An Automated Test Equipment For Calibration Of Energy Meters

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***Abstract*-**Calibration of electrical energy meters (EEM) is coming up as a metrological concern. Latest EU directives, about measuring instruments adopted for commercial transactions, state that their accuracy must be verified in actual operating conditions. This requirement is leading all laboratories involved in EEM calibration in serious difficulty because this kind of metrological verification is, at the moment, still not fully developed or even clarified. In this paper a proper automated measurement station able to perform calibration, also on-site, is presented, the compensation techniques for improving spectral purity of test signals integrity are discussed, finally performance evaluation and examples of EEM metrological verification are shown.

I. Introduction

Directive MID 2004/22/EC [1] states that measuring instruments that engrave in several ways, directly or indirectly, on the daily life of the citizens have to be subjected to "legal metrological controls" intended to verify that a measuring instrument is able to carry out the designed functions in actual operating conditions and it is possible to guarantee its traceability. This statement forces, for the first time, also electrical energy meter to be submitted to legal metrological control, therefore, calibration, accuracy certification, traceability and periodical metrological verification of electrical power/energy meters is coming up as normal requirement of electrical energy customers. Moreover, it must take into account that electrical energy measurements play a crucial role not only in commercial energy transactions but also in evaluation of energy balances in electrical distribution network, for stability purpose and in performance evaluation of machines and energy system. This of course spreads out the problem and greatly increases the number of the energy meter involved. There are two main challenging aspects that stem from the requirement of performing calibration in actual operating conditions. The first is related to the increasing number of non-linear and/or time-varying loads that, as well known, spread out over power network through recent years. These loads make several electrical disturbances normally present in the power network and their impacts in meters accuracy must be taken into account. Power Quality (PQ) issues [2], as any disturbance present in electrical network is addressed, include a lot of phenomena, such as interruptions, harmonic and inter-harmonic distortion, frequency and amplitude fluctuations, over-voltages and voltage dips, transient voltage changes and so on. Accounting all of them or even only main phenomena highly increase the difficulty in achieving an accurate characterization. This could only be achieved laying aside classical power and energy definitions, developed with reference to sinusoidal and balanced systems, because they are no more appropriate to describe the electrical network situations. Meter characterization should be performed with reference to measurement of electrical power/energy in non-sinusoidal and unbalanced conditions. Unfortunately the definition of a universally accepted procedure for calibration or metrological verification of EEM in non-sinusoidal and unbalanced conditions is still one of the most complex aspects of metrology [3]-[6].

This is due to both impossibility of performing direct measurements and difficulty of granting metrological traceability in the more traditional ways. This often gives rise to unavoidable procedural fuzziness in measurement procedure so penalizing fundamental aspects such as metrological confirmation of instruments and the uncertainty estimation. A big contribution comes from the latest IEEE standard about definition for measurements of electrical power quantities under sinusoidal, non-sinusoidal, balanced or unbalanced conditions [3]. But this refers only to steady state phenomena and, more in general, there is a lack of efficient standards that deal with PQ phenomena and how accounting them for instruments calibration [5]. This introduces further complications that make the task harder.

The second challenging aspect is related to the fact that a calibration is really performed in actual operating conditions only if it is performed in actual location of meter. So verification should be performed on-site through portable calibrators. Generally speaking, on-site calibrations are preferable because they are preformed with simpler procedure and in shorter time with remarkable cost reduction. In fact, typically, effective calibration time is negligible with respect of traveling time of the meter to

and back from an accredited laboratory. Moreover, during this time the meter should be replaced by another meter with unavoidable management problem. Nevertheless, performing on-site calibration of energy meters points out specific problems, because portability requirements are in contrast with power requirements and with hardware complexity needed to reproduce actual working conditions.
This paper faces the described challenging aspects presenting an implementation of portable equipment able to perform on-site calibration of the installed EEM in the actual operating conditions. Then, first results relating its metrological characterization and its application with a commercial EEM are presented too.

