frame is discussed to finally come to the conclusion that their paradigms have to be changed in the medium-term. A specific example of the measurement and acquisition model is analyzed in order to evaluate the behavior of the conventional equipment designed for harmonic measurement. The uncertainties model associated with signal adaptation, digitalization and calculus is studied. Once the real measurements from a known signal spectrum are taken, conclusions over the problems that appear in harmonic measurement instruments due to reduced relative value with respect to the fundamental are stated. The appropriateness of computing the Total Harmonic Distortion (THD) from a given number of harmonics is also analyzed. An alternative form to the classic THD measurement method, considering the growing existence of power electronics equipment injecting harmonics or interharmonics out of the measurement range of conventional measurement equipment, is finally proposed.**

I. Introduction

For over than 40 years, technological development and power electronics have contributed to the increase of non linear loads in transmission and distribution networks. Simple dimmers of few of VA to complex stations from $HVDC$[1]systems of thousands of MW are responsible of generating non purely sinusoidal currents at the network frequency. These disturbing currents either have higher frequencies (harmonics) or lower frequencies (sub-harmonics) than the network frequency but they also can adopt interharmonics values.

Current harmonics emitted by a disturbing load are transformed in voltage harmonics in the distribution system. Additional losses in lines and transformers are generated, as well as deterioration and destruction of reactive compensation capacitors. Just to worsen the problem, resonances between these capacitors and the short circuit impedance in the point of coupling are produced.

From a general point of view, disturbing loads can be classified in identifiables and unidentifiables [1].

High power rectifiers with diodes or thyristors (electrolysis, direct current arc furnaces, motors speed drives, UPS[2], $HVDC$), cycloconverters, alternate current arc furnaces, SVC[3], $STATCOM$[4], $TCSC$[5], $UPFC$[6], $BESS$[7], etc are typically identifiables loads. Electric utilities always know about their existence and their location.

On the other hand, small non linear loads distributed along the electric system are impossible to locate. The small rectifier at the input of a home appliance generates an insignificant harmonic current, but thousands of this appliances distributed over a city can become a major problem. This problem gets even worse because the harmonics emitted by these loads are in phase.

If the energy meters for billing purposes are considered, the problem is even bigger, given the fact that these devices do not handle the problem of load unbalance and distorted currents very well [2].

The formal answer to this problem can be partially found in the international normative about Electromagnetic Compatibility (EMC) starting with the IEC61000-1 standard [3]. Generically the objective of the EMC standards is to lead the distributors to give voltages with certain characteristics, and lead the manufacturers to design their equipment with the ability to stand those voltages. On the other hand, consumers and appliances must consume currents in compatibility with those levels. In brief, it is almost exclusively the short circuit impedance in the Point of Common Coupling (PCC) which determines the harmonic voltages that arises as a consequence of the harmonic currents consumed.

In Uruguay, the ”Unidad Reguladora de los Servicios de Energía y Agua” ($URSEA$) will put under public consideration a regulation concerning the quality of the disturbances over the electric energy distribution system. The regulator in Argentina ($ENRE$) has have regulations in that matter for some years now [4] [5] and has got experience from the application of them. In Brazil, the national system operator (ONS) has valid regulations [6] [7] still to be imposed. These regulations not only restrict the THD but also establish limits to the emission of each harmonic.

Whichever the scenario, current and voltage harmonics in distribution networks are being measured or will have to be measured in the region. These measurements will be used to decide whether or not the application of penalties to distribution companies or individual consumers. In consequence, to know how to measure harmonics and to establish the uncertainty of those measurements is of the utmost importance. All of it using conventional meters with affordable prices and according to the up to date technology. The specifications and requirements for the harmonic measurement equipment set by the regulations must be reasonable. Is it logical to ask for measurements up to the 40th harmonic? Is it the procedure of measurement for the THD specified enough? Do standards and regulations include the case of Power Electronics equipment emitting over the 200th (10 kHz) or even over the 300th (15 kHz) harmonic?

