Estimation of Uncertainty in Measurement of Power Quality Characteristics with a Virtual Measurement Instrument

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Abstract—**The paper deals with modeling and estimation of uncertainty in measurement of power quality (PQ) characteristics by using a virtual measurement instrument. The described virtual PQ analyzer is comprised of National Instruments (NI) analog input modules, NI data acquisition board, personal computer and software in LabVIEW™. The main sources of uncertainty are identified and evaluated. A Monte Carlo simulation is used for the model estimation and generation of the combined uncertainty of particular characteristics. Experimental measurement and statistical analysis of the results are made and compared with the simulation results. The experimental results have served for a verification of the model and the Monte Carlo simulation results.**

Keywords - measurement uncertainty; power quality measurement; virtual instrument; Monte Carlo simulation

I. INTRODUCTION

Recently, with the development of different modules for data acquisition and different software platforms [1-4], such as LabVIEW™, Matlab© and other software environments, there is a very fast growth of virtual instruments for measurement of different physical quantities. As it is commonly accepted in the metrological practice, the measurement results without declared uncertainty are useless. Therefore, it is very challenging, the methods for estimation of the measurement uncertainty [5-8] to be applied at the measurement by virtual instruments. The field of measurement of power quality (PQ) characteristics, because the growth of the participation of the unconventional power sources in the production of electricity, as well as the growth of nonlinear industrial and domestic loads using power electronics, becomes more and more important on daily basis [9-11]. Because of this a cheap flexible and upgradeable virtual instrument for PQ measurement is developed. For usage of the results derived through measurements by this device it has been necessary to model, estimate and verify the measurement uncertainty of the virtual instrument.

II. DESCRIPTION OF THE INSTRUMENT

Two modules for the Analog input are used:

1) NI 9225, 3-channel 300 V rms Analog input module with 50 kS/s per channel simultaneous inputs for phase voltage measurement and built-in antialias filters.
2) NI 9227, 4-channel current input, 5 A rms measurement, 50 kS/s per channel simultaneous inputs and built–in antialias filters.

Other equipment used:

3) NI cDAQ-9174, compact DAQ, 4 slot chassis with USB connection. The chassis runs the Analog input modules simultaneously. The chassis has four general purpose 32 bit counter/timers built-in.

The input circuit for one channel of NI 9225 and NI 9227 is shown in Figure 1.

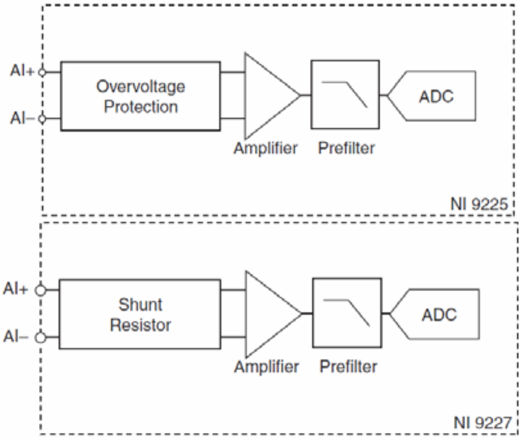

Figure 1. Input circuits for one channel of NI 9225 and NI 9227

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The incoming analog signal in each channel is conditioned, buffered and sampled by the ADC. The Delta-Sigma ADCs are with 24 bits. Each channel provides an independent signal path and ADC, enabling sampling of all channels simultaneously. The internal master time-base is with a f_M=12,8 MHz and accuracy of ±100 ppm. The filter before the ADC discriminates between signals based on the frequency range of the signal. The three important bandwidths are the pass band, stop band and alias free bandwidth. The NI module represents signals within the pass band as quantified by pass band flatness and phase nonlinearity. The pass band flatness is ±100 mdB and the upper frequency is 0,453 of the sampling frequency. The gain drift is declared to be ±10 ppm/°C and the offset drift ±970 μV/°C.

The wiring diagram of the power quality analyzer for direct measurement of the phase voltages and currents is shown in Figure 2.

