

A POWER MEASUREMENT SYSTEM UNDER NON-SINUSOIDAL LOADS

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Abstract - The paper gives an account on a *new power measuring system*, based on digital sampling, which was developed by the National Institute of Metrology (INMETRO) of Brazil. The goal of the project was to achieve the highest possible accuracy at the presence of considerable harmonic distortions, to guarantee full traceability to national standards and to minimize the costs of obtaining a high quality reference system. The system facilitates the calibration of commercialized electronic wattmeters, watt-hour meters, as well as the analysis of non-linear loads, resulting harmonic distortions in power systems.

I. Introduction

In all the industrialized countries there is an ever-increasing demand to measure the electrical power and energy at higher accuracy. Nevertheless, as it was recognized also in Brazil, the proliferation of *non-linear loads* introduces additional errors, which should be investigated. Many new generation commercialised electronic watt-meters support the measurement of harmonic contents, as well as the components of active and reactive power, however, a national metrology institute, like INMETRO, needs more accurate means. The objective of this project was to develop an accurate measuring system, for the 45Hz-65Hz frequency range, up to the 64th harmonic, capable of meeting the new demands in electrical power and energy measurement. Special attention was paid to the measurement of reactive power, according to various definitions.

II. Layout

A double-channel sampling system was developed, applying two Agilent 3458A multimeters, as shown in Fig. 1.

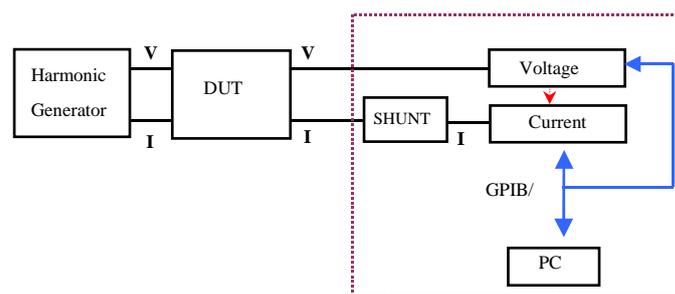


Figure 1: System Layout

In *quasi-synchronous sampling mode* the two instruments work in a master-slave relation. The multimeter, as the master, assumes the role of the voltmeter, while the other, as the slave, the ammeter. Using the attenuator of the voltmeter, voltages up to 700 volts can be measured. To improve the frequency response, a compensated resistive divider is under development. To measure the current, up to 100 amps, a Walhalla 2575A Active Current Shunt is used, which is re-calibrated periodically. For details of the system see [5]. By taking advantage of the GPIB control of the multimeters, the Laboratory developed an interactive program to control the measuring process.

III. Theoretical bases and algorithm

To program the two sampling multimeters, first the *sampling parameters* have to be calculated. As a basic requirement, the product of *sample time*, T_s , and the *number of samples*, N_s , should be equal to an integral number of periods:

$$N_s \cdot T_s = c \cdot T \quad (1)$$

where c is the *number of cycles* and T is *the period time*. To obtain the period time, frequency is measured by one of the multimeters. The number of samples is calculated to be as high as possible, but it is limited by the storing capacity of 3458A. Higher sample time is advantageous, as it allows higher aperture time, which increases the accuracy, but to satisfy Nyquist's criterion is an important limiting factor. The algorithm tries to optimise the sampling parameters, to satisfy equation (1). As a characteristic of 3458A, T_s can be programmed only in discrete steps, as well as the measurement of the period time may be also erroneous. Consequently, equation (1) generally can not be satisfied perfectly, introducing a *truncation error*.

A simple DFT algorithm was applied, where from a block of m samples the harmonic component of order i , for instance that of a voltage, can be calculated of the following basic equations:

$$V_{ci} = \frac{1}{N_s} \sum_{n=0}^{N_s-1} m_n \cos\left(\frac{2\pi}{T} in\right) \quad (2)$$

$$V_{si} = \frac{1}{N_s} \sum_{n=0}^{N_s-1} m_n \sin\left(\frac{2\pi}{T} in\right) \quad (3)$$

and the DC voltage component:

$$V_o = \frac{1}{N_s} \sum_{n=0}^{N_s-1} m_n \quad (4)$$

To calculate the absolute value and the phase angle a simple rectangular to polar conversion is used for each component. The advantage of this method is that to introduce amplitude- and phase-corrections is easier.

In these equations the ideal case is assumed, with correct sampling parameters, without truncation error. To minimise the effect of truncation error, a complex method was developed, to calculate the zero crossings, as follows.

Through the whole block of samples the number of zero transitions is counted and the number of whole cycles is calculated. If this number equals the pre-calculated number of cycles, it indicates a relatively modest harmonic distortion, where interpolation can be used to calculate the correct value of zero crossings. As a first attempt, the initial and terminal zero crossings are calculated by a 9th order polynomial interpolation. Error of interpolation is also calculated and if it is of low value, the application of the interpolation is correct, which happens in the case of low harmonic distortions. Otherwise, the order of interpolation is reduced, until the error becomes acceptable. In equations (2), (3) and (4), using the calculated zero crossings, a corrected value of the number of samples is used, which is generally not an integer number.

