2

Power-quality Monitoring

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2.1 Introduction

Instrumentation for the measurement of conducted disturbances in power systems has undergone great development during the last decade. From the first instrumentation designed for general-purpose measurements, up to the current highly improved transients recorders, this kind of device has continuously evolved, becoming increasingly more specialised. In addition to the evolution of the hardware, there has also been significant activity in all topics related to the development of software for the analysis of measurements. In fact, managing records of power-quality (PQ) events is a problem that is growing day by day. Power-quality (PQ) monitoring should consider some basic questions:

- When to monitor. It is easy to program a power-quality survey after a problem has appeared. The difficulty lies in being able to do that before the problem arises, using a predictive approach.
- Where to connect. A correct choice of the instrumentation location in the power system is essential in order to draw valid conclusions.
- What instrument should be used. The choice between hand-held, portable or fixed equipment has to be made as a function of the time the instrument has to measure, the number of channels and the kind of disturbances we are looking for.
- What magnitudes should be measured. Sometimes a general survey has to be done, so all the power-quality indices have to be measured. In other cases, we are only interested in specific parameters.
- How to postprocess the registered data. After the measurement has been done, raw data and events have to be analysed in order to obtain conclusions.

2.2 State-of-the-art

In the spring of 1989 the European Union published the Directive 89/338/CEE [1,2], which started the countdown for the application of harmonized regulations relative to electromagnetic compatibility in the European Union. Currently, the regulatory process has still not finished, but there is an extensive set of standards that covers almost all aspects of electromagnetic compatibility (EMC) regulations.

It is obvious that EMC is an up-to-date topic, and not only for political reasons. The spectacular growth that has occurred during the last two decades in the utilization of power electronics in almost all kinds of electronic devices has given rise to an increase in the distortion of the distribution network. This growth in the number of electronic devices has not been accompanied, in many cases, by an improvement in the quality of the electronic designs. What is worse, most of them are extremely sensitive to the existing disturbances in the distribution network, so they exhibit malfunction during their operation under disturbed networks. These and other reasons are the motivation behind active research work on PQ instrumentation.

2.2.1 Historical Background

Two decades ago, the available instrumentation for power-quality assessment did not exist, and at best, they had a general purpose like oscilloscopes or spectrum analysers. The use of general-purpose instruments provided raw data that had to be postprocessed in order to obtain any conclusion. In other cases, the engineers and technicians were equipped with real root mean square (rms) voltmeters and ammeters, so the analysis used to be a difficult task only available to experts.

The existing instrumentation that can be utilized for power-quality evaluation could be classified into two sets according to their degree of specialization:

- General-purpose instrumentation.
- Specific-purpose instrumentation.

2.2.2 General-purpose Instrumentation

Basically, general-purpose instrumentation includes oscilloscopes and spectrum analysers. Spectrum analysers can be also divided according to the procedure of analysis:

- Digital signal analysers. These utilize the fast Fourier transform (FFT) or similar techniques to compute the spectrum of the signal.
- Analog signal analysers. These are based on parallel banks of analog filters than can be tuned in order to obtain the value of the spectrum components.

The analysers that use the FFT have standardized features, and in commercial format they are provided with bandwidths from 0 Hz up to 20, 100 and even 200 kHz. These equipments usually have 1 or 2 input channels, though some of them can have 4, 8 or 16: it being possible to carry out graphical representations of the signals in both time and frequency domains. Another characteristic to evaluate, in this type of meter, is the possibility of doing zooms of specific ranges of the spectrum of the signals. In many cases, it is also possible to use different windowing (rectangular, triangular, *etc.*) during the sampling process.

The analysers based on parallel banks of filters were, historically, the first ones to appear. The basic principle behind them is quite simple. A set of analogical bandpass filters divide the spectrum into bands whose union makes it possible to reconstruct the spectrum of the original signal. The main drawbacks are the cost and the complexity, reasons for which their use is reduced to applications of very high accuracy in which cost is a secondary factor. The bandwidth of these analysers is in the 100 kHz range, and they are capable of achieving resolutions of 1 Hz.

Whatever the structure of the meter, it is important to be able to have offline access to the measured information, in order to postprocess the measured data. The majority of the systems that use the FFT provide an output of information in RS232 or IEEE-488 format, with the possibility of programming the instrumentation externally, and to do some type of remote control. Nowadays, many of them also have an ethernet interface, so that they can be connected to a local area network or The internet.

Another important feature is the number of different windows that can be used with them in the process of sampling, usually between 2 and 12. The resolution of the analog-to-digital converter (ADC) is another parameter that changes from one device to another. The majority have between 12 and 16 bits, though many of the existing oscilloscopes have only 8 bits.

With regard to the possibility of analysing interharmonics, some instrumentation devices provide up to 3200 spectral lines free of aliasing and distortions in a bandwidth of 128 kHz. Working in real time, the bandwidths allow the majority of the equipments to go beyond 10 kHz.

2.2.3 Specialised-purpose Instrumentation

Two decades ago the instrumentation to monitor power quality was only a prototype that one could find in some research laboratories. Today, there is a competitive market.

Table 2.1 summarizes the most important features of the instrumentation designed specifically for power-quality measuring. Also included here are the characteristics of an open platform named MEPERT that has been developed at the

Electrical Engineering Department of the University of Cantabria [3–5]. MEPERT is shown in Figure 2.1.

Table 2.1. Typical parameters of a power-quality meter

Type of application	Hand-held Portable Fixed installation
User interface	Alphanumeric Graphic Oscilloscope Text Blackbox
Measured parameters	DC voltage and current Harmonics and interharmonics Ground resistivity Power factor Flicker Power / energy Transients (> 200 μs) Impulses (< 200 μs) Dips Overvoltages Imbalance Frequency Other disturbances
Type of meter	Trends Energy Spectrum analyser Transients recorder
Type of communication	RS-232 Ethernet TCP/IP Modem Power-line communication Other

In general, this type of system makes it possible to carry out the evaluation of any type of conducted disturbance: variations of the nominal frequency of the supply, variations in the magnitude of the voltage supply, transients, flicker, imbalance, harmonics, interharmonics, dips and interruptions as defined by the standard EN 50160 [6]. In many cases they have, in addition, specialized software able to analyse the stored measurements [7,8].

