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Tesi di laurea magistrale

Applications and measurement techniques for a reliable and affordable innovative power quality analysis system

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Abstract

The problem of power quality evaluation and measurement is considered. In the first part the application field is analysed in order to understand the potential market of a *Power quality meter*. Main power quality phenomena are introduced, with a particular attention reserved to voltage dips and harmonic distortion, starting from the most important IEC and IEE standards on this topic in order to understand the *state of the art* of Power quality monitoring. Modelling a real system with *Matlab/Simulink* a monitoring system is simulated to test measurement algorithms and a non-standard technique to evaluate voltage events together with an innovative proposed method useful to understand in an affordable way the origin of the problem. Given that the system is meant to be implemented in addition to a standard power and other electrical variables meter, the measurement chain is analysed, with particular attention to the ADC stage, to give an indication for hardware requirements highlighting the differences between a quasi steady state meter and a power quality meter.

Sommario

Viene preso in considerazione e analizzato il problema della valutazione e della misura della qualità dell'energia elettrica. Nella prima parte viene analizzato il campo di applicazione per comprendere quale sia il mercato potenziale di uno strumento di misura della *Power quality*. Vengono poi introdotti i principali fenomeni di *Power quality*, con particolare attenzione ai buchi di tensione, partendo dalle principali norme internazionali pubblicate dall'IEC e dall'IEE riguardanti la materia al fine di conoscere lo stato dell'arte nella misura della *Power quality*. Nella seconda parte il modello in *Matlab/Simulink* di un sistema reale permette di testare gli algoritmi di misura e una tecnica non standard di valutazione degli eventi di tensione insieme a ulla proposta di un innovativo metodo utile a valutare l'origine del problema. Tenendo conto che il sistema possa essere implementato come funzionalità aggiuntiva a un classico strumento di misura della potenza e delle altre variabili elettriche viene analizzata la catena di misura concentrandosi in modo particolare sullo stadio di conversione analogico-digitale al fine di poter fornire un'indicazione sui requisiti dell'harware e mettere in luce le differenze tra una misura in regime quasi stazionario a uno strumento che fornisca anche una misura dei parametri della *Power quality*.

Contents

Introduction

During the last years power systems have seen a strong development because, though the infrastructure has not changed, at least in most developed countries, the necessities of the users have transformed the requirements of the power system. It is no more considered as static but active, Because of the penetration of distributed generation, large diffusion of electronic equipment and the perception of electricity as a product (essentially as a consequence of the deregulation of the market, the heightened sensibility of electronic equipment compared with older devices and the possibility to quantitatively measure the quality of power supply).
Energy, from one point of view, seems to be a typical product as it is produced in a plant and transported to consumers, but, from a different prospective, it is a very special product, being produced, transported and utilised at the very same time [1], with extremely limited storage possibilities. A peculiarity of the energy in respect with other products, is that often only quantity is considered while the quality is sometimes not taken into account. For most of products, quality defines the value and the price as a consequence, because a high quality implies higher costs. For energy, though a high quality power supply requires huge investments, only the quantity is sold and not the quality.

This work has been developed in collaboration with the *Carlo Gavazzi* company, working for several decades in the electrical and electronic field, and takes origin from the necessity to develop a new range of measurement devices that implements, in addition to the measure of the typical electrical parameters already present in the products available on the market, also the measure of the power quality parameters.
The aim is not to get the final design of the power quality meter but to define, on the basis of a deep analysis of causes and consequences of power quality

disturbances, international standards and properties of possible algorithms, the specification of the device that will be implemented by the R&D department.

The study of power quality is a quite new topic, because ten or twenty years ago electronic equipment was not as widely diffuse as now so that a poor power quality was not a big deal because the amplitude of the related problems was quite limited.

Power quality issues are primarily due to continually increasing sources of disturbances, in interconnected power grids which contain a large amount of power sources, transmission lines transformers and loads [2]. They become problems when they cause system equipment malfunction such as loss of data or wrong behavior of sensible loads (computer, programmable logic controllers, protection and relaying equipment).

When power quality became a problem a big effort in the research field was made to find theoretical explanation of the phenomena and possible solutions to reduce their impact on the system. In the technical literature there are a lot of papers and several books that describe power quality related issues and also measurement techniques, but most of times from the point of view of the user. In this work a different point of view is used. The power quality is considered from the point of view of the manufacturer of a monitoring system with the aim of producing a reliable and affordable device which might adapt to the necessities of the customer that will use the meter to analyze and fix or reduce the problems due to low power quality.

What a power quality meter is primarily expected to do is to detect efficiently power quality events as suggested by the international standards on power quality monitoring; this is the reason because an entire chapter is dedicated to the analysis of them. A further step which might meet the customer expectations is the possibility to automatically detect, when possible, the causes or the origins of the problem. Several techniques have been proposed, based on signal processing, but in this work they are not considered because their implementation requires a computational effort beyond the possibilities of the market range to which the meter is addressed. Anyway a simple method to locate the source of voltage dips is proposed. Not all power quality phenomena are analyzed in detail but only voltage dips, harmonics and flicker (voltage fluctuation) because they are the measurement that will probably be implemented (voltage dips and flicker) or improved (harmonics) in respect with previous models. To understand not only how but also where and why is important to measure and monitor properly the quality of the power supply, each phenomenon has been studied deeply considering both the causes and consequences on the system and on the individual devices.

Possible algorithms are considered in order to evaluate their parametric sensibility when the frequency synchronization is not perfect, when noise is present on the signal or when it is considered that the numeric value obtained is not exactly the *true value* of the signal due to the accuracy of the transducers or to the discretization.

Chapter 1

Power quality

Power quality has become a very important aspect of power delivery in the second half of the 1990s and the passage of time has brought an increased awareness of its effect in terms of economical and technical impact. In particular, we can say that power quality has become more and more important recently, when electronic equipment has become extremely widespread. Power quality is related to the interaction between the utility and the customer, that is the power system and the load. This means that it not possible anymore to consider each load, each generator and each component as isolated by anything else, but it is fundamental to consider generation, transmission, distribution and loads as parts of a whole complex system.

1.1 Interest in Power Quality

In 1968 it has been established the importance of monitoring equipment and in 1970 *high power quality* was considered together with *safety*, *reliability* and *low operational cost*.

The increased attention of recent years on this subjects can be explained in a number of ways of which it is not easily to find the most important one [3]:

- Electronic and power electronic devices has become more sensitive to voltage variations. Moreover an interruption of the power supply has become even less acceptable even if there are no damages or costs related to it. In

1991 it was estimated that the problems related to power quality costed the companies about $ 26 billion a year. The problem is that the issue is not easily solvable because it is about compatibility between different parts of the same system: the user charges the utility with the responsibility but end-user equipment is often seen by the utilities as the main source of problems because of the non sinusoidal current due to rectifiers and inverters that nowadays are strongly widespread together with a large number of small consumer electronic devices that cause a large part of the harmonic voltage distortion.

- In the context of privatization and deregulation of the electricity market electric energy is considered a *product* which must have some specific characteristic, that can be measured, predicted, guaranteed, improved, etc. With the opening of the market it becomes further complicated because it is not clear who is responsible for reliability and power quality.
- In countries where the availability is over 99.9 % voltage sags and harmonic distortion are now the biggest problems.
- The power quality can be measured.

In order to understand where a power quality meter is useful, it seems extremely interesting to analyse how the interest on *Power Quality* has developed during the last years to forecast if further interest is expected over the next years and where the interest will be greater, to understand where solutions are required and therefore the market is potentially bigger.

To get a first indication about this topic a free available tool has been used: *Google trend.* Though absolute values are not available, it gives a first information about the occurrence of search, through the worldwide most used search engine, of a particular combination of key words. In this case, the use of the algorithm available with some keywords like *Power quality* or *Voltage sags* gives an indication on the actual interest in Power quality.

