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On the methodologies for the calibration of static electricity meters in the presence of harmonic distortion

Antonio Cataliotti, Valentina Cosentino, Alessandro Lipari, Salvatore Nuccio

Department of Electrical, Electronic and Telecommunication Engineering, Università di Palermo, Viale delle Scienze, 90128 Palermo, Italy, Phone: +39 091 6615270, Fax: +39 091 488452, Email: acataliotti@ieee.org, cosentino@dieet.unipa.it, alessandro_lipari@dieet.unipa.it, nuccio@unipa.it

Abstract **-** This paper is focused on the problems related to the calibration of static electricity meters with nonsinusoidal test waveforms. This is an up-to-date issue since the harmonic distortion levels are ever increasing, especially in low-voltage power systems, and in such conditions the performances of the modern static electricity meters can be negatively affected, depending on the implemented measurement algorithm. Thus it is important to test the meters with nonsinusoidal waveforms. The paper analyzes the problems related to both the choice of the test signals to be used for calibration and the implemented metric, with a particular focus on the reactive energy meters. The analysis is supported by several experimental results.

I. Introduction

With the steadily increasing amount of the harmonic pollution in power systems, the calibration of the electricity meters in nonsinusoidal conditions has become a very important issue.

In fact, the Directive MID 2004/22/EC of the European Parliament [1] states that the measuring instruments used for commercial transactions “shall not exceed the maximum permissible error” under rated operating conditions, which are defined as “the values for the measurand and influence quantities making up the normal working conditions of an instrument”; as regards this, it has to be observed that in [1] only the meters for active energy are explicitly mentioned, but in point of fact also reactive energy are currently used for the electricity billing. With the increase of nonlinear and/or time-variant loads the amount of harmonic distortion in power systems can be significant and the “normal operating conditions” cannot be considered sinusoidal anymore. Moreover, in Italy the standard CEI 13-4 [2] defines the criteria for the verification of measurement systems for electric energy for billing purposes and fiscal assessments; this standard is applied to systems for measuring active and reactive energy on single phase and three phase circuits. As regard the calibration of the electricity meters, the aforesaid standard classifies the tests from the viewpoint of both the place of execution (lab or on-site calibrations) and the load conditions (real load or dummy load calibrations). Thus, the tests could be performed on the place of installation of the electricity meters (on-site), using the load of the same electrical system; in such conditions, the situation may occur in which the calibration should be carried out in nonsinusoidal conditions.

Nowadays, the static electricity meters (for both active and reactive energy) have almost totally superseded the traditional electro-mechanical (inductive) meters, because of their better stability, accuracy and multi-function metering facilities (for example, the integration of both active and reactive energy and the simultaneous measurements of other significant electrical quantities), as well as because of the possibility of transmitting the data measured at a distance, by means of power line carriers or other data transmission technologies. As regards the measurement performances in nonsinusoidal conditions [3-6], the energy measured by inductive meters was always close to that related to the fundamental components of voltages and currents (because of their frequency response). On the contrary the behaviour of the static meters can be negatively affected by the presence of the harmonic distortion, depending on both the voltage and current waveforms and the implemented measurement algorithm. Therefore, it is necessary to develop proper calibration procedures for the static electricity meters in nonsinusoidal conditions.

The current standardization is lacking on this topic. In fact it is known that the current standards and drafts for reactive energy meters [7-9] take into account only the operation under sinusoidal condition. In detail, for reactive energy meters they refer to “a conventional definition of reactive energy for sinusoidal voltages and currents containing only the fundamental frequency”. As regards the performances of the metering equipment, they define the requirements that instruments have to comply with in sinusoidal conditions; moreover, they provide the test conditions and the accuracy requirements that the meters have to satisfy, when some influence quantities change with respect to sinusoidal reference conditions but the harmonic distortion is not included among these influence quantities. Only for active energy meters [10-11], an accuracy test in the presence of harmonics is reported. Thus, according to the aforesaid standards the electricity meters are basically designed for the operation in sinusoidal conditions and their accuracy specifications which are defined in sinusoidal conditions, can lose their significance in the presence of harmonic distortion.