In 1990, the Electric Power Research Institute (EPRI), which is the organization that coordinates the research on electrical systems in the USA, had already established projects with Electrotek Concepts for the development of an integral software for disturbances analysis [9].

Figure 2.1. PQ meter open platform designed at the Department of Electrical Engineering, University of Cantabria

In the above-mentioned project, an instrumentation developed by BMI was in use. Power-quality surveys are not new. In fact, there are references [10,11] from 1993 that summarize the state of the distribution network in the eastern part of the USA.

Since the beginning of the 1990s, it has been possible to find commercial power-quality meters that do not limit their analysis to harmonics. This study includes more than 5400 points/month of information over two years. The implemented software was designed at Electrotek Concepts by a research team led by E. Gunther.

Nevertheless, and in spite of the fact that there exist documents that specify the requirements for the measurement of harmonics and interharmonics (IEC 61000-4-7) [12], flicker (IEC 61000-4-15) [13], and some other disturbances, there is still no document that draws together all the aspects and specifications necessary for the development of a global power-quality meter. Figure 2.2 includes the results obtained from the comparison of a set of commercial power-quality meters from different manufacturers [5].

From the point of view of the available communications, it is possible to say that in the 50% of the cases the remote management of the instrumentation is implemented by means of modems. The remaining 50% is distributed in almost equal parts between one native ethernet interface and TCP/IP.

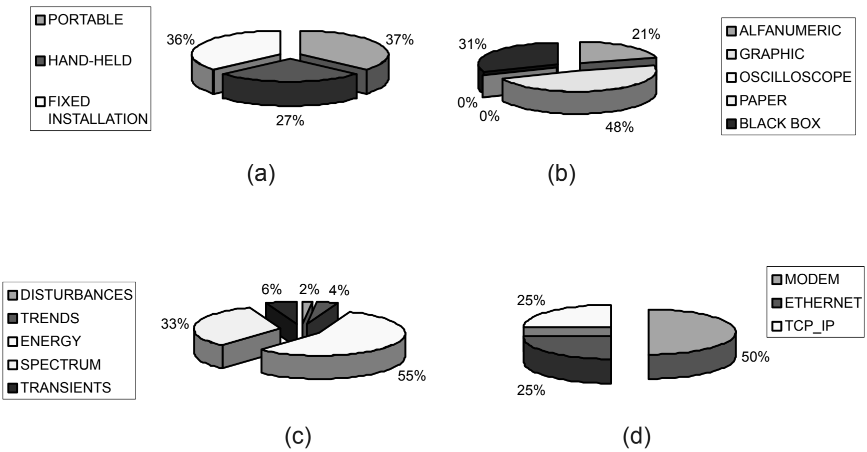

Figure 2.2. Classification of commercial PQ meters by different criteria. (*a*) Type of meter; (*b*) Type of user's interface; (*c*) Type of measurements; (*d*) Type of communication interface

2.3 Instrumentation Architecture

The voltages and currents to be measured can be accessible directly or indirectly in the case of LV and MV/HV systems, respectively. EURELECTRIC [14] established a basic architecture of the measuring system that is shown in Figure 2.3.

The term instrumentation spans, theoretically, V_s to G_e, though in general it is assumed that a power-quality meter includes all the elements from V_m to G_e. This means that the measuring transformers can be considered as an independent system.

This dichotomy of the measuring system can be also observed in the standards, which define specific documents for the instrument transformers and the rest of the electronic system. In addition, Figure 2.4 shows the basic architecture of a power-quality meter.

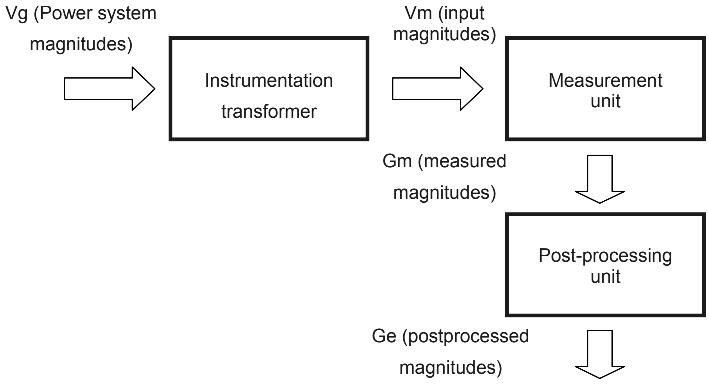

Figure 2.3. Main elements of a PQ instrumentation system

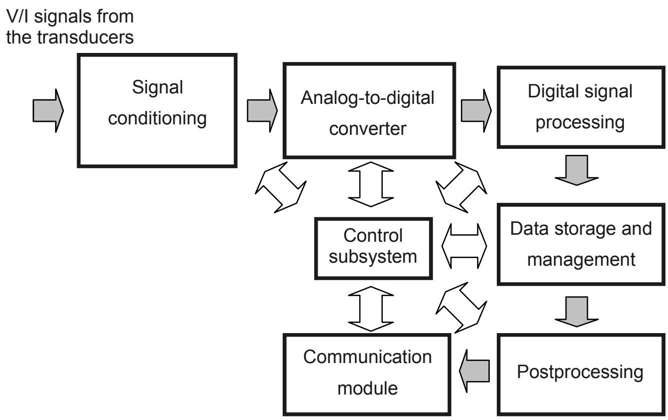

Figure 2.4. Basic architecture of a power quality-meter

2.3.1 Safety Use of PQ Instrumentation

The safety of both the operators and the instrumentation used in the measurement of electrical magnitudes is an aspect that is considered to be an annex to the intrinsic problem of measurement, since in general it is transparent to the user. It seems to be evident that if a manufacturer wants to sell an instrument to monitor the evolution of the rms value of an intensity up to a maximum value of 100 A, the equipment will be capable of supporting at the very least the above-mentioned intensity without suffering any type of damage or malfunction either transitorily or permanently. This type of guarantee is, in many cases, obvious for the users, but perhaps not so much for the designers and manufacturers of the instrument, who must submit the designs to a series of tests that guarantee their safety.

