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ON THE CALIBRATION OF REACTIVE ENERGY METERS UNDER NON SINUSOIDAL CONDITIONS

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Abstract – This paper is focused on the problems related to the calibration of the reactive energy meters on the place of installation of the electricity meter (on-site), using the load of the same electrical system. In the presence of harmonic distortion, the behaviour of the meters can go out of the limits imposed by the theoretical calibration curve, depending on the metric used by both reference standard meters and meters under test.

Keywords: energy measurements, harmonic distortion, reactive energy meters

1. INTRODUCTION

In recent years the deregulation of the electricity market has caused the proliferation of the measurement points and the increase in the number of subjects involved in their management. Thus the issue arises concerning the definition of specific rules for the circuit arrangement, accuracy and verification of the equipment for measuring the electrical energy.

As regard the meters for reactive energy, the current international standards refer to the operation under sinusoidal condition and they do not provide any test condition for the metrological characterization in the presence of harmonics [1-2]. On the other hand, the latest directives state that the measuring instruments used in commercial transactions must be verified in the actual operating conditions [3] (even if the meters for reactive energy are not taken into account in [3], they are currently used for the electricity billing).

In Italy the standard CEI 13-4 [4] defines the criteria for the verification of measurement systems for electric energy; this standard is applied to systems for measuring active and reactive energy on single phase and three phase circuits, for billing purposes and fiscal assessments. 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.

As reported in [4], the calibrations 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, reported by the same standard [4]. 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 [2]:

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

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) [2, 3].

In the case of the calibration of the static meters for the reactive energy, some problems arise, which are related to the fact that these meters can implement different solutions for the measurement of reactive energy. In fact, there is a lack of an univocally defined measuring metric to be adopted in the presence of harmonic distortion and it is not defined the quantity to be assumed as a reference for the evaluation of the percentage error [5].

This is true for both the commercial static meters for reactive energy of classes 2 and 3, which are considered in [1], 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 [6]).

According to the standards [1-2], all the solutions for the measurement of the reactive energy are developed for the sinusoidal working condition; thus they work correctly for the fundamental frequency. On the other hand, they can lead to different results in the same working condition when harmonic components are present [5, 7-9]. Moreover, the accuracy specifications, which are given for the sinusoidal condition [1-2], lose their significance in the presence of harmonic distortion. Thus the results of an on-site calibration in the real operating conditions (which can be nonsinusoidal) 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 this paper several the aforesaid problems are discussed and some possible solutions are suggested, concerning the calibration of the reactive energy meters on the place of installation of the electricity meter (on-site), using the load of the same electrical system. The analysis is supported by the results of some experimental tests, which have been carried out on both commercial and standard meters.

2. OPERATING PRINCIPLES AND METRICS

It is known that the static meters available on the market can be constructed with different solutions. 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.

The different implementations correspond to different mathematical models in which, in nonsinusoidal condition, the various harmonics give different contributions to the reactive power. As an example, three different metrics can be considered [5, 7-9].

For example, in the case of a 90° shifting of the voltage, by means of an integrator (named INT-metric in the following) or a time shifting of a quarter of a period (named T/4-metric), the reactive power can be expressed as follows:

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

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

Moreover, digital meters, which are based on the numerical conversion of voltage and current signals, can also implement the mathematical definition of reactive power. For example, the expression

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

(named N-metric) corresponds to the “nonactive power” of the IEEE Std. 1459-2000 (or to the *Fryze*’s reactive power), but many other formulations can be adopted, which have been already proposed in literature [7, 10]

All the aforesaid metrics can be implemented for the construction of a commercial meter or a reference standard meter for reactive energy and in sinusoidal conditions these solutions lead to the same result. On the contrary, in the presence of harmonics on voltage and current, the solutions based on (2), (3) and (4) are not equivalent anymore. This fact was confirmed in previous papers [5, 7-10], by means of several experimental tests, which were carried out on different meters, both commercial and standard.

2. CALIBRATION OF THE METERS IN THE PRESENCE OF HARMONICS. EXPERIMENTAL TESTS AND DISCUSSION

The experimental tests were carried out on the following static meters for both active and reactive energy:

- a portable reference standard meter (named SM in the following), with declared percentage error e% = 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} = $3 \cdot 10^6$pulses/kvarh;
- a meter of accuracy class 0,5, developed by *STMicroelectronics*, (MUT 1) [11] with a shifting of 90° of the current by means of an integrator circuit, meter calibration factor K_{M1} = 128000 pulses/kvarh
- two commercial static meters of accuracy class 1-2 respectively for active and reactive energy whose operating principles are not declared by the manufacturers (MUT 2 and 3); meter calibration factors K_{M2} = 100 pulses/kvarh, K_{M3} = 1000pulses/kvarh.

Voltage and current were generated by means of a power calibrator Fluke 6100A Electrical Power Standard, with the “Energy” option, which allowed to have a fully independent control of voltages and currents during the tests; the voltage and current terminals of the calibrator were connected respectively with the voltage and current of circuit terminals each MUT. 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 [8-9].