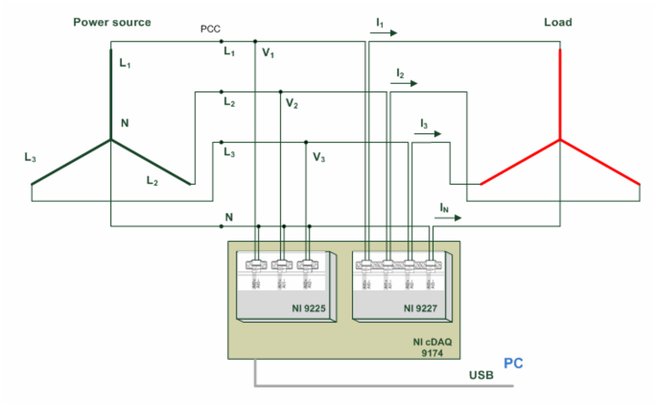


Figure 2. Wiring diagram of the power quality analyzer

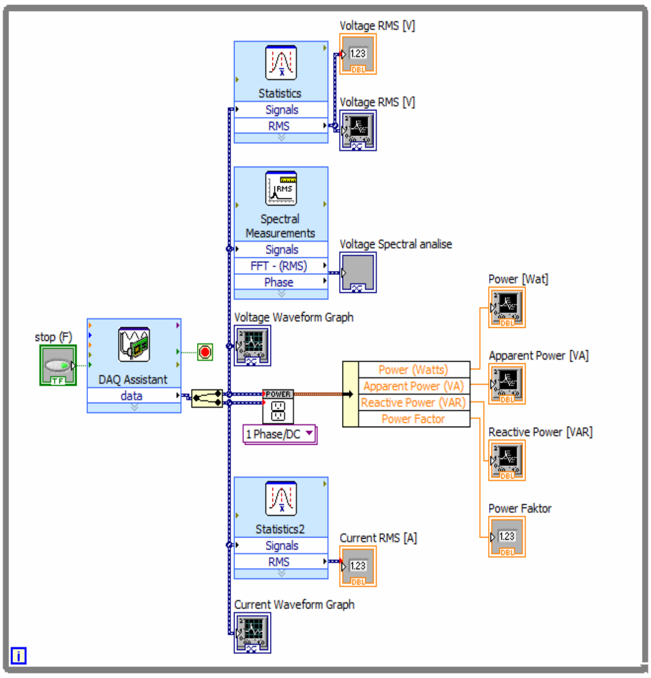


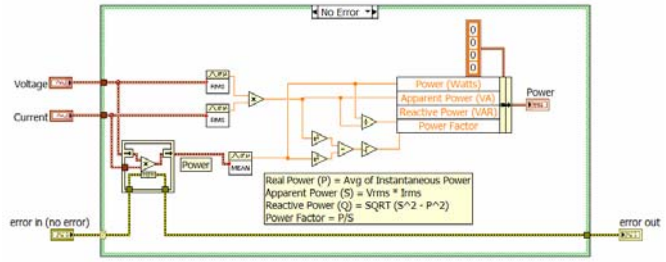
Figure 3. Block diagram of the software of the PQ virtual instrument

The LabVIEW™ graphical programming language was used for creation of the virtual instrument for measurement of the power quality characteristics. The graphical source code of the virtual instrument is shown in Figure 3.

The virtual instrument beside the measurement of the phase voltages, phase and neutral current, contains software modules running in parallel:

- EN 50160 voltage monitor
- FFT analyzer
- Vector analyzer
- Flicker analyzer
- Power monitor.

In Figure 4 the source code for subroutine POWER is shown.



Real Power (P) = Avg of Instantaneous Power
Apparent Power (S) = Vrms * Irms
Reactive Power (Q) = SQRT (S^2 - P^2)
Power Factor = P/S

Figure 4. Block diagram-source code of the subroutine POWER

III. MODELING OF THE UNCERTAINTY

A model of the measurement with the main sources of uncertainty in the form of Ishikawa diagram has been developed as shown in Figure 5.