Another modification was introduced in the numerical integration formula, where the sum is calculated from the first zero crossing up to the last one. As neither of them is an integer number, a modified trapezoidal rule was applied, where at the beginning and at the end of the integration interval the area of triangles is calculated.

If the calculated number of cycles is not equal to the pre-calculated one, it shows that due to excessive harmonic contents there are multiple zero crossings within one cycle. In this case the algorithm simply takes into account the pre-calculated number of cycles and applies the basic equations without corrections. As a consequence, due to a possible truncation error, reduced accuracy can be expected.

The quality of the algorithm was tested by simulations. It was proved that if the 9th order interpolation is applicable, error in the measurement of any of the harmonics remained within a few ppm. If the harmonic contents increases, lower order of interpolation is applied and the errors are slightly increasing, but even in the worst case they remained well within 20 ppm. In the case of highly distorted waves, when zero crossings can not be calculated, the errors remained within 0,01%.

In the application of the algorithm a number of corrections have to be introduced, as detailed in several related papers [1], [3], e.g. Obviously, in this case, due to several sources of error, somewhat worse accuracy can be expected. Making comparisons with the application of purely sinusoidal waves, it was proved that the performance of this algorithm practically equals to that of the Swerlein's algorithm [1], [2].

IV. Errors and Compensations

There are several sources of common errors, well treated in other papers [1-4]. Here only a brief summary of them is given.

A. Errors of the algorithm

To analyze the errors, introduced by the modified DFT algorithm, from the beginning of the development, *simulation* was applied. This program, which is an integral part of the control program, facilitates to define arbitrarily amplitudes and phase shifts, up to the 64th harmonic. It was proved that amplitude errors remain within $\pm 5 \cdot 10^{-6}$ up to the 64th harmonic, whereas phase angle errors within $\pm 5 \mu\text{rad}$ up to the 10th, $\pm 15 \mu\text{rad}$ up to the $\pm 16^{\text{th}}$, $80 \mu\text{rad}$ up to the 32nd and about $\pm 400 \mu\text{rad}$ up to the 64th harmonic. Even if these phase angle errors are relatively big, their contribution to the calculus of the total electrical power is negligible.

B. Errors originating from the multimeters.

3458A uses integrating AD converters for the digitalization. As the integration of a signal is made over a finite time, an error is introduced, called *aperture error*. This error is calculable and even large errors can be corrected with low uncertainty, as detailed, e.g., in [1], [2]. As aperture error depends on the frequency, it is calculated to each harmonic.

As DVM-s work in dc mode, they are calibrated periodically and corrections are introduced.

Input attenuator of DVM, to measure the voltage, especially in the 100 volts and 1000 volts range, will introduce amplitude error and phase angle error. Both errors can be calculated and applied as corrections [1]. Nevertheless, phase angle error can be relatively big and calculated uncertainty may come to about $\pm 20 \mu\text{rad}$. In the measurement of power this may cause relatively big errors. With the application of RVD, DVM will work in the 10 volts range, where this kind of error is negligible.

Originating from the master-slave relation of the two multimeters, the slave DVM responds to the trigger pulse with a certain delay. This results a *time difference* between the sampling instants of the voltage and current, introducing a *phase angle error*. By applying the same voltage to both channels, this time difference is measured and calculated phase angle errors are applied as a corrections to each harmonic.

C. Errors of additional devices.

- *Active Current Shunt*. ACS has amplitude errors and phase angle errors. The device is re-calibrated periodically, errors are known with an uncertainty of $\pm 10 \mu\text{A/A}$ and $\pm 10 \mu\text{rad}$ and are introduced as corrective terms.

- *Resistive Voltage Divider*. Calculations and preliminary tests of RVD under development show that it will decrease considerably the errors of the attenuator.

D. Error budget and uncertainty.

As shown, 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/BIPM GUM*, as well as applying partially the suggestions of [1]. Taking into account all contributions, expanded uncertainty of power metering, applying coverage factor of $k=2$, remains within $\pm 100 \mu\text{W/W}$ and $\pm 100 \mu\text{rad}$.

V. Validation of results.

Validation of the system was carried out at three levels, as follows.

First level is the test of the algorithm by simulations, as was detailed before and is showed in Fig. 2.

