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PERFORMANCE ANALYSIS OF AN ACTIVE ENERGY INDUCTION METER USING AN INNOVATIVE APPROACH

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Abstract: The paper is focused on the performance analysis of an induction energy meter under different voltage and current waveforms, both sinusoidal and deformed, which resemble possible conditions of supply network encountered during normal operation. The measurement test bench and the experimental plan are presented. Experimental results are compared to a reference watthour meter, and the relative error is characterized in terms of dependence on input quantities.

Keywords: Energy meter calibration, induction energy meters, non sinusoidal conditions, electrical quantities measurement

1. INTRODUCTION

Due to the raising diffusion of power electronics and the increased number of competitors on the energy market, some of which produce and distribute electrical energy from renewable sources, the electrical quantities in the power network are far from being sinusoidal. Such new working conditions also pose issues to billing procedures since energy may have a strong reactive portion on both the generation and utilization end, which must be charged only to the one who causes it, e.g., because of the use of a large reactive load.

So, special interest is focused on the characteristics of the devices mandated to the measurement of energy absorbed by costumers.

The authors have proposed in [1] a new methodology to calibrate energy meters, and in the same paper an application to electronic meters to characterize the effects of power signal distortions on energy measurements has also been presented. Though, since the induction meter is still the most widely used device to measure active energy flow, it is important to characterize its behaviour under sinusoidal and distorted conditions as a comparison to its numerical counterpart.

[1] The main problem with energy meters is that they are usually characterized – i.e., calibrated by manufacturers – by means of a sinusoidal signal, so that the behaviour under non-sinusoidal currents and voltages is unknown, which may possibly have some relevant effects on measurement values, and in turn on fees charged to customers.

The watthour coils, working under non-nominal conditions, in fact, could saturate or change their impedance, causing an increased registration error.

Additionally, an issue arises when conditions at which meters are calibrated are supposed to hold under normal operation. Indeed, what can only be assured is that under all combinations of operation conditions, values of network's characteristic quantities remain within limits specified in EN IEC 50160 [2].

Starting from these considerations, the scientific community has undertaken a great effort for providing new definitions of energy which remain consistent even in strongly distorted environments, and for determining rules to define what quantity an energy meter has to measure [3-5], that is which energy has to be paid by customers and which ones by producers. One of the most important contributions to this field comes from IEEE standard about definition for measurement of electrical power quantities [6].

The work presented in the following aims at the characterization of registration error of induction meters under different Power Quality scenarios for the supply voltage powering a resistive load. Sect. 2 will present the test circuit utilized to perform experimental tests and the experimental plan adopted; in Sect. 3 the results will be given, while conclusions will be drawn in Sect. 4.

2. EXPERIMENTAL SETUP

A number of time domain models have been developed in literature to determine the registration error of induction watthour meter [1-4]. These models, however, are difficult to implement, especially in evaluating the voltage coil and disk parameters. The variation of these parameters with frequency have a significant impact upon the meter's operation [5-9].

Therefore, the registration error of an watthour meter has been evaluated by means of experimental tests. In particular, the measured energy at different conditions of

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power supply has been recorded and compared to results obtained by a reference electronic watthour meter.

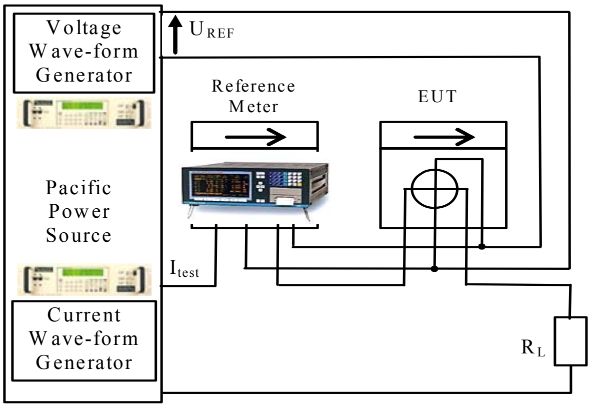

Fig. 1. Measurement station for experimental tests.

The measurement station used for the experimental tests is shown in Fig. 1. A 3120AMX power generator by Power Pacific has been employed as a calibrated voltage and current supplier. Its main characteristics are: *(i)* frequency range: 20 Hz to 50 kHz; *(ii)* maximum generation THD: 0.1%; and *(iii)* voltage ripple and noise: -70 dB. Moreover, it allows to set amplitude, phase and waveform of each phase independently, and to define a wide variety of waveforms by specifying the amplitude percentage of each harmonic component. A virtual load approach has been preferred in order to test the watthour meter under independent voltage and current conditions and for a better control of voltage-current phase displacement.