II. The measurement station

Like typical instrumentation for calibration purposes, it must be able to generate appropriate test signals (i.e. arbitrary non-sinusoidal voltage and current waveforms), to measure influence quantities affecting meter accuracy and to compare its measuring results with those of unit under test.
So, the proposed calibrator must include an arbitrary waveform generator (AWG) that has, as evident, non conventional features both for the amplitudes and the characteristics of the electrical signals that it has to reproduce. In particular, referring to typical Italian low voltage single phase customer [2], the rated amplitudes for voltage and current are respectively 230 V_{RMS}, i.e. about 326 V_{pk}, and 14.4 A_{RMS}, i.e. about 20.3 A_{pk}, which corresponding to 3.3 kW. Moreover, in practice, the peak and rms values might be remarkable higher, in order to include PQ issues as harmonic components or over-voltages. At first glance, it is evident that power requirements are incompatible with transportability constraint. For this reason the "virtual load connection" scheme, for energy meter verification, is adopted [7]-[9]; two waveform generators, one for voltage and one for current, are needed. The waveform generators are composed by two digital generators equipped by analogical front-ends for voltage and current amplification. Furthermore, portable calibrator must include also a power and energy measuring unit able to perform measurements according to all the most important definitions present in scientific literature about energy metering [3]-[6]. In fact, when non-sinusoidal flow of energy occurs, there isn't a full agreement in metrics definitions and there are lots of quantities of interest not yet defined in univocal way. Then, it is possible that different meters to be tested adopt different definitions and, to solve the problem, the calibrator adapt itself to customer implementations.

A. Hardware description

The realized portable calibrator is composed of a general purpose hardware for waveform generation, acquisition and elaboration, and of an analogical front-end made by current and voltage transducers and current and voltage power amplifiers [9] (fig. 1). In particular, a PXI platform has been used: it includes a controller, a module for data acquisition, the NI 6123, which has got 8 synchronous analog inputs at 16 bits, ±10 V input range and 500 kHz maximum sampling rate per channel, and some modules for waveform generation NI 5421, which has got one analog output at 16 bit, ±12 V output range, 100 MHz maximum generation sampling rate. Current and voltage transducers are LEM CV3-1000 and LEM CT 25 T, which have got 500 kHz bandwidth and overall accuracy of 0.2% and 0.1% respectively. In order to meet the requirements, proper current and voltage amplifiers have been designed and realized. Their main characteristics are: 20 MΩ input impedance, 400 V_{RMS}, 0.2 A, 10 Hz-10 kHz rated output for voltage amplifier; 20 MΩ, 20 A_{RMS}, 5 V, 5 Hz-20 kHz rated output for current amplifier.

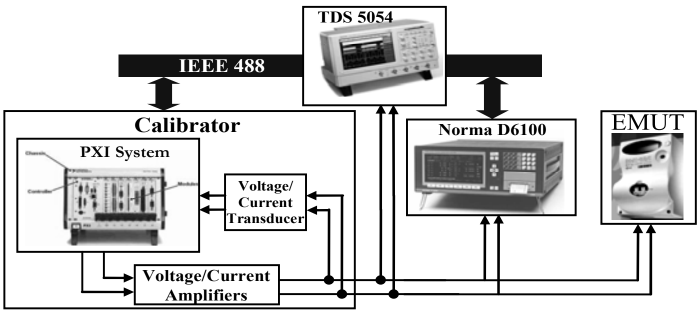

Fig. 1. Block diagram of the measurement station for the experimental characterization of the calibrator.

