Distributed Measurement Station for the Evaluation of the Impact of Power Electronic Equipment on the Power Quality of Electrical Distribution Network

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Abstract – *The quality of the electrical power supply is increasingly becoming a central topic of discussion. The interference sources in the mains are caused by electronic power control with non-linear components that are used more frequently (e.g. PCs and industrial systems with speed-controlled drives), also in domestic appliances (e.g. television sets, economy lamps). High order harmonics, voltage fluctuations and high frequency disturbances with slew-rates of some microseconds or less can be mentioned as examples. In some cases the frequency and width of these voltage variations can produce a physiological irritating phenomenon due to luminance fluctuations of the lighting (flicker effect). These electromagnetic disturbances can cover a large interval of frequencies and can be present in industrial, domestic as well as commercial systems. Therefore in the last years the monitoring of the quality of supply networks has become an issue of international interest. A low-cost distributed measurement system, which allows power supply quality to be monitored in large industrial environments, is then proposed in this work. The paper also goes on to discuss the problem of the characterization of the power monitoring systems, presenting the results obtained with our prototype.*

Keywords – Power quality, power system transient, distortion, voltage measurement, signal analysis, virtual instrumentation.

1. INTRODUCTION

The problem related to the Power Quality (PQ) measurement and monitoring has become a topic of international interest. This is because the actual trend is toward a widespread diffusion of electrical and electronic equipment that both can produce electromagnetic disturbances on the supply system and be sensitive to them. The main effects of power disturbances are reduction of industrial product quality and increase of the process downtime. Moreover, some negative effects can be observed also in domestic and commercial devices. Computer can be mentioned as a basic reference for the equipment, which are more sensitive to these disturbances that can cause lost of spurious data, or other failure.

To introduce the PQ, the main possible disturbances should be mentioned. Power supplies based on switching regulators or variable speed drives can generate high order harmonics on the power line [1,2]. The PQ can be compromised also because of voltage fluctuations, arising from brightness regulators that produce large voltage variations. Additionally, the frequency and width of these voltage variations can produce a physiological phenomenon, due to the fluctuations of lighting. Therefore, a lack of quality concerns the supply interruptions and deviations of the actual voltage from the nominal characteristic.

Many commercial and industrial companies ask for monitoring systems able to evaluate the PQ throughout a plant or a distribution network [3,4]. In this paper we propose a new system, applicable for the monitoring of PQ in large environments. It embodies a PC-based instrument and suitable voltage transducers, linked to LAN and TCP/IP networks. Key features are relatively low-cost, data processing and remote communication capabilities. The paper also goes on to present the experimental results related to the characterization of the system prototype.

2. THE REQUIRED INSTRUMENT FEATURES

As we pointed out, different disturbances can be present in the mains. The design of a PQ analyzer requires defining the instrument features, because they determine the equipment architecture and the required overall accuracy. The first step is the selection of the measurable disturbances. They are in the range of up to some kilohertz (supply harmonics), even if disturbances with slew-rates of some microseconds can be present.

To correctly identify the PQ indexes to measure, an important aspect of this problem should be underlined. 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. The standards of the main international organisations (IEC and IEEE) working in this issue [5,6] are then devoted to maintaining supply voltage within certain limits.

Brief momentary ($<\frac{1}{2}$ cycle) voltage disturbances are classified as impulsive or oscillatory transients (Table 1). They can produce degradation in the insulation of electric equipment like capacitors, transformers and rotating machinery, decreasing the MTBF. Sag and swell refer to momentary (from $\frac{1}{2}$ cycle to 1 min) decrease and increase in the ac voltage amplitude respectively, at the power frequency. Interruptions, sags and swells can produce the equipment shutdown that can require minutes (e.g. computers) or hours (e.g. plastic moulding machines) to restart.

Long duration variations (longer than 1 min) in supply voltage are referred as overvoltages and undervoltages.

