

## Uncertainty evaluation in power measurements with commercial data acquisition boards

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**Abstract-** The paper deals with the metrological characterization of a digital wattmeter developed by using a personal computer, a shunt, two commercial data acquisition boards and commercial software. The uncertainty of the active power measurements is assessed individually characterizing the voltage channel, the current channel and the phase displacement measurement between the two channels. In particular, the uncertainty on the voltage and current rms measurements is evaluated by using an already proposed approach based on the Monte Carlo method and on the usage of five parameters, while the uncertainty on the phase angle is experimentally estimated. In order to validate the proposed approach for the uncertainty evaluation, various experiments were carried out and a comparison with the Italian National Standard wattmeter was made. The results show that the proposed PC-based solution can be suitable for the development of standard instrumentation, since its accuracy is comparable to the accuracy of much more expensive and sophisticated instrumentation.

### I. Introduction

In the last years the improvement of analog-to-digital converters (ADCs) has allowed to develop a huge variety of measurement instruments based on the analog-to-digital (A/D) conversion and the successive digital processing of the acquired data. Also for high-accuracy power measurements, different digital solutions have been developed [1-6] and several metrological national centres have based their electric power standards on digital systems. In most cases these solutions are very expensive and sophisticated, as they make use of high accuracy power calibrators and digital voltmeters (DVM) and of refined digital signal processing. On the other hand the measurement instruments based on data acquisition boards (DAQs) connected to a common personal computer (PC), i.e. PC-based instruments, can offer a more suitable and less expensive alternative. With this aim, the authors have developed and presented different PC-based solutions for the power measurements [7]. Target of this work is to characterize the least expensive of these instruments in order to verify which accuracy it is possible to reach.

The accuracy evaluation of the PC-based instruments is still an open issue. In fact, several sources of uncertainty are present in the whole measurement chain and all of them have to be correctly taken into account and evaluated. Apart from the transducers and conditioning accessories (which generally introduce some of the predominant contributions to the measurement uncertainty), some significant contributions of uncertainty can be introduced during the A/D conversion. But the identification and quantification of the uncertainties introduced by the ADC is a very difficult task because the ADCs manufacturers use to declare different sets of parameters to characterize their products and these parameters are often defined and measured in different ways. This problem is well known by the many authors which have dealt with the uncertainty evaluation in the measurement performed by using an ADC [8-11], proposing different approach to analyse the uncertainty propagation (Monte Carlo approach; propagation law of the GUM; random-fuzzy variables). Also the authors of this paper handled the topic and proposed a numerical approach [12], based on the Monte Carlo method, to study, starting from the values of only five parameters, the way the errors generated in the instrument hardware block combine and propagate through the software block during the digital processing of the acquired data.

The proposed method is here used to evaluate the uncertainty of a PC-based wattmeter based on commercial DAQs, with the aim to investigate if it is possible to set up a standard instrument with such solution. More in detail, the aforesaid method is used to determine the uncertainties on rms measurements of voltage and current, while the uncertainty on the phase displacement is experimentally determined; at the end, the uncertainty on power measurements is evaluated according to the Standard ISO/IEC 13005, "Guide to the expression of uncertainty in measurement" [13].

## II. The PC-based wattmeter

The proposed wattmeter was developed for power measurements in sinusoidal conditions, at electrical power system rated frequency and with voltage range up to 240 V rms and current range up to 20 A rms.

It consists (figure 1) of two DAQ boards connected to a PC via USB interface: a high voltage input range DAQ NI USB 9225 for the voltage channel and a low voltage input range DAQ NI USB 9239 for the current channel. Thanks to this solution the voltage can be sensed directly avoiding the usage of a voltage divider while the current is sensed by a low-inductive Fluke A40B Precision AC Current Shunt ( $I_N = 20$  A,  $R_N = 0,04 \Omega$ ).

The DAQs have the following features (see user guide and specifications [14, 15]): 3 analog input channels for NI 9225 and 4 analog input channels for NI 9239, simultaneous sampling mode, sampling frequency  $f_s = 1,613\text{--}50$  kS/s, ADC Delta-Sigma, analog prefiltering (alias-free bandwidth  $0,453 f_s$ ), 24 bits resolution, input range  $\pm 425$  V for NI 9225 and  $\pm 10,52$  V for the NI 9239.

The LabView 8.5 is the programming language used to drive the DAQs and to extract the rms values and the phase displacements from the acquired samples.

