

THD Uncertainty Estimation for Inductive Current Transformers Using the Accuracy Class Information

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Abstract – The Total Harmonic Distortion (THD) measurement is among the key elements to assess the power quality of a network. However, the Standards does not provide sufficient information to evaluate the uncertainty related to THD, neither voltage nor current one. Therefore, this work tackles the uncertainty estimation of the current THD measured by off-the-shelf inductive current transformers. The uncertainty computation is performed by a consolidated expression presented by the authors. Finally, the actual measurements of THD and the computation of its uncertainty are compared with those estimates with the presented expression.

I. INTRODUCTION

In the last years the world of Instrument Transformers (ITs) suffered a huge change from two perspectives: firstly, due to the introduction of the new generation of Low-Power Instrument Transformers (LPITs); secondly, due to the spread of several new actors like renewable energy sources, intelligent electronic devices, electric vehicles, etc. Regarding the former aspect, new ITs Standards have been published to replace the old IEC 60044 series and to include the new generation of devices. The new standard is the IEC 61869 series of which the IEC 61869-1 and -6 [1,2] represent the general requirements for inductive and low-power ITs, respectively. LPITs have many advantages compared to the inductive ITs, such as low-power outputs, reduced dimensions, flexibility during installation, etc. However, Distribution System Operators (DSOs) and utilities do not completely rely on them for all purposes; hence, it is still possible to continue and improve the studies on the legacy ITs. This is the reason why this paper focuses on ITs, and in particular on inductive current transformers (CTs).

Turning to the latter aspect that affected ITs, the presence of new devices spread among the power networks changed the way DSOs approach the management and control of the grid. In fact, the integration between these new devices and the power network led to a worsening of the so-called Power Quality (PQ). A low PQ results in the degradation

of the electrical assets and of the overall network. For example, it affects microgrids [3,4], electric machines [5], insulators and cable accessories [6,7], wind and solar power plants [8] etc. But, what has to be ensured, considering its critical importance, is the correct behavior of ITs when subjected to low level of PQ. As a matter of fact, their measurements are crucial for all instrumentation that relies on them, like protective and control instruments [9,10], algorithm that manage the grid [11-14], etc.

To answer to these changes, the researchers have developed and invented a variety of PQ indices and techniques to monitor and mitigate the effects of a low PQ. For example, Total Harmonic Distortion (THD), power factor, flicker factor [15,16] are some well-known indices that are used to tackle PQ.

In light of the above, this paper focuses on a fundamental PQ index, the THD. In particular, the aim is to estimate the uncertainty associated to THD by implementing a consolidated expression – developed by the authors in [17] – on the measurements obtained from two off-the shelf medium voltage (MV) inductive CTs.

What follows has been structured as: Section II briefly describes the expression used to estimate the THD uncertainty. The main setup used to collect the THD measurements is summarized in Section III from [18]. Section IV deals with tests and results, while Section V concludes the work with final remarks and comments.

II. THE CLOSED-FORM EXPRESSION

The closed-form expression that is used in Section IV to estimate the THD uncertainty of two CTs has been developed in [17]. Briefly, starting from the definitions of THD and of the ratio error affecting the rms of the harmonic components V_i of the measured signal, the following expression is obtained:

$$THD = \sqrt{\sum_{i=2}^N \left(\frac{V_i(1+\varepsilon_i)}{V_1(1+\varepsilon_1)} \right)^2}. \quad (1)$$

In (1) the values of the ratio error of the 50 Hz component ε_1 and of the harmonic components ε_i have

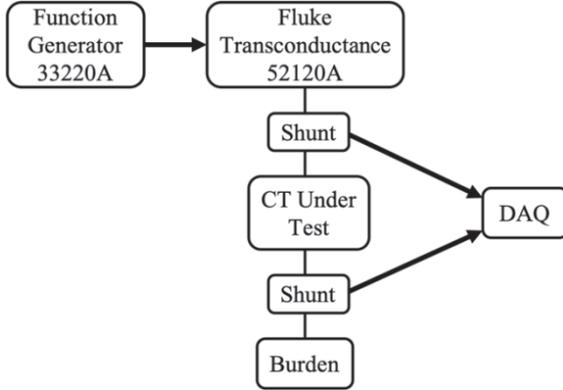


Fig. 1. Simple schematic of the measurement setup

TABLE I. SET OF DISTORTED WAVEFORMS AND THEIR THD

Signals	THD [%]
A	4.4
B	7.1
C	7.7
D	8.7
E	9.9

been taken from the standards [1,2]. Afterwards, (1) has been manipulated and treated like a non-linear combination of uniformly-distributed random variables. Its probability density function has been graphically shown and the closed-form expression for its expected value μ_{THD} and its variance σ_{THD}^2 have been derived. These two parameters have been found to be:

$$\mu_{THD} = P\left(m, \frac{1}{2}\right) * \sqrt{\frac{\Omega}{m}}, \quad (2)$$

$$\sigma_{THD}^2 = \Omega \left\{ 1 - \frac{1}{m} \left[P\left(m, \frac{1}{2}\right) \right]^2 \right\}, \quad (3)$$

where P is the Pochhammer function, while m and Ω are two parameters that only depend on the accuracy class of the ITs involved. The reader can refer to [17] for a detailed description.

III. THE MEASUREMENT SETUP

In [18] the authors developed a test setup to acquire the primary and secondary currents of two off-the-shelf CTs. The acquired signals, among other things, have been used to compute the THD associated to the primary current.

The setup, recalled in Fig. 1, consists of:

- An arbitrary waveform generator (Agilent 33220A) (AWG) which provided the desired waveforms (actual waveforms collected from the grid).
- A Fluke transconductance amplifier 52120A to amplify and convert the waveform generator's output

into a current suitable for the CT under test.

- The two MV CTs under test (T_1 and T_2). Both features a rated power of 6 VA. T_1 has a ratio of 20/5, while T_2 100/5. Finally, their accuracy classes are 0.5 and 0.2 for T_1 and T_2 , respectively.
- Two shunt resistors, S_1 for the primary current is a 1 m Ω resistor; S_2 for the secondary current is a 10 m Ω resistor. The two shunts feature an uncertainty of 0.01 % and 0.005 %, for S_1 and S_2 , respectively.
- A NI9238 Data acquisition board (DAQ) to acquire the voltages at the shunt terminals [19].

In brief, a set of signals with different THD – as detailed in the following section – have been reproduced with the waveform generator and transduced into the CTs under tests. With the shunts + DAQ, the primary and secondary currents have been collected before being further elaborated.

IV. TESTS & RESULTS

This section is composed of 3 subsections: one dedicated to the description of the performed test; a second dedicated to the uncertainty evaluation of the acquired quantities; a third in which the aim of the work is assessed on the bases of the obtained results.

A. Tests description

The main idea is to compare the expected value and the variance of THD measured by the two CTs under test ($\mu_{THD,CT}$ and $\sigma_{THD,CT}^2$) with those estimated with the proposed approach ($\mu_{THD,e}$ and $\sigma_{THD,e}^2$). To this purpose, the measurement datasets obtained during the research conducted in [18] have been employed. In that context, five different waveforms, distinguished by ascending THD value, have been acquired in the laboratory environment and loaded into the AWG. Then, the transconductance amplifier, operated with the AWG's output signal, fed the CTs under test. The primary and secondary currents have been acquired by means of series shunt resistors + DAQ. For an extensive description, the reader can check the referenced article [18]. The waveforms are listed in Table I.

Before moving to assess the quality of the estimated THD uncertainty, there are some considerations that must be done.

The first one addresses the distorted primary current waveforms. Their rms is equal to the rated primary current value for each CT. Then, the harmonic distortion is randomly drawn, yet compliant with the Standard EN 50160 [20]. This means that the number of the harmonics involved is limited to the 25th order and their amplitudes relative to the 50 Hz-component are capped according to the values defined by the standard.

Turning to the closed form expression, which has to be evaluated in this experimental case study, it requires just: (i) the accuracy class of T_1 and T_2 and (ii) the rms values

of the harmonic components included in the current waveform. Concerning (i), the accuracy class information is readily available on the CTs' nameplate and it is reported in Section III (0.5 for T_1 and 0.2 for T_2). From the accuracy class, the ratio errors at 50 Hz and at the higher harmonic frequencies are completely known (given in [1] and [2], respectively).

Concerning (ii), the information is operatively obtained through the processing of the signal coming from the CT's primary winding. This has been done in order to experimentally validate the THD uncertainty estimation closed-form expressions. Of course, if a practical application is considered, the information (ii) is extracted necessarily from the transduced secondary current. This implies that the THD value of the secondary current must be the same as the one of the current at the primary side, i.e. the CT must behave as a linear system in the considered frequency range. In the context of [18], the authors had performed some additional tests to deepen the analysis in this regard. The goal was to verify the repeatability of the CTs almost linear behavior among the experimental observations. The Agilent 33220A has been replaced with Fluke Calibrator 6105A: this solution enabled the CTs' primary winding to be supplied with a random accurate distorted current waveform characterized by a THD = 9.0 %. Consequently, 100 repetitions have been performed. The results have shown that the average THD measured at the primary and the secondary windings of both the CTs are equal to 9.0 % and the standard deviations are 0.001 % for T_1 and 0.0003 % for T_2 . Thus, it is possible to state that (i) the CTs do not add significant distortion to the secondary current, (ii) the behavior is repeatable, (iii) (2) and (3) can be meaningfully applied on the signal measured at the secondary winding for practical applications.