In literature different methodologies have been proposed concerning the calibration of electricity meters in nonsinusoidal conditions, mostly referring to those for active energy. Some of these methods [12-13] are based on the generation of distorted voltages and currents that are supposed to be representative of the normal operating conditions. In [14] the choice of the “best test waveforms” is discussed with the aim is to identify the test conditions that can cause the most significant uncertainty problems while performing the measurements. In [15-16] some voltage and current waveforms are proposed, which are selected by means of a probabilistic approach and in order to maximize the instrumentation errors. Other approaches have been developed, which are aimed to calibrate the meters under normal operating conditions. For example in [17] a method is proposed, which is based on the random generation of voltage and current test signals, whose distorted waveforms are set in order to represent the real operating conditions. In [18] the on-site calibration of energy meters is proposed, together with the development of proper reference measuring equipment; also in this case the set of test waveforms of voltage and current are meant to reproduce the actual operating conditions.

However at present there is not a preferred methodology to be used for the calibration of the electricity meters in nonsinusoidal conditions. Moreover, as regards the meters for reactive energy the issue is particularly challenging, since there are several solutions currently available on the market, which are based on different principles of construction, thus implementing different metrics [19-20]. These metrics are all equivalent in sinusoidal conditions, thus in the same working conditions they lead to compatible results in the measurements within the specified accuracy class limits. On the contrary, in the presence of distorted voltages and/or currents they can give different measurements in the same working conditions and this could lead to different results for customers in terms of energy costs. As regards this, an experimental approach is proposed in [21-22] for the characterization in the presence of harmonic distortion. It is developed starting from the accuracy test condition in the presence of harmonics reported in the standards [8-9], which considers only the presence of one harmonic component on both voltage and current signals. A conceptually similar approach is proposed in [23], where more realistic test waveforms are considered. In both cases the characterization is aimed to identify the metric when it is not declared by the manufacturer or to make previsions on the behaviour of the meters whose operating principle is known.

At the light of all the aforesaid considerations, this paper analyzes the problems related to the calibration of the reactive energy meters in the presence of harmonics and some possible solutions are suggested. Moreover, some of the previous mentioned methodologies for calibration are compared, from the perspective to employ them for the meters for reactive energy. The analysis is supported by some experimental tests, which have been carried out on both commercial and standard meters.

II. Calibration procedures in the presence of harmonics and related problems

As reported in [2], the calibration consist in the evaluation of the percentage errors of the meters under test (MUTs) using a standard meter as a reference. The MUTs have to be verified under given test conditions and they have to show errors, in absolute terms, not higher than the values shown by the theoretical calibration curve. The comparison should be performed for each test and must take into account the uncertainty of the measurement process. The percentage error *e%* is defined as follows:

$$e\% = \frac{W_r - W_t}{W_t} \cdot 100 \qquad (1)$$

where W_r is the energy registered by the meter and W_t is the “true energy”; which is assumed to be the energy measured by the reference standard meter (with a stated uncertainty) [1, 7].

In the case of the calibration of the static meters for the reactive energy, some problems arise, which are mainly related to the fact that the reactive energy is not univocally defined in nonsinusoidal conditions. Thus it is not defined the quantity to be assumed as a reference for the evaluation of the percentage error and there is a lack of an univocally defined measuring metric to be adopted in the presence of harmonic distortion [19-23]. As a result, the meters can implement different solutions for the measurement of reactive energy, which are all equivalent in sinusoidal conditions, while they can give different results in the presence of harmonics on voltage and current signals. This is true for both the commercial static meters and the reference standard meters, for which there are no in-force standards (only a IEC draft is currently available for meters of classes 0,5 S, 0,5, 1S and 1 [11]).

Thus the results of a calibration in nonsinusoidal conditions can depend not only on the working condition but also on the metrics implemented by both the MUT and the standard meter used as a reference for the evaluation

of *e%*. In detail, if these metrics are different, the results of the calibration are not meaningful, because the MUT and the standard meter measure different quantities [20]. In order to avoid this problem the calibration should be carried out by using a standard meter which implements the same metric of the MUT.
However, in most cases the metric is not declared by the manufacturer; thus the calibration procedure for the reactive energy meters should firstly implement a proper test protocol able to individuate the metric of the MUT. For example, the experimental approach proposed in [22-23] can be adopted.
After individuating the metric of the MUT, the calibration can be performed by using a proper reference meter. As regards this, in the viewpoint of an on-site calibration with a standard portable equipment [18], it should implement the different metrics in order to ensure the suitable flexibility (otherwise a complete set of standard meters should be available, each performing the measurements of the reactive energy with a given metric).