In order to accurately compare the performances of the proposed wattmeter with the ones presented in [7], the same acquisition window (0,64 s) is used and, therefore, the instrument acquires 32000 samples at a 50 kS/s rate. A simultaneous sampling was performed for the two channels by providing the same trigger signal to both DAQs (which are placed into a chassis NI cDAQ 9172). The FFT is performed to obtain the rms values of voltage and current and the phase displacement between the two signals (the interpolated FFT block available in the LabVIEW library is used for this purpose). The power measurements are obtained from the aforesaid values of rms and phase displacement.

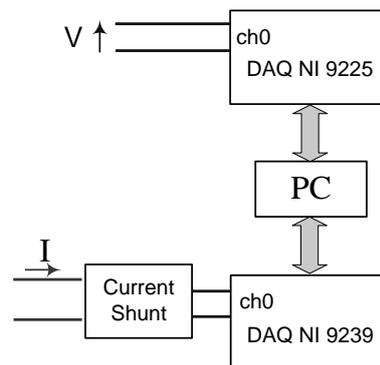


Figure 1. The proposed PC-based sampling wattmeter

## III. Voltage channel characterization

As previously described, the voltage is directly sensed by the NI 9225 DAQ, therefore, for the voltage channel characterization, the only uncertainty sources which have to be taken into account are the ones generated during the A/D conversion process. In order to correctly evaluate the uncertainty of a generic measurement performed by using a DAQ, we should at least consider (for low frequency signals) offset (included its temperature drift and its long term stability), gain (included its temperature drift, its long term stability and uncertainty of onboard calibration reference), integral non-linearity (INL), spurious tones, thermal noise, settling time, timing jitter, quantization, differential non-linearity (DNL) and crosstalk. However, considering all these parameters would require a large usage of time and resource for analysing how the uncertainties combine and propagate during the digital processing of the acquired data; moreover, not always all the aforementioned parameters are available in the manufacturer specifications.

With the aim to overtake these limitations, we studied, by a frequency domain analysis, the effect of each uncertainty source on the data obtained by processing a single tone signal:

- the offset error generates a DC component;
- the gain error produces a variation of the input signal spectral line amplitude;
- the INL produces harmonics of the input signal;
- the spurious signals, which for various reasons can interfere with the A/D conversion process, appear as the corresponding frequency components;
- thermal noise, settling time, timing jitter, crosstalk, quantization and DNL generate a broadband noise, which, with good approximation, can be considered uniformly distributed all over the acquired spectrum.

Summarizing, offset errors, gain errors, INL and spurious tones always operate on well-defined spectral components, while, on the contrary, the other uncertainty sources affect the whole frequency spectrum.

Another useful classification is the following:

- offset errors and spurious tones are input signal independent;
- gain errors and INL are input signal dependent;
- the broadband noise is actually input signal dependent, since some of the uncertainty sources, which generate it, depend on the shape, amplitude and frequency of the input signal; but, it is possible to neglect this dependency considering the worst case.

From the analysis made above, we can state that the parameters, sufficient to perform an accurate measurement uncertainty evaluation of whatever measurement performed by using an ADC, are: offset, gain; a parameter which quantifies the harmonic distortion (THD); a parameter which quantifies the spurious tones (TSD); a parameter which measures what is commonly called noise floor (SNR). In fact, these five parameters take into account all the uncertainty sources, which arise during the A/D conversion, and their specific behavior.

In order to apply this statement, we developed a simple simulator of the A/D conversion. The simulation of the uncertainties represented by the selected parameters is performed in the following way:

- to simulate the offset errors, a constant value is added to each sample of the input signal. This value is a random number within the range declared by the manufacturer. For each trial, the generated random number changes so that it lies in the specification range according to a rectangular distribution;
- to simulate the gain errors, each sample of the signal is multiplied by a constant value. This value is a random number within the range declared by the manufacturer. For each trial, the generated random number changes so that it lies in the specification range according to a rectangular distribution;
- to simulate the THD errors, the transfer function is distorted with components from the second to the tenth order. The amplitude of these components, for each trial, produces an actual THD randomly distributed from 0 to the THD declared in the specifications;
- two sinusoidal signals are added to simulate the presence of spurious tones. The amplitude of these components, for each trial, produces an actual TSD randomly distributed from 0 to the TSD declared in the specifications;
- to simulate the noise floor errors, a gaussian noise equivalent to the worst case noise floor is added to the input signal.