As we can see from figure 1.1 the *search volume index*, that expresses the number of searches for *Power quality* in respect with the total number of searches and then normalized in a scale between 0 and 100 with 100 assigned to the higher value

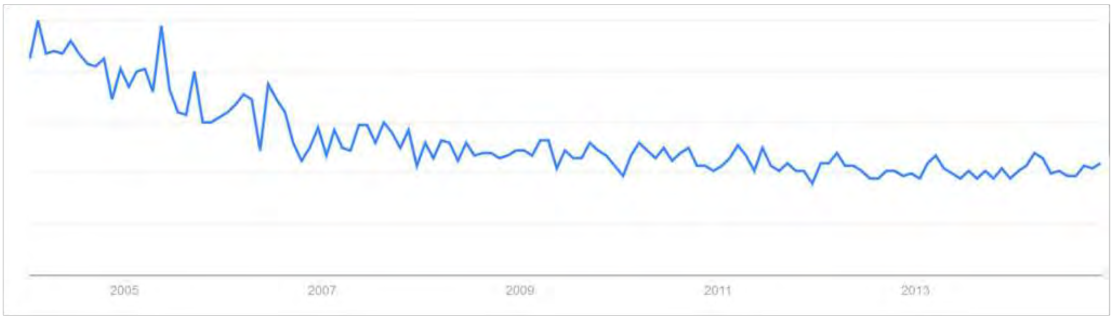

Figure 1.1: Search volume index for *Power quality* (Google Trend)

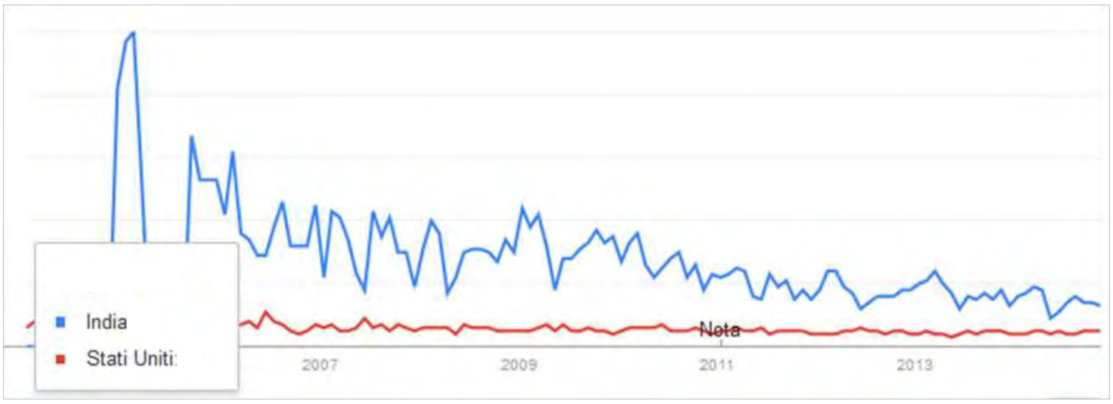

Figure 1.2: Comparison between search volume index in India and USA (Google Trend)

encountered during the time interval under analysis, we can infer that the interest is quite stable during the last years. In figure 1.2 it can be seen a comparison between the interest on this topic between USA and India keeping in mind that it doesn't represent an absolute number but a number related to the total number of searches so that the two values can be compared.

It is manifest from table 1.1, where the search volume index is reported for some countries, that the interest is more relevant in under development countries where the maturity and strength of the power system is well below the standards of the western world with a consequent lower reliability and quality.

Table 1.1: Search volume index for *Power quality* in some countries (*Google Trend*)

Country	Search volume index
India	100
Malaysia	50
South Africa	45
Singapore	44
Iran	37
Pakistan	35
Philippines	35
United States	31
Australia	31

Figure 1.3: Distribution of Power quality interest based on Google Trend analysis

1.2 The term *Power quality*: definitions

In the IEEE dictionary the definition of power quality is:

> *Power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment*

In IEC 61000-1-1 it is given the definition of Electromagnetic compatibility of which Power quality is a part:

> *Electromagnetic compatibility is the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing electromagnetic disturbances to anything in that environment*

while for describing the aim of a project group on *Power quality* it is used the following definition:

> *Set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristic of voltage (symmetry, frequency, magnitude, waveform)*

1.3 Power quality phenomena

The issues related to the power quality are due to the deviations of the voltage or the current (that finally end in voltage variations) from their ideal sinusoidal waveform. Each deviation is a power quality phenomenon that can be:

- a small variation from the reference value in steady state, normally accepted because the voltage and the current cannot correspond exactly to the nominal waveform, considering that, on average, magnitude and frequency are equal to their nominal value but they are never exactly that value. These variations shall be within a certain range because when they deviate from it problems may arise.
- a significant variation from its normal waveform in a certain instant (event) that must be monitored by using a triggering method.

1.3.1 Causes of voltage variation

Increase and decrease of the voltage magnitude are due to

- variation of the total load of a distribution system
- action of transformer tap-changers
- switching of capacitor banks or reactors

whereas frequency variations are due to unbalance between load and generation.

The harmonic voltage distortion, that is the phenomenon for which the waveform is not a single-frequency sine wave but can be described as the sum of sine waves multiples of the fundamental frequency, is due to:

- not exactly sinusoidal voltage generated by a synchronous machine for physical imperfections of the shape of the machine.
- power system which links the generator to the load not perfectly linear. An example is the transformer where the saturation of the iron core is responsible of the non-linearity and another one are the HVDC links.
- non-linear loads : more and more devices are fed through power-electronics converters drawing a non-sinusoidal current.

The main problems, when there are not resonances, are additional losses and heating.

1.3.2 Voltage events

Events can be described through the time between events and their characteristics in a stochastic sense. Example of events are

- Interruption, a condition in which the voltage is close to zero (lower than 1% for the IEC and 10% for the IEEE). They are usually caused by faults and action of the protections as a consequence, protection trip with no fault present, a broken conductor or operator intervention.

- Undervoltages called *Voltage Sags* or *Voltage dips* when there is a recovery within a short time after the reduction. They are mainly caused by short-circuit faults and by starting of large motors.

- Voltage magnitude steps due to load switching, transformer tap-changers and switching actions in the system normally in the range 90-110 %.

- Overvoltages due to lighting strikes, switching operation, sudden load reduction, single-phase short-circuits and non linearities, resonance between the reactance of a transformer and a capacitance (ferroresonance).

Power quality events are usually considered in large part unpredictable events because they are the consequence of stochastic phenomena such as faults, lightning, resonances, geomagnetically induced currents and so on.

1.4 Sources of disturbances

From a general point of view the whole power system can be divided in macro areas to discriminate the sources of disturbances: generation, transmission, distribution and utilization[4].

The impact of generation on power quality is usually small in normal operation, with a very low harmonic content, but its contribute becomes important when maintenance activity is planned or when external events lead to forced outages or load transferring between different substations. Distributed generation in respect with conventional plants is clearly less reliable because the interface with the distribution network is often given by an inverter with a consistent harmonic content.

Some power quality problems takes their origin in the transmission system, even if it is not so much frequent: spike or transient overvoltage due to lightning, voltage dips due to faults, interruptions due to planned maintenance or faults, voltage variations due to an improper operation of voltage regulation devices are just a few examples.

In the distribution network originate voltage dips, spikes, interruptions, overvoltages, slow and fast voltage variations.

Customers produce a large amount of the power quality problems in a power system. Harmonics are generated by non-linear loads, transients by device switching, electrostatic discharge and arcing, frequency variations when secondary and backup power sources are used.

1.5 Economical consequences

The widespread diffusion of electronic devices has the consequence that a bad power quality can have a devastating impact on both industrial and residential activities. Typically, when there is a problem of power quality, there is a possible solution to eliminate or to drastically reduce the impact but often the investments required are not affordable, or at least not convenient, if the cost to suppress the problem is greater than the economical damage caused by the problem itself.

In this scenario becomes important to understand which solution is the most convenient one, but this step can't be made if an estimation of economical losses is not available. To perform this estimation a reliable methodology is required. In [5] an attempt to propose a general methodology is done after the review of different methodologies. The result of the estimation depends essentially on the data available. To obtain the consequences of voltage dips it would be necessary to have information about the number of events per year, susceptibility of the loads and economical losses related to each malfunction. From this observation a simplified method similar to the one proposed in [6] can be obtained: the total cost is calculated as the product of three variables: the number of event per years (N), the percentage of them that cause a damage (P), and the cost of each event (C).

$$Total\, cost = N \times P \times C \tag{1.1}$$

In [7] it is explained that it is not possible to give a linear relation between voltage dip magnitude and economical losses because the outage of equipment due to a shallow or to a deep voltage dip is exactly the same.

