An Advanced Laboratory Architecture for Metrological Confirmation of Measurement Device for Power Quality Evaluation

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Abstract- Continuous monitoring of power grid aimed at assuring compliance of power quality indexes to standard requirements, calls for a wide range of instruments, each devoted to a different measurement. Metrological confirmation of the whole set of devices and instruments turns out to be a complex task – because of the variety of characteristics to be tested – that requires time to be completed which eventually determines high costs, not to mention that during confirmation activities instruments cannot be used. The purpose of the laboratory presented is to provide a complete set of confirmation services through local branches distributed over the territory. A central laboratory plans and supervises activities which are then delegated to peripheral labs employing travelling standards to perform confirmation directly at client's side thus reducing sensibly times of off-line operations. Experimental results from two different kind of measurements that require fast acquisition in one case and accurate acquisition in the other are reported as an example of the wide range of possible applications.

I. Introduction

Power Quality (PQ) has become an important concern for utilities, facility, and consulting engineers in recent years. In fact, end-use equipment is more susceptible to disturbances that flow through the supplying power system into customer's facilities and between apparatuses therein because they contain control systems provided with microprocessors that can suffer from PQ variations like momentary interruptions, voltage sags, capacitor switching transients, and harmonic distortion. To keep disturbances at an acceptable level and to test immunity of power loads specific standards have been issued [1]-[15]. Furthermore, today's equipment is more interconnected in networks and industrial processes so that the effects of malfunctioning of any one piece of equipment are much more severe.

Power quality monitoring is an essential service that many utilities perform for their industrial and other key commercial customers. Thanks to the technology and software now available, this monitoring is highly effective. Not only can a monitoring system provide information about the quality of the power and characterize disturbances helping finding possible solutions, but it can also identify conditions throughout the system before they cause problems. But power quality issues are not necessarily limited to the utility power system. Many surveys have shown that the majority of problems are localized within customer facilities. Thus an appropriate monitoring provides a key opportunity for a utility to protect its reputation and improve its relationship with customers.

For these reasons system monitoring instruments for PQ evaluation are worldwide required. Generally this monitoring can be achieved by performing measurements with a digital instrument that processes raw data of acquired voltage and current waveforms in confined [16]-[18] or distributed [19]-[21] environments. Commercially available PQ measuring instruments present a variety of sizes and configurations, because of the different application area and customer requirements. They can be utilized not only for the outer power grid, but also within customer facilities, and can measure different disturbances, such as flicker, harmonics and transients.

Metrological characterization of these instruments is not easy, because they must satisfy different requirements depending on the application the are intended for. As an example, high-resolution is required to measure stationary harmonics, while a continuous long time monitoring is required to measure fluctuating harmonics [22]. In some cases inexpensive devices that measures voltages and current a few times a second may face up the needs, whereas some applications require very high-speed measurements, i.e. when high frequency transients must be revealed. In these cases a broad range of power system variations should be detected, i.e. voltage swells, sags, transients, distortion and electrical noise [23], [24]. These difficulties are emphasized if metrological confirmation is to be operated on site.

Additionally, multifunction PQ monitoring system may be requested to comply with many different requirements, in which case the major problem is that no one complete standard exists that the user or designer can refer to. Instead, there will be the need to confront with the large number of international standards concerning PQ that are issued by different institutions, which fact may pose a tough challenge in terms of which is the most appropriate standard to apply.

During planning of confirmation activities, a high priority must be assigned to time required for test execution, in that most times the device to be calibrated must be sent to an outer service provider and therefore it cannot be used in the meantime. To the aim of making metrological confirmation an easier task, a distributed laboratory has been set up in order to perform the aforementioned tests as close as possible to client, thus obtaining a sensible reduction in time duration of monitoring outage. The software implementing the test procedures and coordinating the devices is developed in C++, Java and LabVIEW environment and everything has been made automatic through remote control of instruments.

In the following sections, after a brief review of current international standards concerning PQ to give an overview of how broad the range of requirements of measuring systems is, the proposed advanced laboratory architecture for metrological confirmation of PQ indexes measurement device is described. Finally experimental tests are reported and the main results presented with the aim to demonstrate the effectiveness of the proposed approach.

