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A METHODOLOGY FOR QUALITY ASSURANCE IN ENERGY MEASUREMENTS UNDER NON-SINUSOIDAL CONDITIONS

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Abstract: The evaluation of the electrical energy flows is at the base of all operations connected to the commercial transactions in energy market. 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 a new methodology for quality assurance of energy meters in non sinusoidal operating conditions is reported. The description of methodology and some experimental results obtained are discussed in detail.

Keywords: measurement, quality assurance, energy meters verification, non-sinusoidal conditions

1. INTRODUCTION

Electrical energy measurement plays a crucial role not only in the commercial energy transactions but also in the estimation of energy balances in industries and in the performance evaluation of machines and energy systems both traditional and innovative. With the integrated text of the quality of the electrical services it has been introduced the faculty, for the customers that receive high and medium voltage and for the companies of distribution of the electrical energy, of stipulating contracts for the quality implying the fixation of an agreed level of quality ("Custom Power"), an annual fee on the back of the customer and a reimbursement in favour of the customer in the case which the agreed level of quality has not been respected in. The aforementioned aspects point out to a metrological nature problem, which in a modern and civil country must be solved: the possibility to carry out certified measurements of electrical energy in the actual operation conditions [1].

The assessment of "metrological quality" of the measuring apparatuses - intended as the adequacy of the measurement operations (of the instrument and not) to supply results consistent to the correspondent requirements of use - would have to be guaranteed with a high level of reliability. In metrological area, the proper management and the appropriate maintenance of measurement instrumentation represents a crucial aspect. As it is well known, in fact, the performance of a measurement instrument are inexorably destined to get worse during its functioning life; metrological characteristics, especially the uncertainty affecting the measurement results provided by the instrument, then, suffer from the time of use. In order to assure the reliability of results delivered by the instruments, repeated tests and calibrations are required. Calibrations allow controlling instruments uncertainty, with the aim of verifying that uncertainty value is located within a range set according to desired quality specifications.

In particular the electrical energy meters will be fully congruent to the within of the legal metrology placing the problem of the initial verification for the declaration of conformity to the type, based on the verification of product, but also that one of the calibration and the periodic verification of the operation. Metrological characterization of the electrical energy meters in the actual operation conditions is influenced by the presence of several non harmonized standards that leads to an effective absence of clear standards about their metrological confirmation [2]-[4]. Moreover, from a technical point of view, metrological verification of electrical energy meters in the actual operation conditions is difficult because of the presence of many disturbances in the network power quality, regarding both voltage and current, like dips, interruptions, swells, amplitude and frequency fluctuations, etc [5]-[6]. These problems become more relevant in the metrological verification on site, because the meter must be in accordance with electromagnetic environment typical of the industrial buildings. Therefore, regarding the electromagnetic environment, it must account as influence quantities: voltage interruptions, short voltage reductions, voltage transients, electrostatic discharges, radiofrequencies electromagnetic fields, etc. In particular sites it must take into account also: voltage variations, power frequency variations, magnetic fields at industrial frequencies, any other quantity that may significantly influence instrument's accuracy. Reference values for the aforementioned disturbances derive from different sources. In particular, the standard CEI EN 50160, an European standard receipt in Italy, reports levels for many parameters that characterize the quality of electrical network power [7].

The indication in MID [8], together with the market deregulation, will give rise to noticeable effects both technical and economical. In fact the MID applies to the placing on the market and putting into use of measuring instruments. This directive accurately defines maximum acceptable tolerances for each one of the considered instrument type, test environments and also fixes specific links for electromagnetic requirements. Technical consequences of MID and market deregulation will certainly be first of all in the exigency of modifying actual calibration methods that only refers to sinusoidal signals. As a matter of fact, sinusoids nowadays do not represent neither electrical energy characteristics nor MID suggestions. This leads to the need for instruments capable of generating the disturbances, both transient and of long duration, suggested by MID as well as calibration procedures based on non sinusoidal signals. Technical novelties immediately give rise to economical matters. On the basis of MID requirements, in fact, the following items should be applied:

- all the watt-hour meters installed after the application of MID will be placed on the market after type tests that will take into account electrical, mechanical, thermal and electromagnetic environments;
- all the watt-hour meters installed after the application of MID should foresee an on-field calibration able to reproduce electrical, mechanical, thermal and electromagnetic conditions.