This is the reason for which it is not possible to give a general indication about the real economical consequences of power quality issues. In each different case it is therefore necessary to assess the power quality at the point of common coupling and, after that, a relation between power quality events can be find out.

Chapter 2

Standards on power quality

When a new product is to be developed, the starting point is the analysis of the international standards that give some interesting information about the state of the art of that kind of device and all the requirements to comply with, giving the guidelines to obtain a valuable product. The compliance is sometimes not mandatory, that means that a product that doesn't comply with the standard can be sold on the market; on the other hand, compliance with standards is extremely important when the manufacturer wants to asses the quality of its product so that the customer is guaranteed that what he buys will work properly. At regulatory level, the main references about *Power Quality* are the standards **EN 50160**

> *Voltage characteristics of electricity supplied by public distribution systems*

and the **IEC 61000-4-30**

> *Electromagnetic compatibility (EMC)-*
> *Testing and measurment techniques-*
> *Power quality measurement methods*

The former offers a description of the present situation of the voltage quality in Europe, whereas the latter is part of the standard **IEC 61000** intended to define techniques, measurements and methods to analyse the results [1] in 50/60 Hz power

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[1] depending on the purpose the analysis all or some of the parameters described can be measured: frequency, voltage magnitude, flicker, voltage dips, voltage and current harmonics and interharmonics and transients

systems in order to obtain reliable, repeatable and comparable results, regardless of the instrument and of the environment conditions.

In the standard the measurements of flicker and harmonics are not explained because they are described in the standard **IEC 61000-4-7**

> *Testing and measurement techniques –*
> *General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto*

and **IEC 61000-4-15**

> *Testing and measurement techniques –*
> *Flickermeter – Functional and design specifications*

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2.1 Electromagnetic compatibility

Power quality problems fall within the sphere of the electromagnetic compatibility. Electromagnetic waves permit both power supply of the network components and the comunication among them. On the other hand they are also responsible for the disturbances, that may compromise the proper operation reaching the victim through metal wires (*conducted disturbances*) or through radiations (*irradiated disturbances*). It is clear that from an electromagnetic point of view there is not difference between intentional and unintentional exchange of information.
The *electromagnetic compatibility* of a device is defined as follows [8]:

> *The ability of a device or system to work properly within its environment without introducing intolerable disturbances for something else in that environment*

The IEC has published several standards that define different aspects of the electromagnetic compatibility, among which there are some standards on issues related to *Power Quality* such as harmonics and voltage dips.
From the definition of electromagnetic compatibility two requirements are evident:

- the device must be able to operate in its environment
- the device must not introduce disturbances

The consequence is that, in case of a magnetic compatibility problem, there are two possible solutions:

- increase of the tolerance of the victim (immunity)
- reduction of the disturbance (emission)

Usually a compatibility level is defined together with a higher immunity level (the ratio with the compatibility level is called *margin of immunity*) and a lower emission level (the ratio with the compatibility level is called *margin of emission*). Then the margin of compatibility is the ratio between immunity level and emission level. When all the devices in the same environment respect both the limits, then they will work properly.

When the limits can be chosen they should be the values that minimize the overall cost but often, especially for conducted disturbances, it is usual to take present disturbance level as a reference value. The aim of the **EN 50160** is exactly the definition of the present level of power quality disturbances in order to fix the level that is not to be exceeded, so that the future development of transmission and distribution networks will be done without worsen the current situation for instance with insertion of a large number of distributed generators or without improving the performances where a large amount of polluting loads introduce unacceptable disturbances.

Actually, the IEC standard applies only to equipment and not to the network so that disturbances that could be limited like voltage dips are considered as a force of nature even if there are technical actions that, though expensive, could be applied. Therefore, the only limit that can be increased is the immunity level.

There are also disturbances for which it is not possible to modify the immunity level (flicker immunity is given by human eye sensibility).

2.2 Stochastic approach

When dealing with compatibility issues it is clear that if it were possible to test all devices in all possible conditions the compatibility margin could be further reduced. Given instead the necessity of a random testing in a limited number of conditions, an uncertainty is introduced on the definition of the immunity level and the emission level:

- actual operative conditions are never the tested conditions
- small differences in respect of the tested devices could introduce large errors
- the effect of more disturbances at the same time is not considered

2.3 The EN 50160

The European Standard EN 50160 describes and specifies the main characteristics, in terms of range within they are expected to stay, of the voltage at a network user's supply terminals in low, medium and high voltage under normal operating condition. In the standard a difference is made between continuous phenomena, for which some limits are specified, and events, for which only indicative values are given. In the standard it is stated that they are not to be intended to set compatibility levels or to specify requirements in equipment e installations, but anyhow they can be taken as a reference.

- The **frequency** can vary within the range ±1% during 99.5% of the year and $+4\% / -6\%$ during 100% of time.

- The **supply voltage** should remain within ±10% of the nominal value at least during 95% of time considering r.m.s values averaged over 10 minutes intervals.

Table 2.1: Limits for individual harmonics defined in the EN 50160 standard

Order	Relative Amplitude	Order	Relative Amplitude	Order	Relative Amplitude
5	6 %	3	5 %	2	2 %
7	5 %	9	1,5 %	4	1 %
11	3,5 %	15	0,5 %	6. . . 24	0,5 %
13	3 %	21	0,5 %		
17	2 %				
19	1,5 %				
23	1,5 %				
25	1,5 %				

- The **long term flicker severity** should be less or equal to 1 for 95% of time.

- The **unbalance** between 0% and 2%.

- For what regards **harmonic voltages** limits are given for each harmonic up to the 25^{th} (see table 2.1) and the limit for the THD at 8% considering the harmonics up to the 40^{th}.

2.4 The IEC 61000-4-30 standard

The **IEC 61000-4-30** is the part of the **IEC 61000** in which are described tests and measurement techniques of the *Power Quality* .

2.4.1 Measurement classes

For each parameters three measurement classes are defined[2]:

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[2] The class S has been introduced in the last version of the standard to substitute class B which might become obsolete

A when precise measurements are necessary, for instance in case of contractual applications.

S that can be used for statistical surveys where, even though measurement intervals are the same of the class A, processing requirements are lower.

B not reccomended for new models, because it could disappear from the next versions of the standard but not yet deleted in order to not make obsolete products now present on the market

2.4.2 Aggregation method

The aggregation method is useful to obtain a unique value representative of a wider interval. This step is very important because it is one of the feature of a power quality meter which is not present in a steady state meter such as a multimeter. At first glance the differences between the two types of measurements may be not so manifest but it is clear that the approaches are completely different. When a multimeter is used the basic assumption is that the system is in a condition of steady state[3] while, when a meter for a power quality survey is used, the same assumption can't be true because it is exactly the changing in respect of the steady state that must be showed. Both the measurement technique and the meter are therefore different. In steady state the user wants to get a number for each parameter while when the user wants to assess the power quality a continuous measurement has to be guaranteed in order to evaluate the trend and to not lose any events.

A more levels analysis is usually necessary: in normal condition the system is near a steady state condition and only slow variations appear so that a little temporal resolution is required, but in case of a power quality event an higher resolution is required. In any case, the temporal resolution is found as a trade off between two issues: a low resolution is not effective to catch all the events and doesn't permit to analyse the behaviour of the system with enough details but doesn't require high computational performance and memory storage while

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[3] A power systems is in steady state when there is not variation of the parameters that describes its state

an extremely high resolution requires high performance microprocessors and large memory storage with a lot of information that has to be further processed to be studied.

The aggregation is the solution to this problem because it permits to consider a lot of time intervals so that loss of information is extremely rare but then they are put together to give only one value representative of all the samples considered.

In the standard the calculation is suggested as the rms of the values in the intervals:

$$V = \sqrt{\frac{1}{N}\sum_{i=1}^{N} V_i^2} \tag{2.1}$$

- For class A and class S measurements the base time is
  - 10 cycles for 50 Hz systems
  - 12 cycles for 60 Hz systems

  that is approximately 200 ms.

  The base time intervals are then aggregated in three different intervals
  - 150/180 cycle(about 3 seconds), obtained from 15 base intervals
  - 10 minutes
  - 2 hours obtained from 12 intervals of 10 minutes.
- For class B measurements the manufacturers can freely indicate method, number and duration of the aggregation intervals.