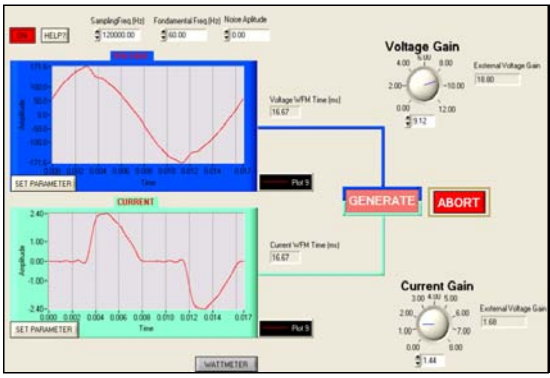

Fig. 2 – Signal generator front panel

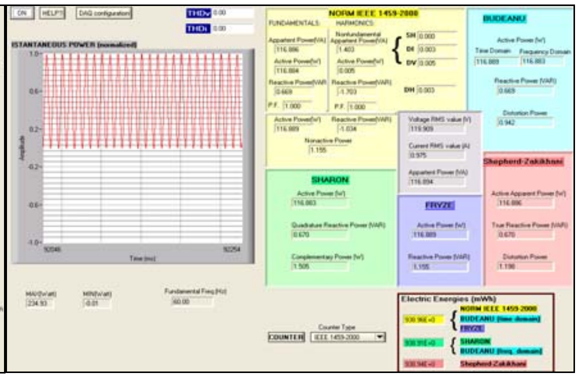

Fig. 3 – Wattmeter Front Panel

B. Software description

It is mainly composed by two procedures, one for waveforms generation and one for power/energy measure-ment. The front panel of both wattmeter and signal generator virtual instrument are shown figs. 2 and 3, during a non-sinusoidal test (table A1 of [3]).

The algorithm developed for waveforms generation can reproduce all the PQ phenomena. Test signals generation is made by calculating the proper waveforms together with the needed generation frequency; this information is sent to the generation modules that perform waveform D/A conversion. Then, the signals are amplified and driven to the output terminals. At the same time, amplified waveforms are sensed by transducers and acquired by the NI 6123. Operating in this way, with a closed loop scheme, it is possible to have a complete control on the generation. For accurate calibration aim, the spectral purity of the test signal is particularly important but the voltage and current channels are imperfect devices: besides the desired spectrum Y_W, unwanted spectral contributions Y_U appear and the generated spectrum becomes non-ideal. Generally speaking there are many phenomena that might affect generation accuracy: amplifiers non-linearity, load effect, temperature variations, transportation effect, electromagnetic environment, etc.. Two simultaneous techniques are adopted to reduce error generation.

The first one correct the gain and phase errors of the linear part of the system (see fig. 4).

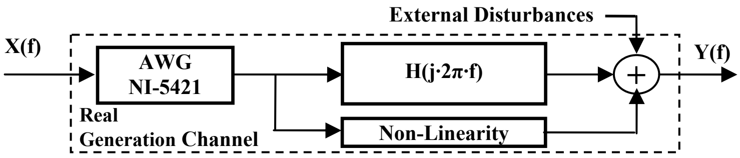

Fig.4. Block Scheme model of generation channels.

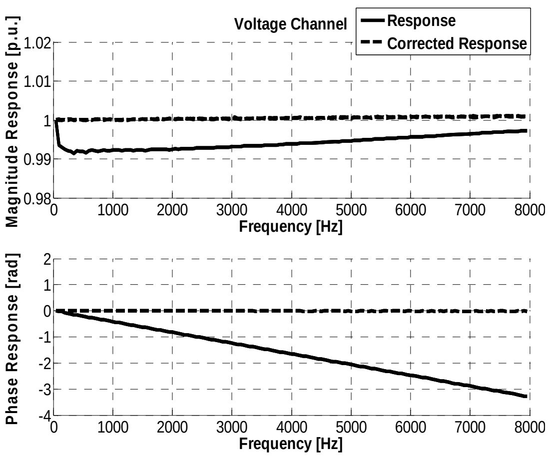

Fig. 5 Normalized frequency responses of voltage channel.

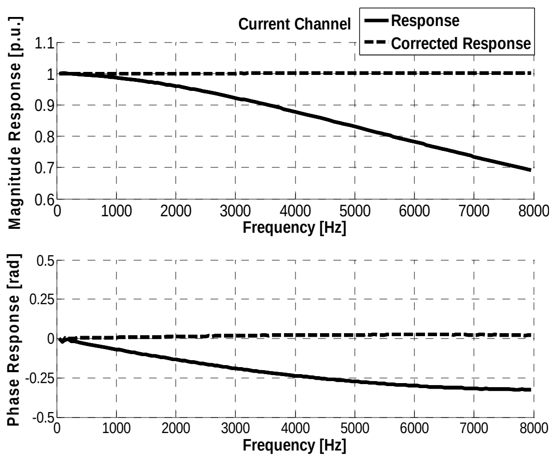

Fig. 6 Normalized frequency responses of current channel.