The metrological verification of the electrical energy meters in the actual operating conditions implies that, from a technical point of view, all the verification procedures have to be carried out in the effective installation site that is the use of the reference travelling standards is necessary.

2. UNCERTAINTY ANALYSIS

Metrological characterization of energy meters is performed through comparison with a reference wattmeter followed by calculation relative error according with following relation:

$$e_{\%} = \frac{E_m - E_R}{E_R} = \frac{E_m}{E_R} - 1\,, \tag{1}$$

where E_m and E_R are the energy measured by equipment under test and by reference meter, respectively. It is useful to express the energy measured by reference equipment in terms of measured power, P_R, and time of integration, T_i, in order to point out the different source of uncertainty related with the characterization procedure:

$$e_{\%} = \frac{E_m}{P_R T_i} - 1\,. \tag{2}$$

In fact, in (2), E_m is calculated by difference of digital readings. It is possible to start and stop reference meter integration in correspondence of increments of measured value so that E_m reading can be considered unaffected by rounding uncertainty. P_R is affected by uncertainty related to adopted reference meter. Uncertainty on T_i is due to delay or advance in starting and stopping the reference meter integration in correspondence of reading increments. According with this consideration, it is possible to obtain uncertainty in error calculation in agreement with ISO guide [9], that is:

$$U(e_{\%}) = \sqrt{\left(\frac{\partial e_{\%}}{\partial P_R}\right)^2 U^2(P_R) + \left(\frac{\partial e_{\%}}{\partial T_i}\right)^2 U^2(T_i)} \tag{3}$$

where the sensitivity factors can be calculated as

$$\frac{\partial e_{\%}}{\partial P_R} = -\frac{E_m}{T_i}\frac{1}{P_R^2}\,, \tag{4}$$

$$\frac{\partial e_{\%}}{\partial T_i} = -\frac{E_m}{P_R}\frac{1}{T_i^2}\,. \tag{5}$$

From (3) it results that uncertainty can be calculated as

$$U(e_{\%}) = \sqrt{\left(\frac{E_m}{P_R^2 T_i}\right)^2 U^2(P_R) + \left(\frac{E_m}{P_R T_i^2}\right)^2 U^2(T_i)} = \left|\frac{E_m}{P_R T_i}\right| \sqrt{\left(\frac{U(P_R)}{P_R}\right)^2 + \left(\frac{U(T_i)}{T_i}\right)^2} \tag{6}$$

For, sake of simplicity, it is worthwhile to express (6) as:

$$U(e_{\%}) = \left|\frac{E_m}{E_R}\right| \sqrt{\left(\frac{U(P_R)}{P_R}\right)^2 + \left(\frac{U(T_i)}{T_i}\right)^2}\,. \tag{7}$$

3. OPTIMAL DESIGN OF EXPERIMENT

A Design of Experiment is a structured and organized method for determining the relationship between influence quantities affecting a process and the output of that process. The role of experimental design is to estimate the effects of several variables simultaneously; it is based on statistically analysis of forced changes made methodically as directed by mathematically systematic tables. In other words, experimental design is a scientific approach that allows an experimenter making intentional changes to the inputs of a process or system to identify and observe the reasons for the changes that occur to the response. So, the experimental design then contains a group of experimental runs [10].

In general, a process is defined as some combination of materials, methods, people, environment and measurement, which, used together, form a service, produce a product, or complete a task. In any experiment, the results and conclusions depend to a large extent on the manner in which the data are collected. The primary reason for using any designed experiment is to use data that can provide answers to well thought questions.