The aggregation methods for class A and S are represented in figure 2.1 and 2.2. It is manifest that in the class S all the overlaps are avoided so that the implementation is simpler but there is a loss of synchronism between different intervals.

The aggregation method, and consequently the result, depends on the real time clock (RTC): an important issue is the uncertainty of the time is consider in respect of the Univesal Time Clock (UTC). The prescribed uncertainty is a cycle for class A, obtainable via GPS or radio synchronization, 5 s for class A and freely defined by the manufacturer for class B.

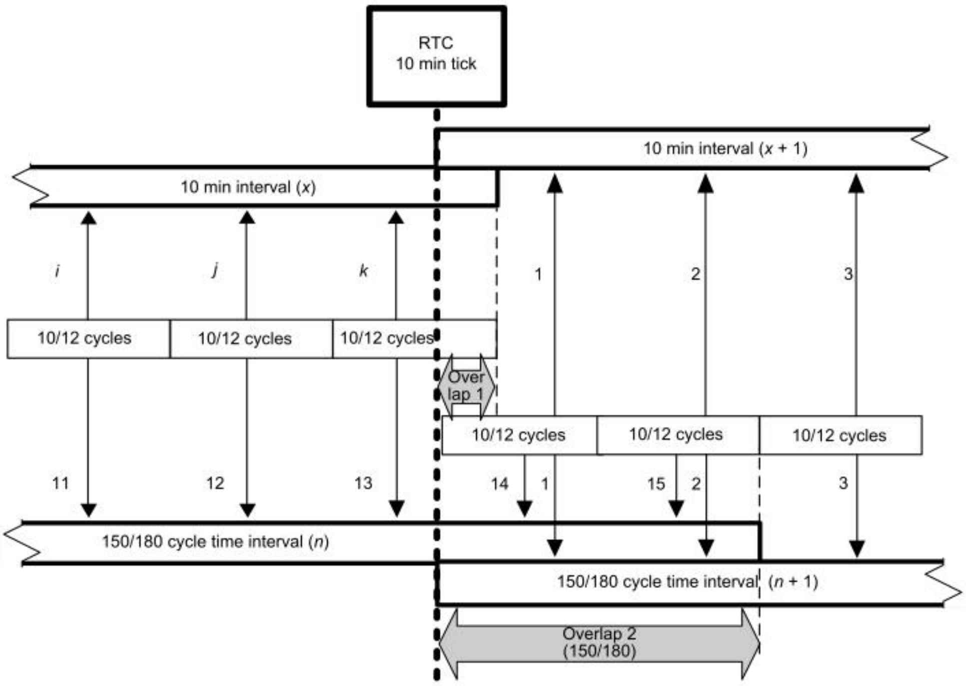

Figure 2.1: Aggregation intervals, class A [8]

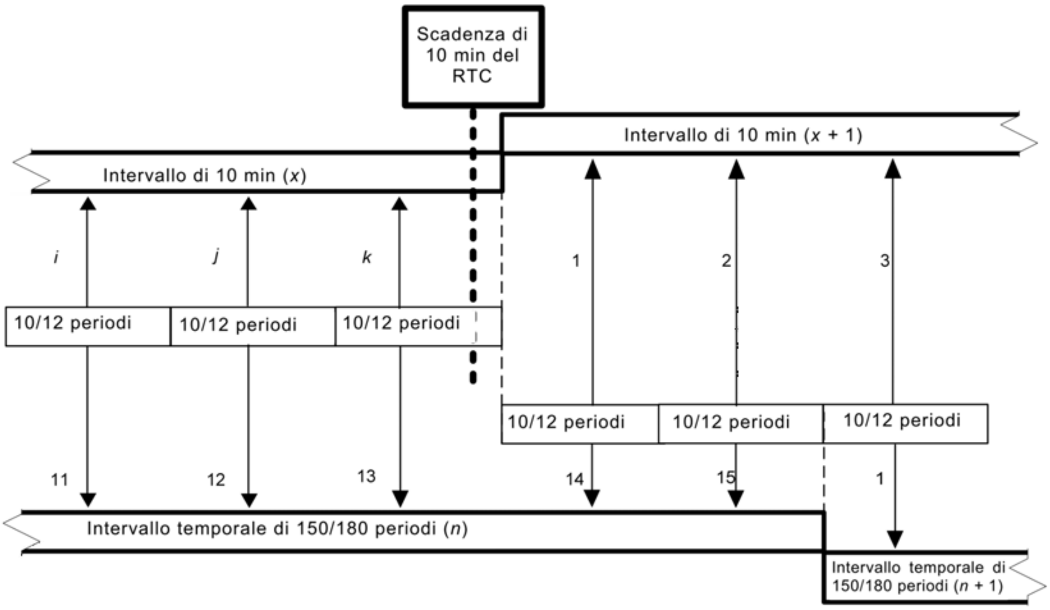

Figure 2.2: Aggregation intervals, class S [8]

2.5 Power quality parameters

Frequency

The measurement of the frequency shall be obtained every 10 s as the ratio between the number of complete cycles and the cumulative duration after the attenuation of harmonics and interharmonics. The uncertainty is 10 mHz for class A and 50 mHz for class S.

Voltage magnitude

For voltage magnitude the uncertainty permitted for class A is 0.1% between 10% and 150% of U_{din} while for class S the requirement is 0.5% U_{din}.

Flicker

The procedure is described in the **IEC 61000-4-15** for class A and S as well as the uncertainty but the range is 0.2-10 P_{st} for class A and 0.4-4 P_{st} for class B.

Voltage dips and swells

The base measure is $U_{rms\frac{1}{2}}$ [8],

> *value of the r.m.s. voltage measured over 1 cycle, commencing at a fundamental zero crossing, and refreshed each half-cycle*

for each phase.

A voltage dip is detected when $U_{rms\frac{1}{2}}$ falls below a treshold given as a percentage of U_{din} or U_{sr}[4] at least in one channel and it ends when it returns above the treshold plus a voltage of hysteresis in all the channels.
The values of the tresholds and the voltage hysteresis are given by the user[5].

A voltage dip is characterized by two values:

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[4] *sliding reference voltage*, mean of the voltage over a specified interval preceding the voltage event

[5] usually the hysteresis is $2\% U_{din}$ and the treshold 85-90% for detection of problems and 70% for contractual applications

- the residual voltage (lowest U_{rms} value measured on any channel during the dip) or the depth (difference between the reference voltage and the residual voltage)
- the duration (time difference between the start time and the end time of the voltage dip)

A voltage swell is characterized by two values:

- maximum swell voltage (highest U_{rms} value measured on any channel during the swell)
- the duration (time difference between the start time and the end time of the voltage swell)

The uncertainty for the magnitude shall not overcome $\pm 0.2, \%$ for class A e $\pm 1\,\%$ for class S. For duration it is half cycle at the beginning and at the ending.

Voltage unbalance

The unbalance is calculated as the ratio between the negative sequence and the positive sequence.

Harmonics

The measurement method is defined in the **IEC 61000-4-7** and the measurements have to be done up to the 50th for class A and to the 40th for class S.

2.6 The IEC 61000-4-15 standard

This part of the standard gives a functional and design specification for flickering measuring devices (*flickermeters*).The IEC flickermeter is based on a 230V 60W incandescent lamp and a 120V 60 W incandescent lamp.

The architecture is divided into two parts (see fig. 2.3): the first one simulates the lamp-eye-brain chain while the second one elaborates a statistical analysis of the flicker signal and gives a presentation of the results.

