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24 November 2024

The INRIM role of inter-laboratory comparison provider for electrical Power and Energy at industrial frequency: a two-year activity report

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ABSTRACT

The technical surveillance of secondary calibration laboratories accredited according to the ISO/IEC 17025 standard for electrical power and energy at industrial frequency is very important, as these measurements are the basis of the commercial relations between an electricity supplier and a user. An effective technical surveillance requires the execution of inter-laboratory comparisons (ILCs). With them, it is possible to verify the competence of the laboratories and the correctness of the dissemination process from the national standards of power and energy, usually maintained at national metrology institutes (NMI), to these laboratories. The paper deals with the ILCs that the National Institute of Metrological Research (INRIM) provided and carried out as reference measurements provider for Italian accredited laboratories for power and energy (active and reactive) at industrial frequency. The ILCs were carried out involving various instrument types and at different uncertainty levels. The 2σ relative uncertainties of the INRIM calibrations ranged from 1.0×10^{-4} to 1.5×10^{-3}. The ILCs had satisfactory results confirming the correctness of both the dissemination from INRIM and the accreditation process by the Italian accreditation body for calibration laboratories.

Keywords: Inter-laboratory comparison, active and reactive power and energy, wattmeter, energy converter, energy counter, measurement compatibility, measurement uncertainty, normalized error.

1. Introduction

The measurement of electricity, in terms of electrical power and energy at industrial frequency, has a practical importance, as it is the basis of the commercial relations between a supplier and a user. Almost all electricity distribution takes place today with alternating voltage and current. In an electricity system, we define this relation about powers:

$$S = \sqrt{P^2 + Q^2} \qquad (1)$$

Where S, P and Q are the apparent, active (real) and reactive powers respectively. As the electricity supplier bills the integrated value of P (active or real energy) and charges penalties to users with high value of reactive energy (integrated value of Q), their interest is to lower Q lowering the phase angle between voltage and current improving the efficiency of their plants (power factor correction). The reactive energy makes no useful work but, being it exchanged on the electric grids, the performance of the transmission and distribution system is degraded. A plant that absorbs a lot of reactive energy requires higher current than it would require if it was correctly rephased. For this reason, reactive energy causes economic damage and it is undesired by the supplier. Therefore, the control of Q and its lowering are important to manage an efficient use of the supply network reducing also the costs. Over several decades instruments have advanced from the electrodynamic-analog wattmeters of the past, to microprocessor-based digital wattmeters [1–3] using sampling methods developed since the seventies. Further improvement was achieved in [4] describing a wattmeter operating at frequencies from 50 Hz to 1 kHz. Recently, a precise and low-cost PC-based wattmeter using data acquisition boards [5] and a high precision wattmeter based on a design of a standard watt converter and using time-division multiplication [6], were realized.

2. The measurement system of active Power at INRIM

In the INRIM primary system for active power measurements, the voltage and current signals are generated by a Fluke 6100A power

standard. The acquisition system consists of two high-precision DMMs used as integrative-analog-to-digital converters. The first one acquires the voltage while the other, being connected to a current transformer with a precision 1 Ω resistor connected at its output, acquires the current. The INRIM system and the power measurement method based on DMMs are described in [7]. INRIM best relative uncertainties are 5.0×10^{-5} and 8.0×10^{-5} for voltages lower or higher than 600 V respectively. With this system, a 0.005 % accuracy class wattmeter (comparator) [8] is calibrated. This instrument acts then as working instrument to calibrate the reference standards of secondary laboratories.

3. Surveillance of the secondary calibration laboratories

Italian calibration secondary laboratories, mainly those accredited according to [9], are equipped with watt-metric converters (single-phase instruments) and three-phase wattmeters. The latter can belong to the 0.01 % and 0.02 % accuracy classes or to the 0.05 % and 0.1 % accuracy classes. The former are used as laboratory reference instruments while the latter (usually portable ones) are used for on–site calibrations of energy counters. Other instruments are multifunction power and energy meters, power to voltage and power to frequency converters, energy counters, energy-pulse converters, active power generators, reactive power meters and generators. In addition, some laboratories are accredited for the metrological verification of electrical energy counters for legal metrology. Currently, there are fifteen Italian accredited laboratories. These laboratories are obliged to participate successfully in inter-laboratory comparisons (ILCs) to maintain their accreditation. ILCs verify the technical competence of the operators of the laboratories, the suitability of their instrumentation, environmental conditions and their technical procedures. With ILCs it is also possible to verify the correctness of the dissemination process of the relevant units from national standards. The electrical metrology technical department of INRIM, signatory of the CIPM MRA [10], has already provided ILCs for other electrical quantities, including DC Resistance [11−14].

