DEVELOPMENT OF A POWER ANALYZER

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Abstract - *These paper gives an account on a new power and energy measuring system, based on digital sampling, that was developed by the National Institute of Metrology (INMETRO) of Brazil. The goal of the project was to achieve the highest possible accuracy at line frequency (50 or 60Hz), even in the presence of considerable harmonic distortions, to guarantee full traceability and to minimize the costs of obtaining a high quality reference system.*
In the new system the programmable A/D converters of two advanced digital multimeters (Hewlett-Packard 3458A) are used to measure the voltage and current simultaneously, by sampling method.
The main advantage of the system is the high accuracy, full traceability to national standards within the country, and the possibility to calibrate watt-converter and watt-hour standards also in the presence of harmonics.

Keywords – Sample methods, Power, Energy, Harmonics.

1 INTRODUCTION

The Power and Energy Laboratory (LAPEN), linked to the Division of Electrical Metrology of the National Institute of Metrology, Standardization and Industrial Quality (INMETRO), still doesn't have necessary resources to reproduce the units of power and electric energy. The conservation of the units of power and energy is obtained by a set of three standards, periodically recalibrated through a traveling standard, assuring in this way the traceability to NIST or to PTB. Losses of time and risks of damages of valuable equipment, during the transport, are involved. The proposed system will allow the reproduction of the units of power and electric energy and will be directly traceable to the other laboratories of INMETRO. This system will enable INMETRO to participate in International Comparisons of the referred units, together with national institutes of metrology of other countries.

Due to the excellent performance of advanced A/D converters and the increasing capacity of personal computers, a project, aiming at the construction of a Power Analyzer, based on digital sampling method, was initiated. A commercially available digital multimeter, the HP-3458A, was applied, due to the freely programmable A/D converter of the instrument.

Principally a modified numerical integration method is applied for the calculation of the RMS values of voltage and current, as well as that of the active power, power factor, apparent power and frequency, even in the presence of harmonics in the wave of voltage and/or of current. To calculate the harmonic contents a DFT algorithm was developed. Currently the new system is still in a phase of tests, it has been shown very good results so far.

2 STRUCTURE OF THE SYSTEM

The components and the connections of the system are shown in Figure 1.

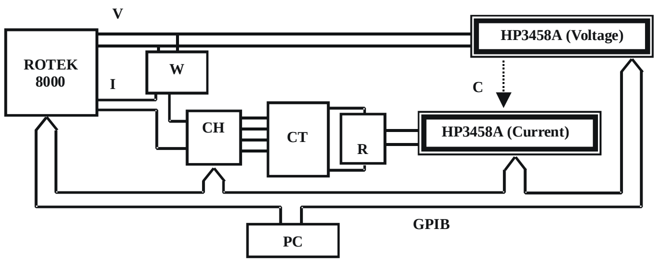

Fig. 1 - The Power Analyzer System

The programmable energy source is the model 8000 of ROTEK, responsible for the supply of the voltage (V), of the current, (I) and of the phase shift between them. W is a wattmeter (or watt-hour meter) to be calibrated. In the case of watt-hour meters, a pulse counter is applied that works as a frequency meter, assuring the time base. An automated switch (CH) is responsible for the connection to the correct derivation of the current transformer (CT). R is an AC standard resistor, where the voltage drop on it is proportional to the applied current.

The digital multimeters (Hewlett-Packard 3458A) are used to measure the voltage and current in digitization mode, in DC voltage (DCV) configuration. The synchronization of the reading of samples is made by the control C. When the multimeter that measures the voltage takes a sample, emits a pulse, forcing the other multimeter, that measures current, to take a sample in the same time, in a “master-slave” relationship.

As Figure 1 shows, it is possible to develop a fully automated system, with all the components controlled by a personal computer (PC). At the present development stage,

ISBN 972-98115-4-7 © 2001 IT

the control of the voltage and current source and that of the CT is still made manually.

In the preliminary tests a resistor of 1Ω and a commercially available CT standard were used. Aiming at a better performance of the system, a special two-stage transformer is being developed, which will be coupled to a standard resistor of 10Ω.

3 APPLIED ALGORITHMS

In the present work three algorithms were used, described as follows:

3.1 Swerlein Algorithm

In 1991 R. Swerlein [1] published an algorithm, specifically for the digitization of sinusoidal signals, using the internal A/D converter of the HP-3458A multimeter. This algorithm has been tested and approved by several laboratories [2,3] and is recognized as the best one in the direct measurements of AC voltage. During the past decade the algorithm of Swerlein was adopted also by several national laboratories of metrology.

