A Hierarchical Power and Energy Meters' Calibration System

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Abstract—This paper gives an account on a three level hierarchical system for *the calibration of power and energy meters*. Major part of the complex system was developed by the Power and Energy Laboratory of INMETRO. First level is represented by a *Reference System*, capable of the highest accuracy measurement of power and energy in a wide range of voltage and current. The second level, a *general purpose calibration system*, serves for the mass calibration of standard instruments. The third level facilitates the calibration of consumers' watt-hour meters as well as the *type tests* thereof. All the three systems are fully automated, traceable to national standards.

1 INTRODUCTION

Right after the foundation of the Institute, in 1973 a Weston 9775 power and energy measuring assembly was installed in the then Electrical Laboratory, which applied an electromechanical watt-converter, offering ±500 µW/W accuracy. At that time it was sufficient for a higher level laboratory. After about 17 year's application, in 1990, the electromechanical watt-converter was substituted by a Yokogawa 2885 electronic watt-converter, improving the accuracy of the calibrations to ±200 µW/W. In those years this accuracy was still enough to calibrate the widely used electromechanical watt-hour standards.

For the calibration of consumers' watt-hour-meters as well as for type tests, a CDC model 50 system was used, which was substituted in 1990 by a three phase test assembly, developed by the Laboratory, facilitating the simultaneous calibration of five watt-hour meters. In this system programmable pulse counters were applied, which made possible the development of a semi-automatic calibration system.

In the early ninetieth a dynamic development began in the field of electronic power-meters and watt-hour meters, the new generations of instruments were offering ever increasing accuracy. The Laboratory had to understand that the existing instruments and methods became obsolete.

Around 1994 a new technological development period was initialized in the Laboratory. The main goals of this period were as follows.

1. Increase significantly the accuracy of calibrations, to make possible the calibration of even the most accurate commercialized instruments. Purchase or develop a calibration system which is traceable exclusively to national standards, ensure independence of other, higher level laboratories.
2. Increase the efficiency of calibrations, to meet the rapidly increasing demand of secondary laboratories in the country.

3. Prepare the Laboratory for the calibration and type test of the new generation of consumers' electronic watt-hour meters.

Major part of these goals was attained by 2004. Results of this development are the topic of this paper.

2 REFERENCE SYSTEM

In 1996 a project was started to develop a *Power Bridge* [1], to which a considerable aid was given by NIST. By 1999 the fundamental circuits were completed [2], facilitating the Laboratory to participate in an international comparison of power metering [3], which gave very good results. Nevertheless, it was recognized that this method had several drawbacks. Beyond the increased sensitivity to line-frequency interference and ambiguities to find an adequate grounding point, to reach balance of the bridge is a time-consuming process, consequently, the rate of efficiency of calibrations is rather poor and, obviously, the cost of calibrations would be very high.

In the mean-time, from 1998 on, the Laboratory began experimenting with and developing programs for measurements, using *sampling method*, applying a HP-3458A digital multimeter (actually product of Agilent), as it is an excellent tool for sampled measurements.

Several control programs were developed for actual calibration services, all of them are still used by the Laboratory. These works resulted in a masters degree dissertation of one of the authors [4] and several publications [5] - [9]. During these developments it was recognized that a *power analyzer* to measure up to high order of harmonic contents or a *reference system* to attain the best possible accuracy in the calibration of advanced standards, are two different tasks that need slightly different approach and different algorithms. Accordingly, the *Reference System* was developed by taking into account exclusively sinusoidal waveforms, as the total harmonic distortion of good quality commercialized sources can be less than THD=0,05%, and restrict calibrations to power line frequencies, that is between 45Hz and 65Hz. By 2002 the new reference system was completed. Sampling algorithm and several details of this method are reported in [9], here only a brief summary is given about the main features, as follows.

2.1 Layout

Layout of the circuit is shown in Fig. 1.

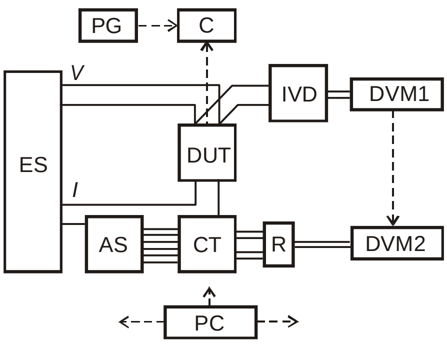

Figure 1. Layout of the measuring circuit.