The measure of voltages and currents with portable equipment constitutes generally risky work, so that it is necessary to reduce or to eliminate any situation of potential risk for the user, the instrumentation or the installation. In many cases the problem can be worse, because there could appear overvoltages or overcurrents that go over and above the nominal values established by the standards, so that it is necessary to introduce additional measures of protection. In order to guarantee the safety of persons and equipment, there exist some regulations that must be followed when the instrument is acquired.

The equipment must indicate clearly the maximum voltage for every type of measurement (DC or AC). In addition, the test points must also indicate the maximum voltage that they support, since, in general, they are not permanently connected to the instrumentation, and therefore, they can be exchanged by others of different characteristics. The equipments have, in general, protection fuses, which will have to clearly indicate the maximum current and the performance speed.

The probes must be suitably isolated, and at the same time the connections with the instrumentation must assure the separation of parts under voltage. If it is necessary to replace some internal element such as fuses or batteries, it will be necessary to give clear warning of the obligation to disconnect the equipment from parts with voltage.

All the previous points must be taken into account for designers and users, who must not forget the existence of regulations relative to safety in equipment. The basic sources of information are: European Union (CENELEC), specific regional Procedure of Canada (CSA), United Kingdom (UL), Germany (VDE), Spain (UNESA) or Switzerland (GS) just to mention some, and that must be certified in order to be sold in the above-mentioned countries; in the case of the European Union, the equipments have to bear the mark CE.

As an example, the standard IEC 61010-1 [15] relative to the safety requirements for electrical equipment for measuring, controlling or use in a laboratory establishes a classification according to different criteria, based on the type of isolation:

- *Basic*, which refers to equipment whose parts under voltage, in normal working conditions, have levels below 30 rms volts, 42.4 peak volts or 60 DC volts.
- *Double*, for all other equipment, or those that are not connected to ground.

2.3.2 Number of Channels

From the point of view of instrumentation design, one of the most important aspects to consider is related to the input channels. First, it is necessary to establish the number of channels. Due to economic criteria, the choice of the number of channels is based on a specification of minimal needs. Figure 2.5 establishes a criterion for the classification of the number of measuring channels according to the application.

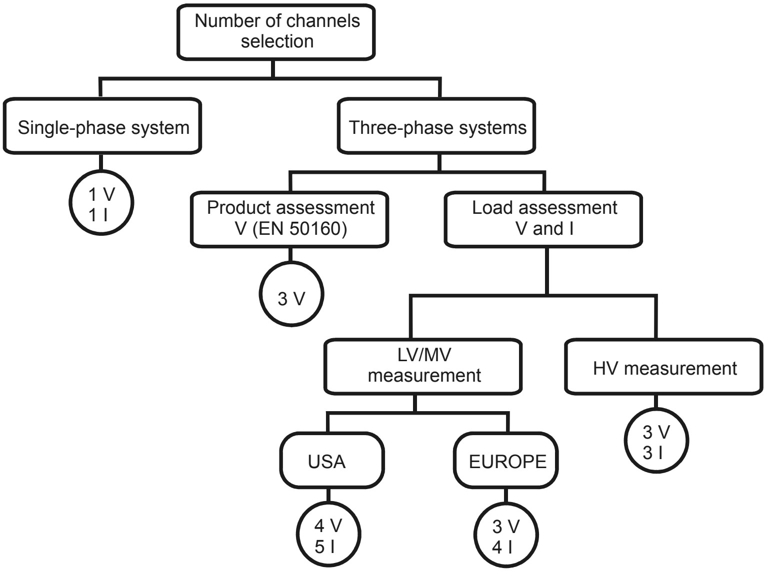

Figure 2.5. Diagram for number and type of input channels

One of the most interesting aspects of the structure shown in Figure 2.5 focuses on the difference in measurement needs on low voltage networks between USA and Europe. The distribution networks in USA are based on the connection of single-phase loads or unbalanced three-phase loads, principally in an open triangle form, which originates the need to control the current of the neutral. In addition, it is quite common for the distribution in medium voltage also to be based on four wires. On the other hand, in Europe, the distribution is based on three-wire systems. This means that if there is any current flowing to ground it can be considered a fault.

In the USA, it is quite usual to install the protection wire, so it is necessary to monitor the voltage between neutral and ground in order to detect certain faults. The measurement of this voltage requires a channel with a very small range of measurement. In Europe, it is normal to meet systems of isolated neutral or neutral connected to ground by means of a high impedance, which is why the measurement of these voltages and the associated current to ground is not important in many cases.

Voltage measurement can be classified according to two different approaches: common unified and independent channels.

2.3.3 Common Unified Channels

In this type of measurement, all voltage channels have the same reference. From a practical point of view they are characterized by having $N+1$ measurement wires for the monitored voltage, with N being the number of channels. It is a measurement system quite commonly used at present, especially in the USA, where the distribution systems have the neutral conductor connected to ground.

This structure is valid only for distribution systems with a neutral conductor. In some cases, if the neutral conductor is not accessible, an artificial one is created. Nevertheless, the utilization of an artificial neutral for the measurement of phase to neutral voltages is subjected to the hypothesis of having a symmetrical voltage.

Figure 2.6 shows a three-phase system where only points A, B and C are accessible. To be able to measure the phase to neutral voltages, a high-impedance wye-balanced three-phase load is used, which does not modify the network.