The concept of the method in the algorithm of Swerlein is summarized as follows.

The RMS value of a periodical voltage is given by:

$$V = \sqrt{\frac{1}{T}\int_{t-T}^{t} v^2(t)dt} = \sqrt{\frac{1}{CT}\int_{t-CT}^{t} v^2(t)dt} \qquad (1)$$

where T is the of period time of the signal. The integration is executed through the time T or a whole multiple of it, CT, where C is the number of cycles.

Using the method of samplings, the integral is substituted by the sum of the samples of the digitized signal. Figure 2 shows a cycle of a sinusoidal signal, indicating the sampling parameters.

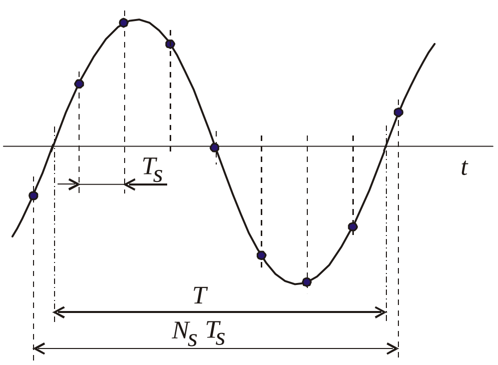

Fig. 2 - A sinusoidal wave and sampling parameters

On the Figure 2 N_s is the number of samples and T_s is the sampling time (equally spaced) among them. Generally the resolution of the time T_s is limited, introducing errors. Therefore, as shown on Figure 2, generally N_sT_s is only approximating the time of period T. When measuring C cycles during time τ:

$$N_sT_s = \tau \neq CT \qquad (2)$$

Consequently, the error introduced by the finite resolution of sampling time is given by:

$$\varepsilon = \frac{\mathrm{sen}\left(\frac{2\pi}{T}\tau\right)}{\frac{4\pi}{T}\tau}\mathrm{sen}\left(\frac{4\pi}{T}t\right) \qquad (3)$$

The Swerlein algorithm is introducing several efficient means to minimize this error. To achieve high resolution of the integrating A/D converter (21 bits), relatively high aperture time is programmed, nevertheless, errors occur when the signal changes during the integration time. These errors are also calculated and compensated. Beyond these theoretical considerations the actual physical parameters of the multimeter were also taken into account and corrections were introduced wherever possible. The algorithm works well in the presence of purely sinusoidal signals, especially at low frequencies. Permissible distortion factor is max. 1%, highest frequency is around 200Hz.

Through comparisons with high accuracy AC standards, it was proven that, in low frequencies and in low voltages, the algorithm can maintain accuracies below 3 ppm [2]. In the mains frequency, up to 700 volts the accuracy doesn't exceed the limit of ± 15 ppm.

Initially a new version of the Swerlein algorithm was developed, interlacing the control of two HP-3458A multimeters, making possible simultaneous measurement of two voltages (actual voltage and the other, proportional to the current). With this new algorithm the high accuracy simultaneous measurement of the RMS value of voltage and current became possible as well as the apparent power and the active power at unity power factor could be calculated. To facilitate measurements at power factors different from the unity, an additional algorithm was developed. Applying sampling method, the algorithm calculates, from a set of samplings, the phase angle between the waves of voltage and current. By this additional algorithm reasonably good results could be achieved, down to ±0.5 power factor.

Successive tests have proven that, for unity power factor the new application makes possible the measurement of the active power well within an uncertainty of ± 30 ppm. It was also verified that, the uncertainty of the measurement of the phase angle is approximately ±30 μrad, which is introducing an additional uncertainty of ±50 ppm at ±0.5 power factor in the calculation of the active power.

At first the Swerlein algorithm assumed the role of a reference for the verification of the new methods under development, however, the comparisons were restricted, because this method is reliable only for small phase shifts and applicable for purely sinusoidal signals.

3.2 Discrete Integration

For the development of the new algorithm, the basic idea was the following. If once a set of samples has been correctly programmed and measured, there must be a method to calculate the time of period of the signal (T or CT) with enough accuracy to satisfy the condition of equation (2). If it is so, an algorithm might be developed to calculate the RMS values of the voltage and of the current, as well as the active power at high accuracy. This should be achieved without making efforts to approximate that the time of measurement be an integer multiple of the period of the signal or to introduce special means to minimize the residual error.

The two multimeters, according to Figure 1, are programmed to measure a block of cycles of the voltage and that of the current, respectively. The beginning of the measurement is synchronized to a zero transition of the voltage. Thereafter, each sampling on the “master” initiates a sampling taken by the “slave”. The multimeters store the values of samples. When completing the measurement of a block, the program reads and stores the samples.