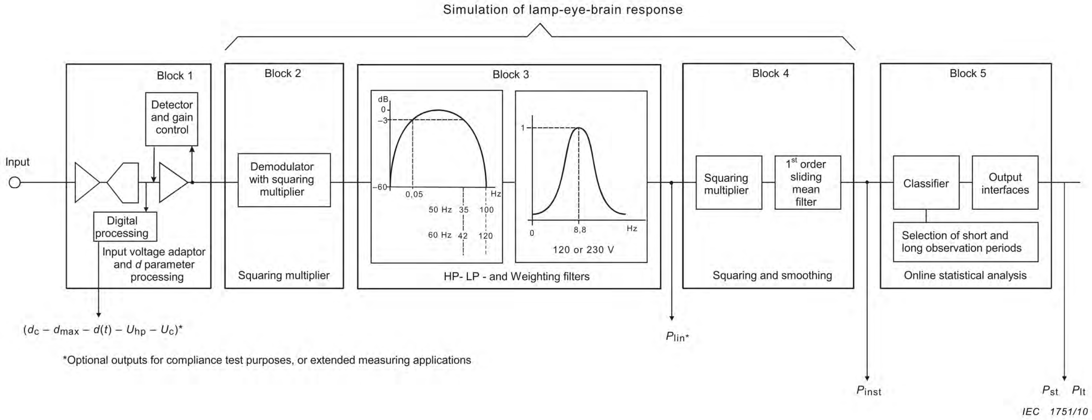

Figure 2.3: Scheme of a digital implementation of a flickermeter [9]

In the first block the voltage is adapted to a reference value in order to express flicker measurements as a per cent ratio indipendently on the present voltage level. The second block (demodulator) simulate the quadratic response of the lamp by squaring the input value. To understand how the demodulator works it is useful to consider a sinusoidal voltage fluctuation [10]:

$$v(t) = Acos\omega_p t \cdot (1 + mcos\omega_m t) \tag{2.2}$$

applying the quadratic demodulator we get:

$$\begin{aligned} v_S(t) = \quad [v(t)]^2 = & \quad (Acos\omega_p t + Am\cos\omega_p t\cos\omega_m t)^2 \\ = & \quad [Acos\omega_p t + Am\,(cos(\omega_p t + \omega_m t) + cos(\omega_p t - \omega_m t))]^2 \\ = & \quad A^2(cos^2(\omega_p t) + m^2\,(cos^2(\omega_p t + \omega_m t) + cos^2(\omega_p t - \omega_m t) + \\ & \quad +2cos(\omega_p t + \omega_m t)cos(\omega_p t - \omega_m t)) \\ = & \quad \tfrac{A^2}{2}\left(1 + \tfrac{m^2}{2}\right) + \tfrac{A^2}{2}\left(1 + \tfrac{m^2}{2}\right)\cos 2\omega_p t + \tfrac{m^2A^2}{8}\cos 2\left(\omega_p + \omega_m\right)t \\ & \quad + \tfrac{m^2A^2}{8}\cos 2\left(\omega_p - \omega_m\right)t + \tfrac{m^2A^2}{2}\cos\left(w\omega_p - \omega_m\right)t \\ & \quad + mA^2\cos\omega_m t + \tfrac{m^2A^2}{2}\cos 2\omega_m t \end{aligned} \tag{2.3}$$

The third block is composed of a cascade of two filters to eliminate the DC components and the ripple of the input with frequency higher than ω_p. It is formed by a first order high-pass filter with a 0.05 cut-off frequency for suppressing the d.c

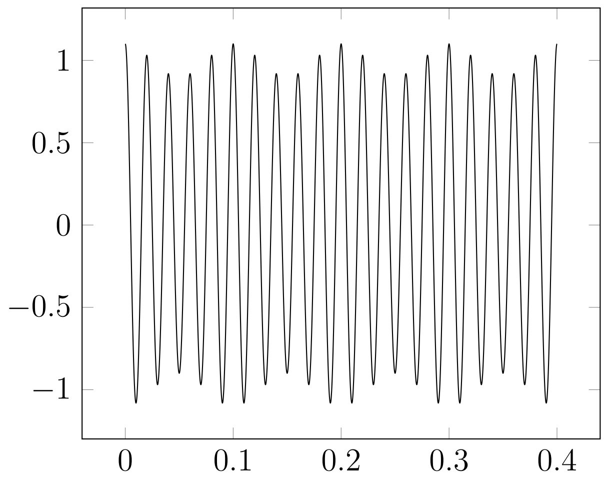

Figure 2.4: 50 Hz sinusoidal voltage with 10 Hz fluctuation

component and a low pass filter to eliminate components with a frequency greater then or equal to the fundamental frequency (cut off frequency of 35 Hz) (fig. 2.5).

Then a weighting filter simulates the frequency response of the human visual system.
A reference coiled filament gas-filled lamp (60 W / 230 V or 60 W / 120 V) is considered (the response to discharge or LED lamps, nowadays widely spread is totally different and a complete modification would be necessary). The maximum gain (between 8 and 10 Hz correspond to the maximum human sensibility). The weighting filter can be described by the transfer function of the weighting filter (see fig 2.6):

$$F(s) = \frac{k\omega_1 s}{s^2 + 2\lambda s + \omega_1^2} \times \frac{1 + s/\omega_2}{(1 + s/\omega_3)\,(1 + s/\omega_4)} \tag{2.4}$$

where the parameters take the values of table 2.2, for a 230V,60W lamp and a 120V, 60W lamp: The effect of the filter is more relevant in the 120 V lamp because, as a consequence of the same power with lower voltage, the current is higher and therefore the filament thicker, with an higher thermal inertia that leads to a lower flicker effect.

The fourth block, together with the second one and the third one, completes the lamp-eye-brain chain simulating the memory effect of the human brain. The output is a signal instantaneously proportional to the visual flicker perception

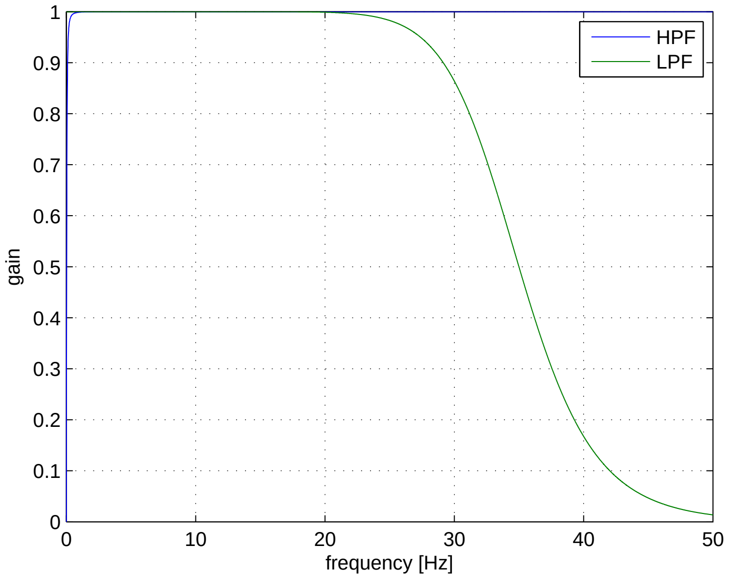

Figure 2.5: Low pass filter and high pass filter frequency response

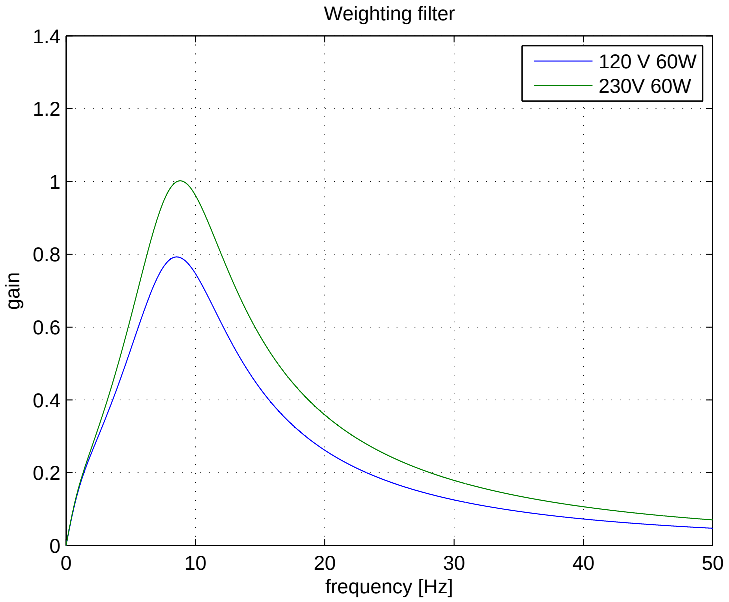

Figure 2.6: Frequency response of the weighting filter to simulate the behaviour of the human eye

Table 2.2: Parameters of the weighting filter

		$230V$	$120V$
k	$=$	1.74802	1.6357
λ	$=$	$2\pi \times 4.05981$	$2\pi \times 4.167375$
ω_1	$=$	$2\pi \times 9.15494$	$2\pi \times 9.077169$
ω_2	$=$	$2\pi \times 2.27979$	$2\pi \times 2.939902$
ω_3	$=$	$2\pi \times 1.22535$	$2\pi \times 1.694468$
ω_4	$=$	$2\pi \times 21.9$	$2\pi \times 17.31512$

scaled down relating it to the perceptibility threshold so that a value of 1 or more means that the flicker is perceivable.