[1]High Voltage Direct Current transmission line
[2]Uninterruptible Power Supply
[3]Static VAr Compensator
[4]Static Synchronous Compensator
[5]Thyristor Controlled Series Capacitor
[6]Unified Power Flow Controller
[7]Battery Energy Storage System

II. International Standards concerning Harmonics

The IEC61000-2-2 [8] standard referred to low voltage networks (LV), sets two procedures to measure the voltage THD: either measuring the instantaneous deviation with respect to the fundamental (pointed as a procedure very rarely utilized) or computing the harmonic residue from the measured individual harmonics. As the standard establishes, in the calculation of the THD can be included up to the 40th harmonic. Interharmonics are not included in the computing. This standard also sets maximum values for individual harmonics and establishes its range or application up to 10 kHz. Even though it is not explicitly stated, in order to perform harmonics measurement, the IEC61000-4-7 [9] standard must be referred. As this standard is applicable up to 2.5 kHz, the procedure to measure between 2.5 kHz and 10 kHz remains obscure. On the other hand, an equipment emitting over 15 kHz (300th harmonic for 50 Hz) would not be comprised by these standards.

Standard IEC61000-2-4 [10] should be used in case of industrial networks. According to the environment, it sets more strict or more tolerant limits than the IEC61000-2-2. Opposite to this last standard, it sets clearly that 40th is the maximum harmonic to be used in computing the THD. It also establishes that interharmonics must be considered when computing the THD. As the other standards, it does not specifies how to calculate the THD. When working with frequencies above 2.5 kHz (50th harmonic for 50 Hz), as it was stated for the IEC61000-2-2 and the IEC61000-4-7 standards, the procedures are not clear.

On the other hand, the IEC61000-3-2 [11] standard, which is applicable in LV and currents below 16 A, sets limits to the emission of harmonic currents only up to the 40th harmonic. Nothing is said about higher frequencies. It does not establish any limit for the THD, so an equipment emitting a big current in the 41th harmonic would remain unpunished. These that may be called omissions are comprised in the IEC61000-3-4 [12] technical report, which is applicable in LV and currents greater than 16A. In this report, the THD is computed using up to the 40th harmonic. Despite that, as the IEC61000-2-2 standard, it sets limits for individual harmonics within all its range of application. However, it refers to the IEC61000-4-7 standard, which, as stated earlier, works up to 2.5 kHz. Again its not clear what happens for frequencies grater than this value.

Finally, the IEC61000-4-7 standard sets limits on the precision accomplished when voltage transformers (VT) and/or current transformers (CT) are used. With the aim to obtain a measurement error related to the fundamental less than 5% in amplitude and less than 5^o in relative phase, it states that when working in LV networks there are no problems within the applicable range (2.5 kHz). It also states that when working in medium voltage (MV) networks the VT would be adequate to up to 1 kHz with reference to amplitude measurements and to up to 700 Hz with reference to relative phase. Still working in a MV network, the CT would be excluded for phase angle measurement for frequencies above 1.5 kHz.

After all the considerations exposed above, the questions asked in the end of section I still remains unsolved. Power electronics causes troubles above the conventional standards scope. Problems arises even when the measurements are taken. There are problems with CT and VT but also with conventional harmonic measurement equipment.

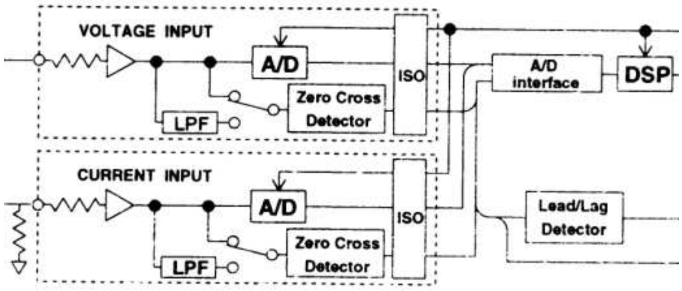

Fig. 1. Diagrama de bloques interno del $meterA$

IEC61000-4-7 standard establishes how to measure harmonics and interharmonics. It emphasizes the existence of measurement equipment for these variables in the time domain and in the frequency domain. The second type of instruments will be the one studied in this work as they are the most common in the market. Basically, this is due to their lower price which is a consequence of the growth in the usage of complex but economical digital systems instead of analogue ones.