In previous papers [7-10] the authors proposed to evaluate the percentage error of equation (1) by assuming as “true energy” the reactive energy related to the fundamental components of voltages and currents (W_r = W_1) [8-9]. On the contrary, for the calibration of the meters, the “reference energy” is the energy measured by a standard meter, which depends on the metric adopted for the standard itself. Thus, as said before, in the presence of harmonics, the percentage errors of a given meter under calibration can depend not only on the operating conditions but also on the metric used to measure the reactive energy by both the standard meter and the meter under test itself. 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. 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.

If the metric of the MUT is not declared by the manufacturer (as it commonly happens), an experimental approach can be adopted [8-9] for the characterization of the meters for reactive energy in the presence of harmonic distortion and for the individuation of their operating principle. It was 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. The test conditions for the experimental approach were developed starting from the only available accuracy test condition in the presence of harmonics required in the standard for active static meters [12-13]. In detail, voltage and current waveforms with a 5th or a 3rd harmonic component (THD_V = 10%, THD_I = 40%,) were considered. The experimental tests were carried out by varying the phase angles between harmonics [8-9]. The approach was applied and verified on some meters of different accuracy classes. It was demonstrated that this approach could give some useful information for the characterization of the meters in the presence of harmonic distortion. In fact when the operating principle is declared by the manufacturer, some previsions can be made regarding the behaviour of the meter also in the presence of harmonics. On the other hand, when the operating principle of a meter is unknown, it can be recognized starting from the knowledge of the different operating principles that can be implemented and the analysis of the response of the meter under the proposed test condition.

As regard the meters under test, the aforesaid experimental approach was applied to the MUTs 2 and 3, whose metrics were not declared by the manufacturer; from the results obtained, it was deduced that the MUT 2 implements the N-metric, while the MUT 3 implements the T/4-metric.

In the viewpoint of an on-site calibration, the real operating conditions can be very far from the test conditions previously mentioned. Thus, for the aim of this paper, some more realistic test conditions were considered, by choosing the harmonic content of voltage and current in accordance with the limits reported respectively in CEI EN 50160 [14] and EN IEC 61000-3-2 [15] The tests were carried out with rms voltage and current equal respectively 230 V, 5A and fundamental power factor equal to 0,894 inductive (senφ=0,447) corresponding at the first threshold of penalization for the consumption of reactive energy in Italy (Q=50%P). The total harmonic distortions are: THD_V=7,9%, THD_I=28%. The harmonic content of voltage and current is detailed in Table I.

Table I: Test conditions. Harmonic voltages and currents (expressed as a percentage of fundamental components) and related phase angles

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°

Firstly, in order to have a common reference for the comparison of the MUTs 1-3 and the SM, the percentage error can be calculated with respect to the reactive energy related to the fundamental components of voltages and currents, assumed as conventional "true value" ($W_t = W_1$ in equation 1) [5-7]. In this case, the calibrator provides the basic values of reactive power Q_1, as well as on reactive energy W_1 at a given time interval T; this value of W_1 was used as a reference for the evaluation of the percentage error $e_1\%$:

$$e_1\% = \frac{W_r - W_1}{W_1} \cdot 100 \qquad (5)$$

The obtained results are shown in Table II; in the table there are also reported the percentage errors $e_{sm}\%$, which were evaluated by assuming as "true value" the energy W_{SM} measured by the standard meter under test:

$$e_{SM}\% = \frac{W_r - W_{SM}}{W_{SM}} \cdot 100 \qquad (6)$$

Table II: Percentage errors of the MUTs evaluated with respect to the fundamental reactive energy and the energy measured by the standard meter

MUT	$e_1\%$	$e_{SM}\%$
Standard Meter	-4,9	--
MUT1	0,79	5,9
MUT2	20	27
MUT3	-4,0	0,85

Secondly, the percentage errors of the MUTs and the standard meter were evaluated by assuming as "true energy":

Case 1): the energy W_{INT} obtained with the mathematical model percentage of the INT-metric (see equation 2), i.e. with respect to an hypothetical reference standard meter which implements the INT-metric;

$$e_{INT}\% = \frac{W_r - W_{INT}}{W_{INT}} \cdot 100 \qquad (7)$$

Case 2): the energy $W_{T/4}$ obtained with the mathematical model percentage of the T/4-metric (see equation 3), i.e. with respect to an hypothetical reference standard meter which implements the T/4-metric;

$$e_{T/4}\% = \frac{W_r - W_{T/4}}{W_{T/4}} \cdot 100 \qquad (8)$$

Case 3): the energy W_N obtained with the mathematical model percentage of the N-metric (see equation 4), i.e. with respect to an hypothetical reference standard meter which implements the N-metric.

$$e_N\% = \frac{W_r - W_N}{W_N} \cdot 100 \qquad (9)$$

The results obtained are reported in figure 1; in the figure the results are compared with the values of $e_1\%$ (equation 5). For aim of completeness, in the table III there are reported the percentage errors $e_1\%$ of the three considered metrics ($W_r = W_{INT}$, $W_r = W_{T/4}$, $W_r = W_N$ respectively in equation 5).