II. Power Quality indexes and instrumentation requirements

As far as PQ monitoring is concerned, the most important task is the definition of the objective of monitoring, because it in turn determines the equipment, the method of collecting data, the data processing and analysis technique and the required overall measurement accuracy. Monitoring equipment should be capable of recording the types of disturbances that can affect the loads, i.e. continuous, low-voltage, high frequency signals, conducted on the power lines, along with other very short signals known as transients. PQ disturbances can range from short interruptions to long duration amplitude variations [6], [7] and flicker. The first step in the implementation of a PQ measuring instrument is then the identification and definition of PQ indexes. A power supply system can only control the quality of voltage, because it has no control over the current that a particular load might draw. This is the real reason why standards are devoted to maintaining the supply voltage within certain limits. Standards refer to both the main voltage characteristics to be measured [9]-[11] and to the voltage and current limits [12], [15]. Moreover they contain measurement equipment requirements [16]-[19]. They include some parameters typically adopted to describe the performance of a wide range of instruments, such as bandwidth, sampling rate, refresh rate and resolution. But other factors can influence the measurement results, for example the way the instrument captures and reports short duration events.

A. IEC (EN) standards for voltage and current harmonics

Standard EN 61000-3-2 [8] specifies requirements for the equipment used to measure harmonic content of current, which may be injected into the public low-voltage distribution system. This standard refers to both time domain and frequency domain instruments for harmonic measurement, like selective amplifiers, heterodyne converters, multiple passive filters, digital filters and Discrete-Fourier-Transform (DFT) analyzers. Actually neither of them is considered as a reference instrument, even if the tendency is to consider a DFT based instrument that uses a rectangular window with a width of 16 cycles of power supply fundamental frequency.

The total measurement error must be ≤5% of the permissible limits or ≤0.2% of the rated current of equipment under test (EUT), in steady-state harmonic measurements. The input impedance of the whole instrument should not introduce a voltage drop exceeding 0.15 V peak. If harmonic components of measured current are expected to exceed the limit value during the test, a first order low-pass filter having a time constant of 1.5 s ± 10% should be adopted, in order to smooth peak values.

Requirements for frequency-domain instrumentation are pointed out for both steady-state (only) harmonics and for all other cases (including fluctuating harmonics). For steady-state harmonics, the required instruments selectivity depends on harmonic order *n*. In addition, if the current harmonic components present fast fluctuations during the test, instruments with a bandwidth in the range from

Table 1 – Maximum measurement error for the measurement of V and I harmonics

Class	Measured quantity	Conditions	Maximum error
A	voltage V_m	$V_m < 1\%\ V_{nom}$	$0.05\ V_{nom}$
	voltage V_m	$V_m \geq 1\%\ V_{nom}$	$5\%\ V_m$
	current I_m	$I_m < 3\%\ I_{nom}$	$0.15\ I_{nom}$
	current I_m	$I_m \geq 3\%\ I_{nom}$	$5\%\ I_m$
B	voltage V_m	$V_m < 3\%\ V_{nom}$	$0.15\ V_{nom}$
	voltage V_m	$V_m \geq 3\%\ V_{nom}$	$5\%\ V_m$
	current I_m	$I_m < 10\%\ I_{nom}$	$0.5\ I_{nom}$
	current I_m	$I_m \geq 10\%\ I_{nom}$	$5\%\ I_m$

3 Hz to 10 Hz can be used. In case of doubt, the allowed instrument bandwidth is of 3 ± 0.5 Hz between points at –3 dB, with a minimum attenuation of 25 dB for a single frequency signal at (f_n -15) Hz or (f_n +15) Hz (f_n being the frequency of the n-th harmonic). In a similar way, requirements for time-domain instrumentation consider both measurement of steady-state harmonics and all other situations. In the first case the main requirements are: i) the measuring window width must be between 4 and 30 cycles of the fundamental frequency, with an integer number of cycles; ii) the window shape is not specified; iii) the sampling rate must be synchronized to the fundamental frequency in case of a rectangular window, with a relative deviation ≤0.03%; iv) no requirements are indicated for gap and/or overlap between successive windows; v) the anti-aliasing filter attenuation must be ≥50 dB for frequencies folded back in the measured frequency band. For all the other cases, including fluctuating harmonics: i) there should be no gap and no overlapping between successive acquisition for rectangular windows, and a 50% overlap and no gap for the Hanning window; ii) in case of doubt, an instrument with a rectangular window width of 16 cycles of the fundamental, or an Hanning window width of 20-25 cycles, should be adopted.