With the aim to verify the effectiveness of this approach and to provide an effective and experimental validation, we applied the method to real measurements and compared the results with the ones obtained by means of experimental tests [12]. The comparison has shown that the choice of the five proposed parameters leads to an accurate estimation of the uncertainties. Therefore, the approach was applied to the voltage channel characterization of the digital wattmeter.

For the NI 9225 board the five parameters for the uncertainty evaluation are: offset =  $\pm 34$  mV; gain =  $\pm 500$  ppm; THD = 95 dB; TSD = 102 dB; SNR = 104 dB. Starting from these values and applying the proposed approach (carrying out 100,000 trials) to a 50 Hz sinewave, we get an expanded uncertainty value not worse, in the range 20 ÷ 240 V rms, than 750 ppm stated to 99 % confidence level ( $k = 2,58$ ). The predominant contribution to the uncertainty is given by the gain, therefore, in order to reduce this uncertainty source we decided to accurately measure the gain error and then to correct it. For this purpose, the actual gain value was obtained by drawing up the static transfer characteristic, which, in its turn, is obtained from a 40 points least minimum squares method. As reference a Fluke 5720A calibrator, in DC voltage mode, was used. After the gain correction, the new gain value to take into account is related to the uncertainty of the correction. In particular, we have to consider the calibrator standard uncertainty, that in the worst case point is 4 ppm, and the uncertainty associated to the stability of the gain error. This was obtained by means of a Type A evaluation, repeating the gain assessment in different days and calculating a 8 ppm value of standard uncertainty. However, considering that we are approximating the 50 Hz transfer characteristic to the static transfer characteristic, we, for sake of security, expand the gain standard uncertainty to 25 ppm. With this new gain value and applying the proposed approach (carrying out 100,000 trials) to a 50 Hz sinewave, we get an expanded uncertainty value, in the range 20 ÷ 240 V rms, not worse than 80 ppm stated to 99 % confidence level. We do not deal with the uncertainty generated during the data processing, since it is intrinsically taken into account by the simulator.

With the aim to validate the assessed uncertainty value, we performed a series of measurements. The test signal is a 50 Hz 120 V rms sinewave generated by the Fluke 5720A calibrator, which, at this voltage rms value, provides an uncertainty equal to 70 ppm (99 % confidence level). In this case the calibrator cannot be considered as a reference, since its accuracy is comparable to the DAQ performances. However, it is possible to compare the measures carried out by the DAQ and to verify if they are compatible with the uncertainty range of the calibrator. Therefore, we carried out (in different days) 100 measurements of the rms value. In figure 2, the 100 measured values are reported; the continuous lines stand for the uncertainty range of the calibrator and the dotted lines stand for the measures obtained by the board plus and minus the estimated uncertainty. All the 100 couples of measures are compatible.

#### IV. Current channel characterization

The current is acquired by the NI USB 9239 board through a non-inductive Fluke A40B Precision AC Current Shunt ( $I_N = 20$  A,  $R_N = 0,04$   $\Omega$ ). For this DAQ the five parameters for the uncertainty evaluation are: offset =  $\pm 840$   $\mu$ V; gain =  $\pm 300$  ppm; THD = 99 dB; TSD = 99 dB; SNR = 100 dB.

Also for this board, the predominant contribution to the uncertainty on a rms measurement is given by the gain, therefore, in order to reduce this uncertainty source, also in this case we have accurately measured the gain error and then have corrected it. The actual gain value was obtained by drawing up the static transfer characteristic, which, in its turn, is obtained from a 22 points least minimum squares method. Using again the Fluke 5720A calibrator and making the same consideration made for the NI 9225 DAQ, it is possible to reduce the gain standard uncertainty to 25 ppm.

To obtain the current values, the DAQ acquired voltage must be divided by the shunt resistance calibrated value corrected with the AC-DC difference. Therefore, beside the uncertainty components generated by the DAQ, also the absolute accuracy of the current shunt resistance must be taken into account. This component can be considered a gain error and its uncertainty value, as stated in the manufacturer specifications [16], is equal to  $\pm 43$  ppm (95% confidence level) at 50 Hz frequency.

Starting from these values and applying the proposed approach (carrying out 100,000 trials) to a 50 Hz current waveform, we get a expanded uncertainty value not worse, in the range 2 ÷ 20 A rms, than 100 ppm stated to 99 % confidence level ( $k = 2,58$ ).

