A Fully Automated Measuring Station for the Calibration of Voltage Transducers

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***Abstract*-**Power quality analyses in the last years has assumed more and more heaviness in industrial environments, due to the presence of non-linear loads: they require suitable and precise measuring instrumentation. Nevertheless, while there are lots of power quality standards fixing high frequency limits for harmonic analyses, there is a lack of standards concerning transducers calibration at amplitude and frequency different from the rated ones. Therefore in this paper a fully automated measuring station for the calibration of voltage transducers in wide amplitude and frequency ranges is discussed. As an application, the results of the calibration of a commercial transducer are presented: they are used to implement a time-domain procedure for real-time correction of the frequency response of the calibrated transducer.

I. Introduction

The growing number of non-linear and unbalanced loads in the electrical systems makes the scientific interest in harmonic and inter-harmonic analysis increase. In scientific literature (especially in Power Quality, Electromagnetic Compatibility and new Power Theory in non-sinusoidal conditions) and in standards' context great efforts have been spent to move up the frequency limits for harmonic analysis. This trend poses a serious issue on the measurement instrumentation to use for such analysis [1].

Power Quality phenomena are typically associated with the presence of frequency components, both higher or lower than the fundamental one, appearing in the grid either periodically (eg. harmonics and interharmonics) or stochastically (eg. transients). In the case of harmonics, the relation between the individual frequency components, both in amplitude and phase, may provide interesting information about the source of disturbance. Therefore, in order to accurately measure other frequency components than the fundamental one, information about the frequency response of measuring instruments is of great interest.

Measurements at high/medium voltage power networks are characterized with problems and difficulties not encountered in measurements applied to other types of systems. They require a precise means for scaling currents and voltages down to usable metering levels. For most practical purposes, this role has been adequately fulfilled by magnetic core instrument transformers, i.e. Voltage Transformers (VT) and Current Transformer (CT).

Nevertheless, the standards related to the type tests for accuracy of measuring instrument transformers [2]-[4], which at now are the only ones to account when calibrating voltage or current transducers, establish the way to test the accuracy only at the rated frequency and amplitude, and they don't say anything about how to find the frequency response and the linearity of such instruments.

This, on the other hand, is in contrast with other standards related to power quality phenomena [5]-[7], in which requirements for harmonic measurement are established: a power quality instrument must have the capability to measure spectral components of the grid voltage at least up to 40th harmonic frequency. Of course, since the harmonic components have amplitude and frequency different from the fundamental one, the accuracy of power quality instruments has to be determined also in these situations.

Therefore, since power quality instruments need suitable voltage and current transformers/transducers for scaling these quantities down to usable metering levels, it is evident that the transducers have to be calibrated in wider frequency and amplitude ranges than the rated ones.

To this aim, in the present paper a fully automated measuring station for the calibration of voltage transducers is described: it is capable to calibrate transducers in the wide frequency range between DC and 9 kHz and in the amplitude range between ±600 V. In the following, the hardware employed to build-up the automated station and all the calibration procedures to test accuracy, frequency response and linearity of the transducers are described. As an application, the calibration of a commercial voltage transducer is presented; the results of such calibration are used for the implementation of a time domain real-time procedure for the compensation of the frequency response of the calibrated transducer.

II. The automated calibration station

The realized automated measuring station [8]-[10] is based on a power source, numerically controlled, and a PXI platform. Its block scheme is shown in Figure 1. A PXI controller by National Instruments has been used: it includes a module for data acquisition, the NI S 6123, which has got 8 synchronous analog inputs at 16 bits, ±10 V input range and 500 kHz maximum sampling rate per channel, and a module for waveform generation, the NI 5421 which has got one analog output at 16 bit, ±12 V output range, 100 MHz maximum generation frequency and a memory of 256 MB. By means of the NI 5421 module, the desired waveforms are generated and then amplified through a Pacific Source 3120AMX. Its main characteristics are: i) maximum power: 12 kVA; ii) frequency range: 20 Hz to 9 kHz; iii) line regulation: 0.027 mV; iv) load regulation: 0.00135 mV; v) THD: 0.1%; vi) voltage ripple and noise: -70 dB. That frequency bandwidth allows to generate up to 160th harmonic component, that is in compliance with power quality standards [5]-[7].