Harmonic current injection from loads can cause harmonic voltage distortion, and then some problems and overheating of power machines and equipment. Harmonics produce steady-state distortion of a voltage or current signal when compared to a pure sine wave, which can be affected by

transient disturbances too. Their measurement requires different contrasting features. Specifically a high-resolution is required to measure stationary harmonics, while a continuous long time monitoring is required to measure fluctuating harmonics [5,6,7,8]. In some cases inexpensive devices that measures voltages a few times a second may face up to the needs. Some applications require very high-speed measurements of voltage, 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.

Table.1 Comparison between IEC and IEEE power quality parameters

IEEE Categories Std 1159-1995 Short duration variations	Typical duration	IEC Categories EN 50160-2000
Instantaneous sag	0.5 – 30 cycles	Supply voltage dip A sudden reduction of the supply voltage to a value between 90% and 1% of the declared voltage, followed by a voltage recovery after a short period of time. The duration is 10 ms – 1 min.
Momentary sag	30 cycles – 3 s	
Temporary sag	3 s – 1 min	
Instantaneous swell	0.5 – 30 cycles	Temporary power frequency overvoltage An overvoltage, at a given location, of relatively long duration.
Momentary swell	30 cycles – 3 s	
Temporary swell	3 s – 1 min	
Momentary interruption	0.5 cycle – 3 s	Supply interruption A short interruption (up to three minutes) caused by a transient fault.
Temporary interruption	3 s – 1 min	

3. THE PROPOSED MEASURING SYSTEM

The monitoring of the network PQ generally requires a distributed measurement system, which allows for finding out quality indexes at the same time, in different node of the power network. It can be achieved by performing the measurements with a digital instrument that processes the raw data of acquired voltage and current waveforms [7,8,9]. Factors that determine the instrument's performance are: dynamic range, frequency response, accuracy, data processing capabilities.

Our basic design idea is to build a measurement system on a wide area, by distributing the processing power, creating a cost-effective and flexible digital system with data processing and remote communication capabilities and a suitable user interface. As shown in the block diagram of Fig.1, the system hardware of a local Data Server Unit consists of a PC that hosts a data acquisition (DAQ) board, linked to the power system by a voltage transducer.

This measurement system allows of monitoring a large plant, verifying the functioning of each single device from a remote location by means of high-level user interfaces.

Many commercial and industrial companies need to install power monitors on a large scale. With the aim of managing the remote communication, we can connect the Data Servers both to a World Area Network (WAN) with a modem card or to a Local Area Network (LAN) with a LAN card. In the

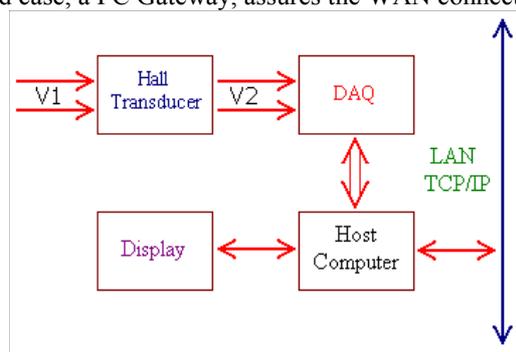second case, a PC Gateway, assures the WAN connection.

Fig.1- Architecture of the local Data Server unit.

The described measurement system makes it possible to monitor a large plant and to verify the functioning of each single station from a remote location by means of high-level user interfaces. The choice of the TCP/IP Internet makes possible a low-cost data communication, in order to evaluate the PQ indexes in wide electric power plant or in industrial zones. This is important for the disturbances source individuation.

In our system the computer controls the acquisition task, processes data and communicates with a remote server. The voltage transducer is a Hall effect closed loop. It guarantees galvanic insulation from the power network, frequency bandwidth of DC-150 kHz, accuracy of ±0.5 %, response time lower than 1 µs.

The main features of the DAQ multifunction board are 8 differential analog input channels with 16-bit resolution, maximum sampling frequency of 333 kS/s, maximum data transfer frequency of 333 kS/s, input range ±5 V, ± 10 V. The host computer is a low-cost PC, with a LAN board and the Windows 98 OS. The cost of the hardware is about 2000 EUR. The main features of the proposed PQ measurement system are: input range of 400 V, dynamic range of 98 dB, frequency bandwidth >150 kHz, response time < 1 µs.