Many disciplines use experimental design methods. Experimentation is viewed as part of the scientific process where opinions are formed about a process and experiments are performed to generate data from the process. Information from the experiment is then used to establish new opinions, which lead to new experiments, and so on. A primary advantage in using statistical methods to analyze experimental responses is to add objectivity to the decision-making process, which ensures that the results and conclusions will be objective rather than judgmental. Statistical methodologies allow you to measure the likelihood of error in a conclusion or to attach a level of credibility to a statement.

In order to execute a full performance test of energy meters, adopting experimental design methods, it is necessary to choose influence quantities taken into account and, for each of them, the possible interval of variation. This interval should be larger than the range recommended in the standard, so that all situations are included. Then, different tests should be performed accounting a proper combination of influence quantities at different levels that are included in admissible range of variation. It is clear that testing all the combinations of influence quantities at different levels requires an amount of experiments that increases exponentially; the optimal design of experiment, however, can help to reduce this number.

Multilevel Factorial designs consist of combinations of specific levels of two or more factors, where the user sets the number of levels. This design class is intended for quantitative factors only and is analyzed as a Response Surface design. An optimized experiment is a subset of original runs used to reach D-optimality. D-optimality is a criterion that measures the variability of the estimated parameters. Because D-optimal designs are often used with mixture experiments, the remainder of this topic uses a simplex-centroid design.

4. EXPERIMENTAL RESULTS

A hardware and software test system was built up in order to perform single phase energy meter tests in sinusoidal and non-sinusoidal situations. A simplified block diagram of the performance verification system is shown in Fig. 1. It is based on a 3 phase arbitrary power waveform generator produced by Pacific Source 3120AMX, whose main characteristics are: i) maximum power: 12 kVA; ii) frequency range: 20 Hz to 5 kHz; iii) line regulation: 0.027 mV; iv) load regulation: 0.00135 mV; v) THD: 0.1%; vi) voltage ripple and noise: -70 dB. First phase of generator is used for voltage waveform generation while the other, in synchronized but separately way, for current waveform generation through a linear load. The adopted reference meter was the Power Analyzer produced by LEM (Norma D6000), whose main characteristics are: i) overall maximum error of 0.05% for current and voltage measurements and 0.09% for power measurements; ii) frequency range: from DC to 1 MHz. Equipment under test (EUT) was one of electronic energy meters that are installed by power distributor in Italy (see Fig. 1).

In [11] preliminary attention was devoted to the frequency bandwidth of EUT, and to determination of adopted algorithms for reactive energy calculation. So, it was shown that measurement bandwidth was about 3 kHz even if instable behaviour was found each multiple of 1 kHz perhaps due to the adopted sampling frequency that could be 2 kHz [11]. Moreover it was found that the algorithm adopted for reactive energy measurements is in agreement with Fryze approach for reference meter while EUT performs power calculation after a time shift in voltage waveform of a fourth of fundamental period, (this correspond to a phase shift of 90° at fundamental frequency), so that the two reactive energy measurements are incomparable. For this reason the described system can be adopted to perform tests in non sinusoidal conditions only with reference to active energy.

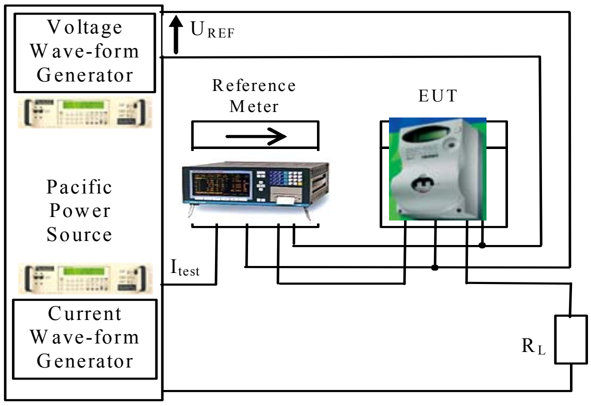

Fig. 1. A block diagram of the performance verification system for single phase energy meters.