B. Uncertainty evaluation

To properly evaluate the quality of the proposed closed-form expressions, a direct comparison with experimental THD uncertainty is needed. The method employed for the evaluation of the uncertainty is the Monte Carlo method described in the GUM [21]. The generated probability distribution function of each primary current harmonic component is a uniform distribution. The mean value is equal to the harmonic component magnitude, whereas the standard deviation is dependent on the gain and offset errors of the transconductance amplifier operated with the AWG. These two errors are shown in Table II (for the 20 A range) and Table III (for the 120 A range). No other sources of uncertainty are involved in the MC computation; in fact, aside from the current input, the implementation of (1) requires only the ratio error information.

The 25 uniform distributions have been propagated through the THD formula in order to obtain the THD probability distribution. The Monte Carlo method has been

TABLE II. FLUKE TRANSCONDUCTANCE'S GAIN AND OFFSET ERRORS GIVEN WITH 99 % CONFIDENCE INTERVAL FOR THE 20 A RANGE

Frequency range [Hz]	% of output [%]	% of range [%]
10 ÷ 65	0.015	0.060
65 ÷ 300	0.030	0.060
300 ÷ 1000	0.100	0.060
1000 ÷ 3000	0.300	0.200

TABLE III. FLUKE TRANSCONDUCTANCE'S GAIN AND OFFSET ERRORS GIVEN WITH 99 % CONFIDENCE INTERVAL FOR THE 120 A RANGE

Frequency range [Hz]	% of output [%]	% of range [%]
10 ÷ 65	0.015	0.020
65 ÷ 300	0.030	0.030
300 ÷ 1000	0.100	0.100
1000 ÷ 3000	0.300	0.250

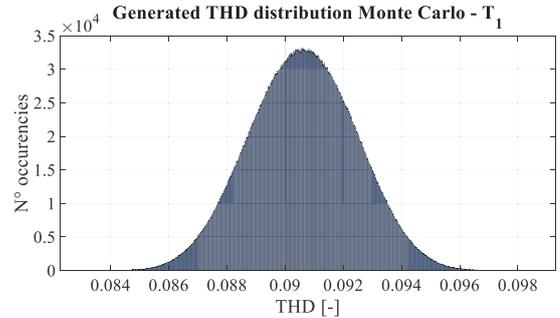


Fig. 2. THD distribution of the T_1 primary current generated via Monte Carlo method

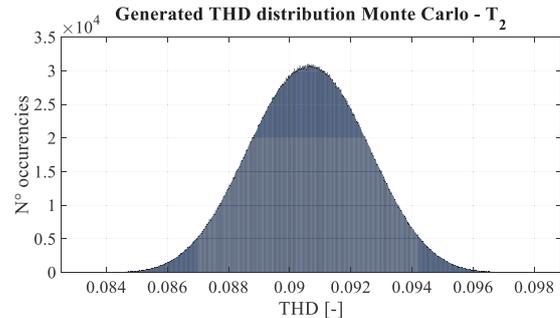


Fig. 3. THD distribution of the T_2 primary current generated via Monte Carlo method

implemented with 10^6 repetitions and the resulting distributions for the case with Signal D are shown in Fig. 2 and Fig. 3 for T_1 and T_2 , respectively. The distributions obtained for the other cases do not differ significantly and so they are not reported. At this point, the standard deviation and the confidence intervals can be easily computed.

C. Discussion of results

Now that the simulations run by implementing the MC are performed, the measured THD and its variance can be

measured with those obtained by using (2) and (3). Therefore, Tables IV and V list, for both measured and estimate quantities, the mean, standard deviation and standard confidence interval (coverage factor $K = 1$) for T_1 and T_2 , respectively. In Figures 4 and 5, the THD confidence intervals defined by the limits in Tables II and III are depicted just for the case with Signal D, as an example of graphical comparison between the two methods.