III. Calibration waveforms: experimental tests and discussion

As mentioned before, several types of waveforms have been proposed in literature for the calibration of the electricity meters. For the purpose of using them for the reactive energy an experimental analysis was carried out on the following static meters for both active and reactive energy:

- a portable reference standard meter (named SM in the following) of accuracy class 0,1 - 0,2 respectively for active and reactive energy constructed with a numeric phase shifting of a quarter of a period of the current, meter calibration factor $K_{SM} = 3\cdot10^6$ pulses/kvarh;
- a meter of accuracy class 0,5, developed by STMicroelectronics, (MUT 1) with a shifting of 90° of the current by means of an integrator circuit, K_{M1} = 128.000 pulses/kvarh;
- two commercial static meters of accuracy class 2 whose metrics are not declared by the manufacturers (MUT 2, 3); K_{M2} = 100 pulses/kvarh, K_{M3} = 1.000 pulses/kvarh.

For the last three MUTs the implemented metric was investigated by applying the experimental approach of [22-23]. In brief, it is based on the comparison of the measurements performed by the generic meter under test with the theoretical results that can be obtained with the mathematical model of the different metrics that can be implemented for the meters. As regards the test conditions, voltage and current waveforms with a 5^{th} or a 3^{rd} harmonic component (THD_V = 10%, THD_I = 40%,) are considered and the experimental tests are carried out by varying the phase angles between harmonics. From the results obtained it was deduced that the MUT 2 implements the *N*-metric, while the MUT 3 implements the *T/4*-metric (see appendix for the description of the metrics).
The analysis of the behaviour of the MUTs with several calibration waveforms was carried out by generating voltage and current signals by means of a power calibrator Fluke 6100A Electrical Power Standard. The reactive energy measured by each MUT were evaluated by counting a specified number of pulses provided by the MUT within a time interval T provided by the power calibrator. The time interval T (or the number of pulses to be counted) was chosen for each test in order to achieve an uncertainty on the measurement of the percentage error up to $1/10^{th}$ of the maximum allowable error for each MUT [22-23].
The voltage and current waveforms were chosen in accordance with some of the methodologies already proposed in literature. For each test, the percentage errors were evaluated, by assuming as “true value”:

1) the reactive energy related to the fundamental components of voltage and current, i.e. $W_t = W_1$ in (1);
2) the reactive energy measured by the standard meter under test (SM), i.e. $W_t = W_{SM}$;
3) the reactive energy obtained with the INT-metric, i.e. $W_t = W_{INT}$;
4) the reactive energy obtained with the T/4-metric, i.e. $W_t = W_{T/4}$;
5) the reactive energy obtained with the N-metric, i.e. $W_t = W_N$.

The obtained percentage errors are indicated in the following with $e_1\%$, $e_{SM}\%$, $e_{INT}\%$, $e_{T/4}\%$, $e_N\%$, respectively.
As an example, a first test condition was defined by choosing the harmonic content of voltage and current in accordance with the limits reported respectively in CEI EN 50160 and EN IEC 61000-3-2 [20] (see table 1). The results obtained for this test condition are reported in table II. It can be observed that the percentage errors of the meters under test can be very different, depending on the metric adopted as a reference. For example, if $e_{INT}\%$ is considered, all the meters show very large values of the percentage error, with the exception of the MUT 1, which implements the INT-metric; similarly if $e_N\%$ is considered, only the MUT 2 show a small percentage error, as this meter implements the N-metric; finally if $e_{T/4}\%$ is considered, only the MUT 3 and the SM (which implement the T/4-metric) are able to respect their class limits. In figure 1 there are reported the percentage errors of the MUTs of accuracy class 2 (MUTs 2-3), which are evaluated with respect to the various metrics and the Standard Meter (SM). The percentage errors are compared with the limit of a theoretical calibration curve, i.e. the maximum permissible error for the meters of accuracy class 2 [2], *MPE*, which is represented with the dotted line in figure 1. From the figure it can be observed if a calibration would be made without preliminarily investigating the metrics of the MUTs and by using a reference the standard meter under test (see results in red), the limits of [2] would be respected only for the MUT 3, which implements the same metric of SM, while the