Its output is sensed by the transducer under test and by a high precision resistive voltage divider, based on a decade resistor produced by IET Labs, Genrad 1433 Decade Resistor, characterized by a tolerance of 0.01 % [11]. The outputs of the two sensing elements are simultaneously sampled and acquired through the NI 6123 module and they are compared. The software for the automated measuring station has been implemented in LabWindows CVI, a C programming environment, measuring instruments oriented, distributed by National Instruments.

A. Calibration procedures

The measuring station is programmed in such a way that it automatically performs the desired number of tests in order to determine, with a prefixed uncertainty level, the mean transformation ratio, the frequency response and the linearity of the transducer under test.

The software operates this way: it activates the generation, it waits until the amplified waveform has become stationary and then it performs the synchronized acquisition of the two signals, which have to be compared. The tests are conducted generating sinusoidal signals, opportunely varying their amplitudes and frequencies; the number of tests is determined by the number of amplitudes and frequencies involved in the analysis. Each test, moreover, is repeated a certain number of times, according to [12], in order to minimize stochastic errors in the measurements, accounting the time-duration of the entire procedure. The full factorial of the experimental chart is performed.

The output waveforms of the sensing elements are sampled at fixed number of points per period: this allows to have an accuracy independent from the frequency. In particular, this fixed number of points is chosen basing on the ratio of maximum sampling rate of the utilized data acquisition board, which is 500 kHz, and the maximum frequency of the calibration signal, which is limited by the power amplifier and it is 9 kHz. However, the value of this ratio might be too low for calibration purposes, which require high accuracy.

Therefore, basing on the fact that, after a certain settling time, the calibration signal becomes stationary, the sampling resolution can be increased opportunely desynchronizing the generation and the acquisition frequencies. The acquisition frequency is chosen in such a way that the generated waveforms are sampled at non-integer number of points per periods; only after a certain number of periods of the generated waveform an integer number of acquired points represents an integer number of periods. In particular, once the actual frequency of the signal to generate for that test has been set, the acquisition frequency can be chosen with the following formula:

$$f_s = f_g\left(N+n\right) = f_g\left(N+\frac{1}{M}\right) \tag{1}$$

where f_s is the sampling frequency, f_g is the frequency of the generated signal, N is an integer number and n is non-integer number less than 1.

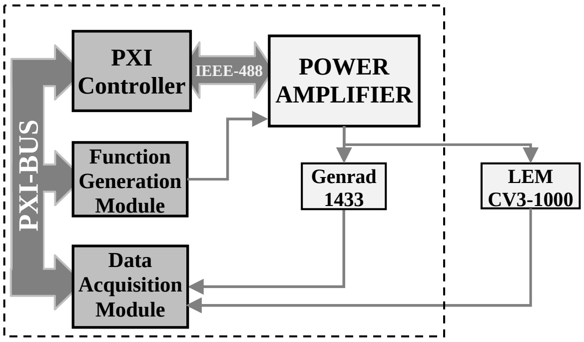

Figure 1. Block scheme of the realized calibration station.

The sum of N and n represents the acquired number of points per period: n can be chosen in such a way that it becomes 1 after a certain number M of periods. Therefore, since the signal is stationary, one period can be reconstructed from M periods, choosing a sampling frequency according to (1): in this way it is possible to increase the sampling resolution by a factor M.

B. Frequency response

The so sampled waveforms are digitally processed in order to evaluate the performances of the transducer under test. In particular, the ratio and the phase displacement, which constitute the frequency response, are found as:

$$A_{UT}(f) = \frac{V_{VD,RMS}(f) \cdot A_{VD}(f)}{V_{UT,RMS}(f)} = \frac{V_{IN,RMS}(f)}{V_{UT,RMS}(f)} \qquad (2)$$

$$\varphi_{UT}(f) = \varphi_{FUND,UT}(f) - \varphi_{FUND,VD}(f) \qquad (3)$$

where f is the frequency of the generated signal, $V_{UT,RMS}$ and $\varphi_{FUND,UT}$ are respectively the r.m.s. values and the phase angle of the fundamental component of the output of the transducer under test and A_{UT} and φ_{UT} are its transduction ratio and phase shift; $V_{VD,RMS}$ and $\varphi_{FUND,VD}$ are respectively the r.m.s. values and the phase angle of the fundamental component of the output of the voltage divider and A_{VD} is its rated transduction ratio. In (2), the first ratio is equivalent to that of the r.m.s. values of the input and the output for the transducer under test.