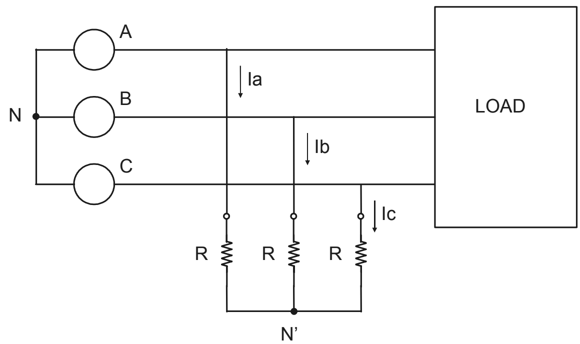

Figure 2.6. Equivalent circuit of virtual wye load for phase to neutral measurements

If the three-phase system, the voltages for which we are trying to measure, is balanced, the point N is equal to N' and then the neutral point of the fictitious load does not suffer any displacement with regard to the neutral of the generating system or, in other words, the phase voltages are the distribution network voltages.

If the voltages to be measured constitute an unbalanced three-phase system, the measured phase voltages are different from the distribution-network phase voltages. In this case, infinite solutions can be found for the phase voltages, thus it is not possible to measure the real ones.

Since, in general, it is not possible to establish whether a distribution network is balanced from the measurement of the phase to phase voltages, the conclusions obtained from these kinds of measurements must be avoided.

2.3.4 Independent Input Channels

This type of input-channel arrangement constitutes the most widely used architecture. From a practical point of view it also enables the unification of all the input-channel references. In a general case, completely independent measurements can be done without additional elements. The latter possibility can be really interesting in cases in which different voltages without common references have to be monitored, since it can be the case of different measurement points in substations (*e.g.* different potential transformers).

2.3.5 Transducers

The aim of transducers is to provide a small voltage signal (with typical amplitudes between –10 and 10 V), which are proportional to the levels of voltage and current that have to be measured. In general, a correct utilization of the transducers means that their frequency response has to be completely characterised, both in magnitude and phase.

Although according to EURELECTRIC [14], voltage and current transducers are physically independent from the instrumentation, it is very important to have a good understanding of the basic criteria for their correct selection and utilization. An appropriate selection of current transducers has to take into consideration, among others, the following features: nominal values, geometry, maximum value, accuracy, range of frequencies to measure, *etc*.

There are some different technologies available for current measurement. Table 2.2 summarizes a comparison between current transducers for low-voltage usage.

Potential transformers (PT) usually have an accuracy greater than 1% between 40 Hz and 1500 kHz. At MV and HV the capacitive effects become more dominant. From a practical point of view, the accuracy itself is not as important as their linearity. This is because voltage harmonics are computed as a percentage of fundamental, and not as absolute, values. The phase displacement in that range is typically over 40 minutes or more.

On the other hand, current transformers (CT) have an accuracy of over ±0.5% for frequencies from 20 to 1000 Hz. The performance at 1 kHz starts to decrease and the maximum bandwidth is about 10 kHz.

Independently of the kind of current transducer being used, all of them have a set of common parameters that have to be understood. Figure 2.7 shows the equivalent electric circuit for a generic current transducer.

Table 2.2. Current transducer comparison

	Input Range	Over-range Capacity	Accuracy	Sensitivity	Bandwidth	Security
Resistive *Shunt*	+	+	++++	++++	++++ DC-100 MHz	+ No isolation
Inductive	++++	+++	++ ±0.5% 0.5º	++	++ 20 Hz–1 kHz	+++ Single isolation
Hall effect	++++	+++	+ ±1% 1.5º	++ 1.5-3.0 V/FSA	+++ DC–50 kHz	++++ Double isolation
Rogowski Coil	++++	+++	+ ±1% 1.5º	+ 0.2 V/FSA	+++ 1 Hz–10 MHz	++++ Double isolation
Optical	+++++	+++++	++	+	++++	+++++ Double isolation

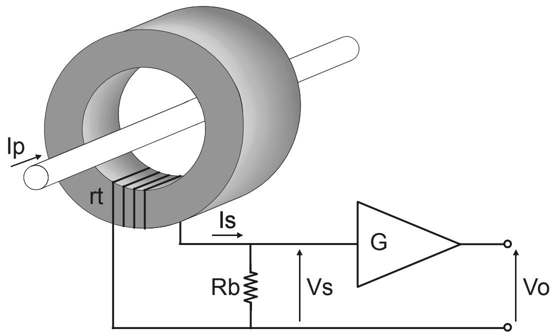

Figure 2.7. Equivalent circuit of a generic current transducer

The circuit shown in Figure 2.7 allows us to obtain the relation between the current I_p that has to be measured and the proportional output voltage V_o,

$$I_p = \frac{V_o r_t}{G R_p} \tag{2.1}$$

where,

I_p is the current to be measured,
V_s is the voltage before the amplifier,
V_o is the output voltage,
G is the amplifier gain.

From the point of view of the user of the instrumentation, the most important aspects are: transformation ratio, measurement range, bandwidth and geometric dimensions. The manufacturer is required to provide the curves of magnitude and phase versus frequency. In [16-18] some procedures are commented on in order to accomplish the contrast of PQ meters and transducers. Figure 2.8 shows the Fluke 6100A, which is a commercial test system that can be used for instrumentation and current transducer tests.

One of the problems that is still not completely solved in the design of instrumentation for power-quality measurements in high-voltage systems is the direct measurement of voltage and current, especially when transitory phenomena have to be registered.

Classical instrument transformers include both current transformer (CTs) and potential or voltage transformers (VTs). These kinds of devices are designed for 50 or 60 Hz, so their behaviour at high frequency could exhibit nonlinearities and other unwanted effects.

Figure 2.8. PQ meters and transducers test and calibration unit Fluke 6100A

One of the solutions to this problem can be the utilization of optical transducers. In the early stages, optical elements were introduced only in the signal transmission between the classical transducer and the instrumentation. In recent years, much effort has been made towards the design of totally optical transducers [19].