We supplied the measurement instrument with a constant-voltage backup supply system, to provide adequate voltage during short duration voltage reductions. Moreover the backup system embodies surge protective devices.

4. THE MEASUREMENT ALGORITHM

The proposed instrument uses digital signal processing to perform PQ analysis of the voltage waveform. Processing the voltage samples v_i acquired through periodic sampling, carries out the measurement of the previously discussed quantities by the DAQ.

Non steady-state events are evaluated through a time-domain analysis. Specifically, we analyze amplitude, duration time, rise and fall times and rate of rise (dV/dt) maximum value of disturbances [6]. As has been previously stated, sags and swells describe voltage variations which duration is typically ½ cycle to 1 min, and are referred to as rms events. Instead of looking at the instantaneous waveshape, we examine the rms value of the wave. If this is below 10% the nominal value V_{nom}, then a sag or swell occurs. Occurrences of rms voltage 10% above or below normal value last longer than 1 min are over or under voltages. The voltage effective value is:

$$V_{rms} = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (v_i)^2 \cdot w_i} \qquad (1)$$

where w is a window function. We use different thresholds for triggering the instrument to register power system variations: sag: -10% V_{nom} ; swell: +5% V_{nom}; transient: +100% V_{nom}; noise: 1% V_{nom}.

The overload on the electric and electronic components due to the disturbance is evaluated by the Specific Energy:

$$E = \Delta T \cdot \sum_{i=1}^{N} (v_i)^2 \cdot w_i . \qquad (2)$$

The frequency-domain analysis is based on the FFT of the sampled disturbance waveform. The most significant information, for this kind of analysis, is the bandwidth, the maximum frequency value and the spectrum area of the disturbance waveform. The permanent harmonic distortion is evaluated by means of a global index, i.e. the Voltage Total Harmonic Distortion (VTHD) index [5], defined as:

$$VTHD = \frac{100 \sqrt{\sum_{n=2}^{40} (V_n)^2}}{V_1} \qquad (3)$$

where n is the order of the harmonic. The VTHD is widely used to compare differently distorted waveforms, when amplitude and phase spectra of the acquired waveforms are not directly comparable.

Moreover, we evaluate the Telephone Influence Factor (TIF):

$$TIF = \frac{\sqrt{\sum_{i=1}^{N} (V_i \, p_i)^2}}{V_{rms}} \qquad (4)$$

where p_i is the i-th element of a weighting coefficient array [10]. The TIF is a dimensionless parameter used to evaluate the effect of power harmonics on telephone lines and generally to evaluate the degree of distortion of the power signal (voltage and current). The VTHD and TIF indexes don't express information about the amplitude spectrum diagram of each acquired waveform; therefore the IEC standards fix additionally the maximum value for the first 25 harmonics of the voltage amplitude spectrum [5].

The flicker effect is due to a periodical amplitude modulation of the voltage sinusoidal waveform, whose frequency is 0.5-25 Hz [11,12]. This modulation produces luminance fluctuations in incandescent lamp, with consequent annoying results. To measure flicker effect we simulates the process of physiological visual perception (lamp-eye-brain response), to supply information about the human reaction to the voltage amplitude modulation, according to [11]. The severity level of flicker is evaluated by considering the short time flicker severity index P_{st}, obtained from the cumulated probability function of the instantaneous perception, for signal acquired for 10 minutes time intervals [13]

$$P_{st} = \sqrt{0.0314 P_{0.1} + 0.0525 P_{1s} + 0.0657 P_{3s} + 0.28 P_{10s} + 0.08 P_{50s}}$$

where $P_{0.1}$, .. P_{50s} are the flicker levels exceeded for 0.1%, .. 50% of the time during the observation period.

As concern the signal processing, different VIs, implemented using the NI LabVIEW graphical programming language,

have been implemented. In detail, it is possible to distinguish the disturbance simulation VIs, the measurement VIs, the acquisition VIs and the data server VI.

The simulation VIs generate voltage waveforms affected by transient disturbances, amplitude modulation or permanent harmonic distortion. They provide reference signals to evaluate the performance of the other VIs. The measurement VIs include a Spectrum Analyzer, a Transient Disturbances Analyzer, a voltage rms (Vrms) Statistic Analyzer and a Flickermeter (Fig.2).