TABLE IV. MEAN, STANDARD DEVIATION AND CONFIDENCE INTERVAL UPPER AND LOWER LIMITS (IC MAX AND IC MIN, RESPECTIVELY) OF THE PRIMARY CURRENT THD FOR T_1

Signal	Technique	Mean [%]	Standard deviation [%]	IC min [%]	IC max [%]
A	Estimate	4.43	0.09	4.34	4.51
	MC	4.44	0.03	4.40	4.47
B	Estimate	6.9	0.1	6.8	7.1
	MC	6.93	0.03	6.90	6.97
C	Estimate	7.6	0.1	7.5	7.8
	MC	7.63	0.03	7.59	7.66
D	Estimate	8.7	0.2	8.5	8.9
	MC	8.71	0.04	8.67	8.75
E	Estimate	9.8	0.2	9.7	10.0
	MC	9.85	0.04	9.81	9.88

TABLE V. MEAN, STANDARD DEVIATION AND CONFIDENCE INTERVAL UPPER AND LOWER LIMITS (IC MAX AND IC MIN, RESPECTIVELY) OF THE PRIMARY CURRENT THD FOR T_2

Signal	Technique	Mean [%]	Standard deviation [%]	IC min [%]	IC max [%]
A	Estimate	4.40	0.03	4.36	4.43
	MC	4.43	0.03	4.40	4.46
B	Estimate	6.94	0.05	6.89	6.98
	MC	6.95	0.03	6.92	6.98
C	Estimate	7.65	0.06	7.59	7.71
	MC	7.66	0.03	7.63	7.69
D	Estimate	8.71	0.07	8.65	8.78
	MC	8.73	0.03	8.69	8.76
E	Estimate	9.84	0.07	9.76	9.91
	MC	9.85	0.03	9.82	9.88

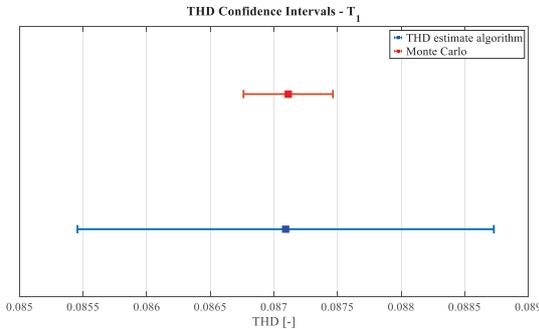


Fig. 4. Comparison between the T_1 primary current THD estimate obtained with the proposed algorithm (blue interval) and the THD evaluation through the Monte Carlo method in the case of Signal D.

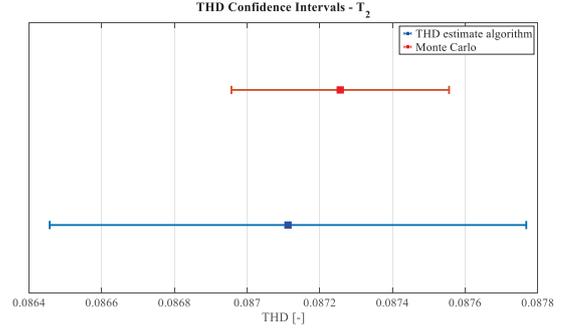


Fig. 5. Comparison between the T_2 primary current THD estimate obtained with the proposed algorithm (blue interval) and the THD evaluation through the Monte Carlo method in the case of Signal D.

From both the pictures and the tables, it is possible to confirm the effectiveness of the proposed closed-form expressions. As a matter of fact, the two confidence intervals are perfectly coherent one with the other for both the CTs under test (with different accuracy class and rated current) and for the different distorted signals. Due to the stochastic nature of the confidence intervals, even the case in which the two confidence intervals are slightly or partially not superimposable because of different lengths or the presence of a relative shift, the test would be still considered as passed and the expressions proved.

Finally, it is possible to conclude that what presented in [17] works even in the case of experimental measurements performed on off-the-shelf CTs. Hence, the closed-form expressions can be used by DSOs operators, even during in-field measurement campaigns, to estimate the expected value and the uncertainty associated to the THD measurements.

V. CONCLUSION

This paper tackles the uncertainty evaluation and estimate associated to the THD measurements. Even if it is typically not straightforward to obtain it, the authors developed in a previous publication a closed-form expression for it. In this work, such expression has been tested on a real use case involving current transformers adopted for the THD measurements. After evaluating the uncertainty associated to the measured THD by using the Monte Carlo approach, it has been compared with those obtained from the proposed approach. The obtained results clearly confirm the applicability of such an approach and its effectiveness in terms of accuracy of estimation of the uncertainty associated to the THD. Therefore, this new developed tool could be of great help for DSOs and utilities to provide uncertainty information along with the THD measurements performed in-field.