To generate a calibrated current waveform with the voltage generator, one phase has been used to power a 12 Ω resistance. A PM100 power meter by Voltech has been employed as the reference meter, with a ±0.2%·*rdg* ±0.2%·*rng* ±5mW accuracy characteristic for power measurements, and a band covering up to 250 kHz.

A USB web camera is mandated to detect the watthour meter disk revolutions, by detecting the black marker crossing. Power generator and power meter are controlled via IEEE 488 protocol, through a software developed in National Instruments LabVIEW™ environment. The same software controls, via serial communication protocol the web camera. The measurement procedure is performed through the following steps: (i) the AMX power generator is configured with the desired voltage and current output characteristics, and the test is started; (ii) when the camera detects the first marker crossing, the software starts a timer and queries the reference meter for the measured power every 0.2 seconds; every time the camera detects a disk revolution, a counter is increased; (iii) when at least 90 seconds have elapsed, the software stops the measurement at the next disk revolution. The energy measured by the watthour meter under test is evaluated by $E = K \cdot N_{rev} \cdot t$, where $K = 1/900$ kWh/revolution is the meter calibration factor, and N_{rev} is the number of revolutions counted during t [h]. By integrating the power measured by the Voltech over the interval t, the reference energy is obtained.

Experimental tests aim at characterizing the device under test when voltage and current characteristics are not at their nominal values, and compare measurements with a reference meter. Variations of input quantities are limited within the range allowed by the EN IEC 50160, related to the main characteristics of voltage at the customer's supply terminals in public low and medium voltage distribution systems under normal operating conditions. This standard gives the limits or values within which any customer can expect the voltage characteristics to remain.

Tests have been performed following the methodology presented in [1], by carrying out experiments based on a design-of-experiment approach involving the quantities that are most likely to vary during normal operation. Table I shows factors and the corresponding levels considered to assess the watthour meter performances under sinusoidal conditions, while test for estimation of the registration error in distorted conditions use factors and levels in Table II.

Parameter	**Lev 1**	**Lev 2**	**Lev 3**
Frequency, $\omega/2\pi$ [Hz]	50	42,5	57,5
Rms Voltage, V_1 [V]	230	253	207
Rms Current, I_1 [A]	5	1	10
Phase Angle, θ_1 [deg]	0	60	-35

Table I. Parameters and levels for active energy in sinusoidal conditions

Parameter	**Lev 1**	**Lev 2**	**Lev 3**
Harmonic order, h	3	11	21
Fundamental Phase, θ_1 [deg]	0	60	-35
Rms Harmonic Current, I_h [%]	20	40	80
Harmonic Phase, θ_h [deg]	0	60	-35

Table II. Parameters and levels for active energy in distorted conditions

To test all possible combinations of the four parameters with three different values each, 81 measurements would be required. Therefore, a standard resolution III $L_9(3^4)$ plan has been preferred, which reduces the number of experiments to 9, yet reducing the amount of information which can be obtained from measurement result [9,10]. Namely, only *main* effects of factors can be determined, not joint effects (*interactions*) of two or more factors. The adopted test plan is shown in Table III.

Test Number	Factor 1	Factor 2	Factor 3	Factor 4
1	Lev 1	Lev 1	Lev 1	Lev 1
2	Lev 1	Lev 2	Lev 2	Lev 2
3	Lev 1	Lev 3	Lev 3	Lev 3
4	Lev 2	Lev 1	Lev 2	Lev 3
5	Lev 2	Lev 2	Lev 3	Lev 1
6	Lev 2	Lev 3	Lev 1	Lev 2
7	Lev 3	Lev 1	Lev 3	Lev 2
8	Lev 3	Lev 2	Lev 1	Lev 3
9	Lev 3	Lev 3	Lev 2	Lev 1

Table III. Reduced factorial experimental plan

3. EXPERIMENTAL RESULTS

Based on the reduced factorial plan in Table III, two different experiments have been designed, for active energy measurement in both sinusoidal and distorted conditions. The output quantity is the relative error between the reference meter and the meter under test:

$$e = \frac{E_{Whm} - E_{ref}}{E_{ref}} \qquad (1)$$

3.1. Sinusoidal active energy

Results of the relative error obtained after application of the experimental plan of Table III populated with factors and levels in Table I are reported in Fig. 2. Each subplot shows the main effect of a quantity, i.e., the mean registration error obtained by averaging measurement results obtained for each level of the input quantity. Registration error, with regards to frequency variations, behaves as expected: induction watthour meter, in fact, acts as a low-pass system, then the higher the frequency of supply voltage and current the lower the measured energy. Interesting results have also been attained with respect to voltage-current phase displacement: the watthour meter error seems to increase with the displacement, i.e. when the reactive energy increases. While frequency and phase seem to have a monotonic behaviour, the effect of voltage and current *rms* value is not clear.