Standard EN 61000-4-7 [9] specifies requirements for instrumentation used to measure voltage or current harmonic and interharmonic components. Specifically, it concerns measurement of: i) quasi stationary (slowly varying) harmonics, ii) fluctuating harmonics, iii) rapidly changing harmonics (or very short burst of harmonics), iv) interharmonics and other spurious components. Instrumentation may be differentiated according to: i) the signal characteristics, ii) the accuracy classes and iii) the type of measurements (voltage, current etc.). The input circuit must be designed for the nominal voltages 115, 230, 400 V. The characteristics and accuracy of input circuit should be unaffected up to 1.2 times the nominal voltage. Generally a crest factor of at least 1.5 is sufficient for normal measurement. For highly distorting loads in industrial networks, a crest factor of al least 2 may be necessary. The power absorption of the input circuit should be ≤3 VA; for high sensitivity instrument, the input resistance should be ≤10 kΩ/V.

The nominal values of input current circuits are: 0.1, 0.2, 0.5, 1, 2, 5, 10, 16 A. Two classes of accuracy are reported (A, B), both for voltage or current harmonics, as shown in Table 1. Power absorption of the current input circuit must be ≤3 VA for B class instrumentation; for class A instrumentation, the input voltage drop should be ≤0.15 V. Both frequency-domain and time-domain instrumentation may be used. Frequency domain instruments should satisfy EN 61000-3-2 [8] requirements. Special requirements are fixed out for time-domain instruments based on DFT; instruments using the Fast Fourier Transform (FFT) algorithm, consist of: i) anti-aliasing filter, ii) A/D converter with sample and hold unit, iii) synchronization and window-shaping unit if necessary, iv) FFT-processor, v) arithmetic-processor providing spectral amplitudes.

Quasi-stationary harmonics can be measured point by point and not continuously. The window width is related to the desired selectivity. In case of rectangular window the sampling rate should be synchronized to the fundamental frequency, to avoid erroneous frequency measurements. A strict synchronization is not necessary with Hanning window, but new spectral lines may be induced in the original signal. Fluctuating and rapidly changing harmonics should be measured continuously. Both off-line and on-line measurements are accepted; however, there should be no gap during signal observation. If a Hanning window is adopted, a

Table 2 – Basic requirements for FFT-instrumentation

Category of harmonics	Recommended window width	Additional requirements
Quasi-stationary	T_w =0.1-0.5 s	Gaps between windows may exist
Fluctuating	Rectangular window	
	T_w =0.32 s	No gap
	Hanning window	
	T_w =0.4-0.5 s	Overlapping half by half
Rapidly changing	Rectangular window	
	T_w =0.08-0.16 s	No gap

half-by-half overlapping is necessary; for rectangular window no overlapping is allowed. To measure fluctuating harmonics, an instrument with a rectangular window width of 16 cycles of the fundamental frequency, or a Hanning window width of 0.4-0.5 s, should be adopted. A small window about 8-cycle wide can be used to carry out the measurement of rapidly changing and transitory harmonics. This gives a compromise between selectivity, time response and smoothing of other transients phenomena. However, a width less than 4 cycles is not recommended.

In Table 2 a synthesis of basic requirements of harmonic measurement using FFT instrumentation is shown. Quasi-stationary interharmonics can be measured with instrumentation specified for quasi-stationary harmonics. Frequency-domain instruments are not appropriate to measure rapidly changing interharmonics. Time-domain instruments with a 16-cycle window width can be used, as a good compromise between bandwidth and ability to track rapidly changing amplitudes or frequencies. Optionally instruments may measure distortion factors and weighting functions. The most widely used index is the normal distortion factor *d*, which can be used to evaluate the thermal stress of electrical equipment: $d = \sqrt{\sum_{n=2}^{40} U_n^2} / U_1$.