As for characterization of EUT for active energy measurement in sinusoidal conditions, four parameters are accounted as influence quantities: voltage amplitude, V_{rms}, current amplitude, I_{rms} , phase relation, Phi, and system frequency, f. For each parameter are selected three level of amplitude so that a full factorial analysis would require 81 experiments at different combination of levels of influence quantities.

In order to evaluate the uncertainty in performed measurements, (7) can be applied accounting the accuracy of adopted reference meter:

$$\frac{\Delta P_R}{P_R} \le \frac{0.09}{\sqrt{3}}\% \tag{8}$$

Moreover, it is useful to plot combined uncertainty as function of integration time and uncertainty in integration time synchronization as shown in fig. 2.

In the performed measurements, time integration was synchronized in correspondence of reading increments with an estimated uncertainty of less than ±1 s, so that choosing integration time equal to about 5 minute, it results:

$$\frac{\Delta T_i}{T_i} \cong \frac{1}{\sqrt{3}} \frac{\pm 1}{300} = \pm 0.19\% \tag{9}$$

and overall uncertainty results

$$\Delta e_{\%} = 0.20 \cdot \left| \frac{E_m}{E_R} \right| \tag{10}$$

Form fig. 2, it is evident that with a more accurate synchronization, the same level of accuracy can be reached with shorter integration time that consequently makes the overall calibration time shorter.

In Tab. 1 is reported the reduced test-set obtained with an optimal design of experiment able to analyze second order effect. Effect is the change in the average of the responses between two factor-level combinations or two experimental settings. As an example, for a two-level factor, the effect of the factor is the average response at the high level of the factor, minus the average of the response at the low level of the factor. Moreover, in Tab. 1 the measured values of error and calculated uncertainty

No estimate of sampling variability is available since there are no degrees of freedom remaining to estimate the experimental error because the experiments are performed only once and there are no degrees of freedom available to estimate the error.

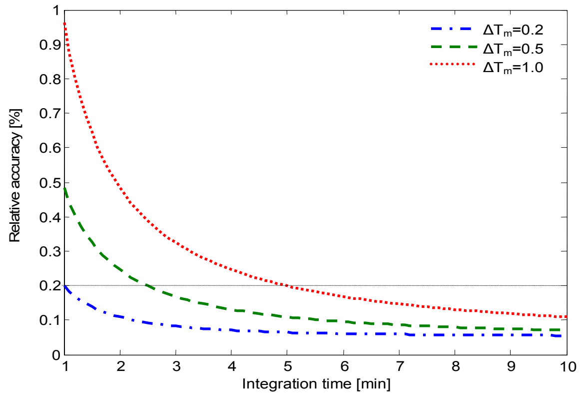

Fig. 2. Accuracy versus integration time

Table 1. Experiments designed for sinusoidal active power

First results from data of table 1 are obtained by Pareto analysis that is reports in Fig. 3. This plot shows each of the estimated effects and interactions in decreasing order of importance. In this way, it is possible to determine which effects are significant and which are insignificant. The prevalent effects that influence active power measurement appear to be current and phase. Voltage and frequency produce only minor effects.

In order to confirm and deepen these results, main effect analysis is performed to estimate the influence of a single factor on the response when the factor is changed from one level to another. In practice, each experimental factor of interest varies from its lowest level to its highest level, while all the other factors remain constant at their central values. The plot shows each of the main effects with a line drawn between the low and high levels of the corresponding factors. Pareto results are confirmed and quantitatively more precisely assessed.