These ILCs involved the department as reference measurements provider and the Italian secondary laboratories. The ILC [15] was a bilateral one with a Dutch accredited laboratory. In this kind of ILC, to determine the reference values, only the NMI measurements are taken into account. It is also important to correctly calculate the correlation between the measurements of the NMI and of the participant secondary laboratories (accredited or not) as usually these send their reference standards to the same NMI for calibration. Suggestions for this evaluation are reported in [14]. Since 2016, INRIM acts as an ILC provider according to [16] because the Italian accreditation body ACCREDIA, signatory of the EA MLA [17], ceased to provide this service.

4. Travelling standards of the ILCs provided by INRIM for power and energy

In the ILCs for power and energy at industrial frequency provided by INRIM different types of travelling instruments, were involved. As the ILC measurand, the relative error given by the following relation was considered:

$$\varepsilon = \frac{L_x - L_s}{L_s} \times 10^6 \qquad (2)$$

Where L_s and L_x are respectively the power (energy) readings from a standard instrument and from an instrument under calibration. In addition, a correlated relative uncertainty component of 5.0×10^{-5} was considered, as all participant laboratories send their power and energy reference standards periodically to INRIM for calibration. The instruments had to be calibrated with the phantom load method with the instruments in thermal equilibrium at 23 ± 1 °C, after a settling period of four hours with a sinusoidal voltage of 230 V, frequency 50 Hz and distortion less than 1%. The instruments had to be calibrated as single-phase or three-phase power and/or energy meters. Calibration as a single-phase meter had to be carried out on phase 1. The calibration as three-phase meter had to be performed both in the configuration with three systems (meters) and four wires and in the configuration with two systems (meters) and three wires (Blondel, Aron) setting the instruments on:
• MAN range;
• Single-phase voltage connections L1-N, neutral connected to the ground terminal;

• Three-phase voltage connections L1, L2, L3-N, neutral connected to the ground terminal. The details of the ILCs are reported in Table 1.

5. Technical considerations on the ILCs

Before the execution of ILCs, technical protocols were sent to the participant laboratories. These protocols, besides the measurement instructions, also contained issues for the management and transport of the instruments. These have to be transported in suitable packages with impact-resistant materials. The transport had to be carried out by personnel of the laboratories by car or by means of reliable couriers. In the protocols, forms to report to INRIM eventual damages to the instruments at the reception and at the expedition and malfunctions during the measurements, were also inserted. The measurement points were established according to the laboratories requests or according to their accreditation schedules. Normally, the most critical measurement points of the instruments ranges (as the extreme values) were checked as well as the points required by legal metrology, when relevant.

6. Evaluation of the results

INRIM and the laboratories carried out their measurements according to approved procedures and reported the measurement results in calibration certificates or reports. The ILCs results were evaluated by means of the normalized error E_n according to [16]. Therefore, the errors of INRIM and of the laboratories were respectively defined as:

$$\varepsilon_I \pm U_I \qquad (3)$$
$$\varepsilon_L \pm U_L \qquad (4)$$

Where U_I and U_L are their expanded uncertainties. From them, the standard uncertainties, were obtained:

$$u_I \cong \frac{1}{2} U_I \text{ and } u_L \cong \frac{1}{2} U_L \qquad (5)$$

Table 1. Details of the performed ILCs

ILC	Quantities	Instrument	Class (%)	Voltage range	Current range	cosΦ	sin Φ	f (Hz)
Bilateral	Single-three ph. act.- react. energy	Tree-phase counter ISKRA TEMP 100	0.05 [18]	230 V	1 mA to 80 A	1, 0.5 0.1, ind.cap.		53
2 Bilateral	Single-three ph. act- react. power energy, phase diff.	energy power meter Zera RMM3006	0.02 [19]	57.7 V to 480 V	30 mA to 120 A	1, 0.5 0.1, ind.cap.	1 ind.cap.	47 53 63
Bilateral	Single-three ph. act- react. energy	Tree-phase counter ZERA MT786	0.05 [20]	30V to 420 V	10 mA to 100 A	1, 0.5 0.1, ind.cap.		53
Multilateral[1]	Single-three ph. act- react. energy	Prometer-W active reactive energy counter	0.2 [21]	57.73 V and 23 V	250 mA ÷6 A pulse constant: 60000 imp/Wh	1, 0.5 ind.cap 0.8 cap	one point phases 2,3	50
Bilateral	single-phase active power	Power calibrator Fluke 6105A	[22]	30V to 480 V	100 mA÷ 20 A	1, 0 ind.cap.		53

[1]In this ILC were involved four applicant laboratories for the metrological verification of electrical energy counters for legal metrology. The calibration as three-phase phase had to be carried out in a four-wire three-phase configuration. The measurements consisted in counting the pulsations of the LED for active energy.