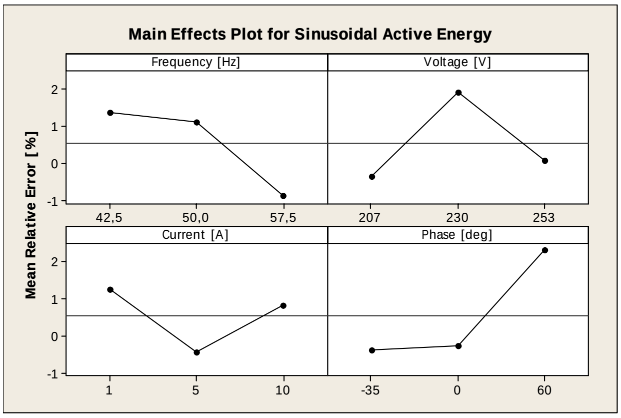

Fig. 2 – Main effects of input quantities in Active Energy Measurements under sinusoidal conditions

To better interpret results, it must be noted however that because of the incompleteness of the designed plan, test performed at a level of any one factor does not include the complete set of all possible combinations of the other factors. As an example, each frequency level is common to only three experimental points (see column of Factor 1 in Table III), instead of the 27 points that a complete factorial of the other three factors would yield. That must be taken into proper account when associating an effect or dependence to a factor, because the main effect may indeed suffer from a confusion due to the actual combination of other factors that have been tested.

3.2. Distorted active energy

The relative error when voltage and current have the same distorted waveform has also been measured with the experimental plan in Table III with factors and levels in Table II. Results are shown in Figure 3. Subplots show in most cases an effect of input quantities, though the amplitude vary with the level of factors under observation. It is important to notice the quite large error introduced by the third harmonic, whereas the error does not show significant sensitivity with higher harmonic order.

Another interesting result is related to the harmonic amplitude: when current waveform is highly distorted, the error becomes much larger.

Focusing on effects of phase displacement, the minimum mean error's absolute value occurs when such factor is set at 0 degrees.

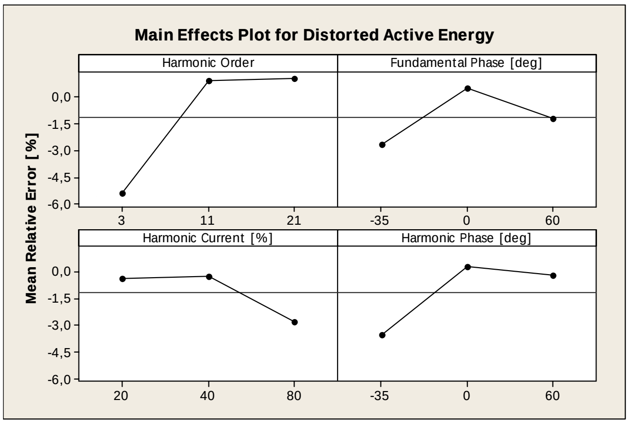

Fig. 3 – Main effects of input quantities in Active Energy Measurements under distorted conditions

3.3. Response surface of active energy

Once a *qualitative* analysis of the effects of the input factors like the ones performed in Sections 3.1 and 3.2 has been carried out, it may be useful to determine the measurement error from a *quantitative* point of view. By a two-factor Central Composite Rotatable Design (CCRD) it is possible to obtain the coefficients of a second-order regression curve which describes the behaviour of the output factor, i.e., the relative registration error, within the experimental space. Most noticeably, the response variance, that is the uncertainty associated to the regression curve depends only on the distance from the centre of the experimental space (that is where the adjective *rotatable* comes from) and it increases when moving from the centre to the boundaries. CCRD has been applied with regards to the two factors that seemed to mainly affect watthour meter error, i.e. RMS current and voltage-current phase displacement.