MUT 2 would be out of the limits because its metric is different from the one implemented by the SM.
Further experimental tests were carried out on the by using the voltage and current test waveforms proposed in [16]. These test conditions were proposed in order to test the dynamic range of the instruments and to maximize the errors in the measurements of voltage and current harmonics and related power, by means of proper voltage and current waveforms with maximum number of zero crossings, maximum zero values, maximum positive or negative peaks (equal or not). Differently from [16], where only the measurement of active power was considered, a phase shifting was operated between the voltage and current waveforms, in order to perform the measurement of the reactive power (or energy). Moreover, the amount of the voltage distortion was reduced in order to have some more realistic conditions (while the harmonic currents were maintained at the values reported in [16]). Some of the test conditions are synthesized in table III, where there are reported the harmonic voltages and currents and the related phase angles. For the MUTs 2 and 3, both the active and the reactive energy were measured and the percentage errors were evaluated by taking as a reference the active and reactive energy measured by the standard meter. From the obtained results it can be observed that the percentage errors for the measurement of the reactive energy are very high for the MUT 2, which implements the N metric; on the contrary, the percentage errors are low (under the *MPE*) for the MUT 3 which implements the T/4 metric (the same implemented by the Standard meter used as a reference). Otherwise, in all the tests the percentage errors of both the MUTS 2 and 3 were under the *MPE* for the measurement of the active energy.

IV. Conclusions

In this paper the problems have been analysed concerning the calibration of static electricity meters with nonsinusoidal test waveforms, with a particular focus on the reactive energy meters. These problems mainly concern the choice of the test signals to be used for calibration and the implemented metric, which is not univocally defined for the measurement of the reactive energy. The theoretical and experimental analysis showed that a given meter under test is able to respect the class limits only when its percentage errors are evaluated with respect to the metric implemented by the meter themselves. On the contrary, if the percentage errors are evaluated with respect to a different metric, the meter under test can show very large percentage errors. This means that, in practical cases, if the metrics are not a-priori known it is impossible to correctly understand the results of a calibration. In order to avoid these problems, the calibration should be carried out by using a standard meter which implements the same metric of the meter under test. However, the manufacturer not often declare the modalities of measurement of the reactive energy; thus a suitable calibration procedure should firstly implements a measurement protocol for the identification of the metric of the meter under test. Moreover, in the perspective of an "on-site" calibration, it would be helpful to have a portable standard meter which implements the various metrics, in order to ensure a complete flexibility and adaptability to the different situations. Otherwise, an assortment of standards should be had, each implementing a different metric.

Table I: Test condition 1. Harmonic voltages and currents and related phase angles. V = 230 V, I = 5 A (RMS values); fundamental power factor 0,894 inductive. THD_V=7,9%, THD_I=28%.

Harmonic order	Voltage [% of fundam.	Current [% of fundam.]	Phase angle between harmonics [°]
3	6	27	90°
4	1	2,69	0°
5	5	10	-90°
7	1	7	90°

Table II: Experimental results. Percentage errors e_1%, e_{SM}%, e_{INT}%, $e_{T/4}$%, e_N% of the MUTs. Test condition 1 (see Table I.

MUT	e_1%	e_{SM}%	e_{INT}%	$e_{T/4}$%	e_N%
SM	-4,87	--	-6,21	-0,04	-21,6
MUT 1	0,79	5,95	-0,63	5,91	-17,0
MUT 2	20,5	26,6	19	26,6	-0,77
MUT 3	-4,02	0,89	-5,3	0,85	-20,9

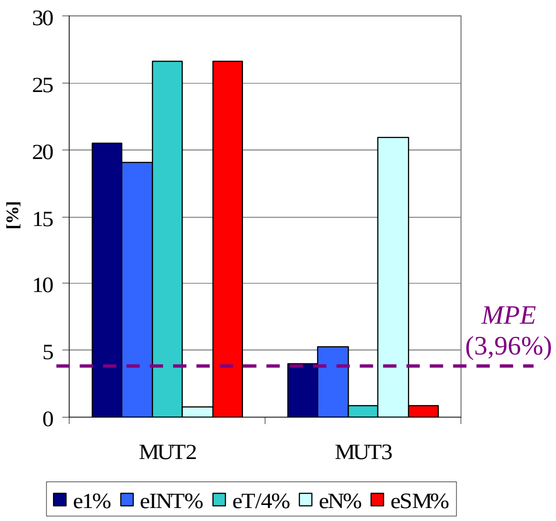

Figure 1. Experimental results. Percentage errors (absolute values) of the commercial MUTs (2 and 3) evaluated with respect to the various metric and the Standard Meter (SM). Test conditions of Table I.

Table III: Test condition 2. Harmonic voltages and currents and related phase angles. V = 230 V, I = 5 A (RMS values); fundamental power factor 0,866 inductive.