Frequency domain equipments are based on the digitalization of continuous signals in order to calculate the *Discrete Fourier Transform* (DFT) and optimized calculus methods are used in order to reduce the calculation effort so called *Fast Fourier Transform* (FFT).

III. A measurement equipment example: $meterA$

The block diagram of the meter that will be known from now as $meterA$ is shown in Fig.1. It is just that of a conventional equipment where it can be clearly recognized the signal conditioning block intended to adapt the signal to standardized levels, the possibility of filtering the signal (LPF) for synchronization purposes (Zero Cross Detector or PLL), the A/D conversion, the galvanic isolation (referred as ISO) and the digital signal processing (DSP). Despite it is not shown in the diagram, the meter has a CPU that processes all its functionalities.

A. Measurement uncertainties of $meterA$

A meter with a continuous real input signal which is digitalized in order to perform some calculations to give a result, has several errors that must be considered and that, given their nature, can redound in type A and B uncertainties [13]. The error is the difference (with sign) between the measured and the actual value. The uncertainty is the doubt interval with respect to the measured value and it is characterized by a statistical distribution with a given variance.

In [14] the measuring uncertainty of this equipment for a given harmonic is modelled as

$$u^2 = 2u_{\varepsilon_0}^2 + 7u_{\varepsilon_c}^2 \qquad (1)$$

where u_{ε_0} is the uncertainty introduced by the analogical signal conditioning stage that affects the signal in order to take it to a standardized level prior to the A/D conversion. The absolute errors[8] of this stage are kind of "proportional" to the magnitude of the signal being measured. They are generally specified

[8]Difference with sign between the measured and the actual value. The relative value is obtained dividing this difference by the measured value.

as relative uncertainties with respect to the measured signal (referred as rdg in $meterA$'s specifications). This adaptation stage of the signal also introduces *offset* uncertainties which result in uncertainties associated with the measuring range as they are independent of the magnitude of the measured signal.

On the other hand, three types of uncertainties are introduced in digital systems. The quantification uncertainty that arises when the analog-digital transformation is done and the rounding and the truncation (overflow) uncertainty after a numerical operation. This last one can be avoided and it is almost negligible compared to the rounding uncertainty. These uncertainties are constant and independent from the measured magnitude but they are proportional to the measuring range (referred as rng in $meterA$'s specifications). As a consequence, the second term of (2) depends of

$$u^2_{\varepsilon_c} = \frac{2^{-2b}}{12} \tag{2}$$

which is the squared uncertainty of the normalized signal caused by the A/D conversion with b bits plus sign. The 7 value comes from considering the A/D conversion uncertainty, the rounding uncertainty in the DFT's calculation, the uncertainties propagation of the DFT's calculation, the operations to transform the obtained value of DFT to harmonics and the rounding uncertainty associated to the meter's display (rng). In [14] it is concluded that from the $7u^2_{\varepsilon_c}$ term, associated to the measuring range, 29% is attributed to the A/D conversion, 57% comes from the DFT calculation and the remaining 14% is a consequence of calculating the harmonic final value from the DFT calculation (basically this last statement comes from dividing by the number of samples taken for the DFT calculation and from scaling the normalized result to the meter's display).

B. Uncertainties in the calculation of the THD for $meterA$

The $meterA$ displays a value of the THD but the accuracy of this measure (statistical information) does not appear in its specifications. This fact has an explanation if the procedure of computing this uncertainty is observed. If the THD definition is given as

$$THD = \frac{\sqrt{\sum_{i=2}^{50} V_i^2}}{V_1} \tag{3}$$

and the conventional propagation of uncertainties is computed given the functional expression that determines it [15] [16], then, the uncertainty of the THD computed from the uncertainty of its factors (u_{V_i} y u_{V_1}) is expressed as

$$u^2_{THD} = \frac{THD^2}{V_1^2}u^2_{V_1} + \frac{1}{THD^2V_1^4}\sum_{i=2}^{50} V_i^2 u^2_{V_i} \tag{4}$$

Given the procedure of calculation of the THD from its individual harmonics, the manufacturer does not know beforehand which spectrum will the measuring signal have, as a consequence, he can not calculate the propagation of the measure uncertainty.