Test Number	I [A]	Φ [°]	ε [%]
1	2.32	-21.09	-0.58
2	8.68	-21.09	-0.58
3	2.32	46.09	2.47
4	8.68	46.09	0.78
5	1	12.5	0.98
6	10	12.5	-1.03
7	5.5	-35	-0.29
8	5.5	60	2.41
9	5.5	12.5	0.51 (0.09)

Table IV. CCRD experimental space

As an example of such tool, the response surface for active energy measurement error in sinusoidal conditions versus current and phase in the intervals [1; 10] A and [-35; 60] degrees respectively has been obtained. Experiments have been run at the 9 points of Table IV, the last one being repeated 5 times to obtain an estimate of the experimental variance requested for the evaluation of the response variance mentioned above.

Results are also shown in Table IV. The value corresponding to test number 9 is the average value of all 5 repetitions with the estimate of variance (with 4 degrees of freedom) in round parenthesis.

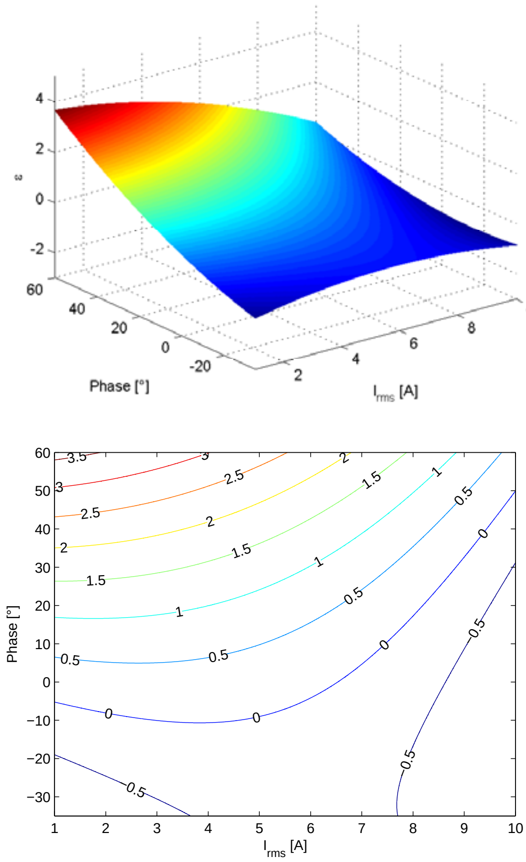

Fig. 4 – Response surface and contour plot of relative error in Active Energy Measurements under sinusoidal conditions

Table V contains the regression coefficients returned by such experiment. They can be used to plot the resulting response surface shown at the top of Figure 4 along with the corresponding contour plot (bottom). The coefficients to be included in the final expression have been determined through a *t*-test of significance [9].

	b_0	b_I	b_φ	b_I^2	b_φ^2	$b_{I,\varphi}$
value	0.51	-0.57	1.03	-0.26	0.28	-0.42
t		17.43	31.56	7.53	7.96	9.17

Table V. Coefficients of response surface and significance values

This consists in comparing the experimental *t* value (shown in the second line in Table V) obtained for each coefficient other than the constant term b_0 to the theoretical value obtained for a fixed significance level α and with 4 degrees of freedom. By choosing α = 99%, the decision criterion is set at $\hat{x} = 4.54$; since all *t*-values are larger than it, we could conclude that all coefficients are significant and must be included in the regression curve.

Response surfaces cannot be correctly interpreted without an evaluation of the associated uncertainty. The graph at the top of Figure V shows cuts for response surface and the corresponding uncertainty interval (with coverage factor k = 1) at three different current *rms* levels. Likewise, the bottom graph shows the behaviour of relative error versus current for three different phase levels.

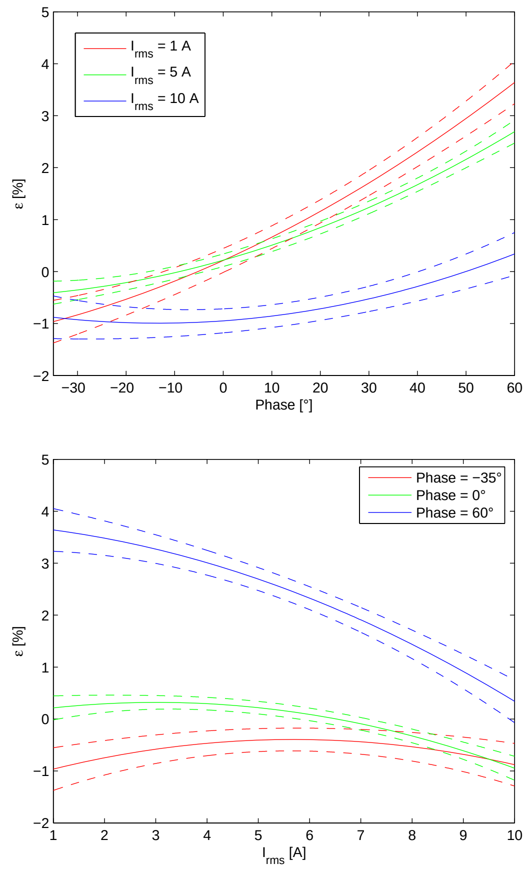

Fig. 5 – Current and Phase uncertainty intervals for Active Energy Measurements under sinusoidal conditions