Test N°	I rms [A]	Phi [deg]	V rms [V]	Freq [Hz]	Error [%]	Absolute Uncertainty
1	1	0	210	42.5	1.32	0.20
2	1	60	210	42.5	3.09	0.21
3	10	60	210	42.5	0.90	0.20
4	10	0	250	42.5	0.23	0.20
5	1	60	250	42.5	3.09	0.21
6	5.5	60	210	50	1.23	0.20
7	1	30	230	50	1.52	0.21
8	1	0	210	57.5	1.16	0.20
9	10	0	210	57.5	0.11	0.20
10	10	60	210	57.5	0.80	0.20
11	5.5	0	230	57.5	0.46	0.20
12	1	0	250	57.5	1.18	0.20
13	5.5	30	250	57.5	0.73	0.20
14	1	60	250	57.5	2.56	0.21
15	10	60	250	57.5	0.82	0.20

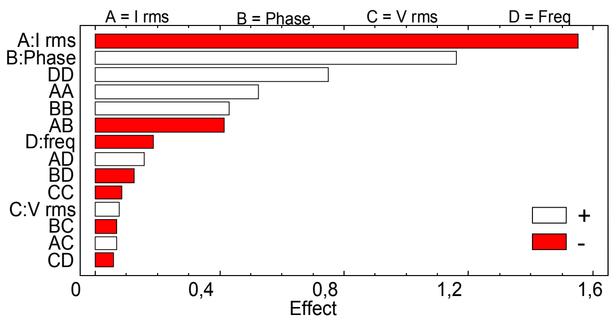

Fig. 3. Pareto chart for active energy error in sinusoidal conditions

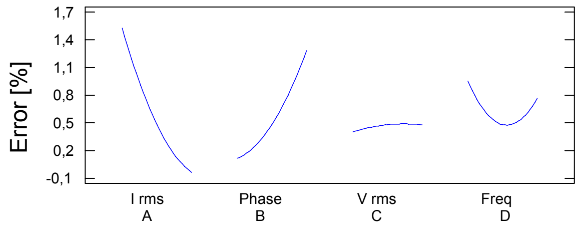

Fig. 4. Main effects for active energy error in sinusoidal conditions

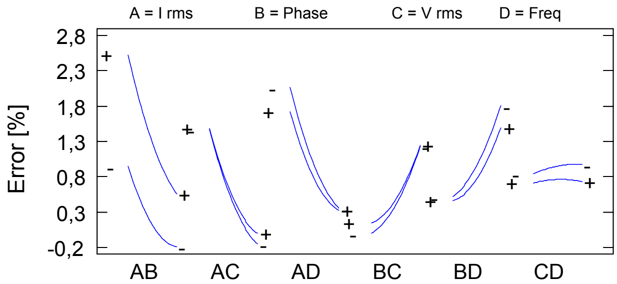

Fig. 5. Interaction plot for active energy error in sinusoidal conditions

In analysis of variance, the tendency for the combination of two factors to produce a result that is different from the mere sum of their two individual contributions is called multiplicative effect dependence. In practice it shows the existence of joint factor effects in which the effect of each factor depends upon the level of other factors. The interaction plots (Fig. 5) show the estimated variable as a function of pairs of factors. In each plot one factor varies from its lowest level to its highest level. On one line, the second factor is held at its lowest level, while on the other line, the second factor is held at its highest level. All other factors, except the two involved in the interaction, are held constant at their central values. It appears evident that current and phase have multiplicative effect dependence, while other parameters seem to not remarkably interact.

Moreover, it is possible to calculate the regression equation which fit to the experimental data:

$$
\begin{aligned}
e_{\%} &= 10.45 - 0.47 I_{rms} + 0.04\phi + 0.06 V_{rms} + 0.64 f + \\
&+ 0.0131 I_{rms}^2 + 0.0002\phi^2 + 0.0001 V_{rms}^2 + 0.0067 f^2 + \\
&- 0.0016 I_{rms}\phi + 0.0046 I_{rms} V_{rms} + 0.0023 I_{rms} f + \\
&+ +0.0003 f\phi - 0.0002 V_{rms} f
\end{aligned} \tag{11}
$$

where the values of the variables are specified in their original units. Fig. 6 reports the response surface plot, obtained by evaluating this function.