IV. An alternative method to measure the THD

As stated in II, the market has a wide offer of measuring equipment that measure in the frequency domain. Generally, they use expressions like the ones shown in (3) which generates some problems in the presence of interharmonics or if the distorting frequency is higher than the measuring range of the equipment, for instance, $n = 50$ for the $meterA$ (2500 Hz for f=50 Hz).

An alternative would be to measure the THD from its definition: "relative value to the first harmonic of the harmonic residue" It will be just enough to measure indirectly the harmonic residue substracting the rms value of the first harmonic from the rms value of the signal as stated in (5)

$$THD = \frac{\sqrt{V^2_{rms} - V_1^2}}{V_1} \tag{5}$$

Finally, (6) shows the uncertainty in the measurement of the THD from the measurement and the measuring uncertainty of V_{rms} and V_1

$$u^2_{THD} = \left(\frac{THD^2+1}{THD}\right)^2 \frac{1}{V_1^2}u^2_{V_1} + \frac{V^2_{rms}}{THD^2V_1^4}u^2_{V_{rms}} \tag{6}$$

Comparing (6) to (4), it is easy to see that the uncertainty of the alternative method is larger than the uncertainty of first method, but it must be remarked that (6) was developed under the hypothesis that no correlation exists between V_{rms} and V_1. In most real cases, some correlation exists, and the total uncertainty is lower than that predicted by (6). It is not possible to develop an equation that includes all correlations, because it depends on the actual implementation of the measuring system. Anyway, the alternative method has the advantage that all residuals are included, as interharmonics

V. Measurements

In order to evaluate the ability of the $meterA$ to measure individual harmonics and the THD, two sets of measurements were taken.

One of them was taken from a square voltage wave generated with a wave generator considered stable.

On the other set of measurements, the THD was determined using the proposed alternative method with a 50 Hz sinusoidal wave contaminated with another sinusoidal wave whose frequency changes between 100 Hz and 15 kHz.

A. Measurement from a square wave

The laboratory setup utilized to perform the measurements is shown in Fig. 2

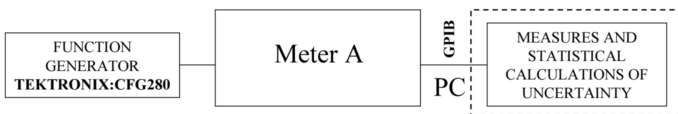

Fig. 2. Measurements and calculation laboratory setup

The computing and measuring procedure consisted in the evaluation of the probable value (measurement) and the uncertainties [15] of the measurement taken with the $meterA$. Twenty consecutive samples were taken with a time interval of 10 seconds. The mean value, the experimental variance and the uncertainty for these samples were statistically computed. The statistic calculations were done on the PC after acquiring the data from the $meterA$ through its $GPIB$ port.

As it is well known, the harmonic content of a square is determined by odd harmonics being inversely proportional to the harmonic index and null even harmonics.

Top of Fig. 3 shows the obtained measurements for odd harmonics. In the middle it can be appreciated that the scaled

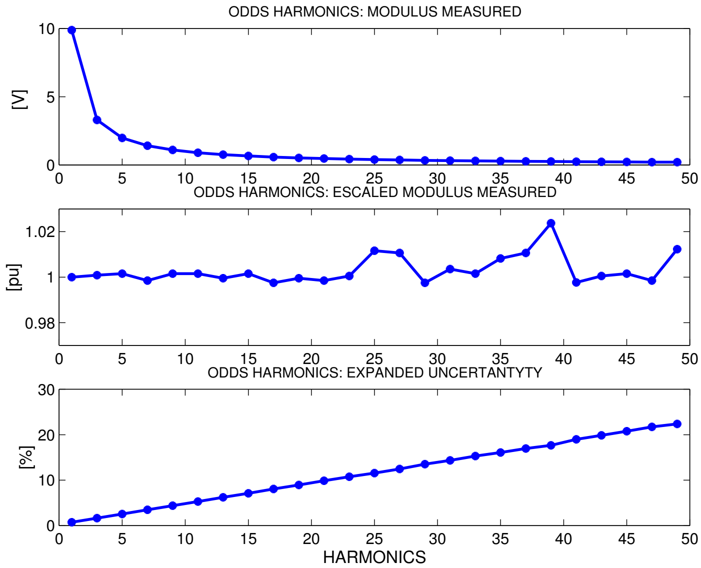

Fig. 3. Measurements with $meterA$. Odd harmonics. Top: Modulus. Lower part: Expanded uncertainties. Middle: Scaled modulus (multiplying the modulus by n).