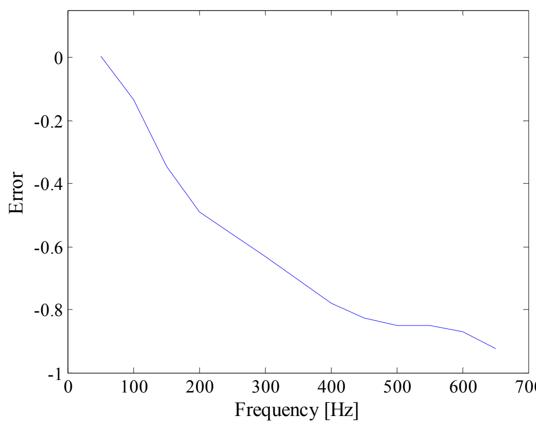

Fig. 6 – Registration error versus fundamental frequency.

3.4. Meter's frequency response

As shown in Figures 2 and 3, watthour meter proves to be quite sensitive to frequency variations. To further investigate such characteristic, a more detailed analysis of meter's frequency response has been carried out by setting voltage and current at nominal *rms* value, and varying frequency in the range 50-650 Hz with steps of 50 Hz.

Results are shown in Figure 6 where the error as defined in eq. (1) versus fundamental frequency is plotted. The low-pass behaviour of the induction meter is apparent, with the cutoff frequency located around 150 Hz.

4. CONCLUSIONS

The experimental activity presented in this paper is focused on the characterization of an active energy induction meter according to a new methodology based on the Design Of Experiment approach. Energy measured under different working conditions has been compared to values from a reference electronic meter in order to determine dependence on various input quantities such as frequency, amplitude and harmonic content of the powering voltages and current. A response surface has also been obtained to gain knowledge of the quantitative dependence on input factors. Application of such technique provides an innovative tool to quantitatively determine performances of energy meters on an *a priori* basis in each situation in which the electrical characteristics of the power network are known.

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REFERENCES

[1] D. Gallo, C. Landi, A. Liccardo, N. Pasquino, N. Polese, "A methodology for quality assurance in energy measurements under non-sinusoidal conditions", *XVIII IMEKO World Congress*, September 17 – 22, 2006, Rio de Janeiro, Brazil.

[2] EN 50160, "Voltage characteristics of electricity supplied by public distribution systems", CENELEC, 1999.

[3] A. A. Girgis,; T. L. Baldwin, E. B. Makram, H. S. Fortson, "Testing the performance of three-phase induction watthour meters in the presence of harmonic distortion", IEEE Transactions on Industry Applications, Vol. 26, Issue 4, 1990, pp. 689 – 695.

[4] D. Gallo, C. Landi, N. Pasquino, N. Polese, "An Advanced Laboratory Architecture for Metrological Confirmation of Measurement Device for Power Quality Evaluation" 13th Int. Symp. on Measurements For Research And Industry Applications, IMEKO 2004, Athens – Greece, Sept., 2004.

[5] Filipski, P.S.; Baghzouz, Y.; Cox, M.D. "Discussion of power definitions contained in the IEEE Dictionary". *IEEE Trans. on Power Delivery*, Vol. 9, No 3, pp.1237 - 1244, July 1994.

[6] IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced or Unbalanced Conditions, IEEE 1459, 2000.

[7] A. Jalilian, V. J. Gosbell, B. S. P. Perera, "Performance of a 7.5 kW induction motor under harmonically distorted supply conditions", 2000 Canadian Conference on Electrical and Computer Engineering, Vol. 1, 7-10 March 2000, pp. 355 – 359.

[8] IEC 61000-4-30, 2003, Testing and measurement techniques – Power quality measurement methods.

[9] D:C: Montgomery, "Design and analysis of experiment", NY, Wiley, 1997.

[10] M.S. Phadke, "Quality Engineering using robust design", Englewood Cliffs, NJ, Prentice Hall, 1989

[11] Diamond W.J., *Practical Experiment Designs: for Engineers and Scientists*, 3rd ed., Wiley, 2001