We implemented two acquisition VIs, the Multiscan Acquisition Board Controller and the Continuous Acquisition Controller. The first is used to acquire voltage waveforms simultaneously with a particular event, e.g. a load transitions, the start of a high power induction motors or a change on the electric supply network configuration. The second is used to acquire waveforms continuously, for off-line measurements.
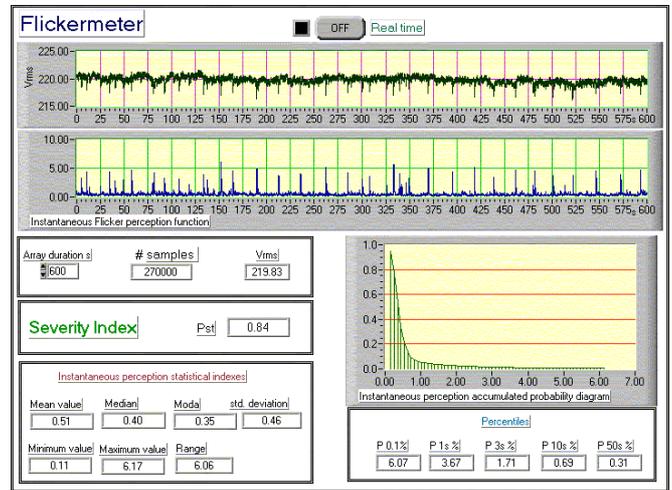

Fig.2 - User interface panel for the flickermeter

The Integrated Acquisition and Measurement VI controls the main parameters of the described VIs. It allows the operator to acquire a voltage waveform from one input channel, modify the sampling frequency and length of the sampled waveform for the different analysis requirements, execute the measurement algorithms of the PQ indexes and store only the waveforms whose disturbance exceed fixed values.

In our tests we generally set the sampling frequency at 13.6 kHz and the buffer length at 4096, in order to acquire 15 cycles of the fundamental (0.3 s). We use a double buffer on the DAS. The samples stored in the first are transferred to the PC for the data processing, while the system stores the samples in the other one.

The spectrum analyzer VI, which estimates the signal spectrum, processes each of these buffers. The transient disturbance analyzer VI divides the same buffer into 15 blocks (1 cycle) for the voltage analysis. The flickermeter VI processes 2000 buffers of data samples, corresponding to a 10 min period. It decimates the data to the more manageable sampling rate of 450 Hz, by using a rolling average technique and then operates the flicker measurements. Data processing is carried out concurrently with the data acquisition, in order to allows for a continuous monitoring of the PQ.

5. CHARACTERIZATION OF THE PROPOSED SYSTEM

We applied the implemented prototype to carry out some experimental tests, oriented towards the investigation of its performance, in terms of acquisition error and both data transmission errors and speed. First of all we used reference data supplied by the simulation VIs and checked the right working of the measurement algorithms.

Then we generated a reference low-voltage signal, to directly supply the DAQ board (without the voltage transducer) in order to both evaluate the acquisition and transmission errors and measure the data transfer speed. An arbitrary 16-bit signal generator supplied the low-voltage signal, in order to change both signal amplitude and shape. Typical voltage disturbances have been reproduced and compared to the measured values. In our test the DAQ sampling frequency was set at 13.6 kHz, so the sampling period was $Tc=73.5$ µs. For the sake of simplicity, in order to better compare the measured performances, in the following we reported the results obtained with low-voltages with reference to the corresponding high-voltages of the transducer (product between reference voltage and transducer attenuation factor)