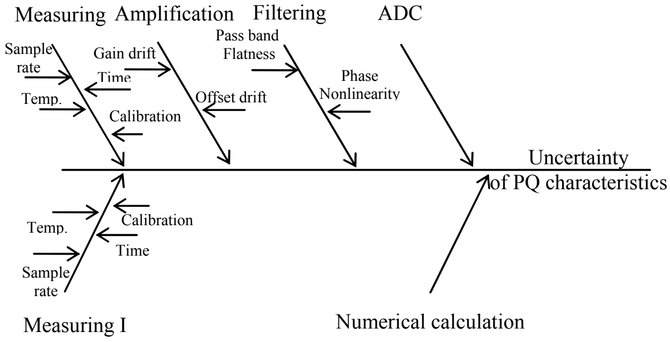


Figure 5. Ishikawa diagram of the uncertainty

Based on the Ishikawa diagram, the mathematical model for estimation of uncertainty in measurement of the voltage will be in the form of multiplication product of particular variable quantities, and the relative combined uncertainty u_{cv} of voltage measurement is:

$$u_{cv} = \sqrt{u_{AS}^2 + u_{Cal}^{\;2} + u_{Amp}^{\;2} + u_F^2 + u_{ADC}^{\;2}} \qquad (1)$$

Where is:

u_{AS} – uncertainty of the analog sampling;

u_{Cal} – uncertainty of the calibrator;

u_{Amp} – amplification uncertainty;

u_F – uncertainty of the filter converter;

u_{AS} – uncertainty of the ADC converter.

For modeling the filter, the passband signal is quantified primarily by passband flatness and phase nonlinearity. The signals within the passband have frequency dependent gain, characterized by small gain variation with respect to frequency-passband flatness.

IV. QUANTIZATION OF UNCERTAINTY SOURCES

The quantization of the uncertainty sources should be done very carefully. The producer NI has given detailed technical specification of the input module NI 9225. The amplification gain drift is ±10 ppm/°C and the offset drift ±970 μV/°C. Passband flatness is ±100 mdB maximum. The passband frequency is $0,453 \cdot f_s$ and the phase linearity is maximum 0,22°. The quantization error of the 24 bits ADC will be very small. For typical operating range of 300 V (rms), typical scaling coefficient is 50,66 μV/LSB. For the module NI 9227, data are given for the amplification gain drift ±21 ppm/°C and offset drift of ±51 μA/°C, as well as for the filter passband frequency of $0,453 \cdot f_s$ and flatness of ±100 mdB. For the phase match channel-to-channel 0,1 °/kHz and module-to-module maximum of 0,1 °/kHz+360°$\cdot f_{in}/f_M$. The input delay is $38,4/f_s$ + 3,2 μs. The typical scaling coefficient is 1,785397 μA/LSB.

The evaluation of the sources of uncertainty and estimation of the relative combined uncertainty u_{cv}, using the National Instruments specifications for the voltage analog input module NI 9225, such as gain drift, offset drift, etc., as well as the relative uncertainty of the calibrator Fluke 5500A, derives that u_{cv} is approximately 0,046 % for 25 °C ± 5 °C. This result is close to the NI specified value. The producer specifications are given in Table I.

TABLE I. NI 9225 ACCURACY SPECIFICATIONS

Measurement conditions	**Percent of reading (Gain Error)**	**Percent of Range (Offset Error)**
Calibrated max (-40 °C to 70 °C)	±0,23%	±0,05%
Calibrated type (25 °C, ±5 °C)	±0,05%	±0,008%
Calibrated max (25 °C, ±15 °C)	±0,084%	±0,016%
Uncalibrated max (-40 °C to 70 °C)	±1,6%	±0,66%
Uncalibrated type (25 °C, ±5 °C)	±0,4%	±0,09%

The mathematical function of the dependence of the measured quantity will be different for particular PQ characteristics C_{PQ} and will be in the general form of (2):

$$C_{PQ} = \pm f\big(u(t,T), i(t,T), t\big) \qquad (2)$$

where are: *u(t,T)* is voltage signal, *i(t,T)* is the current signal, *t* is the time and *T* is the temperature. This nonlinear function can be estimated by using Monte Carlo simulation. For example, the standard uncertainty of the total harmonic distortion *THD* is done by using the model as in (3):

$$THD(\%) = \frac{\sqrt{\sum_{i=2}^{25} V_i^2}}{V_1} \cdot 100 \qquad (3)$$

where V_i is the RMS of *i*-th harmonic.