According to [3], [4], phase displacement is found as in (3), while ratio error and composite error are found as in the following formulas:

$$\Delta A_{UT}(f) = \frac{A_{R,UT} \cdot V_{UT,RMS}(f) - V_{IN,RMS}(f)}{V_{IN,RMS}(f)} \cdot 100 = \left(\frac{A_{R,UT}}{A_{UT}(f)} - 1 \right) \cdot 100 \qquad (4)$$

$$\varepsilon_c = \frac{100}{V_{IN,RMS}} \sqrt{\frac{1}{T} \int_0^T \left(A_{R,UT} \cdot v_{UT} - v_{IN} \right)^2 dt} \qquad (5)$$

where $A_{R,UT}$ is the rated ratio of the transducer under test, $\Delta A_{R,UT}$ is the ratio error, ε_c is the composite error, v_{UT} and v_{IN} are the time domain output and input signals of the transducer under test; it is worth noting that ε_c is determined at every frequency involved in the calibration procedure.

C. Linearity

A generic system is considered linear if it produces an output as a linear function of its input. The non-linearity error of an instrument is generally considered as the maximum deviation of its output from the output of an ideal linear instrument, that is an instrument that implements a linear relationship among the input and output data, obtained as the best linear fit of the input and output data pairs of the real instrument.

The non-linearity error is found this way. For each frequency a set of data, constituted by pairs of independent and dependent quantities, is constructed: the dependent quantity of each pair is the r.m.s. value of the voltage divider output, scaled by its rated ratio; the independent quantity is the r.m.s. value of the transducer output. Then, for each set a least squares linear regression is performed, i.e. each set is fitted with the linear function that minimizes the sum of the squared errors; in formulas:

$$y^* = a_0 + a_1 x \qquad (6)$$

$$S_e = \sum_{i=1}^{n} e_{yi}^2 = \sum_{i=1}^{n} \left(y_i - y_i^* \right)^2 = \sum_{i=1}^{n} \left(y_i - a_0 - a_1 x_i \right)^2 \qquad (7)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(y_i - a_0 - a_1 x_i \right)^2} \qquad (8)$$

In (6), a_0 and a_1 are the two parameters of the linear function and they are obtained minimizing the S_e in (7), i.e. the sum of the squared errors. In (8), $RMSE$ is the root mean squared error; it has been chosen used as an indication of non-linearity at a particular frequency, expressing it as a percentage of the full scale range.

III. Experimental results

The automated measuring station has been used to calibrate a commercial transducer, LEM CV3-1000 [13], produced by LEM, which is a hall effect voltage transducer and it has got a rated ratio of 100, an overall accuracy of 0.2 % and a -1 dB bandwidth of 500 kHz. Ten amplitude values, one hundred frequency values have been chosen and each test has been repeated thirty times: in total they represent an amount of 30000 tests. Moreover, sampling frequency has been chosen according to (1) with M equal to 30; for each test 150 periods of the generated signal have been totally acquired. In Figures 2-5 respectively ratio error, phase displacement, composite error and non-linearity error of this transducer are shown.

The curves shown in Figures 2-4 have been obtained averaging on the amplitude values. The mean value for ratio error is about 0.36 %, for phase displacement is 6.6 mrad, for composite error is 1.74 %, for non-linearity error is 11 p.p.m. of full scale range, which is about 707 V_{RMS}. In Table 1 the values of these errors and their combined standard uncertainties are reported: the uncertainty analysis has been executed following a type A calculation approach, [12].

IV. Frequency response compensation

In the digital signal processing algorithms transducers are generally considered as ideal devices, i.e. linear systems with constant gain/ratio and null phase displacement. Such assumptions are wrong in most cases and they could lead in big mistakes; it is known, in fact, that the transducers are the main sources of uncertainty in measurement digital equipments. Referring to electrical power quality and power measurements, since these types of measurements are used for billing, or for making customers pay penalties in case of low quality energy absorptions, it is important to have measuring/metering equipments with uncertainties as low as possible. It is also known, however, that transducers costs grow, sometimes exponentially, with their performances, and, especially for power and energy metering lowest cost measurement equipments are needed; therefore, transducers choice is always linked to the specific application.