In formal terms, the current that is passing through a conductor can be expressed as the integral of the magnetic field in a closed path that includes the conductor. This is,

$$I_p = \oint H dl \tag{2.2}$$

where,

I_p is the current to be measured,
H is the magnetic field,
dl is the closed path of integration.

The previous equation serves as a background for the design and manufacturing of the classic transducers that are used nowadays, and it also, certainly, constitutes the theoretical basis for optical transducers.

In a basic form, optical transducers are physical devices that modify some of the properties of the light that travels through them, because they have been immersed in a magnetic field, the intensity of which changes with time. One of the most used phenomena is named the "Faraday's effect" or the "magneto-optic effect" in the technical literature.

To understand the mechanism that gives rise to this effect, it is necessary to know that a beam of light with an arbitrary polarization can be expressed as a combination of two orthogonal components polarized linearly, or as a combination of two orthogonal components circularly polarized. An analogy can be established between these circular basic elements and the components of positive and negative sequence in a three-phase system.

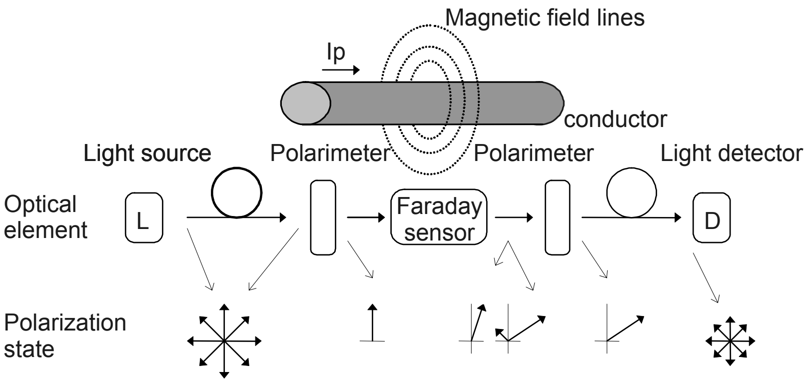

Figure 2.9. Structure of a current transducer based on the Faraday effect

The Faraday effect is, basically, a process of optical modulation, that is, a process of rotation of the plane of polarization of a beam of light polarized linearly, and proportional to the magnetic field that is passing through the material. The variation between the angle of rotation and the intensity that flows through the conductor is a constant named Verdet's constant. The law that defines the angle of rotation is,

$$\theta = \mu_r v \int H.dl \tag{2.3}$$

where,

θ is the rotation that the light beam component undergoes when it passes through the material,
μ_r is the relative permeability of the medium,
ν is Verdet's constant.

The following problem to solve is rooted in the fact that it is difficult to measure the degree of polarization of the light directly, hence it is necessary to perform a previous transformation of the degree of polarization of the light in optical power (square of the field E). This transformation is done by means of a light polarimeter. Figure 2.9 shows the block diagram of a Faraday-effect sensor. The measure of the intensity is computed as a ratio between the input and output optical power.

There are also optical voltage transformers. These are based on an electro-optical effect that produces a rotation of the polarization plane.

As a conclusion, it can be said that optical sensors for current measurement are small, accurate and do not suffer from the isolation problems, lack of accuracy and poor frequency response of the classic transformers. Nevertheless, they have not led, at least at present, to a reduction in volume compared with the conventional instrument transformer, since the electrical companies demand elements similar to the classical ones, in order to be able to replace them without mechanical changes.

2.3.6 Signal-conditioning Module

The signal-conditioning module acts as an interface between the transducers and the analog-to-digital converter. It can be seen as a glue element between the analog and digital worlds. Their main objectives can be summarized as follows:

- To provide galvanic isolation between the power system and the user of the instrumentation.
- To amplify and/or to attenuate adequately the voltage or current signals in order to obtain the maximum dynamic signal range, guaranteeing in this way a high signal-to-noise ratio.
- To avoid aliasing problem by means of low-frequency filters.

Figure 2.10 shows a block diagram of this module, where the described elements can be seen.

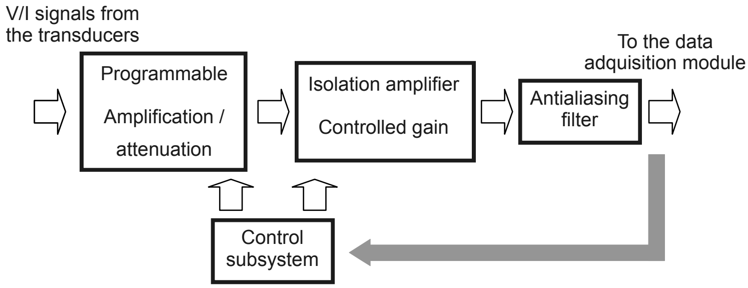

Figure 2.10. Diagram block of the signal-conditioning module

2.3.7 Analog-to-digital Converter

The analog-to-digital converter (ADC) is the module that has the responsibility of translating the signal from the analog to the digital domain. It carries out two basic tasks [20]:

- i) Signal discretization. This is the process of periodic sampling of the signal using the Nyquist–Shannon theorem [21]. It allows us to obtain a sequence of samples $x[n]$ obtained from a continuous-time signal $x(t)$.
- ii) Signal quantization. This is a mathematical transformation that assigns a fixed-point binary number to a sampled signal value that belongs to the real numbers.

The resolution of analog-to-digital converters in power-quality instrumentation has values between 8 and 24 bits. Other values can also be found, but are not typical.

From a numerical point of view, quantification is a nonlinear transformation that produces an error. The error range depends on the number of bits of the ADC and the input range.

2.3.8 Signal-processing Module

The signal-processing module is the core of the instrumentation. It includes the task manager, which controls the device and the set of algorithms that compute the power-quality indexes, the file manager and the communication facilities. The main features of this module are:

- Reprogrammed firmware. This characteristic allows us to programme and to reschedule the functionality of the system without hardware modification, which reduces the development costs enormously. For instance, a system can be updated to measure harmonics with different algorithms or standards without changing the hardware.