ES is the *energy source* of the circuit. As a reasonable choice, it may be a ROTEK 8000 calibrator, which has been upgraded by Rotek for the research, run by this laboratory, providing voltages up to 700 volts and currents up to 50 amps. Beyond this current other sources, e.g. a EMH PPS 120.3 can also be used, providing current up to 120 A. DUT is the device under test, which may be a *wattmeter* or a *watt-hour meter*. The voltage is reduced by an *inductive voltage divider*, IVD, to 6 volts rated value, to facilitate the sampling of the voltage by *digital voltmeter* DVM1, a HP-3458A, always in the 10 volts range. The programmable IVD, model DI-4 of CONIMED, offers four voltage ranges from 60 volts up to 600 volts. Restrictions to measure exclusively sinusoidal currents at power line frequency made possible the application of a *current transformer*, CT, developed by CALIN for this project, which ensures measurements between 250 mA and 60 A. By the application of a cascade standard current transformer, the current range can be extended up to 120 A. CT is a two-stage, passive device, providing 100 mA rated secondary current. The special compensation method of the CT requires *twin standard resistors*, R. 2×10 ohms or 2×20 ohms can be applied, offering 1V or 2V rated voltage on the output, respectively. The output voltage of the resistors, proportional to the current, is sampled by digital voltmeter DVM2, another HP-3458A. The two digital voltmeters work in a *master-slave relation*. DVM1, as the master, takes the samples at a programmed rate, at each instant emitting a trigger pulse, to control the sampling of DVM2, as a slave. AS is an *automated switch*, developed by this laboratory, to change the ranges of the CT automatically. When watt-hour meters are to be calibrated, a high precision *pulse generator*, PG, is applied, to provide the time base. C is a special, *programmable counter*, developed by CALIN for this laboratory, to count the number of pulses emitted by PG and DUT. Control of the equipment is done partially by IEEE 488.2, partially by RS 232 control, as the case may be.

2.2 Control program

The *fully automated calibration process* is controlled by an interactive program, which was developed in LabWindows/CVI (product of National Instruments).

The program maintains several *data banks*, as follows.

- Data of the clients.
- Specification of the instruments under test, along with their parameters and IEEE 488.2 or RS 232 commands (which can be introduced flexibly for new types of instruments).
- Test schemes, to meet the requirements of clients;
- Resources, including the correction factors of the standard devices used in the system, parameters and control commands of the energy sources and that of some auxiliary equipment.
- Results of the calibrations.

Parameters of the calibration process can be programmed flexibly, including the number of repeated measurements and that of repeated complete test cycles. To reach more reliability, generally the laboratory executes normally three times a complete test scheme.

Calibration results are passed to MS Excel where, after post-processing, calibration certificates are created in the standard format of the laboratories of INMETRO.

2.3 Performance

Contribution to the errors of all components is known and/or calculable and is applied as correction. Uncertainties were thoroughly analyzed, following the directives of the *ISO GUM* [10]. Taking into account all contributions, expanded uncertainty of the calibrations, applying coverage factor of k=2, remains within ±30 μW/VA and ±30 μrad, to measure both active power and reactive power, in any test points.

Additionally, calibrations of power- and energy- travelling standards by PTB and NIST have proven that the accuracy of the new reference system is well within the uncertainties declared by the Laboratory.

In 2004 the Laboratory participated in a “SIM International Comparison of 50/60Hz Energy”. Results are still not known. At the end of the past year a comparison was made between the Latin-American national metrology laboratories, organized by PTB, as the pilot laboratory. In the selected test points all the differences remained within ±20 μW/VA.

After having proven the accuracy and reliability of the Reference System, from the past year on the Laboratory became independent of other international metrology laboratories (goal No.1 of par. 1.).

3 GENERAL PURPOSE CALIBRATION SYSTEM

As the first advancement, in 1996 a simple automated system was developed, based on three Radian RM11 electronic watt-hour standards, which worked either as a bank of standards for single phase calibrations, or separately, in three phase calibrations, facilitating the measurement of reactive energy as well. These instruments are stable enough to ensure ±50 μWh/Wh accuracy, after periodical re-calibrations. A considerable advancement was the acquisition of a Hamburger K2005 power standard, which, for many years, served as a reliable travelling standard and reference standard. At the beginning the control program of this system was rather simple, developed in LabWindows for DOS (product of National Instruments), which later had to be modified several times to meet the increasing demands.