With the aim to validate the assessed uncertainty value, we performed a series of measurements. The test signal is a 50 Hz 5 A rms sinewave generated by the Fluke 5720A calibrator plus the Fluke 5725A amplifier, which, at this current rms value, provides an uncertainty equal to 500 ppm (99 % confidence level). Also in this case the calibrator cannot be considered as a reference, since its accuracy is comparable to the current channel performances. However, it is possible to compare the measures carried out by our system and to verify if they are compatible with the uncertainty range of the calibrator. Therefore, we carried out (in different days) 100 measurements of the rms value. In figure 3, the 100 measured values are reported; the continuous lines stand for the uncertainty range of the calibrator plus the amplifier and the dotted lines stand for the measures obtained by the current channel of the proposed system plus and minus the estimated uncertainty. All the 100 couples of measures are compatible.

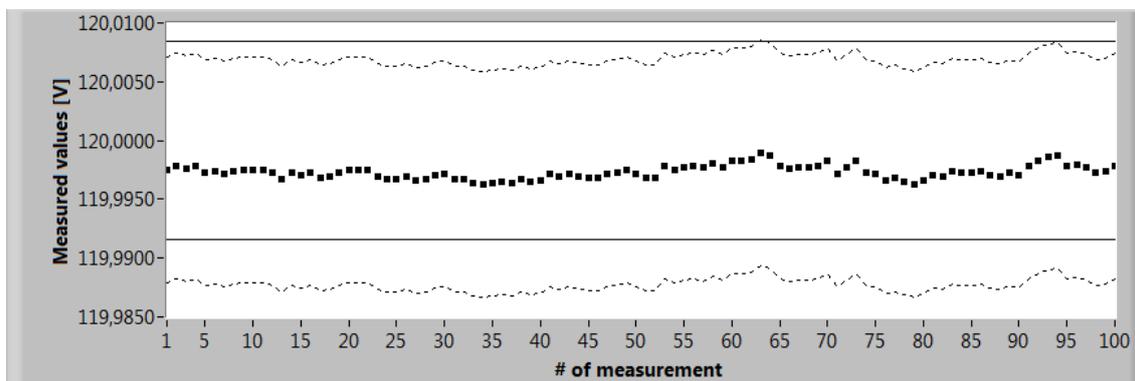


Figure 2. Voltage measurements performed by using the NI 9225 DAQ

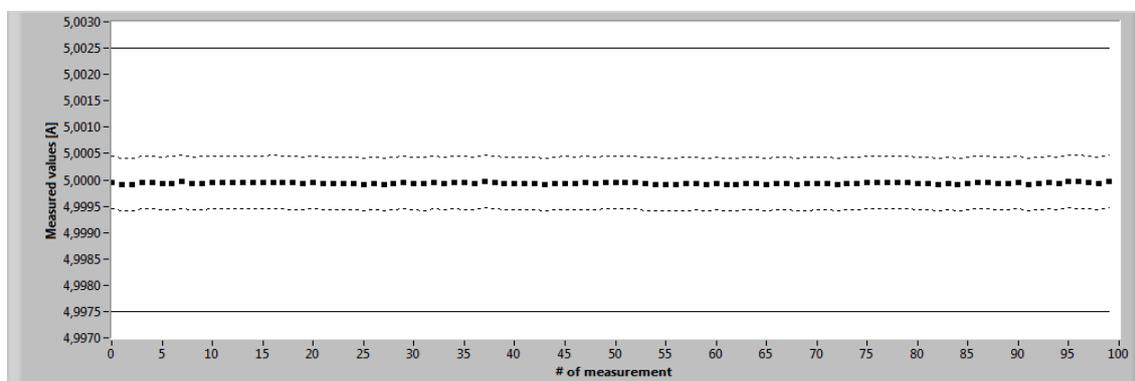


Figure 3. Current measurements performed by using the Fluke A40B Current Shunt and the NI 9239 DAQ

## V. Phase displacement measurement characterization

To evaluate the uncertainty associated to the phase displacement measurement, four uncertainty sources must be considered: the phase displacement caused by the shunt, the time delay between the two channels, the long term stability of this delay and the repeatability of the measurement. The first one has been assessed by using a Type B evaluation, starting from the manufacturer specification where it is stated that the phase displacement produced by the shunt is minor than  $0,008^\circ$ . Actually the shunt phase displacement is a systematic error with defined sign (always inductive phase displacement). Anyway, for sake of simplicity, we consider a symmetric distribution with a 0 mean and a  $0,004^\circ$  standard deviation.