The results of the Monte Carlo simulation for *THD* uncertainty estimation for a measurement at the low voltage level of a 400 kVA transformer in household area are shown in Table II and Figure 6.

TABLE II. MONTE CARLO THD SIMULATIONS RESULTS

	V_1	**V_3**	**V_5**	**V_7**	**V_9**	**V_{11}**	**V_{13}**	**V_{15}**	**V_{17}**	**V_{19}**	**V_{21}**	**V_{23}**	**V_{25}**	***THD***
Average	230,001	1,15025	5,75131	4,1394	0,69027	0,69047	0,92015	0,69066	0,46049	0,34461	0,41452	0,23045	0,22979	0,03208
Std Dev	0,1694	0,05177	0,05494	0,05423	0,05257	0,05233	0,05228	0,05247	0,05171	0,05222	0,05221	0,0525	0,05239	0,00024
Std Err	0,00169	0,00052	0,00055	0,00054	0,00053	0,00052	0,00052	0,00052	0,00052	0,00052	0,00052	0,00053	0,00052	2,4E-06
Max	230,725	1,33419	5,97297	4,35145	0,87102	0,88657	1,13437	0,89024	0,64992	0,52788	0,61971	0,42335	0,40678	0,03301
Min	229,352	0,94543	5,518	3,93773	0,46522	0,4678	0,70696	0,48842	0,24937	0,14858	0,23627	0,02726	0,03127	0,03111

When the active power uncertainty is evaluated, it is started with the definition:

$$P = \frac{1}{kT} \int_{t_1}^{t_1+kT} u(t) i(t) dt \qquad (4)$$

$$P = UI \cos\varphi \qquad (5)$$

which can be differentiated with respect to the magnitudes and the phase difference

$$\frac{\Delta P}{P} = \frac{\Delta U}{U} + \frac{\Delta I}{I} - \tan\varphi \cdot \Delta\varphi \qquad (6)$$

This equation expresses the relative active power error due to the voltage magnitude error, current magnitude error and the phase angle difference error. It is not a linear function, because it depends on tanφ, which changes from 0 to ∞ as the power factor is changing from 1 to 0. So, it may be more convenient to analyze the apparent power and to multiply it to cosφ.

Magnitude uncertainty

If only the magnitude uncertainty is considered, it may be derived from:

$$\frac{\Delta P}{P} = \frac{\Delta U}{U} + \frac{\Delta I}{I} \tag{7}$$

The uncertainties of the voltage and the current magnitudes were analyzed previously. Here it may be added that the magnitude error should comprise also the contribution of the shunts and voltage dividers if used. They are calibrated separately and their calibration uncertainty will contribute to the system uncertainty. The magnitude uncertainty of the used voltage divider is small. The magnitude uncertainty of the shunts because of the temperature variation of ±5 °C is estimated to ±20 ppm.

Phase-angle uncertainties

The error of the phase angle difference will depend on the difference of the phase errors of the voltage module and the current module. The phase match module-to-module is given:

$$\Delta\Phi = 0.1^{\circ}/kHz + 360^{\circ} f_{in}/f_{M} \approx 112 \cdot 10^{-6} rad \tag{8}$$

Phase-angle error may also be a result of the delay-time errors caused by the module-to-module delay time differences. The delay-time difference Δt will cause a phase-angle error of $\Delta\Phi=\omega\cdot\Delta t$, which varies with the frequency. The delay-time variability specifications will be 77 ns and $\Delta\Phi=2\pi f\cdot 75\cdot 10^{-9}$ rad.