The following differences for each measurement point were then calculated:

$$y = \varepsilon_L - \varepsilon_I \qquad (6)$$

Whose standard uncertainties are:

$$u_y^2 = [u_L^2 + u_I^2 - 2u_L u_I \times r(\varepsilon_L, \varepsilon_I)] \qquad (7)$$

Where $r(\varepsilon_L, \varepsilon_I)$ is the correlation coefficient between INRIM and laboratories errors. r was evaluated following the rules defined in [14]. Finally, the normalized errors E_n were evaluated as:

$$E_n = \frac{y}{U_y} \qquad \text{with } U_y \cong 2u_y \qquad (8)$$

An ILC result is satisfactory if $|En| \leq 1$ implying the compatibility of the results.

5. Results of the ILCs

Analyzing the results, the drift of the instruments involved in the ILCs were very low and well within the measurement uncertainties. The drifts were checked by means of INRIM calibrations made normally before and after those of the laboratories. In addition, as reference values, the mean values of the INRIM calibrations were considered.

No problems due to harmonics were detected as the measurements were made in laboratories where the quality of mains respects suitable parameters. Moreover, the measurements were not made at 50 Hz to avoid interference with the mains operating at the same frequency. Anyway, eventual errors due to harmonics would be also within the measurement uncertainties. A different situation would be in calibration of meters installed on photovoltaic or wind plants where often the measurements cannot be made due to excessive noise. As the instruments involved in the ILCs were used in temperature and humidity ranges narrower than those stated in their specifications, these were correctly respected in the ILCs measurements. Table 2 shows the uncertainties ranges and the results of the ILCs while the figures 1 to 5 show the obtained E_n values. In the horizontal axis the number of points in which the compatibility tests were made, is shown.

Table 2. Uncertainties and results of the provided ILCs.

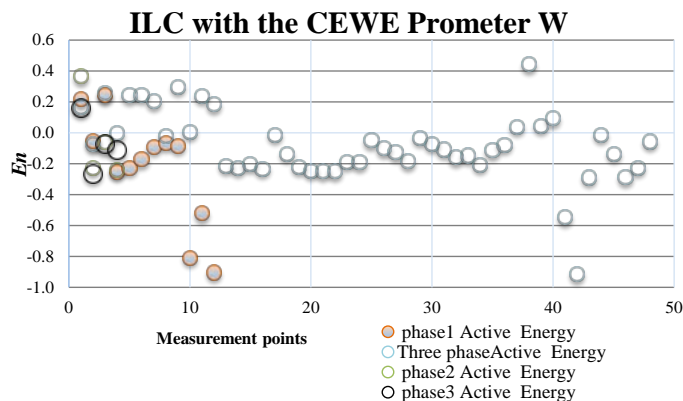| Instrument	U_I range	U_L range	U_y range	$|E_n|$
Counter ISKRA TEMP 100	1.0×10^{-4} to 1.0×10^{-3}	1.8×10^{-4} to 2.0×10^{-3}	1.6×10^{-4} to 2.2×10^{-3}	≤1
energy power meter Zera RMM3006	1.2×10^{-4} to 1.5×10^{-3}	1.6×10^{-4} to 3.2×10^{-3}	1.6×10^{-4} to 3.4×10^{-3}	≤1
Tree-phase counter ZERA MT786	1.3×10^{-4} to 4.8×10^{-4}	1.4×10^{-4} to 4.7×10^{-4}	1.7×10^{-4} to 6.7×10^{-4}	≤1 1.1 one point
Prometer-W ac. reac. energy counter	4.0×10^{-4} to 8.0×10^{-4}	5.0×10^{-4} to 1.3×10^{-2}	6.0×10^{-4} to 1.3×10^{-2}	≤1
Power calibrator Fluke 6105A	1.0×10^{-4}	2.3×10^{-4} to 3.3×10^{-4}	2.4×10^{-4} to 3.4×10^{-4}	≤1
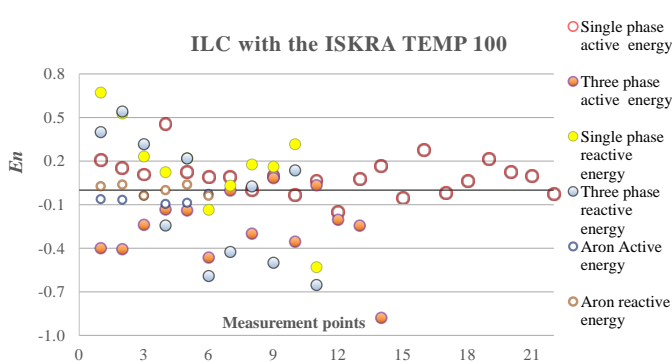
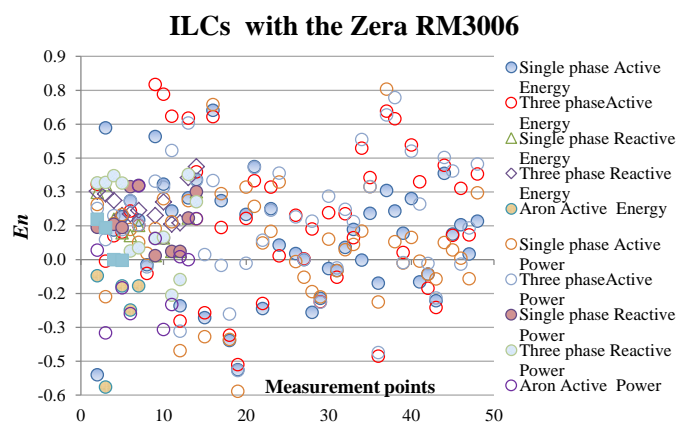**Fig. 1.** *En* values in the bilateral ILC with the ISKRA mod. TEMP100 energy counter.