The fifth block analyses the flicker level to derive severity indications by means of statistical analysis obtaining the flicker probability density function for each class in which the samples are divided. The necessity to do this statistical analysis comes from the fact that the phenomenon has a random behaviour and the annoyance depends on its temporal distribution and especially on what percentage of the period considered a certain flicker level is exceeded.

Two parameter are calculated: the P_{st} and the P_{lt}. The P_{st} comes from the cumulative probability function of the instantaneous flicker sensation over 10 minutes. The possible flicker values are divided into a number of classes and every time a value of a certain class occurs, the counter of that class is incremented by one.

From the cumulative probability function some points are taken and the P_{st} is calculated as follows:

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}} \tag{2.5}$$

where $P_{0.1}$ is the percentile of the flicker levels exceeded for more than 0.1% of time and the same for the others but with the s suffix that stays for *smoothed* being them calculated as an average:

$$P_{1s} = \frac{P_{0.7} + P_1 + P_{1.5}}{3} \tag{2.6}$$

$$P_{3s} = \frac{P_{2.2} + P_3 + P_4}{3} \tag{2.7}$$

$$P_{10s} = \frac{P_6 + P_8 + P_{10} + P_{13} + P_{17}}{5} \tag{2.8}$$

$$P_{50s} = \frac{P_{30} + P_{50} + P_{80}}{3} \tag{2.9}$$

The formula that will be implemented is therefore:

$$\begin{aligned} P_{st} \;=\; & \sqrt{0.0314 P_{0.1} + 0.0175\left(P_{0.7} + P_1 + P_{1.5}\right) + 0.0219\left(P_{2.2} + P_3 + P_4\right) +} \\ & \overline{+0.056\left(P_6 + P_8 + P_{10} + P_{13} + P_{17}\right) + 0.02667\left(P_{30} + P_{50} + P_{80}\right)} \end{aligned} \tag{2.10}$$

The P_{lt} is calculated as the average of 12 P_{st}:

$$P_{lt} = \sqrt[3]{\sum_{i=1}^{1} 2 \frac{P_{st_i}^3}{12}} \tag{2.11}$$

2.7 The IEC 61000-4-7 standard

This part of the standard is relative to the measurement of harmonics in the frequency range up to 9 kHz and defines the measurement instrumentation. From the observation that the design of modern instruments is based on, the discrete Fourier transform (DFT) this standard is considered, even though other implementations are not forbidden. The analogue signal $f(t)$ is sampled, digitally converted and stored to be analysed in a group of M samples, which forms the time window, multiple of the fundamental period, on which the Fourier transform is performed, determining also the frequency separation of the spectral lines and thus the resolution.

The instrument is composed by input circuits with anti-aliasing filters, A/D converter with sample and hold, synchronization and window-shaping unit, DFT processor.

Two classes of accuracy are considered: I, for emission measurements and II, for general purpose measurements but also for emission measurements if values are far away from the limits . For full compliance the window width must be 10 cycles (50 Hz) with a maximum permissible error of 0.03% in the range ±5% of the nominal frequency with rectangular weighting and a maximum error of the time window of 0.03% and error of 0.05% for voltages 0.15% of currents and 1% of power for class I and 0.15% of voltages and 0.5% of current for class II.

Chapter 3

Voltage dips

Voltage dips[1] are short duration reductions in rms voltage, due to a sudden increase of the current absorption usually caused by

- short circuits
- overloads
- starting of large motors

The voltage dips due to short circuits are the most important because they are responsible for the majority of equipment trips but also those that come from the starting of large induction motors, with a longer duration, must be taken into account because, especially in large industrial plants where the number of inductive motors is high, the problem can't be neglected.

The study of this kind of events has become more and more urgent since they cause problems to several types of equipment: adjustable speed drives, process control equipment and computer just to mention a few examples. Some devices trip when the rms voltage drops below 90% for more than one or two cycles and the consequences may become tremendous: if the piece of equipment that trips is the process control equipment of an industrial plant, for instance a paper mill, the damage can be enormous. Furthermore, if we consider that the problem could

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[1] also referred to as voltage sags

occur tens of times a year, it can lead to a relevant economical impact. Usually the consequences are less severe than an interruption, but as the probability and hence the frequency of a voltage dip is much higher than an interruption, then the overall damage can be much higher[2].
The reason because which this event is much more probable than an interruption is that the former can be due to short-circuit faults hundreds of kilometers away in the transmission line and while the reduction of the number of interruption can be obtained through improvements on the feeder, the reduction of voltage dips requires several interventions that can lead to unaffordable costs.

3.1 Characterization of voltage dips

Definition A **voltage dip** is a sudden reduction of the voltage at a particular point of an electricity supply system below a specified threshold followed by its recovery after a brief interval longer than half cycle (10 ms in a 50 Hz power system)[10].

A voltage dip is usually characterized as a two-dimensional electromagnetic disturbance by its magnitude (depth or residual voltage) and its duration even if there are other features that should be taken into account such as the higher frequency components content and the overshoot after the sag.

Definition The **depth of a voltage dip** is the difference between the reference voltage and the residual voltage during the event (usually expressed as a percentage of the reference voltage)

Definition The **reference voltage** (U_{ref}) is the base value to which all the other values are compared.

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[2] a proof of the impact of voltage dips on power quality issues is that most of complaints is related to them.

Definition The **duration of a voltage dip** (U_{ref}) is the time between the instant when the voltage drops below the dip start threshold and the moment when it rises above the dip end threshold .

3.1.1 Magnitude of a voltage dip

The magnitude can be obtained in different ways [3]. Usually the dip magnitude is obtained from the rms voltages. Other methods are the measure of the magnitude of the fundamental component or the peak voltage over each cycle or half cycle. The results would be the same if the waveform were sinusoidal but this is not the case.

Rms voltage

If the voltage dip is recorded as sampled points in time the *rms voltage* will be calculated using the following equation:

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} v_i^2} \tag{3.1}$$

where

- N is the number of samples per cycles
- v_i are the sampled voltages

If we use the (3.1) for a practical case and then we compare the result with the time domain voltage waveform we see that there is a lag between the time domain event and the rms voltage drop, because it is evaluated with the contribution of the samples of the previous cycle. A way to reduce the transition is to consider only half cycle as prescribed by the **IEC 61000-4-30**. The lag is irrelevant when the duration is given by several cycles but is a problem when the duration is limited to a few cycles.

Fundamental Voltage Component

With this method it is possible to determine also the *phase angle jump*. The fundamental voltage component as a function of time may be calculated as:

$$V_{fund} = \frac{2}{T}\int_{t-T}^{t} v(\tau)e^{j\omega_0\tau}d\tau \tag{3.2}$$

where

- $\omega_0 = \frac{2\pi}{T}$
- T the period of the fundamental frequency

The result is a complex number whose absolute value is the voltage magnitude and its argument the phase angle jump.
The calculation can be repeated for each harmonic component we want to analyze giving rise to a *time-frequency analysis*. The fundamental component can be obtained through a fast-Fourier transform algorithm that lead to a result very similar to the rms method.
A problem is that it is more difficult to consider only half cycle; a possible solution can be obtained by using the relation

$$cos(\omega t + \phi + \pi) = -cos(\omega t + \phi) \tag{3.3}$$

so that the fundamental voltage calculated by taking the Fourier transform of the series:

$$v_1, v_2, \cdots v_{\frac{N}{2}}, v_{\frac{N}{2}+1}, \cdots v_N$$

is calculated with the Fourier transform of the series:

$$v_1, v_2, \cdots v_{\frac{N}{2}}, -v_1, \cdots - v_{\frac{N}{2}}$$

with a transition between pre-fault voltage and during-fault voltage faster.

Peak Voltage

The peak voltage can be obtained by using the following expression:

$$V_{peak} = \underset{0 < \tau < T}{max} |v(t-\tau)| \tag{3.4}$$

with

- v(t) the sampled voltage
- T and integer multiple of one half-cycle

It shows a sharp drop and a sharp rise but not coincident with the beginning and the end of the event.