B. IEEE standards for voltage and current harmonics

Standard IEEE 519-1992 [12] points out recommended practices and requirements for current and voltage harmonics. Measurements of steady-state harmonic component should be performed with an uncertainty ≤5% of the applicable limit. Selectivity is defined with specified minimum attenuation values for injected frequencies, as shown in Table 3. If the measured harmonics vary in time, it is necessary to smooth out the rapidly fluctuating components over a period of time, for example using a first order low-pass filter with a time constant of 1.5 ± 0.15 s. The bandwidth should be 3 ± 0.5 Hz between the –3 dB points with a minimum attenuation of 40 dB at frequency (f_n + 15) Hz. Time-variable harmonics can be presented as a function of time.

Table 3 – Minimum required attenuation

Frequencies [Hz]	Frequency-domain attenuation [dB]	Time-domain attenuation [dB]
60	0	0
30	50	60
120 to 720	30	50
720 to 1200	20	40
1200 to 2400	15	35

C. IEC standards for voltage fluctuation and flicker

Standard EN 61000-3-3 [13] specifies the required accuracy to measure voltage fluctuation and flicker impressed on the public low-voltage system. In this standard, flicker measurement is based on the voltage waveform variation at the terminal of the EUT, by evaluating the difference between two successive values of phase-to-neutral *rms* voltages (relative voltage change). The *rms* voltages should be measured or calculated. An on-line evaluation is required for unknown voltage fluctuation, while simulation is allowed if the voltage fluctuation law is defined. Current magnitude should be measured with an accuracy of 1% or better. Relative voltage changes should be defined with a total accuracy ≤8% with reference to maximum value of voltage change. Reference impedance values are defined in this standard; the stability and tolerance of the adopted one should guarantee an overall accuracy of 8% .

Standard EN 61000-4-15 [10] reports the specifications and performance testing of flicker measurement apparatus. The flickermeter architecture mainly consists of two parts, performing the following tasks: i) simulation of the response of the lamp-eye-brain chain; ii) on-line statistical analysis of the flicker signal and presentation of the results. The described apparatus has been thought for an analog implementation. The overall accuracy should be evaluated starting from the instantaneous flicker sensation carried out by the lamp-eye-brain simulation block; one unit of output corresponds to the reference human flicker perceptibility threshold. The prescribed accuracy is achieved if the input values for sine and square-wave modulations are within ±5% of the tabulated values, for one unit of perceptibility. A performance testing should be carried out with a regular series of rectangular voltage changes. In each case, the flicker severity P_{st} should be 1.00 ± 0.05.

D. IEEE standards for power quality instruments

IEEE 1100-1999 [14] reports some considerations about bandwidth, sampling rate, refresh rate, resolution and true *rms* response characteristics of PQ instruments. Bandwidth is not a problem for steady state monitoring, but for fast and high frequency transients it should be high enough to accurately measure the faster rise time of the event to be captured (typically in the MHz range). To obtain accuracy roughly within 3%, a vertical resolution ≥8 bits is required. Particularly interesting is the comparison between results carried out by different instruments: the same input waveforms can produce different *rms* measurements if the chosen instrument is based on peak-method, average-responding or true *rms*.

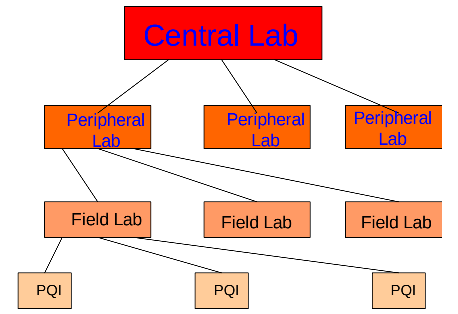

Figure 1: Laboratory Architecture

III. Laboratory Architecture

The proposed laboratory is organized in a hierarchical cluster structure. In particular there are three main levels (Figure 1): i) Central Lab (CL), ii) Peripheral Labs (PL) and iii) Field Labs (FL). CL coordinates the activities of PL's (in the actual implementation there are three PL's, but the network can be expanded without modification of the interaction procedures), which in turn supervise activities of FL's devoted to control on site power quality instruments (PQI). FL is capable of performing the metrological confirmation for both working and reference instruments, with the difference that in the latter case calibration must be carried out by a higher level calibration laboratory than that at which an instrument is used. Operations must be done under conditions and with uncertainty levels compatible with user's laboratory requirements, and it is essentially composed of three step: the initial verification, the adjustment and the final verification.