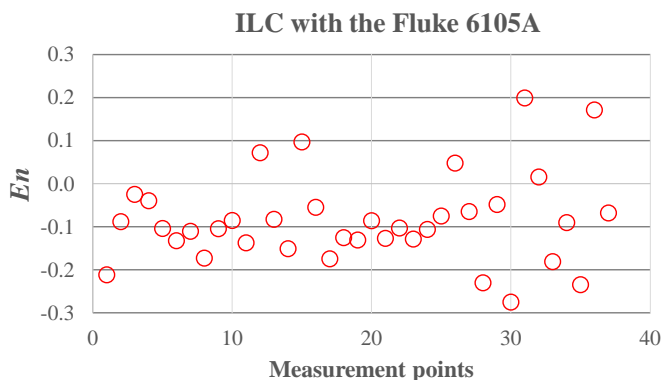**Fig. 2.** *En* values in the two bilateral ILCs with the Zera RM3006 multifunction power-energy meter.
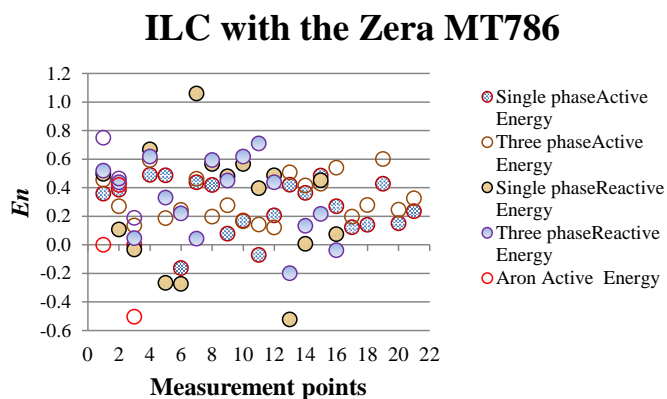

Fig. 3 *En* values in the bilateral ILC with the Zera mod. MT786 energy counter.

In this ILC E_n was 1.1 in one point in single-phase reactive energy. The laboratory promptly presented to INRIM and to the accreditation body corrective actions to overcome the failure in this point.

Fig. 4 *En* values in the multilateral ILC with the CEWE mod. PrometerW energy counter.

Fig. 5. *En* values in the bilateral ILC on single-phase active power with the power calibrator J. Fluke mod. 6105A.

In this ILC the measurand is defined as:

$$\varepsilon = \frac{L_m - P}{S} \times 10^6 \qquad (9)$$

Where L_m are the power readings from the reference instrument or standard while P and S[2] are respectively the active and apparent power values set on the power calibrator. For all the ILCs INRIM provided the results in official ILC reports that the laboratories can exhibit to their accreditation body.

Conclusions

A report of the ILCs provided by INRIM to the Italian accredited laboratories for electrical power and energy at industrial frequency over two years was given. In all cases (except one point in one ILC), the compatibility between the INRIM and

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[2] The term *S* (VA) was introduced to divide for any cosΦ value, including 0.

the measurements of the accredited laboratories, was obtained. In the ILCs several travelling instruments were involved to better exploit the capabilities of the laboratories. The positive result of the ILCs means that the traceability transfer from INRIM to the laboratories through the periodical calibration of their reference standards and the accreditation process are effective. This is an important achievement for the importance of these measurements in a global market. Future aim will be the delivery of this service to the industrial framework and the improvement of the INRIM capabilities for the ILCs involving also the recently acquired instrument [8].

ACKNOWLEDGMENT

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