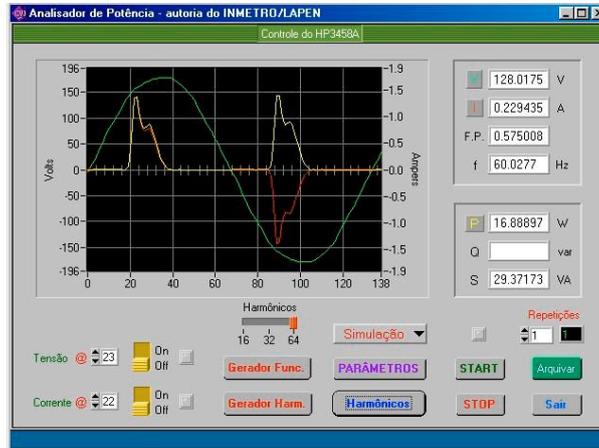


Figure 2: Simulation of an analysis of a compact fluorescent lamp

Second level is testing the performance of the multimeters. For these tests good quality two channel Arbitrary Waveform Generators were used. The principle of the tests was to program special waves, where the harmonic contents can be calculated, like a rectified half wave, triangle, etc. First a HP 3425A function generator was used, which approximates a curve with 2048 discrete steps. This finite resolution could be well detected and, for example, in the case of a rectified half wave, odd harmonics have also appeared. Later two phase-locked Agilent 33120A Arbitrary Waveform generators were used, which allow the programming of 16000 points. With these generators tests became more reliable, quantization error can not be detected. Obviously, there are differences between the mathematically calculated harmonics and the measured values, but it would be very difficult to say, whether due to the performance of the measuring system or due to the characteristics of the function generator. Maximum deviation between calculated and measured values remained within $\pm 30 \cdot 10^{-6}$ for any of the harmonics.

Third level of validation means testing the whole system, under real conditions. In this case, due to several sources of error, somewhat worse accuracy can be expected and exact testing is difficult.

One kind of measurements was to test the system, applying sinusoidal waves. The results are shown in Fig.3. Voltages in the 0,5V – 200V range were measured by three methods. First, a Fluke 792A was used, traceable to international metrology laboratories. Second, measurements were made by Swerlein's algorithm [1]. Third, the modified DFT algorithm was used for the measurements.

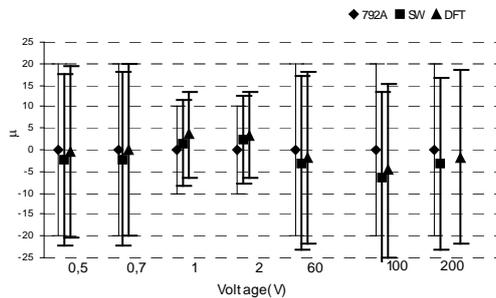


Fig. 3 Comparison of three methods at 60 Hz

For the time being, to specify the overall uncertainty of the system, known errors of the additional devices are used.

Implementation

An interactive program, written in language C, in the environment of LabWindows/CVI, serves to use and test the system. Here, as an example, the result of the analysis of a compact fluorescent lamp is presented in Figure 4.

Calculated data of the voltage and of the current are represented in the first two columns, indicating the percentage value and phase angle of each harmonic, the fundamental value, their DC component and distortion factor, as well as their spectra. As can be seen, in this case the odd harmonics of the current are dominant, the third harmonic arrives up to 86% and the distortion factor to 125% .The third column shows the result of the analysis of the powers. For the reactive power the two more important definitions are shown. QB in agreement with the definition of Budeanu and QF in agreement with the definition of Frize [4]. This example is to show, that in the case of distorted waves the value of the reactive power depends on the adopted definition.

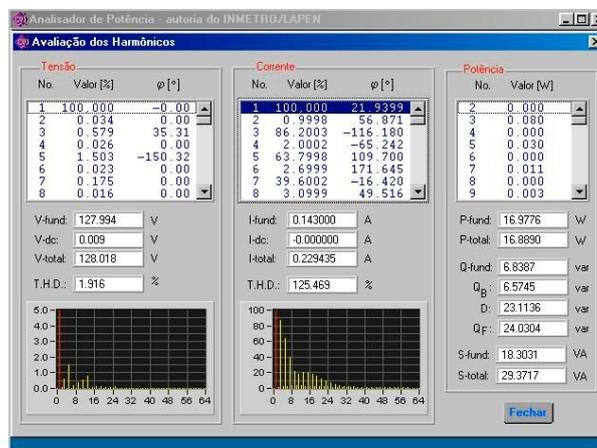


Figure 4: Results of the analysis of a compact fluorescent lamp

Conclusions

Based on a modified DFT algorithm, a new measuring system was developed suitable for the accurate measurement of power under non-sinusoidal situations. Beyond the accuracy, the algorithm is fast, one measurement takes less than two seconds, offering the possibility of several repeated measurements. An interactive program allows to calculate the components of the active power, reactive power, apparent power and power factor in the presence of harmonics. The estimated accuracy of this method is generally within $\pm 0,01\%$. The system has also been used for type tests of electronic watt-hour-meters according to the IEC 61036[6] and NBR 14519 [7] standards.

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