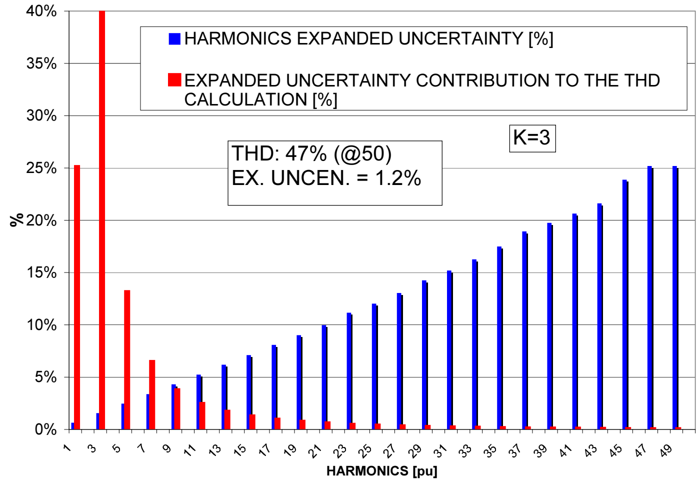

Fig. 4. Square wave. Relative expanded uncertainties in harmonic content measurements and their relative contribution in the calculation of the expanded uncertainty of the THD (1.2%). For example, 40% of the 1.2% is responsibility of the third harmonic uncertainty.

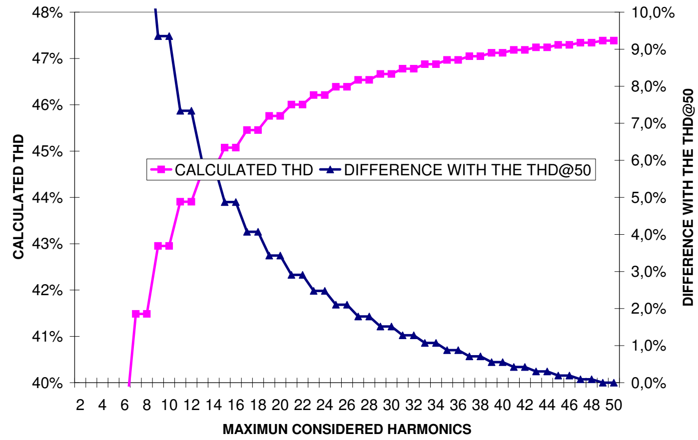

Fig. 5. THD changes with the number of harmonics considered in the calculation and the difference between the value obtained when computing the THD with 50 harmonics (THD@50). For example, if the THD is calculated considering up to the 15th harmonic, the result obtained is 45.1% with an expanded uncertainty of 4.9%.

modulus (multiplying the modulus by n) remains approximately constant as expected. In the lower part of the figure, the expanded uncertainties[9] obtained from the measurements and from the accuracy[10] specifications of $meterA$ are shown. It is emphasized that the expanded uncertainty of the measurement in this kind of wave for the 50th harmonics reaches a 25%. This is a normal situation in "real" signals where the harmonic content is inversely proportional to the harmonic index and the measuring range utilized on the A/D stage has to be scaled to the first harmonic. This implies that the quantification absolute uncertainty and the rounding uncertainty of the $meterA$ takes significant values compared to the small value that is really present in the measured signal (with respect to the first harmonic)

1) Uncertainties on the THD calculation: In order to evaluate the uncertainties on the THD calculation the expression (4) has to be utilized. The u_i values are estimated from the expanded measurement uncertainties shown in Fig. 3 as it was specified earlier. After obtaining the u_{THD}, the expanded uncertainty was estimated (with K=3), giving result of 1.2%. If the big uncertainties with which harmonics are measured are taken into account (25% for the 50th harmonic), the key to explain the result is the uncertainties propagation utilized. Although the 50th harmonic has a great uncertainty, its relative incidence in the final result is negligible. Fig. 4 shows relative uncertainties in harmonic content measurements and their relative contribution in the 1.2% obtained.