- System stability. This involves repeatability of the implementation and of the response. It is easy to understand that a digital system provides the same answer to the same question. This is not so with analog systems, where the response is a function of the temperature, age, humidity, *etc*.
- Suitable for implementing adaptive algorithms and special functions such as linear phase filters. The utilization of numerical algorithms allows external errors due to changes in the operating conditions to be corrected dynamically.
- Able to compress and store measurement data. It is not necessary to highlight here the importance of computers in the storage, treatment and recovery of information.
- User-friendly interfaces. The utilization of graphical user interfaces (GUIs) facilitates the interaction of the user with the instrument.
- Low power consumption. These kinds of devices have a power consumption less than 3 VA.

2.4 PQ Instrumentation Regulations

Standards provide a common reference framework that allows us to compare the qualities of the products that we, as consumers, use in our daily lives. The set of standards that regulate power-quality measurements belongs to different groups of documents. Firstly, the whole regulation that defines the technical characteristics of the instrumentation. Secondly, the measuring procedures and finally, the legal limits of the power -quality indices.

In Spain, the legal framework began with Law 54/1997, which was later given greater depth in Law 1955/2000.

Almost all the technical documents are generated by IEC and CENELEC, and have to be applied in all of the European Union. In 1996 the European Commission ratified the directive 89/336/EEC [1]. This has been applied since 1996 and can be considered as the first step in a series that facilitates the globalization of power-quality procedures. The compliance with these standards is shown by the CE marking of the product. This global framework enables the European power-quality-meter manufacturers to gain access to a wider market. Among others, the most active groups that define and publish standards and reference documents are:

- IEC. International Electrotechnical Commission.
- CENELEC. European Committee for Electrotechnical Standardisation.

There are other standards within the European union, at the local level, like:

- UNESA. Spanish Standards Institute.
- BSI. British Standards Institute.

Figure 2.11 shows the standards structure both in Europe and Spain. The countries that are included in the European Union have to harmonize the CENELEC documents and requirements to their national standards. On the other hand, CENELEC also adopts, in some cases, international regulations, like those generated by the International Electrotechnical Commission (IEC). This fact can be readily observed if the standard reference is compared in the IEC and CENELEC environments. The same happens with the Spanish standard editor UNESA. A good example could be the standard IEC 61000-4-7, which defines the characteristics of the instrumentation for harmonic and interharmonic measurement. At the European level, this standard has been adopted by CENELEC in Europe as EN 61000-4-7 and by UNESA in Spain as UNE EN 61000-4-7.

In the USA, the Institute of Electrical and Electronic Engineers (IEEE) is working on the new standard IEEE 1159 [22] entitled "Recommended Practice on Monitoring Electric Power Quality". This work is sponsored by the Power Quality Subcommittee of the IEEE Power Engineering Society.

Figure 2.12 shows the Dranetz PX5, a power-quality meter that fulfils the standard IEC 61000-4-30 [23]. Among other available synchronization techniques, the utilization of the GPS could be a good tool for synchronizing power-quality meters in different locations.

Generic standards are general-purpose documents that all electrical equipment should comply with. One example is the standard IEC 61000-6, which has been adapted by CENELEC as EN 50081 (generic emission standard) and EN 50082 (generic immunity standard).

From the electrical point of view, a device can be considered a product or part of the distribution network.

From one point of view, product standards cover the aspects of specific product lines where the application of the generic standard would not be the right choice. From another, network standards include the documents that cover different aspects related with the power system: general considerations, description and classification of the environmental levels, emissions and immunity limits, testing and measuring techniques, installation and mitigation guidelines, generic standards and miscellaneous topics.

As an example, IEC 61000 (EN 61000) covers almost all aspects related with low and high-frequency disturbances.

The IEC 61000-4-30 [23] defines the methods for measurement and interpretation of results for power-quality parameters in 50/60 Hz AC power-supply systems.