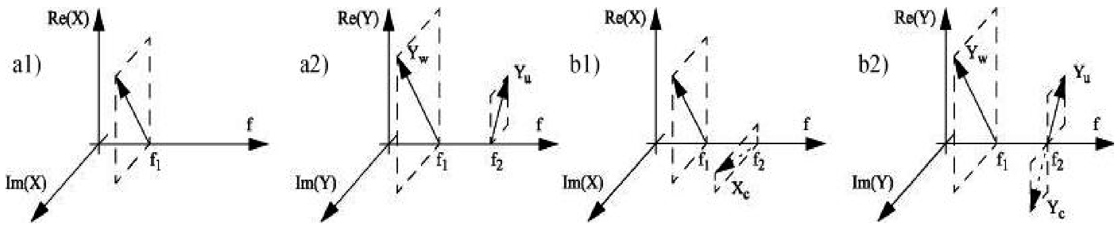

Fig. 7. Basic Idea for the correction: a) before correction; b) after correction.

It evaluates the harmonic amplitude and phase response of both voltage and current channels than it computes and stores fitting look-up tables. This technique's result is an overall frequency response with approximately constant gain and zero phase in the operating frequency range. As it can be seen in Fig. 5 and Fig. 6, the corrected frequency responses of voltage and current channels allow considering the used amplifiers approximately as simple gains.

All the previously listed phenomena, of course, cannot be corrected simply using generation look-up tables so the second procedure is to properly reduce the remaining generation errors due principally to output power amplifiers' non-linearity but also to all the other effects, treated as external disturbances. The real generation channel is considered to consist of an AWG, followed by a network that introduce some distortions (see fig. 4). An additive source at the output is used to describe external disturbances to model spurious spectral components due to other error sources. If one could invert the system between X(f) and Y(f), one could calculate the changes for X(f) needed to obtain a clean Y(f). However, inverting the nonlinear system is a very difficult task; therefore, the linear part has been used to obtain a correction. Basic Idea for this correction technique is shown in fig. 7. Subfigures a1 and a2 show the original ideal X(f) and practical Y(f) signals before correction. Input X(f) is a pure sine wave (see a1), but unfortunately, the output contains a wanted spectral component YW and an unwanted contribution YU at frequency f2 (see a2). YU cannot be created by the linear system, since X(f2) = 0. So it must originate from nonlinearities or from an external additive disturbance. For the correction, an extra input component XC is added at the same frequency f2, as shown in b1. Since the system is assumed to be dominantly linear, this will create a new output component YC at frequency f2; YC has the same amplitude and opposite phase as YU, so that the unwanted output contribution YU is cancelled, as it is shown in b2. Adding this new component XC can result in new unwanted spectral components at the output. For this reason the correction algorithm operate in iterative way until the maximum error is coerced within acceptable limits.

The measurement software acquire both voltage and current signals. Than it performs an accurate evaluation of the fundamental frequency. The numeric synchronization procedure performs first of all a signal filtering on voltage waveform to clean up disturbances. Than it finds the zero-crossings of the signal adopting a linear interpolation technique. The numeric wattmeter locks its acquisition buffer on the so computed frequency; in fact, automatically tuning the number of processed samples for execution cycle, it is able to follow input frequency variations. The wattmeter, of course, performs a spectral analysis, considering spectrum bins up to 160th harmonic component. Than it evaluates the power and energy, with related quantities (power factor, apparent, reactive and distorted power, THD, etc.), adopting most accredited metrics in scientific literature: IEEE 1459-2000, Budeanu, Fryze, Shepherd-Zakikhani, e Sharon [3]-[6].

III. Experimental performance evaluation.

In order to evaluate the performances of the realized equipment, both in generating calibration signals and in measuring power quantities, an automated test station has been built-up [10][9]. It is composed by a reference wattmeter, Norma D6100 Power Analyzer, produced by LEM, with accuracy better than 0.1 % on power measurements, and by a digital oscilloscope, Tektronix 5054, connected with the calibrator through IEEE 488 bus. The block scheme of the measurement station is shown in fig. 1.