For estimation of the combined uncertainty of the active power a Monte Carlo simulation of the active power model with the temperature variation of ±5 °C, signal frequency of 50 Hz and power factor from 1 to 0,5 is made. The uncertainty of the active power measurements is 1612 ppm and the main source of uncertainty is the measurement of the current.

The value of the uncertainty is frequency dependent, power factor dependent and sampling rate dependent and it has to be estimated for different particular conditions.

Other PQ characteristics are similarly modeled and simulated by the Monte Carlo method to estimate the probability distribution function (PDF) and the uncertainty of the measurement result.

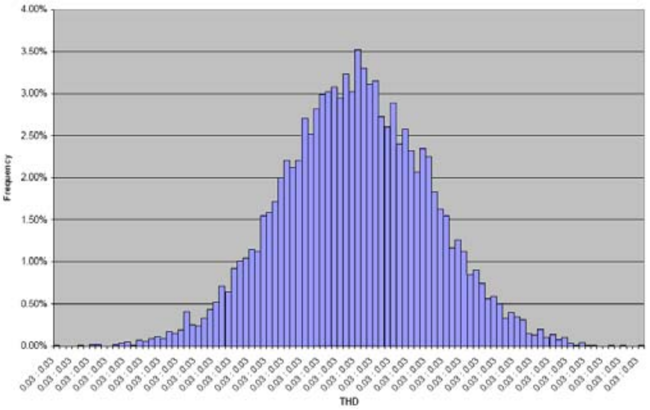


Figure 6. THD pdf

V. EXPERIMENTAL DETERMINATION OF THE UNCERTAINTY OF THE MEASURED PQ CHARACTERISTICS

For experimental determination of the uncertainty in the measurement of the PQ characteristics, the virtual instrument was connected directly to a laboratory calibrator FLUKE 5500A as shown in Figure 7.

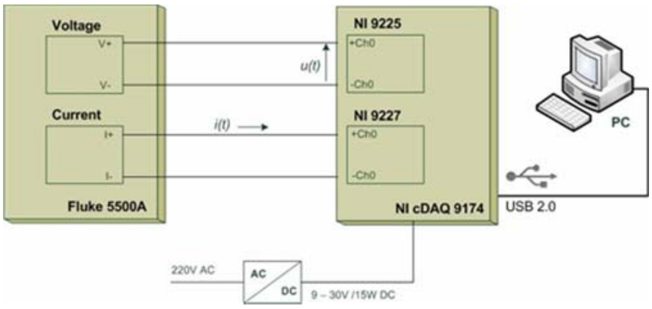


Figure 7. Experimental set-up for verification of the uncertainty model.

The virtual instrument was calibrated with a histogram test [1], [12-14] for determination of the static parameters through a statistical analysis and the sine wave curve fitting method [15, 16] to determine dynamic parameters.

The dynamic parameters analyzed are:

- *SINAD* (Signal-to-Noise-and-Distortion is the ratio of the rms signal amplitude to the mean value of the root sum-square of all other spectral components, including harmonics, but excluding dc).
- *THD+Noise* (the ratio, expressed in dB or in percentage, of the rms signal amplitude to the mean value of the root-sum-square of all other spectral components plus all spectral noise components),
- *ENOB* (Effective Number Of Bits),
- frequency,
- phase and
- magnitude of the sinusoid input signal.

By using the calibrator FLUKE 5500A different input values of voltages and currents at different frequencies are generated and the measurement results gained by the virtual instrument are recorded. Through statistical analysis of the recorded results the PDF and the standard deviation of the measurements of different voltages and currents at different frequencies are derived.

The Ishikawa diagram for estimation of uncertainty of measurement is given in Figure 8.