Test condition	Harmonic voltages and current [% of fundamental] and phase angle between harmonics [°degrees]														
	3			5			7			8			9		
	V_h [%]	I_h [%]	φ_h [°]	V_h [%]	I_h [%]	φ_h [°]	V_h [%]	I_h [%]	φ_h [°]	V_h [%]	I_h [%]	φ_h [°]	V_h [%]	I_h [%]	φ_h [°]
2	10	10	-90	10	10	-150	0	0	-210	2,5	2,5	-240	0	0	-270
3	4	40		2	20		2	20		2	20		0	0	
4	4	40		4	40		4	40		4	40		0	0	
5	3	20		3	20		3	20		3	20		3	20	

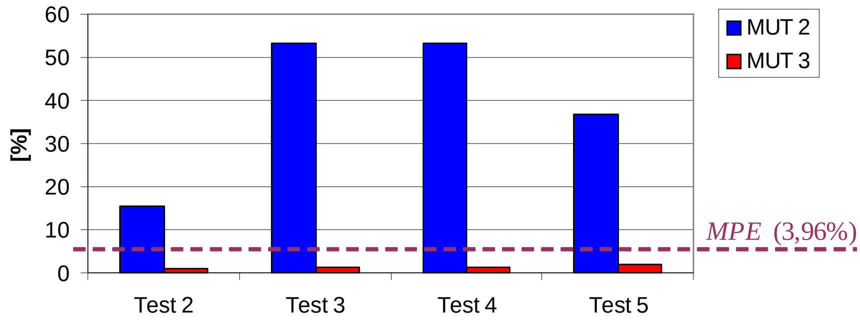

Figure 2. Experimental results. Percentage errors (absolute values) of the commercial MUTs (2 and 3) evaluated with respect to the Standard Meter (SM). Test conditions of Table III.

V. Appendix: mathematical models of the metrics

It is known that the static meters available on the market can be constructed with different solutions [19-23]. For single-phase applications, the measurement of reactive energy (or power) can be obtained by means of an analogue or digital multiplication of current and voltage; the voltage (or the current) is preliminarily shifted by 90° by means of an integrator circuit, a time shifting of a quarter of a period, a filtering stage or another numeric technique. Moreover, digital meters, which are based on the numerical conversion of voltage and current signals, can also implement the mathematical definition of reactive power; as regards this, it is known that several definitions have been proposed in literature (*Budeanu*, *Fryze*, ecc.). The different metrics correspond to different mathematical models in which, in nonsinusoidal condition, the various harmonics give different contributions to the reactive power.

In the paper, three different metrics are considered.

– INT-metric: 90° shifting of the voltage, by means of an integrator:

$$Q_{INT} = \frac{1}{T}\int_0^t \omega_1 \cdot \left(-\int v(t)dt\right)\cdot i(t)dt = V_1 I_1 \sin\varphi_1 + \frac{V_2 I_2 \sin\varphi_2}{2} + \ldots = Q_1 + \frac{Q_2}{2} + \frac{Q_3}{3} + \ldots \quad (2)$$

– T/4-metric: 90° shifting of the voltage, by means of a time shifting of a quarter of a period:

$$Q_{T/4} = \frac{1}{T}\int_0^t v(t)\cdot i\left(t - \frac{T}{4}\right)dt = V_1 I_1 \sin\varphi_1 - V_2 I_2 \cos\varphi_2 - V_3 I_3 \sin\varphi_3 + \ldots = Q_1 - P_2 - Q_3 + P_4 + Q_5 \ldots \quad (3)$$

– *N*-metric: digital implementation of the definition of the "nonactive power" of the IEEE Std. 1459-2000 (or the *Fryze*'s reactive power):