The accuracy evaluation of such calibrator is a difficult task, due to a lack of complete standards. In fact, currently, the correct interpretation of the physical phenomena related to the energy flows in presence of distortion and then the set of the tests which a calibrator has to reproduce, in order to verify the validity of Energy Meter Under Test (EMUT) operation, independently from its measuring algorithm, is still a research task [5], [6].

Several experimental tests, using the described errors compensation procedures, have been performed. In particular, tests in sinusoidal and non-sinusoidal conditions have been executed.

Table I. Values of quantities utilized in sinusoidal tests.

Value	Fundamental Frequency [Hz]	Voltage (r.m.s.) [V]	Current (r.m.s.) [A]	Phase Angle [rad]
1	42.5	115	2	-π/2
2	45	140	5	-π/3
3	47.5	172.5	10	-π/4
4	50	200	15	-π/6
5	52.5	230	20	0
6	55	-	-	π/6
7	57.5	-	-	π/4
8	-	-	-	π/3
9	-	-	-	π/2

Table II. Mean squared deviations in sinusoidal tests.

Parameter	Mean Squared Deviation
Phase Angle	0.61 [mrad]
Frequency	0.67 [mHz]
Voltage (r.m.s.)	30 [p.p.m.]
Current (r.m.s.)	94 [p.p.m.]
Active Power	430 [p.p.m.]
Reactive Power	600 [p.p.m.]
Non Active Power	600 [p.p.m.]
Apparent Power	130 [p.p.m.]
Power Factor	0.002 [p.u.]

Table III. Values of quantities utilized in non-sinusoidal tests.

Values	Voltage (r.m.s.) [V]	Current (r.m.s.) [A]	Phase Angle [rad]	Harmonic Order
1	115	2	-π/2	3
2	140	5	-π/3	4
3	172.5	10	-π/4	9
4	200	15	-π/6	10
5	230	20	0	21
6	-	-	π/6	22
7	-	-	π/4	29
8	-	-	π/3	30
9	-	-	π/2	39
10	-	-	-	40

Table IV. Mean squared deviations in non-sinusoidal tests.

Parameter	Mean Squared Deviation
Fundamental Phase Angle	0.64[mrad]
Frequency	0.67[mHz]
Voltage (r.m.s.)	41[p.p.m.]
Current (r.m.s.)	140[p.p.m.]
Active Power	610[p.p.m.]
Reactive Power	0.43[%]
Non Active Power	620[p.p.m.]
Apparent Power	150[p.p.m.]
Power Factor	0.002[p.u.]
Voltage Harmonic (r.m.s.)	72[p.p.m.]
Current Harmonic (r.m.s.)	230[p.p.m.]
Harmonic Phase Angle	3.1[mrad]

With the aim of performing accuracy evaluation in sinusoidal conditions, five values for voltage and for current, seven for frequency and nine for phase angle have been selected and reported in Table I. The full factorial of the experimental chart has been executed, performing an amount of 1575 tests.
For each test, measured quantities are: frequency, voltage and current r.m.s. values, phase angle, voltage and current fundamental components, active and fundamental active, reactive, non-active, apparent powers and power factor [3]. In Table II for each measured quantity, mean squared relative deviation with respect of reference wattmeter is reported.
Regarding non-sinusoidal conditions, for each test, an harmonic component has been added to voltage and current waveforms, and its order has been varied according to [2]. Funda mental frequency, for each test, has been selected to 50 Hz. The values for the other quantities employed in the tests are reported in Table III; in total, they represent an amount of 2250 tests. In Table IV mean squared deviations, in non sinusoidal conditions, on each measured quantity, of the presented calibrator with respect to the utilized reference wattmeter, are reported.
The preliminary metrological characterization demonstrate that it is suitable to calibrate commercial EEM. Some other experiments have been executed using the proposed instrumentation to verify the