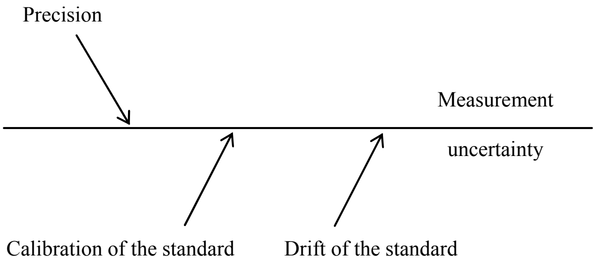


Figure 8. Ishikawa diagram of the experimental estimation of measurement uncertainty

The measurement model of the error of the virtual instrument when measuring a harmonic voltage is defined in (3), where V_{hx} is the h-*th* voltage indication of the instrument, V_{hs} is h-*th* voltage configured in the standard (corrected by its calibration certificate), δV_{hs} is the correction of the standard due to drift and other errors.

$$E_x = V_{hx} - V_{hs} - \delta V_{hs} \tag{9}$$

The standard uncertainty of this error could be evaluated as:

$$u(E_x) = \sqrt{u^2(V_{hx}) + u^2(V_{hs}) + u^2(\delta V_{hs})} \tag{10}$$

The measurement model of the error of the instrument when measuring *THDV* is defined in (3). So the standard uncertainty of this error could be evaluated by:.

$$E_x = THDV_x - THDV_s - \delta THDV_s \tag{11}$$

$$u(E_x) = \sqrt{u^2(THDV_x) + u^2(THDV_s) + u^2(\delta THDV_s)} \tag{12}$$

When measuring the active power *P*, the uncertainty of the power error will be:

$$u(E_p) = \sqrt{u^2(P) + u_s{}^2(P_s) + u^2(\delta P_s)} \tag{13}$$

With the calibrator FLUKE 5500A a seria of 440 measurements under repeatable conditions are done. The measurements presented in the paper were done with sinusoidal voltage and triangular current waveform from the calibrator FLUKE 5500A. The frequency is 50 Hz at power factor *PF*=1.

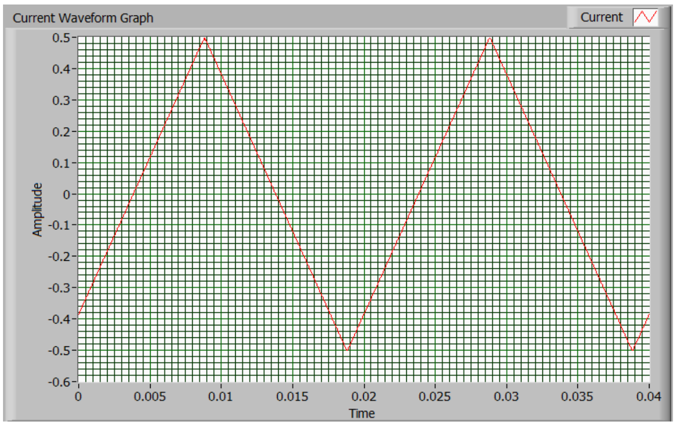


Figure 9. Current wave-form (triangle).

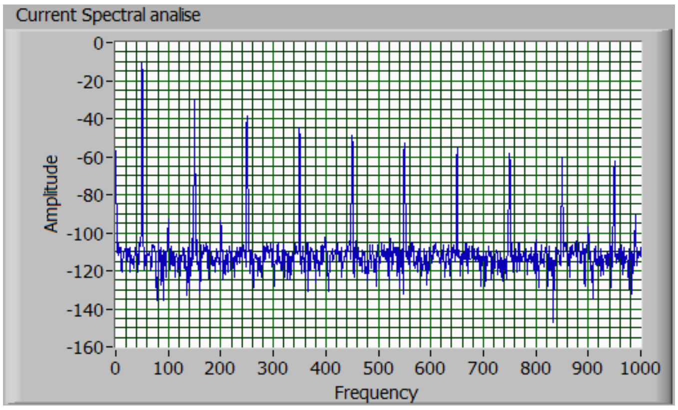


Figure 10. Current spectral analysis.

In Table III the measurement results, their standard deviations and the combined uncertainty for the voltage, current, the total harmonic distortion THDI and active power *P* are shown.