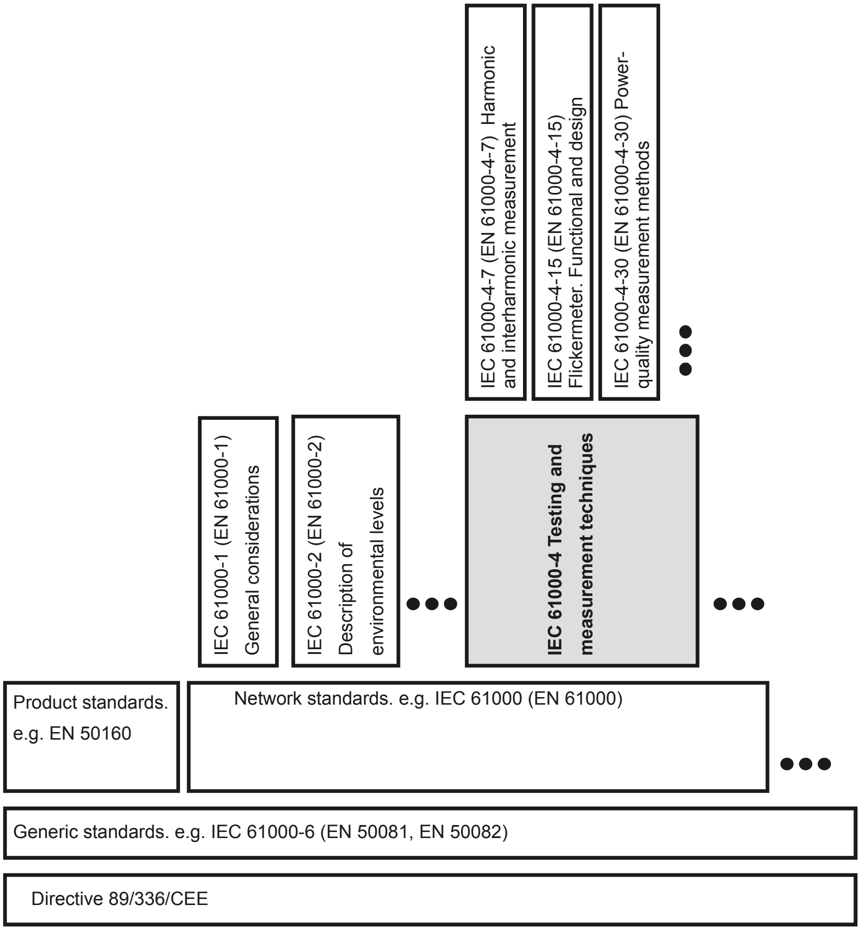

Figure 2.11. Structure of the standards related to PQ measurement

The basic aim of this document is to define measurement methods that will make it possible to obtain reliable, repeatable and comparable results independently of the power-quality-meter manufacturer. The standard does not provide information about instrumentation design. This kind of information is devoted to other standards like IEC 61000-4-7 and IEC 61000-4-15.

2.5 Harmonic Monitoring

Both harmonics and interharmonics can be measured using various techniques. In order to obtain results that can be compared between different equipments and manufacturers, a standard document has been published by the IEC, CENELEC and other regional agencies like the Spanish AENOR. The standard IEC 61000-4-7 [12] defines a general guide on harmonics and interharmonics measurements and instrumentation, for power-supply systems and equipment connected thereto. The basic architecture of digital equipment based on the FFT is shown in Figure 2.13.

Figure 2.12. Dranetz-BMI PX-5 power-quality meter

In a first step the input signal is low filtered in order to fulfill the Nyquist–Shannon sampling theorem. This element is also named an antialiasing filter. The cutoff frequency is fixed to the 50th harmonic. The filtered signal is sampled and stored using a frequency that is obtained with a phase-locked loop (PLL).

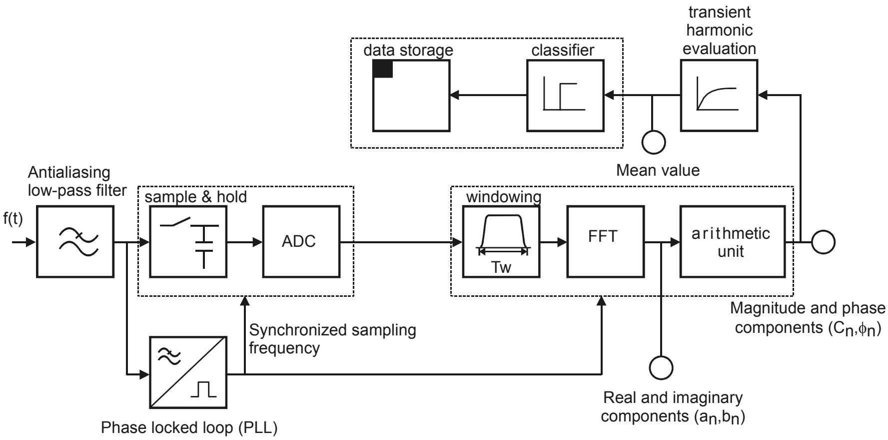

Figure 2.13. Block diagram of the FFT harmonic meter proposed by the IEC 61000-4-7

The FFT is then applied to a block of 2^k samples included in a period $T_w=NT_0$, where N is an integral number and T_0 is the fundamental period of the signal. The sampling frequency is then $f_s=2^k/(NT_0)$. The block of 2^k samples is sometimes multiplied by a window function that reduces the spectral leakage. The FFT subsystem computes the Fourier coefficients a_n and b_n of frequencies $f_h=h/T_w$ for $h=0, 1, 2, \ldots, 2^{k-1}$. The terms $n=h/N$ with $n \in Z$ are the nth harmonic of the fundamental frequency.

The standard defines almost all the basic aspects of the harmonics and interharmonics measurement: accuracy, type of application, hardware architecture, FFT application, evaluation methods, data-aggregation method, immunity test, *etc*.

2.6 Flicker Monitoring

Flicker measurement can be done according to the IEC 61000-4-15 [13]. This document defines the architecture and some test procedures that have to be followed in order to obtain the harmonized flicker perception P_{st} and P_{lt}. The block diagram of the IEC flickermeter is shown in Figure 2.14.

The flickermeter has two main parts. The first one attempts to simulate the behaviour of the set lamp-eye-brain, considering the lamp as incandescent with a power of 60 W. The second part is focused on the statistical analysis of the instantaneous flicker perception.

It produces the short-term flicker severity index P_{st} with a 10-min period between samples and the long-term flicker severity index P_{lt} every 2 h.

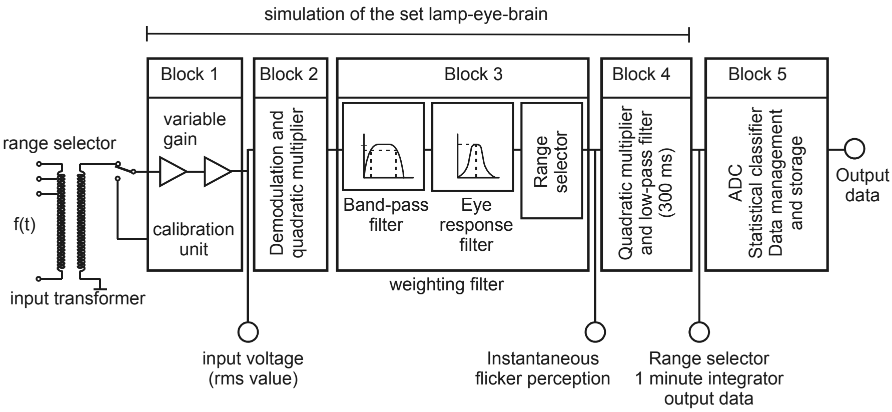

Figure 2.14. Block diagram of a flickermeter based on the IEC 61000-4-15

2.7 Data Postprocessing

Power-quality instrumentation should have not only good hardware architecture, but also powerful software that permits the measured data to be managed and analysed. Figure 2.15 shows the architecture of a postprocessing application.