The magnitude is calculated as a function of time but now we need to obtain one value representative of the sag. Most monitors take the lowest value, corresponding to the precautionary assumption that the equipment trips instantaneously. The number is usually the percentage of the residual voltage. A problem is the choose of the reference voltage (pre fault voltage or nominal voltage). The second one appears to be more effective because equipment trips as a consequence of an absolute drop, not in comparison with the previous voltage.

3.2 Thoretical calculations of voltage drop magnitude

A fault in the transmission network causes a serious dip for both substation bordering the faulted line and then is transferred down to all customers. The impedence of the transformers is high enough to limit the volage drop at the high voltage side if the fault is at lower voltage. To quantify sag magnitude in radial systems, the voltage divider model can be used. The magnitude of the voltage dip depends, in case it is due to a short circuit, on the electrical distance of the observation point from the site of the short circuit and the source of supply [10]. In figure 3.1 a simplified scheme where equivalent impedances are considered is depicted.

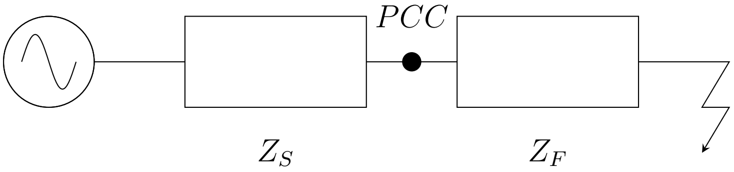


Figure 3.1: Voltage dip due to short circuit

The voltage at the pcc is:

$$\underline{V_{res}} = \frac{\underline{Z_F}}{\underline{Z_S} + \underline{Z_F}} \underline{V_n} \tag{3.5}$$

where
$\underline{Z_F}$ is the impedance between the pcc and location of the fault
$\underline{Z_S}$ is short-circuit impedance of the source upstream the pcc
$\underline{V_n}$ is the nominal voltage.

Depending on the relative magnitudes of the impedances, the residual voltage can vary from 0% (if $Z_2 \simeq 0$, that is short circuit near the user) to 100% ($Z_2 >> Z_1$, in case of short circuit far away from the user). As it can be easily seen the dip becomes deeper for faults electrically closer to the PCC. The magnitude can be therefore calculated as a function of the distance to the fault. For cable lines the influence of cross section is higher than overhead lines because the reactance is significantly smaller. In fact the equivalent impedance can be calculated, in a simplified model, as:

$$\underline{Z} = rl + jxl \tag{3.6}$$

where
r is the resistance of the feeder per lenght unit (Ω/km)
x is the reactance per unit lenght (Ω/km)
l is the lenght of the feeder (km)

The impedance of the transformer also contribute to the voltage drop so that a critical situation is when the customer is linked to the pcc to the same voltage level of the fault even though in a different line.

The depth of a voltage dip depends on the kind of short circuit and connection of windings of the transformer.

3.3 Sources

The most frequent source of voltage dips is an electrical short circuit: it causes a very large current which gives rise to a large voltage drop across the feeder of the power supply. Known the source of the problem it is clear that in most of cases the presence of voltage dips must be considered as an unavoidable part of the system operation but if the system is designed properly the probability that voltage dips with low residual voltage appear can be greatly reduced. Enhancement of the reliability and the quality of the system that require investments so that the system is designed as a trade off between economical and technical expectations.

As well known, supply systems are equipped with protective devices to disconnect the short circuit, with a consequent recovery of the voltage more or less to its previous value.

3.4 Effects

3.4.1 Adjustable-speed drives

Adjustable-speed drives are extremely sensitive to voltage sags, because operation can be interrupted and it is quite difficult to make them more tolerant. Often used in critical process control environments the consequence is potentially highly dangerous in terms of cost implications.

When the power supply voltage decreases below the DC bus voltage, only the capacitors supply the load. As a consequence, the DC voltage decreases to a level where the inverter will be disconnected.

Possible problems that follow a voltage drop are [10]:

- damage of the power switches of the inverter if the control method implies constant power to the load (if the voltage decreases, the current increases)

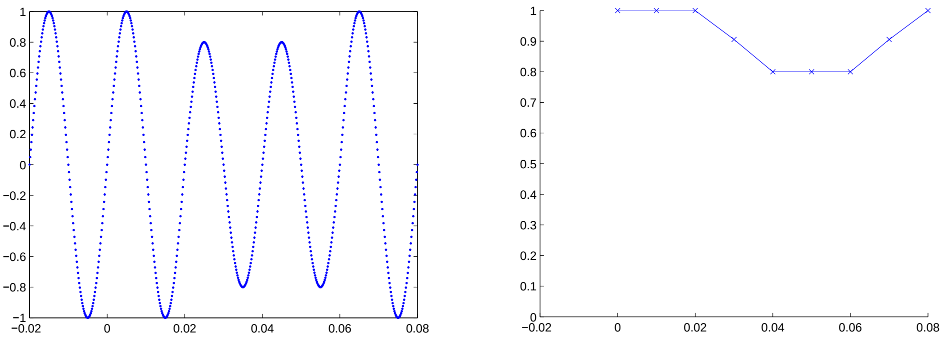
- if the ratio between voltage and current is kept constant to have maximum torque and avoid motor saturation, the frequency decrease proportionally to the voltage drop and so does the load speed.
- control electronics and IGBT drivers can be powered off if they are supplied from the DC bus.
- rectifiers can be damaged due to charge overcurrents of capacitors on the voltage recover.

When an unbalanced voltage dip occurs (type C or D), the drive works in single phase mode. To avoid this situation, there is always an undervoltage protection that disconnect the inverter when the voltage drops below the set value.

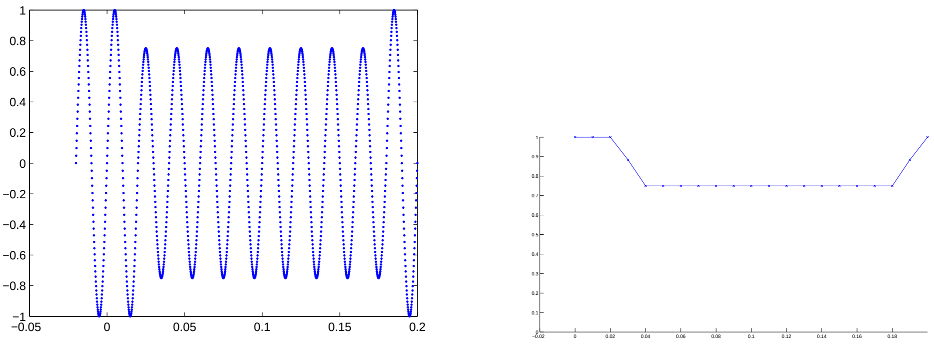
The sensibility is expressed as a voltage tolerance curve in terms of magnitude and duration values. for each magnitude the corresponding duration represents how long that voltage level is sustainable without trip or malfunctioning. The use of this curve is strictly correct only for single phase equipment or balanced voltage dips and in general is not valid in case of poly-phase unbalanced voltage dips. The susceptibility mainly depends on the capability of the capacitor on the DC link to store energy, usually small so that when the voltage decreases, the energy is absorbed by the induction motor in a few milliseconds. When the possibility to achieve higher immunity is taken into account, several factors must be considered, but the cost of the mitigation compared with cost of the disturbance is the most critical. Most of the solutions consist of increasing stored energy: batteries, supercapacitors, flywheel energy storage systems, super conductive energy storage and fuel cells are some example.The installation of uninterruptible power supply (UPS) is often used but not always it is the better one because it is expensive and requires intensive maintenance.

3.5 Presentation of results

The procedure described above is done for each events. When a number of events are collected, a further step can be done: derive from the data on voltage dips over a certain period, to get the so called site-indices, extremely useful to find the better



(a) Ideal 2-cycles dip (samples and calculated rms)



(b) Ideal 8-cycles dip (samples and calculated rms)

Figure 3.2: Voltage dip due to the connection of a large load of the user

position for sensible equipment or to understand mitigation possibilities. The aim of the analysis of voltage dips is, at the end, to evaluate how many times per year will the equipment trip and a possibility, probably the faster and most efficient one, is to carry out the analysis through monitoring. To understand the quality of the system for the supply point, it is then necessary to compare the monitored performances of the system with equipment voltage tolerance, that can be found doing tests or taking typical values and determine expected impact presenting, at the end, the results in a suitable form.