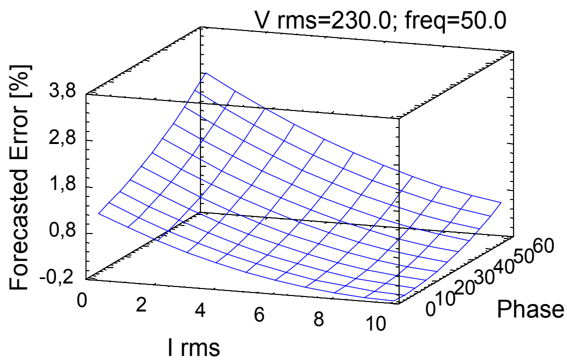

Fig. 6. Estimated response surface for active energy error in sinusoidal conditions

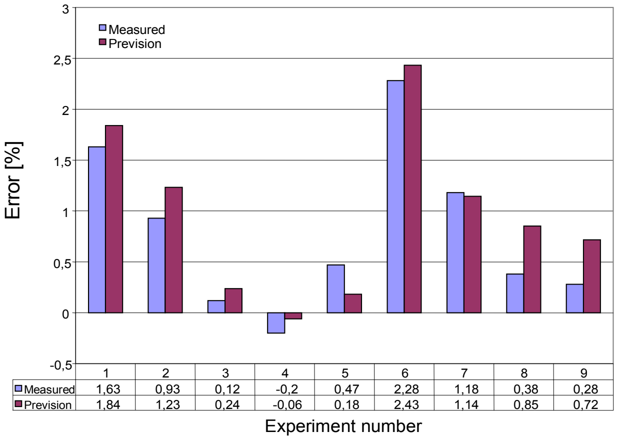

Fig. 7. Forecasting test for active energy error in sinusoidal conditions

Fig. 7 contains a comparison among values of error generated using the fitted model and values measured in working condition not included in test set and that are described in [11].The results obtained are quite satisfactory: model reproduces considered situations with a tolerance compatible with measurement accuracy.

Another design of experiments similar to that performed for active power is conducted also for reactive power in sinusoidal conditions and Tab. 2 reports the analyzed reduced test-set of working conditions.

From errors reported in Tab. 2, it appears evident that very high values of error are reached in particularly unfavourable working conditions. Also in this case, it useful to investigate the source of this behaviour by a Pareto analysis (Fig. 8) and by the plots of the main effects (Fig. 9). In both plots, the prevalent sources of error appear to be frequency deviation and phase angle, especially as joint factor effect. Voltage and current levels produce only minor effects. This hypothesis is confirmed by interaction plots (Fig.10) that shows a very strong influence of joint effect of these two parameters.

Also for this analysis, it is possible to calculate the regression equation which fits to the experimental data:

$$\begin{aligned} e_{\%} &= 280.34 + 0.63 I_{rms} - 1.07\phi - 1.26 V_{rms} - 3.52 f + \\ &- 0.0666 I_{rms}^2 + 0.0011\phi^2 + 0.0027 V_{rms}^2 + 0.0211 f^2 + \\ &- 0.0010 I_{rms}\phi + 0.0006 I_{rms} V_{rms} + 0.0001 I_{rms} f + \\ &+ +0.0165 f\phi - 0.0002 V_{rms} f \end{aligned} \tag{12}$$

where the values of the variables are specified in their original units.