Fig. 5 shows how the value obtained for the THD changes with the number of harmonics considered in the calculation and the difference between the value obtained when computing the THD with 50 harmonics (THD@50). For example, if the THD is calculated considering up to the 15th harmonic, the result obtained is 45.1% with an expanded uncertainty of 4.9% which can be acceptable in a regulation concerning electric energy quality. If the calculation takes up to the 40th harmonic, which is the number required in most standards, the expanded uncertainty is now 0.6%. This clearly has no sense if it is reminded the error introduced by the CTs and the VTs. It has no sense either if it is considered that a square wave has a theoretical THD value of 48.3% when all the residue is taken into account and the value obtained considering 50 harmonics (47.4%) is only a 2% far from that value. In this case, if the proposed alternative method is utilized to compute the THD, the number obtained is 47.5% (just a 1.6% less than the theoretical value)

B. Measurements of THD using the proposed alternative method

The $meterA$ has two operating modes. In the "harmonics" mode, in addition of computing the value of harmonics from

[9] In order to estimate the expanded uncertainty, a K=3 covering factor is used as a criteria which assures with a 99.5% probability that the measurement lies within the considered range. As a consequence, the expended uncertainty will be tree times the uncertainty ($3u$) [15].

[10] It is assumed that the accuracy with which the manufacturer gives the data corresponds to an expanded uncertainty with a covering factor of K=3. As a consequence, the measurement uncertainty will be the accuracy given by the manufacturer divided by 3.

1 to 50, it computes the rms value of the signal based on the values obtained for the harmonics, as stated in (3). It also computes the THD based on the calculated harmonics values. On the other hand, in the "normal" mode it computes the rms value as the integral of the quadratic value in one period.

In order to analyze and compare how other meters work, the rms value was measured with a device that will be called $meterB$ and the rms value, fundamental V_1 and THD were measured with other devices that will be calles $meterC$, $meterD$ and $meterE$ respectively.

The measured signal had a 50 Hz, 6 V fundamental and a 2.88V harmonic component whose frequency was varied within 100 Hz and 15 kHz. Given these numbers, the theoretical rms value of the voltage would be $\sqrt{(6^2+2.88^2)} = 6.66V$ and the THD would be 48%. Table 1 shows the obtained results. It can

TABLE I

MEASUREMENTS WITH A SET OF 5 METERS OF THE V_{rms}, V_1 AND THD. V^* DENOTES $meterA$ IN "NORMAL" MODE.

Arm.	A				B	C			D			E		
Hz	Vef	V1	THD	Vef *	Veff	Vef	V1	THD	Vef	V1	THD	Vef	V1	THD
100	6,7	6,0	48%	6,7	6,7	6,7	6,0	48%	6,7	6,0	48%	6,7	6,0	48%
500	6,7	6,0	48%	6,7	6,7	6,7	6,0	48%	6,7	6,0	48%	6,7	6,0	48%
1000	6,7	6,0	48%	6,7	6,7	6,7	6,0	48%	6,7	6,0	48%	6,7	6,0	48%
1025	6,7	6,0	48%	6,7	6,7	6,7	6,0	5%	6,7	6,0	0%	6,7	6,0	48%
1500	6,7	6,0	48%	6,7	6,7	6,7	6,0	48%	6,7	6,0	48%	6,7	6,0	48%
2400	6,7	6,0	48%	6,7	6,7	6,2	6,0	1.5%	6,7	6,0	48%	6,7	6,0	48%
2600	6,0	6,0	<1%	6,7	6,7	6,0	6,0		6,7	6,0	<1%	6,7	6,0	48%
10000	6,0	6,0	<1%	6,7	6,7	6,0	6,0		6,0	6,0		6,0	6,0	0%
15000	6,0	6,0	<1%	6,7	6,7	6,0	6,0		6,0	6,0		6,0	6,0	0%

be seen that the $meterA$ (in "normal" mode) and the $meterB$ had good results for the V_{rms} value in every case (up to 15 kHz). It also can be noticed that $meterA$, $meterC$, $meterD$ and $meterE$ compute the fundamental voltage properly in every case. Those meters also compute properly the V_{rms} up to the range for which they are specified (2500 Hz, 1500 Hz, 2500 Hz and 3000 Hz respectively). Nevertheless, they do not compute properly neither the $Vrms$ value nor the THD over those frequencies given they have exceded the maximum frequency they are able to measure according to their specifications. With reference to interharmonics, the $meterA$ and the $meterE$ are able to compute properly the THD even in the presence of a 1025 Hz interharmonic while the $meterC$ and the $meterD$ do not measure the actual THD in that case.