The steps of the algorithm for the calculation of the RMS value of the voltage, for example, are as follows.

− Of the block of samples an interval is selected that has C complete cycles, of N_a samples.

− The algorithm makes an analysis for the whole interval and computes the initial and final zero crossings, applying an interpolation of seventh order. The time base (τ) of the integration is calculated between the crossings. By this the approximation of equation (2) becomes an equality:

$$\tau = N_{sc}T_s = CT \tag{4}$$

where N_{sc} is usually not an integer number of the samples (number of samples corrected).

For the execution of the discrete integration a modified trapezoidal rule was applied, by taking into account that the first (v_0) and last (v_n) samples should be corrected according to the non-integral number of samples. By applying "a" and "b" corrections, the RMS value of the voltage:

$$V = \sqrt{\frac{1}{N_{sc}}\left(\frac{v_0^2}{a} + \frac{v_n^2}{b} + \sum_{i=1}^{N-1} v_i^2\right)} \tag{5}$$

To calculate the active power, the algorithm multiplies the corresponding samples of the voltage and of the current and applies the same method, as detailed above.

By taking advantage of the measured RMS values and active power, other parameters are also calculated, as: the apparent power, the power factor, the frequency and, in the case of sinusoidal waves, the reactive power (the power’s triangle in the case of non-sinusoidal waves is not applicable).

The maximum capacity of the internal memory of the HP-3458A multimeter is used, allowing a total number of 5000 samples. A relatively great number of cycles, up to C ≅ 100, is programmed, which facilitates increasing the aperture time. This allows high resolution of the integrating A/D converter (21 bits), assuring a resolution of ± 0,5 ppm in the measurement of the voltage (or current). The lack of stability of the power source in the short term can also be compensated by the increase of the number of cycles.

Comparing this method with the Swerlein algorithm, it should be pointed out, that the same accuracy could be reached for sinusoidal signals, nevertheless, it is possible to ensure high accuracy measurements even in the presence of high harmonic contents.

3.3 Harmonic Analysis

While the method of Discrete Integration makes the analysis in the time domain, this third method applies the Discrete Fourier Transform (DFT) making the analysis in the frequency domain.

If the time of period of the signal is unknown, the solution is to carry out an approximation, using the minimum squares method. For example, to calculate the voltage V_{ci} and V_{si}, the equation used is:

$$\sum_{n=0}^{N-1}\left[\left(V_{c0} + \sum_{i=1}^{M}\left(\sqrt{2}\,V_{ci}\cos(2\pi if\ t_n) + \sqrt{2}\ V_{si}\,\mathrm{sen}(2\pi if\ t_n)\right)\right) - m_n\right]^2 = \min \tag{6}$$

where N is the number of samples m_i, M is the maximum order of the harmonic component to be calculated and V_{ci} and V_{si} are the RMS values of the cosine and sine components, respectively. The solution of this equation is complicated, involving matrix operations. The paper published by Pogliano [4] suggests this method.

As, a result of this work, a method for the correct calculation of the time of period has been developed, this value can be applied also to calculate the harmonics. By this, simply the fundamental formulae are applicable:

$$V_{ci} = \frac{1}{N_{sc}}\sum_{n=0}^{N-1} m_n \cos\left(\frac{2\pi}{T} in\right) \tag{7}$$

$$V_{si} = \frac{1}{N_{sc}}\sum_{n=0}^{N-1} m_n\ \mathrm{sen}\left(\frac{2\pi}{T} in\right) \tag{8}$$

and the DC voltage component

$$V_0 = \frac{1}{N_{sc}}\sum_{n=0}^{N-1} m_n \tag{9}$$

where N_{sc} is the corrected number of samples, proportional to a multiple of the period time, according to equation (4).

It has been proven that the analysis in the time domain and in the frequency domain results the same voltage and current values.

The active power is calculated by the sum of the products of the voltages and currents of the same order:

$$P = V_0 I_0 + \sum_{i=1}^{M}\left[V_{ci}I_{ci} + V_{si}I_{si}\right] \tag{10}$$

4 COMPENSATION OF ERRORS

The algorithms developed allow the compensation of amplitude and phase errors, as detailed below.

4.1 Amplitude Error

− As the multimeters are used in the configuration of DC voltage, they can be calibrated with an uncertainty of ± 2 ppm and the errors are used as corrections.

− The integrating A/D converter of the multimeter doesn't make the measurement of the signal within an infinitely small interval of time, but integration is carried out during the aperture time, t_a, producing a systematic error, given by:

$$\varepsilon = \frac{\text{sen}(\pi i f t_a)}{\pi i f t_a} \qquad (11)$$

where i is the order of harmonic component.