TABLE III. EXPERIMENTAL RESULTS

	Voltage	**Current**	**THDI**	**P**
Average	229,939408 [V]	0,289455 [A]	12,087070 [%]	66,074660 [W]
Standard Deviation [ppm]	263	2700	3820	3196
Combined Uncertainty [ppm]	504	2814	3980	3320
Max	229,941182 [V]	0,289468 [A]	12,089464 [%]	66,077726 [W]
Min	229,937490 [V]	0,289101 [A]	12,084863 [%]	65,993695 [W]

The experimental results compared with the results produced by the Monte Carlo simulation of the model are similar. The difference may be a result of different environmental conditions.

VI. CONCLUSION

A virtual instrument for measurement of power quality characteristics based on National Instruments analog input modules, NI data acquisition board, personal computer and software in LabVIEW™ was developed. The virtual instrument enables measurement of all PQ characteristics, flexibility and upgradeability. The measurement uncertainty of the PQ characteristics has been modeled, estimated and verified through experimental measurement using a laboratory calibrator.

REFERENCES

[1] M. Caciotta, S. Giarnetti, G. Lattanzi Cinquergrani, F. Leccese, D. Trince, “Development and characterization of a multi-platform Data Acquisition System for Power Quality metrological certification”, in Proc. ICREPQ, 2011, P. No. 362.

[2] S. Chen, “Open design of networked power quality monitoring systems”, IEEE Transactions on Instrumentation and Measurement, Vol. 53 , Iss. 2 , 2004 , pp. 597 - 601

[3] A. Delle Femine, D. Gallo, C. Landi, M. Luiso, “Power-Quality Monitoring Instrument With FPGA Transducer Compensation”, IEEE Transactions on Instrumentation and Measurement, Vol. 58 , Iss. 9, 2009, pp. 3149 – 3158

[4] R. Iuzzolino, W.G.K. Ihlenfeld “High-Accuracy Methods and Measurement Procedures for Power Quality Parameters Using the Digital Synchronous Sampling Technique”, IEEE Transactions on Instrumentation and Measurement, Vol. 56 , Iss. 2, 2007, pp. 426 - 430

[5] EA-4/02 Expression of the Uncertainty of Measurement in Calibration.

[6] ISO/IEC GUIDE 98-1 ed1.0 (2009-08), Uncertainty of measurement - Part 1: Introduction to the expression of uncertainty in measurement, 2009

[7] ISO/IEC GUIDE 98-3 ed1.0 (2008-09) Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), 2008

[8] ISO/IEC GUIDE 98-3 SUP ed1.0 (2008-11) Supplement 1 - Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM:1995) - Propagation of distributions using a Monte Carlo method, 2008

[9] M. H. J. Bollen, Understanding Power Quality Problems: Voltage Sags and Interruptions, Wiley-IEEE Press, New Jersey, 1999

[10] CEI EN 50160: 2010, Voltage characteristics of electricity supplied by public distribution systems.

[11] IEC 61000-4-7 ed2.1 Consol. with am1 (2009-10).: Testing and measurement techniques–general guide on harmonics and interharmonics measurements for power supply systems and equipments connected thereto.

[12] A. Ferrero, M. Lazzaroni, S. Salicone, “A calibration procedure for a digital instrument for electric power quality measurement”, IEEE Transactions on Instrumentation and Measurement, Vol. 51, Iss. 4, 2002, pp. 716 - 722

[13] M. M. da Costa, T. Brito, T. M. Soares, “Metrological Confirmation of Total Harmonic Distrotion of Voltage Meters used in Brazilian Electrical Power System”, in Proc. ICREPQ, 2010, P. No. 647.

[14] C. de Capua, C. Landi, G. C. Malafronte, “Measurement Uncertainty in Evaluating Total Harmonic Distortion Factor”, IEEE Trans. On Instrumentation and Measurement, v. 1, 2001, pp. 675-679.

[15] W. Kester, “Analog-Digital Conversion,” Analog Devices press, 2004.

[16] D. Dallet and J. Machado da Silva, (eds.), “Dynamic Characterisation of Analogue-to-Digital Converters,” Springer, 2005.