The presented automated measuring station for the calibration of voltage transducers can be used for reducing errors coming from them, without increasing their costs; in fact, it has been proven its accuracy in the calibration of voltage transducers, and in particular in the evaluation of their frequency responses. Once a transducer has been metrologically characterized, its frequency response can be properly accounted in digital signal processing algorithms in order to be compensated . One possible way to correct it is through the use of the FFT and the multiplication in frequency domain; that is, when a certain portion of the transduced signal has been acquired, it can be transformed in frequency domain via FFT and multiplied by the inverse of the frequency response of the utilized transducer and then anti-transformed in time domain. This method, as it is conceptually simple, is impracticable in most cases, since it has got a lot of disadvantages.

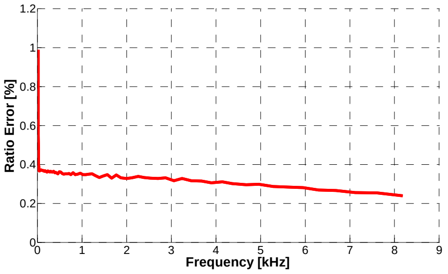

Figure 2. Ratio error

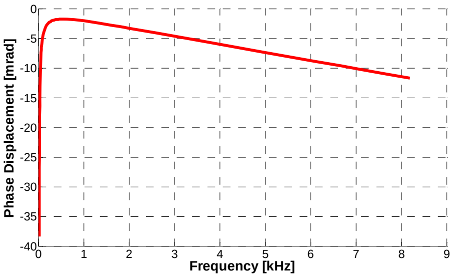

Figure 3. Phase displacement

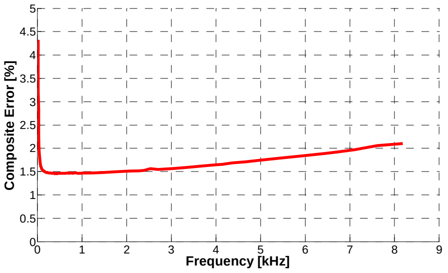

Figure 4. Composite error

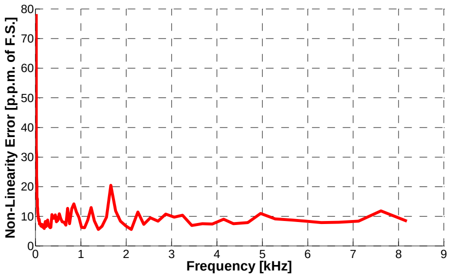

Figure 5. Non-linearity error

Table 1. Results of the commercial transducer calibration

Quantity	Mean Value	Combined Standard Uncertainty
Ratio Error [%]	0.36	0.032
Phase Displacement [mrad]	6.6	0.15
Composite Error [%]	1.74	0.042
Non-Linearity Error [p.p.m. of F.S.]	11	4.9

First of all, it is not adapt for real-time implementations, so it cannot be used in all the situations where real-time is a critical constraint. Second, it requires the execution of a FFT and of a IFFT, which can take a lot of CPU time and might be non realizable in low cost hardware. Third, and maybe the most important thing, is that the transform to the frequency domain requires the synchronization among sampling frequency and signal frequency; that is, in order to avoid gross blunders which might compromise the validity of the entire method, an entire number of periods of the input signal should be analysed. Since the sampling frequency is never synchronized with the signal frequency, a synchronization procedure is necessary and it, obviously, adds computational burden to the signal processing.

Therefore, a time domain procedure for the correction of the transducer frequency response has been developed. It is based on the identification [14], [15] of a digital filter which has got as frequency response the inverse of the utilized transducer.

If the transducer has got a low linearity error, it can be considered as a linear system. Its frequency response is given by:

$$Y(f) = \frac{1}{A(f)} X(f) \tag{9}$$

where X is the input, Y the output and A the ratio. Therefore, in order to eliminate the frequency dependence in (9), a digital filter has to be found, which has got a frequency response given by:

$$H\left(e^{j2\pi f T_s}\right) = A(f) = \frac{X(f)}{Y(f)} \tag{10}$$

where H is its frequency response and T_s is the sampling period. Such identification problem is an optimization problem and so an objective function has to be defined and an optimization algorithm has to be used.