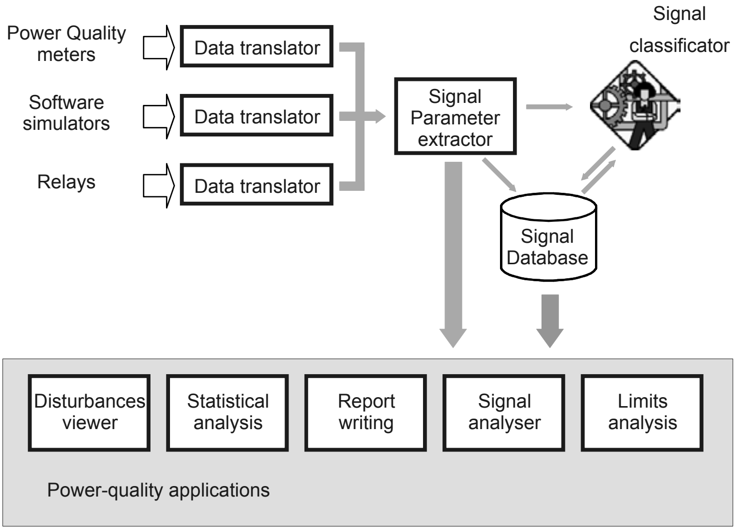

Figure 2.15. Architecture of a power-quality postprocessing system

In a complementary way, a power-quality survey involves the postprocessing analysis after the measurements. The analysis can be supported by specialized tools with some degree of automation [24–34]. The most powerful tools include some kind of automatic disturbance classification.

Disturbance classification includes all aspects related with the problem of determining the degree of similarity between a signal and a set of classes that act as a dictionary of reference. This problem involves three main actors: i) the unknown signal to be classified. ii) the database with the classes of reference and iii) the set of classification algorithms.

In spite of the fact that multiple classification methods or data-mining techniques can be used, it is possible to compile them into three large families:

- Statistical classification or theoretical decision methods. The foundation of this type of method consists in obtaining an index that allows the degree of similarity between the unknown signal and the information stored in the database to be quantified. Euclidean distance classifiers belong to this set of groups, where they use the Euclidean distance between two points in a multidimensional space. This space can be obtained as the Fourier transform or the wavelet transform of the signal.
- Syntactic classification, which uses a structural representation of the disturbance and an expert system in order to model human know-how.
- Classification based on nonlinear methods. The utilization of neural nets is included here. Supervised learning can be considered a classic method of classification. Correlation methods can be also included here. They exhibit

a good behaviour when the signals are distorted with white noise. Another method to be included here is the use of the geometrical properties of the phase-space representation of the signal.

2.8 Management of PQ Files

Some years ago, the interchange of information stored by different equipments was difficult and almost impossible. This came about because the manufacturers had their own format files. In order to solve this problem, some standards have been defined, providing a way to store and interchange power-quality data with a well-known structure. The most important formats are the IEEE Standard C37.111 "COMTRADE" [35] and the power-quality data-interchange format "PQDIF" [36].

2.8.1 COMTRADE

The IEEE defined in 1991 the standard C37.111 entitled "IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems". This work was sponsored by the Power System Relaying Committee of the IEEE Power Engineering Society.

The main purpose of this standard was to define a common format for the data files and exchange medium needed for the interchange of various types of fault, test, or simulation data. Among others, the standard defines as sources of data the following: digital fault recorders, analog tape recorders, digital protective relays, transient simulation programs and analog simulators.

2.8.2 PQDIF

The power-quality data-interchange format, also known as PQDIF was developed by the Electric Power Research Institute (EPRI) and one of its contractors, Electrotek Concepts, Inc. The main aim of this project was to develop a vendor-independent interchange format for power-quality-related information. This power-quality data-interchange format (PQDIF) has been in use since 1995.

In 1996, EPRI and Electrotek placed PQDIF in the public domain to facilitate the interchange of power-quality data between interested parties. EPRI and Electrotek have also offered the format, sample source code, and documentation to the IEEE 1159.3 task force as a possible initial format to meet that group's requirements.

2.9 Summary

The evaluation of the future evolution of this type of instrumentation is always a complex topic, since it involves, besides the classical problems of electronic instrumentation, new aspects that are independent from the process of measurement.

From a technical point of view, current meters are capable of registering all the phenomena of interest: harmonics, flicker, dips, transients, imbalance, *etc*., with the possibility of registering the measurement in a constant way or by means of trigger mechanisms such as thresholds, slopes, logical events, *etc*.

An aspect to improve is the synchronization between different equipments for the accomplishment of measurements synchronized in geographically distributed environments. In this respect there are already developing projects that are starting to use advantages such as the GPS (global positioning system), which is a set of satellites provided with synchronized clocks, and that act in a way that might be seen as a universal time base, which is accessible from almost any part of the world.

As regards control and remote monitoring, it is important to be able to include the equipment in an integral system of measurement. In order to do that, it is necessary to establish common protocols for all the manufacturers, and to facilitate the interchange of data between them.

The current trend is focusing on the use of standardized protocols such as MMS (manufacturing message specification), which is simply a protocol meeting the OSI stack. It has been designed for the control and remote monitoring of industrial devices such as PLCs (programmable logic controller), or instrumentation devices, allowing remote access to variables, programs, tasks and events.

However, it is necessary not only to standardize the communication protocols, but also to establish mechanisms that define the types of allowed information and their structure. In this sense, PQDIF constitutes a good example that can be used as a starting point.

In short, power-quality meters have evolved enormously over the last few decades, so the next steps will have to be directed towards the standardization of information and protocols and towards the development of software for the automatic analysis of the measurements according to international standards.

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