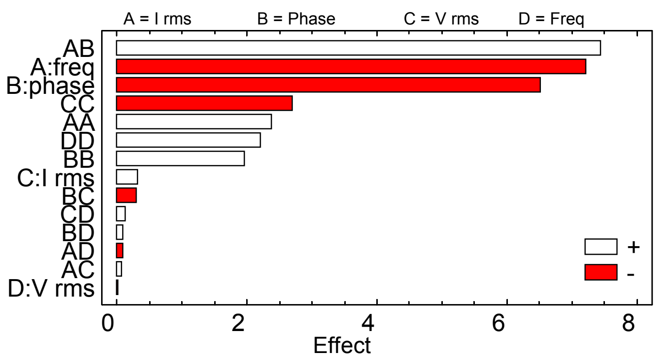

Fig. 8. Pareto chart for reactive energy error in sinusoidal conditions

Table 2. Experiments designed for sinusoidal reactive power

Test N°	I rms [A]	phi [deg]	V rms [V]	Freq [Hz]	Error [%]	Absolute Uncertainty
1	1	30.0	210	42.5	13.64	0.23
2	1	90.0	210	42.5	-0.11	0.20
3	10	90.0	210	42.5	-0.26	0.20
4	10	30.0	250	42.5	14.16	0.23
5	1	90.0	250	42.5	-0.08	0.20
6	5.5	90.0	210	50	0.13	0.20
7	1	60.0	230	50	-0.17	0.20
8	1	30.0	210	57.5	-0.99	0.20
9	10	30.0	210	57.5	-0.44	0.20
10	10	90.0	210	57.5	0.11	0.20
11	1	30.0	250	57.5	-0.99	0.20
12	1	30.0	250	57.5	-1.29	0.20
13	5.5	60.0	250	57.5	-0.03	0.20
14	1	90.0	250	57.5	0.00	0.20
15	10	90.0	250	57.5	0.21	0.20

Fig. 12 and Fig. 13 report the response surface and the corresponding contour plot, obtained by evaluating this function. Equation (12) was adopted to estimated error in a situation characterized by very low frequency (42.5 Hz) and low angular value (15 °). The obtained value is -30% and it was experimentally confirmed.

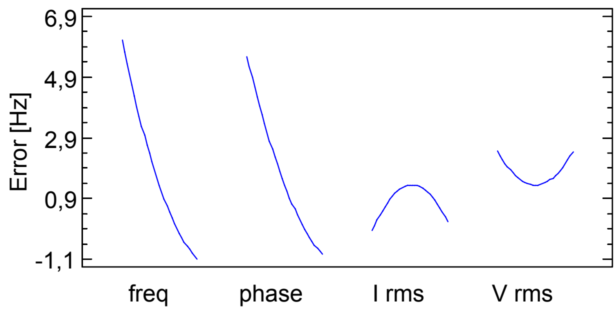

Fig. 9. Main effects for reactive energy error in sinusoidal conditions

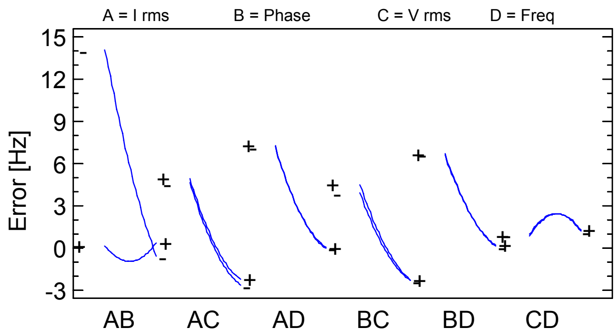

Fig. 10. Interaction plot for reactive energy error in sinusoidal conditions

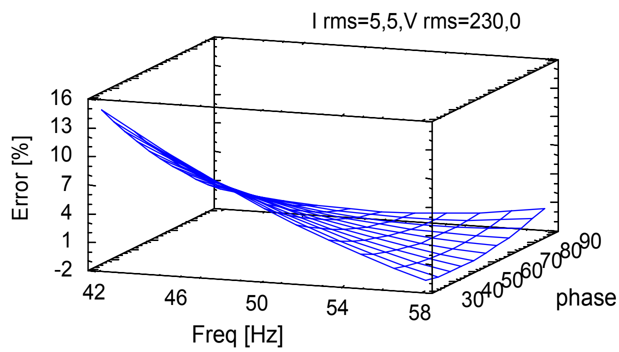

Fig. 11. Estimated response surface for reactive energy error in sinusoidal conditions