$$N = \sqrt{S^2 - P^2} \quad (4)$$

References

[1] *Directive 2004/22/EC* of the European Parliament and of the Council, Official Journal of the European Union, March 2004
[2] *CEI 13-4*: "Equipment for measuring electrical energy. Circuit arrangement, accuracy and verification" Ed. IV + Ec 1, Fasc. 7525, 2005 (in italian).
[3] R. Arseneau, M.B. Hughes, "Selecting Revenue Meters for Harmonic Producing Loads", *Proc. of 11th International Conference on Harmonics and Quality of Power*, pp. 227-231, 2004.
[4] A. Din, D. Raisz, "What do and what should digital revenue meters measure on distorted networks?", *Proc. of 11th International Conference on Harmonics and Quality of Power*, pp. 283-288, 2004
[5] P. S. Filipski, P. W. Labaj, "Evaluation of reactive power meters in the presence of high harmonic distortion", *IEEE Trans. on Power Delivery*, vol. 7, n. 4, pp. 1793-1799, October 1992.
[6] M. D. Cox, T. B. Williams, "Induction varhour and solid-state varhour meters performances on nonlinear loads", *IEEE Trans. on Power Delivery*, vol. 5, n. 4, pp. 1678-1686, November 1990.
[7] *EN 62052-11*: "Electricity metering equipment (a.c.) – General requirements, tests and test conditions - Part 11: Metering equipment", November 2003.
[8] *EN 62053-23*: "Electricity metering equipment (a. c.) – Particular requirements - Part 23: Static meters for reactive energy (class 2 and 3)", December 2003.
[9] *Project IEC 62053-24 Ed. 1.0*, current document 13/1436/NP: "Electricity metering equipment (AC) - Particular requirements - Static meters for reactive energy (classes 0,5 and 1)", (Status: ANW, Approved New Work)
[10] *EN 62053-21*: "Electricity metering equipment (a. c.) – Particular requirements - Part 21: Static meters for active energy (class 1 and 2)", March 2003.
[11] *EN 62053-22*: "Electricity metering equipment (a. c.) – Particular requirements - Part 21: Static meters for active energy (class 0,2S and 0,5S)", March 2003.
[12] P. S. Filipski and R. Arseneau, "Calibration of three-phase revenue meters under distorted waveform conditions," *Proc. of 6th International Conference on Metering Apparatus and Tariffs for Electricity Supply*, pp. 236–240, 1990.
[13] R. Arseneau and P. Filipski, "A calibration system for evaluating the performance of harmonic power analyzers", *IEEE Trans. on Power Delivery*, vol. 10, n. 3, pp. 1177–1182, Jul. 1995.
[14] A. Ferrero, C. Muscas, "On the selection of the best test waveform for calibrating electrical instruments under nonsinusoidal conditions," *IEEE Trans. on Instrumentation and Measurement*, vol. 49, n. 2, pp. 382–387, Apr. 2000.
[15] D. Georgakopoulos, P. S. Wright, "Exercising the dynamic range of active power meters under nonsinusoidal conditions", *IEEE Trans. on Instrumentation and Measurement*, vol. 56, n. 2, pp. 369–372, Apr. 2007.
[16] D. Georgakopoulos, "Selecting calibration waveforms for power analysers and meters under nonsinusoidal conditions", *Proc. of 13th International Conference on Harmonics and Quality of Power*, pp. 1-5, 2008.
[17] A. Ferrero, M. Faifer, S. Salicone, "On Testing the Electronic Revenue Energy Meters", *IEEE Trans. on Instrumentation and Measurement*, vol. 58, n. 9, pp. 3042-3049, September 2009.
[18] A. Delle Femmine, D. Gallo, C. Landi, M. Luiso, "Advanced Instrument For Field Calibration of Electrical Energy Meters", *IEEE Trans. on Instrumentation and Measurement*, vol. 58, n. 3, pp. 618-625, March 2009.
[19] A. Cataliotti, V. Cosentino, S. Nuccio: "The measurement of reactive energy in polluted distribution power systems: an analysis of the performance of commercial static meters", *IEEE Transactions on Power Delivery*, vol. 23, n. 3, pp. 1296-1301, July 2008.
[20] A. Cataliotti, V. Cosentino, A. Lipari, S. Nuccio: "On the calibration of reactive energy meters under non sinusoidal conditions", *Proc. of XIX IMEKO World Congress, Fundamental and Applied Metrology*, pp. 719-723, 2009
[21] A. Cataliotti, V. Cosentino, S. Nuccio, "A theoretical and experimental comparison among reactive energy meters in nonsinusoidal working conditions", *Electrical Engineering Research Report*, n. 22, pp. 9-14, June 2007.
[22] A. Cataliotti, V. Cosentino, A. Lipari, S. Nuccio, "Metrological characterization and operating principle identification of static meters for reactive energy: an experimental approach under nonsinusoidal test conditions", *IEEE Trans. on Instrumentation and Measurement*, vol. 58, n. 5, pp. 1427-1435, May 2009.
[23] A. Cataliotti, V. Cosentino, S. Nuccio, "Static meters for the reactive energy in the presence of harmonics: an experimental metrological characterization", *IEEE Trans. on Instrumentation and Measurement*, vol. 58, n. 8, pp. 2574-2579, August 2009.