Table V. Experiments designed for sinusoidal active power

Test N°	I rms [A]	Phi [deg]	V rms [V]	Freq [Hz]	Error [%]
1	1	0	210	42.5	1.32
2	1	60	210	42.5	3.09
3	10	60	210	42.5	0.90
4	10	0	250	42.5	0.23
5	1	60	250	42.5	3.09
6	5.5	60	210	50	1.23
7	1	30	230	50	1.52
8	1	0	210	57.5	1.16
9	10	0	210	57.5	0.11
10	10	60	210	57.5	0.80
11	5.5	0	230	57.5	0.46
12	1	0	250	57.5	1.18
13	5.5	30	250	57.5	0.73
14	1	60	250	57.5	2.56
15	10	60	250	57.5	0.82

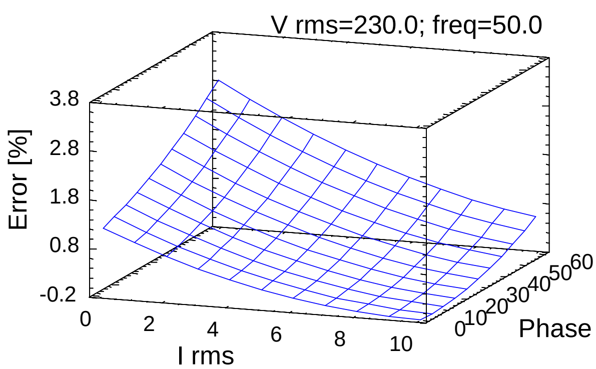

Fig. 8 Response surface for active energy error in sinusoidal conditions

Table VI. Experiments designed for sinusoidal reactive power

Test N°	I rms [A]	phi [deg]	V rms [V]	Freq [Hz]	Error [%]
1	1	30.0	210	42.5	13.64
2	1	90.0	210	42.5	-0.11
3	10	90.0	210	42.5	-0.26
4	10	30.0	250	42.5	14.16
5	1	90.0	250	42.5	-0.08
6	5.5	90.0	210	50	0.13
7	1	60.0	230	50	-0.17
8	1	30.0	210	57.5	-0.99
9	10	30.0	210	57.5	-0.44
10	10	90.0	210	57.5	0.11
11	1	30.0	250	57.5	-0.99
12	1	30.0	250	57.5	-1.29
13	5.5	60.0	250	57.5	-0.03
14	1	90.0	250	57.5	0.00
15	10	90.0	250	57.5	0.21

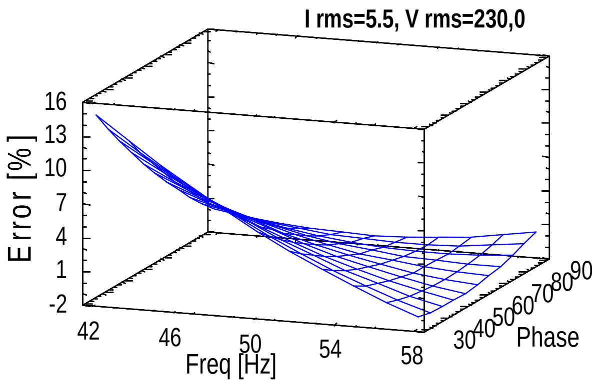

Fig. 9 Response surface for Reactive Energy error in sinusoidal conditions

accuracy of a commercial Energy Meter. In tables V and VI are reported the values of parameter adopted in sinusoidal tests respectively for active and reactive power. In figs 8 and 9 are reported the response surface plot of EMUT relative error respectively on active and on reactive energy, during this tests. Like previously discussed the definition of a procedure for calibration of EEM in non-sinusoidal and unbalanced conditions is still one of the most complex aspects of metrology, in this context the proposed instrumentation is able to execute whatever desired calibration protocol like experimental results demonstrate.

IV. Conclusion

The assessment of "metrological quality" of the power/energy measuring apparatuses is well establishes in ideal sinusoidal conditions. But, with increasing diffusion of power electronics the typical characteristics of power network are far from sinusoidal one. In this paper the implementation of a measurement equipment for the metrological verification of EEM has been presented. Its weight and portability, its accuracy in the generation and measurement of actual distorted network signals and its ability to adapt itself to most metric and power theory make it suitable for on-site calibration of fixed EEM. A description of generation and measuring procedures, a preliminary metrological characterization and experimental results of calibration of a commercial EEM was been presented too.

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