The performance on measuring impulsive disturbances was evaluated by supplying the system with reference impulsive transients superimposed on the 220 V, 50 Hz sinewave voltage. The impulse duration influences the measurement error, in the sense that with duration of some sampling periods the instrument performs a correct disturbance reconstruction and then an accurate estimation of both duration and amplitude. When the duration is reduced to less than two sampling periods, the measurement error increases, because it is more arduous to reconstruct the signal shape. The effects are imprecise amplitude and duration values. As an example of the obtained results, a plot of the percentage error related to the measurement of both amplitude and duration vs. the transient amplitude is given in Figs.3 and 4, respectively.
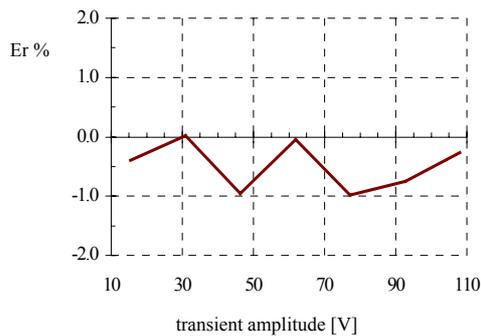

Fig.3 - Amplitude measurement error for impulsive transients with a constant duration of 147 µs.

The disturbance duration is of 2 $Tc=147$ µs and the amplitude of the voltage (without the sinewave) is ranging from 15 to 110 V. Even if this is the borderline case, the maximum percentage error is bounded to 1.0 % for the amplitude and to 1.8 % for the duration.

A transient disturbance with a duration lower than 2 Tc cannot be correctly calculated by the measurement algorithm, because less than two samples are affected by it. In order to show this effect, in Figs.5 and 6 the results obtained for disturbance duration of 1.5 $Tc=112$ µs are reported.
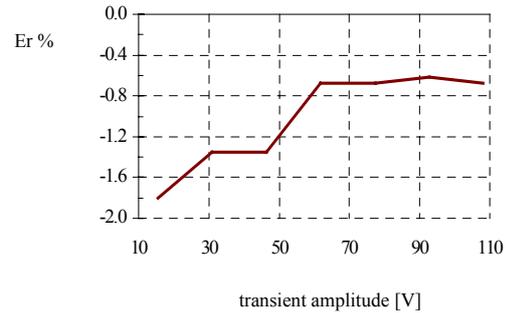

Fig.4 - Duration measurement error for impulsive transients with a constant amplitude of 147 µs.

In Fig.6 the error is plotted vs. the delay of the disturbance peak from the sampling instant. In these cases the maximum percentage error increases to 1.5 % for the amplitude and to 8 % for the duration. With a transient duration less than Tc, the instrument supplies unreliable results.
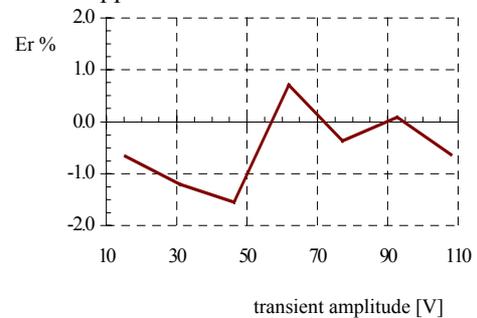

Fig.5 - Amplitude measurement error for impulsive transients with a constant amplitude of 112 µs.

The flickermeter characterization was carried out by changing the input modulation amplitude, so that the value of the perceptibility is unity, for different values of the modulation frequency. The modulation amplitude measured by the instrument, compared with the standard values specified in the [13], must be within ±5 %. The test results, shown in Fig.7, show a good agreement with the requirements, with a percentage error generally lower than 3 %.
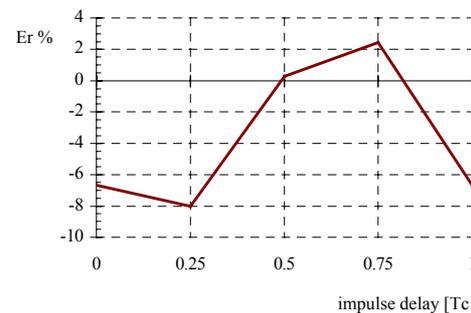

Fig.6 - Duration measurement error for impulsive transients with a constant amplitude of 112 µs vs. the delay.

To verify the performance on measuring the VHTD we applied to the instrument a sinewave signal that includes the first 25 harmonics. In Fig.8 the obtained errors are reported, for VHTD up to 10 %. Maximum value is 2 %, even if the error is lower than 0.25 % when VHTD is greater than 4 %.