Last design of experiments, similar to those previously fully described, was conducted also for active power in non-sinusoidal conditions. The selected influence parameters were harmonic order, h, fundamental phase, θ_1, amplitude of harmonic current, Ih, harmonic phase, θh. Fundamental frequency, current and voltage amplitude are accounted at nominal condition and amplitude of harmonic voltage was chosen equal to 10% of fundamental amplitude. The results are reported from Fig. 12 to Fig. 15 and show that a strong interaction among influence parameters exists and direct interpretation is not straightforward. For a more exhausting analysis, also influence of current amplitude should be included in the design of experiment.

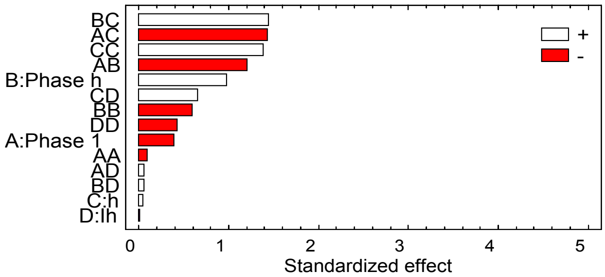

Fig. 12. **Pareto chart for reactive energy error in non-sinusoidal conditions**

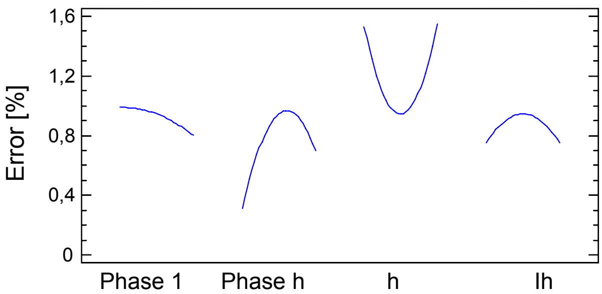

Fig. 13. **Main effects for reactive energy error in non-sinusoidal conditions**

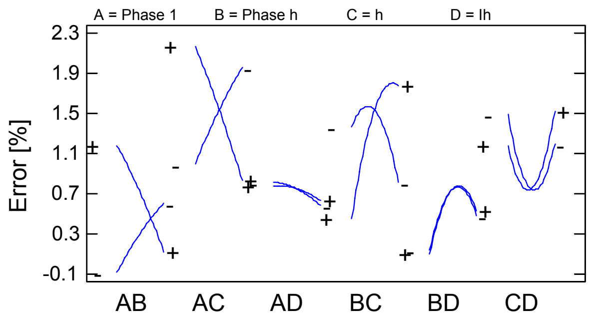

Fig. 14. **Interaction plot for reactive energy error in sinusoidal conditions**

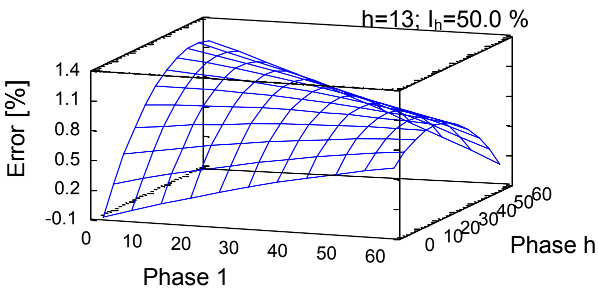

Fig. 15. **Estimated response surface for reactive energy error in non-sinusoidal conditions**

3. 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 a new methodology for quality assurance of energy meters in non sinusoidal operating conditions was reported. The description of methodology and some experimental results obtained were discussed in detail.

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