The increasing importance of power and energy metering was officially recognized and the Laboratory gained a project, which gave a considerable aid to purchase the most advanced commercialized standard instruments, various types of sources and auxiliary equipment. This new development was justified by several factors, as the appearance of a new generation of power and energy standards of enhanced accuracy, development and proliferation of electronic watt-hour meters, increasing demands of accredited and industrial laboratories, etc. In 2001 the temporary energy shortage in this country and consequently the strict restrictions made practically all the consumers interested in more accurate energy metering as well.

An important part of this development was a *new control program*, written in LabWindows/CVI (National Instruments). The fundamental goal was to develop a high efficiency, fully automated calibration system, suitable for mass calibrations. The new system is flexible enough for the calibration of power and energy calibrators, power meters and watt-hour meters, with the application of any of the new standard instruments of the Laboratory. Single phase or three phase calibrations can be carried out, both for active and for reactive power or energy. All these combinations resulted in sixteen different configurations, which can be chosen flexibly. As an example, Figure 2 shows two frequently used configurations. In Figure 2. a) a bank of three standard instruments is used to calibrate a single phase watt-hour meter. The energies and powers measured by the units of the bank, as well as their mean values are indicated, along with the errors measured in each repeated measurement. After completing the programmed number of repetitions, the result, the error and the calculated uncertainty in the test point are indicated in the upper rightmost area. Figure 2. b) shows an inverse calibration, where three instruments are calibrated simultaneously and the measured errors are indicated in three separate windows. On completing the programmed number of repetitions, the mean values and standard deviations are indicated separately.