As for the uncertainty components related to the DAQs, by using our simulator it is possible to point out only the repeatability, not the interchannel delay and its stability. Therefore, we decided to carry out a Type A evaluation considering that for this kind of measurement we can use a perfect reference measurand, that is the same sinusoidal signal applied to the two channels ( $\Delta\phi = 0$ ). Obviously the maximum amplitude of the signal cannot exceed the input range of the NI 9239 DAQ (10,52 V). We performed various set of experiments (100 measurements), varying the amplitude of the signal. Analysing the data (Table I), we find out that the interchannel delay is approximately constant and does not depend on the signal amplitude. Therefore it is possible to correct this delay by subtracting the  $\Delta\phi$  mean value. After the correction, it is necessary to take into account the uncertainty of this correction, namely its long term stability, that, repeating the experiment in different days, was assessed with a standard deviation equal to  $0,0002^\circ$ . On the contrary, the repeatability of the measurement (quantified by the  $\sigma_{\Delta\phi}$  value) is strictly depending on the signal amplitude. Actually, since the NI 9225 DAQ will never be used with these very low amplitudes signals, in order to consider a more suitable value of the repeatability, we should perform the test acquiring a 20 V rms waveform with the NI 9225 DAQ and a 80 mV rms (2 A rms shunt output) waveform with the NI 9239 DAQ. However, considering that our simulator practically assessed the same values of repeatability experimentally evaluated (see Table I), we decided to use the value obtained by using the simulator, that is  $0,0014^\circ$ . Carrying out the rss of the uncertainties of the abovementioned sources, we get an expanded uncertainty on the phase displacement measurement equal to  $0,011^\circ$ .

Table I. Phase displacement measurements. Mean values and standard deviations

Test signal (RMS) [V]	5	2	1	0,5	0,2	0,1
$\Delta\phi$ [deg]	0,0081	0,0082	0,0085	0,0081	0,0082	0,0084
$\sigma_{\Delta\phi}$ [deg] (experiments)	0,0005	0,0009	0,0011	0,0037	0,0088	0,0190
$\sigma_{\Delta\phi}$ [deg] (simulations)	0,0005	0,0010	0,0013	0,0040	0,0100	0,0220

## VI. Active power uncertainty evaluation

The uncertainty on power measurements was evaluated by composing the aforesaid uncertainty contributions on voltage, current and phase displacement measurements according to the uncertainty propagation law [13] (applied to the expression of the active power,  $P = V I \cos \phi$ ).

The obtained results are synthesized in Table II, for different  $\cos \phi$  values (expanded uncertainties, at 99% confidence level,  $k = 2,58$ ). The worst case values are reported, which refer to the lower range limits for voltage and current (20 V and 2 A, respectively).

Table II. Power measurement uncertainties (99 % confidence level,  $k = 2,58$ )

V [V]	$\dot{U}_V$ [ppm]	I [A]	$\dot{U}_I$ [ppm]	$\cos \phi$	$\dot{U}_\phi$ [deg]	$\dot{U}_P$	
						[ $\mu$ W/W]	[ $\mu$ W/VA]
20	80	2	100	1	0,011	100	100
				0,8		150	120
				0,5		280	140
				0,1		1500	150

## VII. Conclusions

In this paper the metrological characterization was carried out of a digital PC-based wattmeter, which was developed by the authors, by using a personal computer, two commercial data acquisition boards and commercial software. The voltage channel, the current channel were characterized individually, by using an approach, already proposed by the authors in previous papers, which is based on the Monte Carlo method and the usage of five parameters proposed by the current Standards on ADCs; the uncertainty on the phase displacement between the two channels was experimentally and the uncertainty on power measurements was evaluated according to the Standard ISO/IEC 13005. The obtained results show that with the proposed PC-based solution it is possible to set up high accuracy instrumentation, obtaining metrological performances which are comparable with the much more expensive and sophisticated traditional instrumentation.

Currently a further validation of the metrological features of the proposed instrument is also in course, by means of a comparison with the Italian National Standard sampling wattmeter available at INRIM, which makes use of two high-precision voltmeters and a current-to-voltage converter (a double-stage current transformer with a precision shunt resistor) [3]. The comparisons with the National Standard are in course for both power and rms values; the preliminary results show that the measurements performed by the proposed instrument and the National Standard are compatible, with small errors (between the values measured by the two instruments) and standard deviations. This confirms the feasibility of the proposed solution and the validity of the uncertainty evaluation previously described.

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