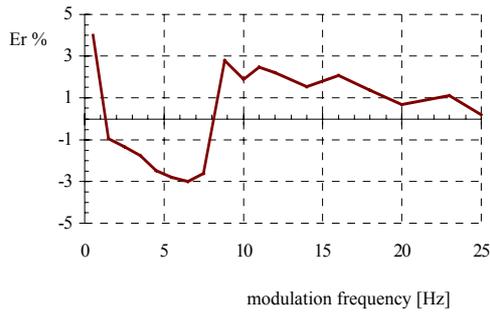The sensitivity of the system for each harmonic is 0.01%

Fig.7 - Flickermeter response for different values of the modulation frequency

Finally the field testing of the overall instrument has been carried out supplying it with a real line voltage (0-260 V), generated by a reference disturbance generator. This is an EMC PARTNER AG, model Transient 2000 that generates different kind of disturbances. We verified the prototype performance generating some dips, as required by the standard IEC 61000-4-11 (15).
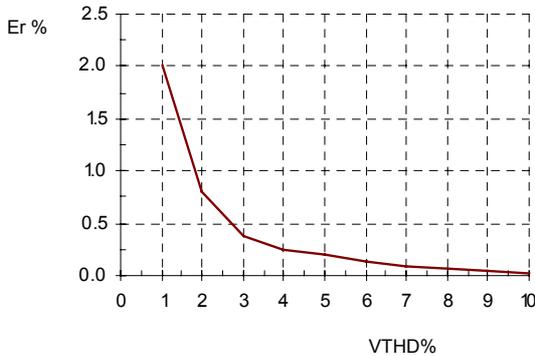
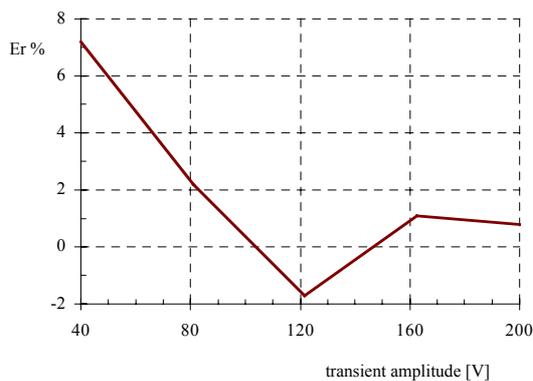Fig.8 - VHTD measurement error for different values of distortion

Fig.9 - Amplitude measurement error for impulsive transients with a constant duration of 166 μs.

The reference power signal has been applied to the voltage transducer of the instrument prototype. The measured quantities have been compared with those programmed on the generator. Representative results are reported in Figs.9 and 10. They show the percentage error related to the measurement of both amplitude and duration vs. the transient amplitude. The disturbance duration is of Tc=166 μs and the amplitude of the dip is ranging from 40 to 200 V. The maximum percentage error is bounded to around 7 % for the amplitude and to 6 % for the duration.
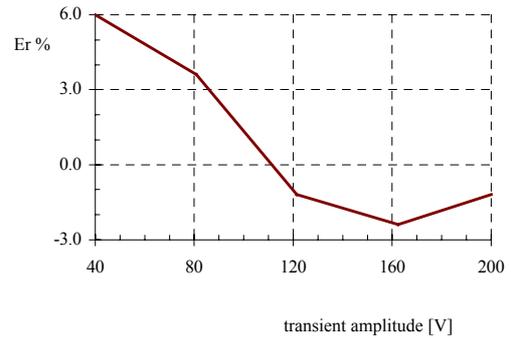
Fig.10 - Duration measurement error for impulsive transients with a constant amplitude of 166 μs.

6. CONCLUSIONS

In this paper a distributed measurement system, characterized by low-cost, flexibility and user friendship is proposed. Flexibility is guaranteed by software VIs that can be modified and adapted to different measurement features. User friendship is due to the high level of the graphical language adopted that permits to realize graphical user interfaces, working on Windows environments. The low-cost is due to the wide diffusion of both PC and related boards. In the paper the experimental results related to the system characterization are reported. All the tests appear to confirm the effectiveness of the proposed solution.

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