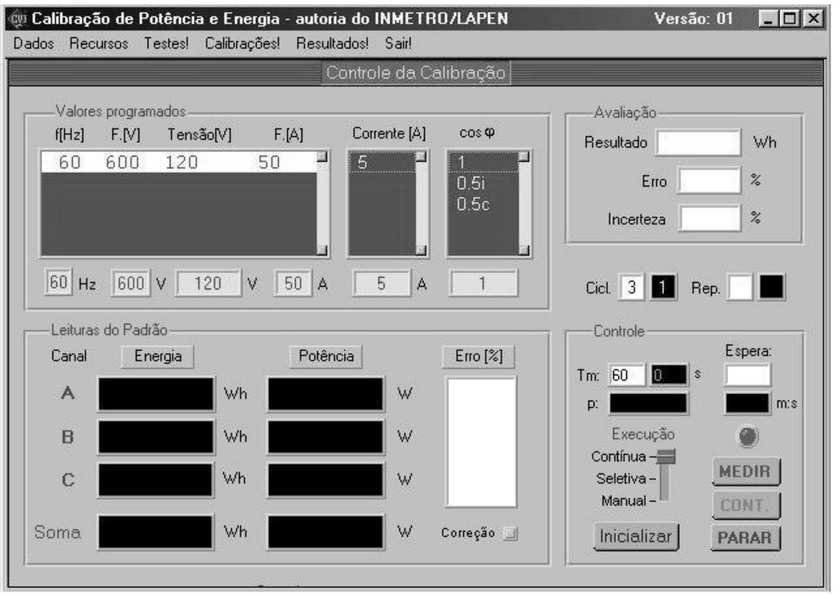

Figure 2 a) Calibration of single standard

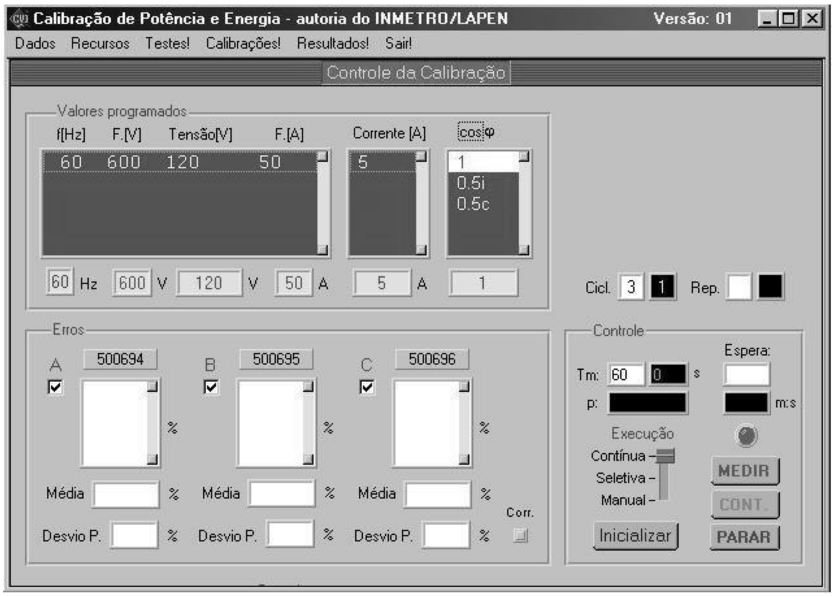

Figure 2 b) Calibration of three standards

Other resources of this program are very similar to that of the Reference System, which are summarized in paragraph 2.2. That is, similar data banks are maintained and final results are transmitted to MS Excel for post-processing. During this procedure the operator carries out a detailed analysis of the uncertainties, taking into account also the characteristics of the instrument under test, among several other factors. For the majority of calibrations the Laboratory declares

70 μWh/Wh uncertainty.

Standard instruments of the system are periodically re-calibrated by the Reference System of the Laboratory and by this, are traceable to national standards.

The acquisition of new standard instruments and other auxiliary equipment facilitated to install three identical secondary level calibration systems, to meet the increasing demands for calibrations. To characterize the capacity of the Laboratory, in 2004 altogether 70 calibrations were performed. The demand to calibrate the instruments in an increasing number of test points can also be observed. Some laboratories, e.g., have asked the calibrations in approximately 200 test points. Taking into account, on the one hand, that measurement at each test point is repeated at least three times and, on the other, that a complete measurement cycle is carried out normally three times, such calibrations without a fully automated, efficient system would be impossible.

By the development of this system the requirements of goal No.2 in paragraph 1 were fulfilled.

4 TYPE TESTS OF WATT-HOUR METERS

Third level of the hierarchical calibration system of the Laboratory serves for the calibration of consumers' watt-hour meters and type tests of such new models.

From the seventieths' on Inmetro has done type tests of energy meters of the traditional electro-mechanical type. For this purpose in 1990 the Laboratory has developed a semi-automatic calibration assembly, consisting of a manually controlled energy source, a Brazilian made watt-hour standard and pulse counters, a working bench for the simultaneous calibration of five instruments and a model 286 PC to control the process by a program written in Turbo Pascal. This system was used up to the nineties' end.

In the same period a Precigyr 9000 fully automated calibration system of Landis&Gyr was also installed. This system had several drawbacks and due to the closed control program, in many cases could not be adapted to the needs of the Laboratory. Nevertheless, this system is still used for some kinds of calibrations.

From the beginning of the year 2000 electronic energy meters have appeared also in the Brazilian market. This novelty forced the Laboratory again, to become adequate to the new realities of the country. To meet the new demands of type tests of such watt-hour meters, at the beginning, the standard instruments were used, belonging to the second level of the hierarchical system, as outlined in this paper. This method was used until the acquisition of an advanced, fully automated commercialised calibration system of Zera GmbH.

The new standards for the type tests of electronic watt-hour meters require tests under non-sinusoidal conditions as well. For this purpose the Laboratory has developed a Power Analyser, which facilitates the measurement of active power, reactive power (according to different definitions) and harmonic analysis up to the 64^{th} order of harmonics [4], [5], [6], [7]. To produce the required waveforms, as for odd or even harmonics, sub-harmonics, etc., two Agilent 33120A arbitrary function generators are used, which control, on the one hand, a voltage amplifier, on the other a transconductance amplifier. Sampling is carried out by two HP 3458A digital multimeters, the samples are processed by a special DFT algorithm, which was developed by the Laboratory. To reduce the voltage to a suitably low level, a resistive voltage divider is being developed. For the measurement of the current a Valhalla 2575A wide range shunt is used, which is re-calibrated periodically. Estimated extended uncertainty of power measurements, for any non-sinusoidal waveform, is within 200 μW/VA.

5 CONCLUSION

In a relatively short period of time the Laboratory developed a new hierarchical calibration system for up-to-date power meters and energy meters, to meet the requirements of the country both in enhanced accuracy and in increased efficiency to do a great number of services.

First level is represented by a self-sufficient Reference System, traceable exclusively to national standards, which offers better uncertainties than the best commercialised standard instruments. Second level combines adequate accuracy and high efficiency, suitable for mass calibrations of the ever-increasing number of such demands. Third level serves for the type tests of advanced watt-hour meters, according to the regulations of the international standards.

With this development INMETRO made a considerable contribution to meet the requirements of the country, guaranteeing to the consumers that electrical energy metering becomes more correct, more adequate to the international regulations.

6 ACKNOWLEDGEMENTS

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