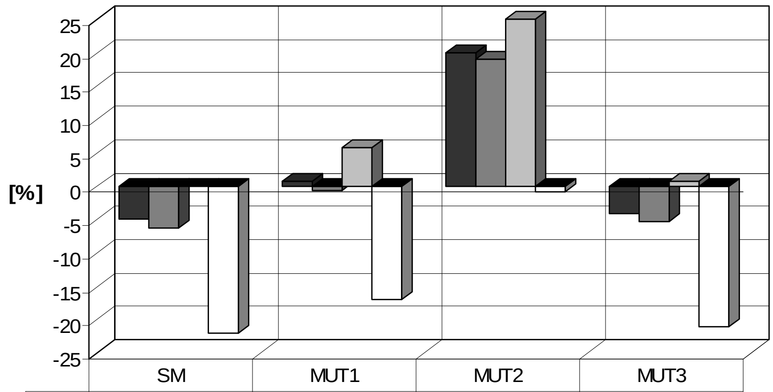
As shown in the figure, the percentage errors of the meters under test can be very different, depending on the metric adopted as a reference (i.e., in practical cases, depending on the hypothetical reference standard meter used for the calibration). For example, in the case 1) (INT-metric) all the meters show very large values of the percentage error, with the exception of the MUT 1, which, as declared by the manufacturer, implements the INT-metric. Thus, for the meters MUT 2-3 and SM, the percentage errors should not allow the meters to respect the limits of a theoretical calibration curve (where the maximum permissible error for that condition is equivalent to 3,96% for the commercial meters [4]). Similarly, in the case 2) (T/4-metric) the standard meter and the MUT 3 (which implement the T/4-metric) should respect the class limits, while in the case 3) these limits are respected only for the MUT 2 (which implements the N-metric). On the contrary, the results of table II show that the percentage error was lower than the class limit only for the MUT 3, which implements the same metric of the standard meter.

In conclusion, the meters under test are able to respect the class limits only when their percentage errors are evaluated with respect to the metric implemented by the meters themselves. On the contrary, if the percentage errors are evaluated with respect to a different metric, the meters under test can show very large percentage errors.

This means that, in practical cases, the results of a calibration in nonsinusoidal conditions can vary, depending on the metric implemented by the meter under test and the standard meter used as a reference. In such conditions, if the metrics are not a-priori known it is impossible to correctly understand the results of a calibration.

Table III: Percentage errors $e_1\%$ of the metrics evaluated with respect to the fundamental reactive energy

Metric	$e_1\%$
INT	1,4
T/4	-4,9
N	21



	SM	MUT1	MUT2	MUT3
e1%	-4,9	0,79	20	-4
eINT%	-6,2	-0,63	19	-5,3
eT/4%	-0,04	5,9	27	0,85
eN%	-22	-17	-0,77	-21

■ e1% ■ eINT% □ eT/4% □ eN%

Figure 1: Experimental results. Percentage errors of the SM and the MUTs 1-3 evaluated with respect to the fundamental energy ($e_1\%$), the INT-metric ($e_{INT}\%$), the T/4-metric ($e_{T/4}\%$) and the N-metric ($e_N\%$). Test conditions of Table I.

4. CONCLUSIONS

The problem of the calibration of the static meters for reactive energy in the nonsinusoidal conditions is a still open issue. The current standards do not define the metrological characteristics of the static meters for reactive in the presence of harmonic distortion, as well as some proper accuracy tests for their verification. In this situation, the manufacturers are allowed to implement different operating principles of construction of the meters, both commercial and standard. These metrics are all in accordance in sinusoidal conditions, but they can lead to the measurement of different quantities in the presence of harmonics. Thus, in the presence of harmonics, the performances of a given meter under calibration can depend not only on the operating conditions but also on the specific metric used to measure the reactive energy both by standard meter used as a reference and the meter under test itself.

In the paper, the problems related with the aforesaid consideration were presented and discussed, by means of several experimental tests. It was shown that for a given meter under test can respect the limits of a theoretical calibration curve or not, depending on the metric adopted for the standard meter used as a reference for the percentage errors. In real operating conditions and in the presence of distorted signals, a given MUT can present different percentage errors if they are evaluated with respect to different metrics.

At the light of these considerations, it is clear that there is a need of a more complete standardization concerning the characterization of the meters for reactive energy in nonsinusoidal conditions. in detail, the standards should define the metric to be implemented, the accuracy requirements in the presence of harmonics and the test conditions to verify that these requirements are satisfied.

On the other hand, in the current situation, where different meters are available on the market, implementing various metrics, suitable methods should be introduced, such as the one proposed by the authors, for the characterization of the meters in the presence of harmonic distortion and the individuation of the metrics when they are not declared by the manufacturers. This should be made also in the perspective of performing the on-site calibration of the meters in nonsinusoidal conditions, where the knowledge of the metric implemented by the meter is necessary, as the standard meter used as a reference for the evaluation of the percentage error should implement the same metric of the meter under test.

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