The core part of the system is the CL: it collects requests from users and dispatches the activity to the nearest PL. In order to execute the metrological confirmation of devices installed in the power plant, the PL is organized with some traveling standard which traces the behavior of field instruments without transportation to the lab. All activities, managed by an information network which connects all the blocks which constitute the lab system, as required by the purpose of a metrological confirmation system which is to keep the risk of production of measurements with unacceptable errors within acceptable limits, are made in accordance to the definition of metrological confirmation given by ISO 10012 [25].

First of all, CL, which is part of the Italian Calibration System (SIT), performs a series of inter-laboratory comparisons that permit to check the whole measurement process. Then, in the application of above mentioned concepts, the distributed lab is able to: 1) execute the calibration process; it is the most remarkable operation, because it carries out two important features: the traceability transfer from higher level standard instruments, and the verification of instrument metrological characteristics. Therefore, an appropriate calibration procedure must be set up which describe the whole process in an accurate way, and acceptance limits of calibration results must also be stated. This activity is made at the CL; 2) perform periodical verification between successive calibrations, with the objective of keeping instrument characteristics under observation and possibly identify unexpected malfunctioning before the next calibration, to avoid invalidation of measurement performed during calibration validity period. Frequency of such check depends primarily on the type of instrument, but on-site verifications can be carried out easily by comparison with a traveling standard controlled by a FL. If measurements stay within compliance limits for each point, then the instrument can be considered to have maintained the evaluated uncertainty for the year after its last calibration. Consequently, the evaluated uncertainty of procedures which utilize that instrument as a reference are confirmed too. If measurements overcome the limits, it is necessary to understand whether there has been an instrument malfunctioning, in which case it must be sent for fixing, or an underestimate of instrument's metrological characteristic uncertainties. To this aim the instrument is sent to CL which verifies functionality and can reevaluate uncertainty. It is also necessary to review the calibration certificates emitted in the past to detect those that are possibly invalid. Of course all these operations must be described in the laboratory quality manual.

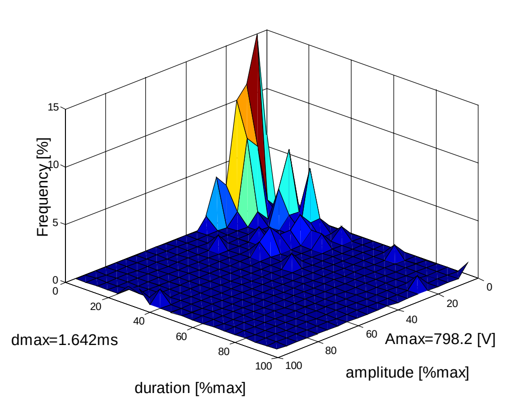

Figure 2 – Occurrences vs amplitude and time duration

IV. Experimental results

Table 4. Example of test in Flicker calibration

LEM NORMA D6000 – Linearity Test					
Number of changes per minute	Fluctuation Amplitude [%]	Reference P_{st}	Upper tolerance limit	Upper tolerance limit	Measured P_{st}
1056	0.06	0.20	0.09	0.31	0.20
1056	0.28	1.00	0.95	1.05	1.00
1056	0.56	2.00	1.80	2.20	2.00
1056	1.40	5.00	4.65	5.35	5.04
1056	2.80	10.00	9.40	10.60	10.12
1056	5.60	20.00	18.90	21.10	20.24

As application of proposed laboratory, some examples of experimental results are reported. In particular the objective of the monitoring activity shown in Figure 2 is the assessment of occurrences of impulsive disturbances as a function of their duration and amplitude, while Table 4 contains data from a flicker calibration of a Norma D6000 device. These applications has been chosen for their peculiarity. In fact the former requires high sampling rates, while the latter requires high resolutions. It can be seen that limits are strict and therefore very high accuracy, both in time and amplitude is required during measurement activity.

V. Conclusions

In the paper an architecture for a measurement laboratory has been presented. It is aimed at providing a complete set of confirmation services through local branches distributed over the territory through a central laboratory that plans and supervises activities which are then delegated to peripheral labs employing travelling standards to perform confirmation directly at client's side, thus reducing sensibly times of off-line operations. Experimental results show that the lab is suitable for operations that require both fast and accurate acquisition as shown by some experimental results. The lab is primarily conceived for PQ multifunction instrument verification and can also operate on-site by means of traveling standards.

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