REFERENCES

- [1] IEC 61869-1: 2010. Instrument Transformers—Part 1: General Requirements for Instrument Transformers; International Standardization

- Organization: Geneva, Switzerland, 2010.
- [2] IEC 61869-6: 2016. Instrument Transformers—Part 6: Additional General Requirements for Low-Power Instrument Transformers; International Standardization Organization: Geneva, Switzerland, 2016.
- [3] Jadeja, R., Bizon, N., Trivedi, T., Ved, A., & Chudasama, M. (2020). Power quality issues and mitigation techniques in microgrid.
- [4] Micallef, A. (2019). Review of the current challenges and methods to mitigate power quality issues in single-phase microgrids. *IET Generation, Transmission and Distribution*, 13(11).
- [5] Reddy, B. G., Maheswari, L., & Devendranath Reddy, N. (2017). Power quality issues of induction generator for wind power plants. Paper presented at the Proceedings of the International Conference on IoT in Social, Mobile, Analytics and Cloud, I-SMAC 2017, 377-380.
- [6] Kalla, U. K., Sharma, K., Singh, B., & Suthar, R. (2016). An experimental study of power quality issues in ceramic insulator industry. Paper presented at the 2016 IEEE 6th International Conference on Power Systems, ICPS 2016.
- [7] Mingotti, A., Ghaderi, A., Mazzanti, G., Peretto, L., Tinarelli, R., Valtorta, G., Danesi, S. (2018). Low-cost monitoring unit for MV cable joints diagnostics.
- [8] Kumar, V., Pandey, A. S., & Sinha, S. K. (2016). Grid integration and power quality issues of wind and solar energy system: A review. Paper presented at the International Conference on Emerging Trends in Electrical, Electronics and Sustainable Energy Systems, ICETEESES 2016, 71-80.
- [9] Hunt, R. (2012). Impact of CT errors on protective relays - case studies and analyses. *IEEE Transactions on Industry Applications*, 48(1), 52-61.
- [10] Kezunovic, M., & Naodovic, B. (2005). A methodology for assessing the influence of instrument transformer characteristics on power system protection performance. Paper presented at the 15th Power Systems Computation Conference.
- [11] Mingotti, A., Peretto, L., & Tinarelli, R. (2017). A novel equivalent power network impedance approach for assessing the time reference in asynchronous measurements. Paper presented at the I2MTC 2017 - 2017 IEEE International Instrumentation and Measurement Technology Conference, Proceedings.
- [12] Mingotti, A., Peretto, L., & Tinarelli, R. (2017). An equivalent synchronization for phasor measurements in power networks. Paper presented at the AMPS 2017 - IEEE International Workshop on Applied Measurements for Power Systems, Proceedings.
- [13] Filipiak, S. (2013). Application of evolutionary algorithm in optimisation of medium-voltage distribution networks post-fault configuration. *International Journal of Electrical Power and Energy Systems*, 44(1), 666-671.
- [14] Kitak, P., Pihler, J., Ticar, I., Stermecki, A., Magele, C., Bíró, O., & Preis, K. (2006). Use of an optimization algorithm in designing medium-voltage switchgear insulation elements. *IEEE Transactions on Magnetics*, 42(4), 1347-1350.
- [15] Lin, H. (2014). Perfecting power quality indices and prospect. *Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering*, 34(29), 5073-5079.
- [16] Shin, Y. -, Powers, E. J., Grady, M., & Arapostathis, A. (2006). Power quality indices for transient disturbances. *IEEE Transactions on Power Delivery*, 21(1), 253-261.
- [17] Mingotti, A., Peretto, L., Tinarelli, R., (2020). A Closed-form Expression to Estimate the Uncertainty of THD Starting from the LPIT Accuracy Class. *Sensors MDPI Journal*, 20(6).
- [18] Mingotti, A., Peretto, L., Bartolomei, L., Cavaliere, D., & Tinarelli, R. (2020). Are inductive current transformers performance really affected by actual distorted network conditions? an experimental case study. *Sensors (Switzerland)*, 20(3).
- [19] http://www.ni.com/pdf/manuals/376138a_02.pdf.
- [20] EN 50160:2011. Voltage characteristics of electricity supplied by public electricity networks. European committee for standardization: Brussels, Belgium, 2017.
- [21] ISO/IEC Guide 98 - 3: 2008. Uncertainty of Measurement—Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995); International Standardization Organization: Geneva, Switzerland, 2008.