Referring to the voltage transducer, whose calibration has been presented in sec. III, for the optimization problem an hybrid technique has been used [16], [17]: it consists in the combined use of a stochastic and a deterministic algorithm, which are, respectively, genetic algorithm and simplex algorithm. The objective function has been defined as the weighted sum of the squares of the errors among the modules of the two functions, i.e. the inverse of the transducer and the one to identify, and the phases of the same two functions. As sampling frequency 25 kHz has been chosen. Moreover, a non-linear constraint has been used in the optimization problem: it has been imposed that all the poles were in the unit circle, in order to assure the filter stability.

Several runs of the optimization algorithm have been conducted, and it has been found the best digital filter, in the sense that it gives the best value for the defined objective function, is an IIR filter with four poles and four zeros. The transfer function of the filter is shown in (11):

$$Y(z) = \frac{100.5359 + 8.5689 z^{-1} - 50.1060 z^{-2} - 10.9578 z^{-3} - 44.9490 z^{-4}}{1 + 0.1021 z^{-1} - 0.5129 z^{-2} - 0.1031 z^{-3} - 0.4550 z^{-4}} \tag{11}$$

In Figures 6-7, respectively, ratio errors and phase displacements, according to (4) and (3), of the transducer, before and after compensation, are shown. In particular, in Figure 6 curves before calibration, after calibration and after compensation are shown: curve before calibration refers to transducer rated ratio, while curve after calibration refers to transducer mean ratio, found from the calibration procedure shown in sec. III. It is clear that phase displacement doesn't change before and after calibration. The results of the compensation of the frequency response by means of the presented digital filter are shown in Table 2.

The presented results have some important consequences. First of all, it allows to build up an automated measuring station for the calibration of voltage transducers even with low cost reference transducers, opportunely calibrated with high precision reference ones: therefore the cost of a calibration station comes in a large reduction.

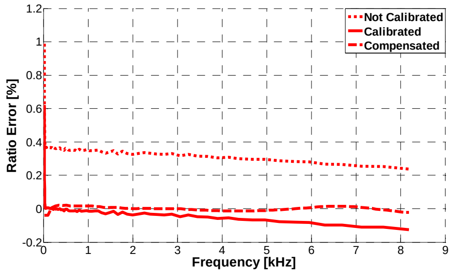

Figure 6. Ratio errors

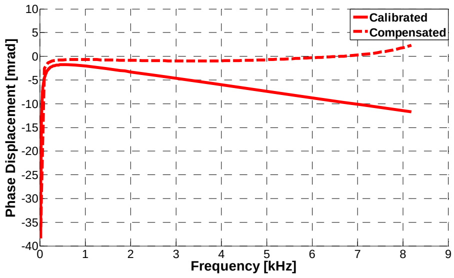

Figure 7. Phase displacements

Table 2. Results of the frequency response compensation

	Ratio Error [%]	**Compensation Improvement Factor**	**Phase Displacement [mrad]**	**Compensation Improvement Factor**
Mean Squared Value Before Calibration	0.31	25.8	8.0	2.1
Mean Squared Value After Calibration	0.057	4.7	8.0	2.1
Mean Squared Value After Compensation	0.012	-	3.7	-

Moreover, this procedure allows to improve the performances of the transducers installed in electrical energy utility points, in particular measuring transformers: they have not to be substituted but only real time corrected, even with low cost digital equipment, for being employed in much more accurate resulting energy and power quality measurements.

V. Conclusions

In this paper a fully automated measuring station for calibration of voltage transducers has been presented. It has got the capability of evaluating the performances of voltage transducers over wide amplitude and frequency ranges, according to power quality standards. As an application, calibration results of a commercial voltage transducer have been presented: the evaluated combined standard uncertainty shows that the realized automated station is suitable for the calibration of high precision voltage transducers. Moreover, since the transducer are the main sources of uncertainty in digital measurement equipments, a time domain real-time procedure for the correction of their frequency response has been presented, too. It consists in the identification of a digital filter that realizes the inverse of the frequency response of the calibrated transducer: using a 4th order IIR filter improvement factors of 4.7 and 2.1 can be obtained, respectively, for ratio error and phase displacement. Studies for the flux compensation of a current transformer by means of the presented real-time correction procedure are still in progress.

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