These last three verifications respond to different reasons. In the case of $meterA$ in "harmonics" mode and $meterE$, they compute the V_{rms} from the harmonics, but as they are able to measure (or estimate) them properly, even in the presence of interharmonics, they do not have any problems until the maximum harmonic calculated is exceeded. On the other hand, the $meterC$ and the $meterD$ compute the V_{rms} from the quadratic integral of the sampled values for which they do not have any problems until the anti aliasing filter frequency that they have is exceeded over the maximum frequency for which they are specified.

It seems clear that if the proposed method in IV is applied, all the meters will measure the fundamental value properly. In the cases that they also mesure the V_{rms} properly, the THD could be measured (calculated) correctly up to frequencies as high as 15 kHz, even in the presence of interharmonics. When using the $meterA$, the "normal" mode should be selected in order to measure V_{rms} over 2500 Hz and the "harmonics" mode should be selected to measure V_1. In every other case, the THD would be properly computed up to the frequency they are specified as they measure V_{rms} and V_1 correctly. Finally, in the presence of frequencies higher than the equipments range, an additional device that measures the V_{rms} without anti aliasing filters or similar to the $meterB$ should be utilized.

VI. CONCLUSIONS

The operation of a digital harmonic measurement equipment based on A/D conversion and subsequent calculus of the harmonic content using FFT methods was analyzed.

In order to perform an experimental evaluation of the difficulties that can arise when measuring individual harmonics and THD, a set of measurements were done over known signals with diverse harmonic content. Specifically, measures were taken over a square wave signal as it has a harmonic content very similar to common real situations: just odd harmonics whose values decrease inversely proportional to the frequency (conventional rectifiers).

The uncertainties propagation obtained as a result of the application of the method of computing the THD from its individual harmonics and as a result of the application of the alternative method proposed was analyzed. It was shown how useless it is to consider too many harmonics when computing the THD with the traditional method from the calculated harmonics components. It is just enough to consider the 15 first harmonics (750 Hz). This is compatible with the limitations imposed by the CT and the VT.

On the other hand, it was shown how different meters may or may not have problems when measuring harmonics and THD in electric systems with higher harmonics and intherarmonics. It was concluded that in every case, the proposed alternative measurement method offers a better detection of problems than conventional meters with FFT computation.

Nowadays every inverter connected to the electric network (active filters, $STATCOM$, $UPFC$, $BESS$, distributed generation, etc.) produces harmonics in the electric systems from 1 kHz to 10 kHz and even up to 15 kHz. As a consequence, a regulation also has to be aware of these frequencies. If they appear in the spectrum having significant amount (not proportionally inverse to frequency), they could be measured with adequate uncertainties. Nevertheless, measuring a 200th harmonic (10 kHz) seems to be out of the measuring range of commercial meters, as they can measure up to 2.5 kHz (compatible with IEC61000-4-7 standard)

Aiming to be able to regulate harmonic problems up to as high frequencies as 15 kHz (harmonics and interharmonics), maybe it is just time to change the measure paradigm of the THD, promoting the return to its first definition: residue/fundamental. Measuring the fundamental value is a trivial matter task. Measuring the residue is as simple as measuring the rms value and subtracting the measured fundamental value from it. Using this method all harmonics and interharmonics are measured properly. The bandwidth covered will depend on the ability of measuring the rms value correctly. Obviously, the calculation of the rms value should not be made using their harmonic components. Perhaps the comment included in IEC61000-2-2 standard, regarding the use of measurements of the instantaneous deviation with respect to the fundamental (referred as rarely utilized) should be revised.

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