As much in the method in the time domain, as in the method in the frequency domain, the program calculates this error and applies this error as a correction.

– The bandwidth, limited by the input circuits of the HP-3458A, also introduces an error of amplitude, which is dependent on the range of voltage applied. In the ranges of 100V and 1000V this error is significant. This error is proportional to the frequency (f) applied and the frequency that characterizes the bandwidth (f_c), in the form:

$$\varepsilon = \frac{1}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}} - 1 \qquad (12)$$

This error is calculable and is also considered in the correction. The introduction of this error is important especially in the evaluation of the harmonics.

4.2 Phase Shift Errors

The knowledge and the compensation of the phase errors is very important for the measurement of the power in power factors different from unity. The components that contribute to the existence of the phase error are, as follows:

– The control of two multimeters, in the "master-slave" configuration is responsible for the existence of a phase error, caused by the latency time. As a result, the slave (multimeter to measure the current) begins a new measurement a bit later than the arrival of a new trigger. As specified in the manual of the instrument, the maximum latency time is of 175ns, that in power factor 0.5, provokes an error of 114 ppm. Additionally, this delay is not constant, does exist a jitter of ± 50 ns, resulting an uncertainty of ± 32 ppm, at power factor 0.5.

Applying the same voltage simultaneously in the two multimeters the phase error, due to the latency time, can be measured and introduced in the program, as a correction. However, only increasing the number of repetitions can reduce the uncertainty caused by the jitter.

– The multimeters have attenuators at the input, which also introduce phase error. As the two multimeters work in different voltage ranges, their phase errors are also different, which will cause an additional phase error between the measured signals. For example, in the voltage range of 1000V the phase shift can reach 200 μrad, while in the range of 10V (where the other multimeter, measuring the current, works) the phase error is negligible. Therefore the phase shift between the two signals can be as much as 200 μrad. By means of a good quality inductive divider the phase shift in the higher voltage ranges can be measured and corrected in the program.

– The set of the current transformer and standard resistor also introduces phase errors, which are measurable and are smaller than the other errors (within 10 μrad).

Experiences of the laboratory have verified that the phase error can be measured, can be taken into account as a constant and can be introduced in the program as a correction. The additional uncertainty of the measurement, at power factor 0.5, is not larger than ± 30 ppm. Experiences also have shown that the first two sources of error are dependent on the applied instruments and on the connections between them.

5 IMPLEMENTATION OF THE PROGRAM

The program was written in language C, in the environment of LabWindows/CVI (product of National Instruments).

Figure 3 shows the user interface of the control panel. It is possible to select the algorithm Swerlein or the algorithm DCV (Discrete Integration). Figure 3 shows the result of the latter option. A simulation also can be chosen, that facilitates the evaluation of the accuracy of the applied algorithms. In each option it is possible to adjust several parameters used in the algorithms. The RMS values and the powers are shown in this panel at the end of the measurement. The results of the harmonic analysis are shown in an auxiliary panel.

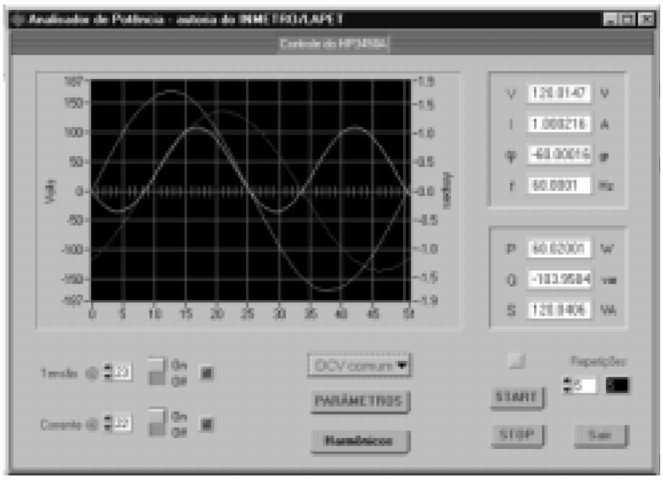

Fig. 3 - User Interface of the Power Analyzer

6 RESULTS

Taking advantage of the best resources of INMETRO, where the national standards are traceable to the superior laboratories, a great number of comparisons were executed to verify the accuracy of the new system. In this paper only a brief summary is given of the calibrations, to demonstrate the current level. More details can be found in [6].

The calculation of the uncertainties is based on the Guide for Expression of the Uncertainty of Measurement [5] that was adopted by INMETRO since 1996.

The results in the measurement of voltage, obtained by the discrete integration method (DCV) and by the Swerlein algorithm (SW), were compared with the AC/DC transfer standard measurements, by the model 792A of FLUKE. This standard was calibrated by PTB, and it serves as the national standard for the measurement of the AC voltage. The results are shown in Figure 4. Specified uncertainties are shown in the figure in the standard way.

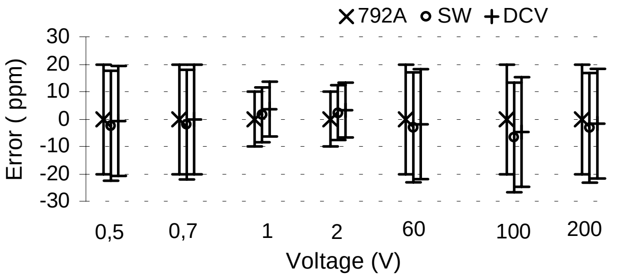

Fig. 4 - Results in voltage measurements

In lower voltages (in the measurement of the current) the differences between the sampling methods and the 792A transfer are inside of ± 5ppm. In higher voltages the differences are bigger, but in any condition, they are inside of ± 10ppm. The difference between the Swerlein algorithm and the algorithm DCV is inside of ± 3ppm.

The Power and Energy Laboratory has two traceable standards. The power comparator K-2005 (of Hamburger) is traceable to PTB, while the standard watt-hour meter RM-11 (of Radian) is traceable to NIST

The RM-11 standard was used to measure the active and reactive energy. As the K-2005 standard do not measure reactive power, RM-11 was chosen as the reference (level zero). K-2005 measures the active power directly, while RM-11 the active energy. Therefore, a high accuracy frequency meter was used to measure the frequency of the train of pulses emitted by RM-11, proportional to the power. On the other side the active power was measured by the three algorithms implemented in the program of Power Analyzer: the Swerlein algorithm (SW), the new algorithm using Discrete Integration (DCV) and the algorithm applying Fourier analysis (DFT).

Figure 5 shows the results in the measurement of the active power in 120V, 240V and 480V, with 1A, in unity power factor.

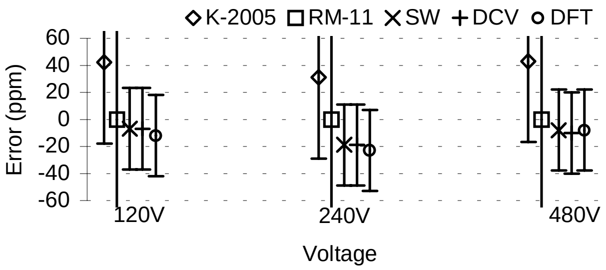

Fig. 5 - Results in the measurement of active power

The difference between the three algorithms is within ± 5ppm, in any condition. The difference between the three algorithms and the reference (RM-11) is within ± 15ppm at 120V and 480V and within ± 30ppm at 240V. As for the latter result, currently it is impossible to prove "which one is better", probably the results of the sampling methods are approaching the reality better.

Figure 6 shows the results in the measurement of the reactive power for –90º phase shift.

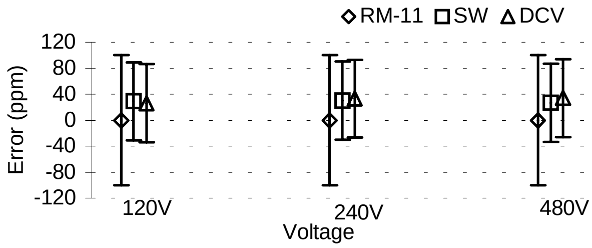

Fig. 6 - Results in the measurement of reactive power

The difference between the results of the two sampling algorithms (Swerlein and DCV) is within ± 10 ppm.

7 CONCLUSIONS

This project has great importance for the following reasons.

- The new method permits the reproduction of the units of power and energy by resources totally traceable to national standards within the country. Instead of a dependency of international metrology laboratories, INMETRO can participate in international comparisons in the future.
- A superior accuracy could be attained both in the measurement of active and reactive power and that of energy. This will facilitate the calibration of high accuracy advanced instruments appearing currently on the market.
- The system ensures high accuracy measurements also in the presence of distorted waves, which facilitates testing the response of power and energy meters to harmonics, according to the new international standards.

The experimental version of the program has proven the good performance and attainable high accuracy of the new method. The project is continued and currently a completely automated complex calibration system is being developed, which will ensure high efficiency in the calibration of advanced power and energy meters.

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