The scatter diagram

Each event is plotted as a point in a duration-magnitude plot. As it is possible to see from fig. 3.3 it shows at one glance all basic information about the characteristic of the events occurred during the monitoring period giving an indication about their distribution.

The sag density table

Each element gives the density of events within a given range of magnitude and duration as exemplified in the table below.

	>0.8s	0.6-0.8 s	0.4-0.6	0.2-0.4	0-0.2 s
80-90%	0	1	2	2	8
70-80%	0	0	0	0	2
60-70%	0	0	0	0	1
50-60%	0	0	0	0	0
40-50%	0	0	0	0	1
30-40%	0	0	0	0	0
20-30%	0	0	0	0	0
10-20%	0	0	0	0	0
0-10%	0	0	0	0	1

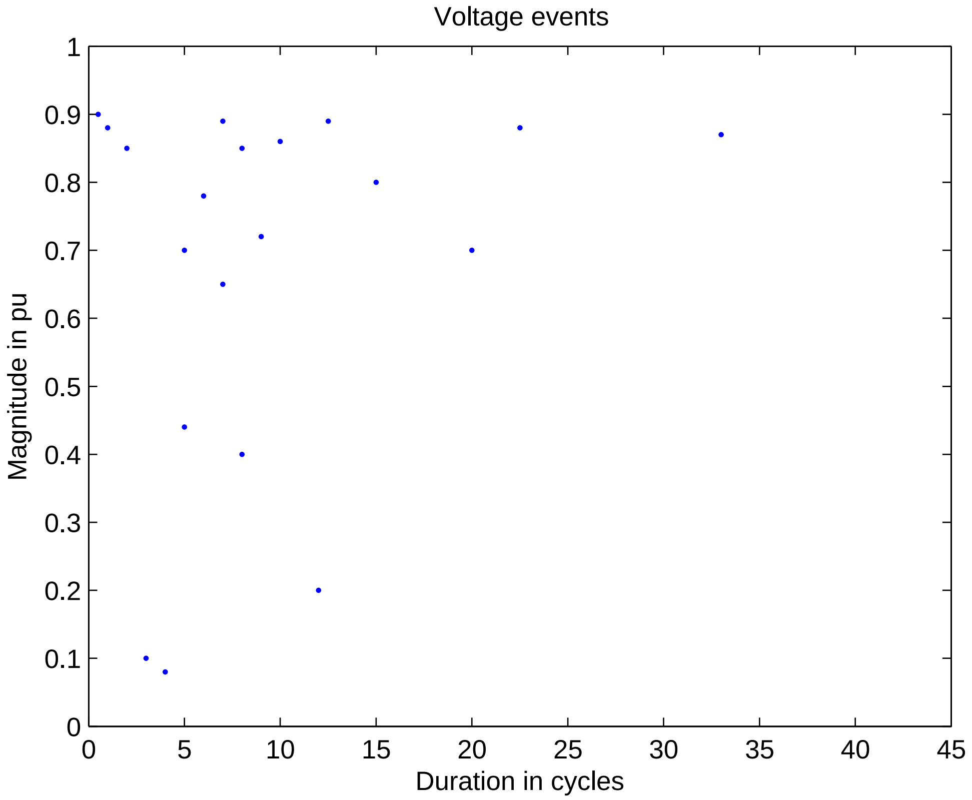


Figure 3.3: Scatter diagram

The cumulative table

The cumulative table gives the number of sags worse than a given magnitude and duration range and can be derived from the sag density table.

	>0.8s	0.6-0.8 s	0.4-0.6	0.2-0.4	0-0.2 s
80-90%	0	1	3	5	18
70-80%	0	0	0	0	5
60-70%	0	0	0	0	3
50-60%	0	0	0	0	3
40-50%	0	0	0	0	2
30-40%	0	0	0	0	2
20-30%	0	0	0	0	2
10-20%	0	0	0	0	2
0-10%	0	0	0	0	1

The voltage sag coordination chart.

It is a contour chart in which can be seen a simple method to predict the number of equipment trips.

In figure 3.4 it is clear that by comparing the levels to which devices A and B are supposed to trip and the major line the intersect that regions an hypothesis can be given for the number of malfunctions that will occur. For instance in the case represented the most reliable solution is B because in that region there are a smaller number of voltage dips per year.

3.6 ITIC and CBEMA curves

All this kind of visualization of monitoring results have their own advantages but it is clear that if it is not possible to compare them with the immunity level of the equipment they are quite useless.Given that immunity of equipment is not always known a possibility is then to use the ITIC (fig. 3.5) or the CBEMA curve that show values of magnitude and duration that must be tolerated by the equipment.

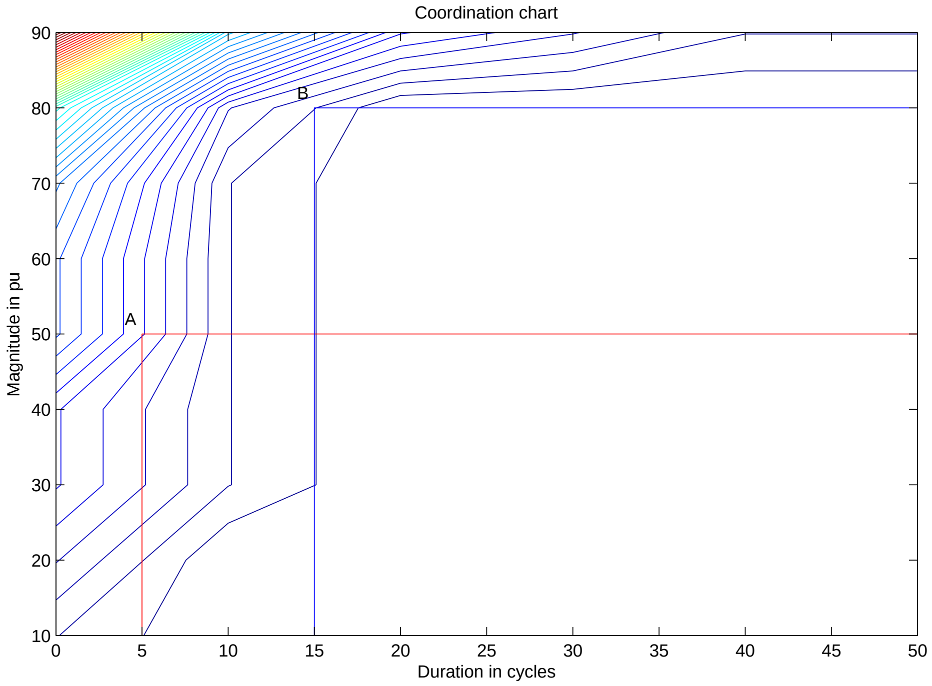


Figure 3.4: Coordination chart

They are generic curve so that all devices should tolerate those voltage dips so that a less critical event should be easily tolerated.

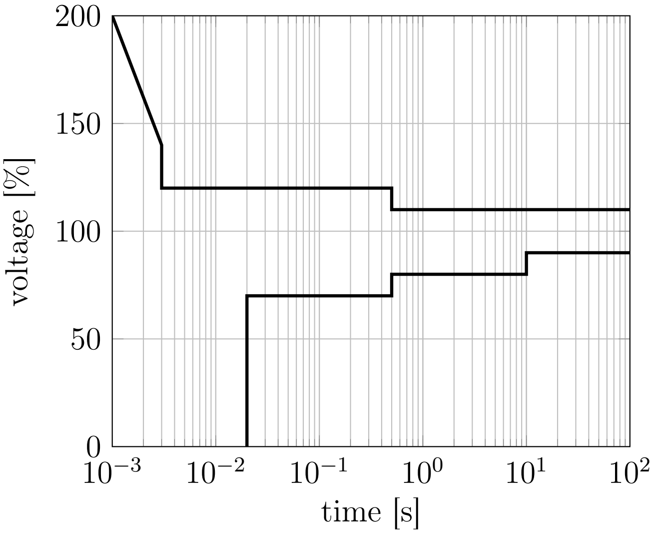


Figure 3.5: ITIC curve

It is also possible to consider a particular curve for a specific device if the scope is to evaluate only that compatibility.
In [11] the curve has been calculated for different LED lamps, that as well as other electronic devices, suffer voltage dips (see fig. 3.6).

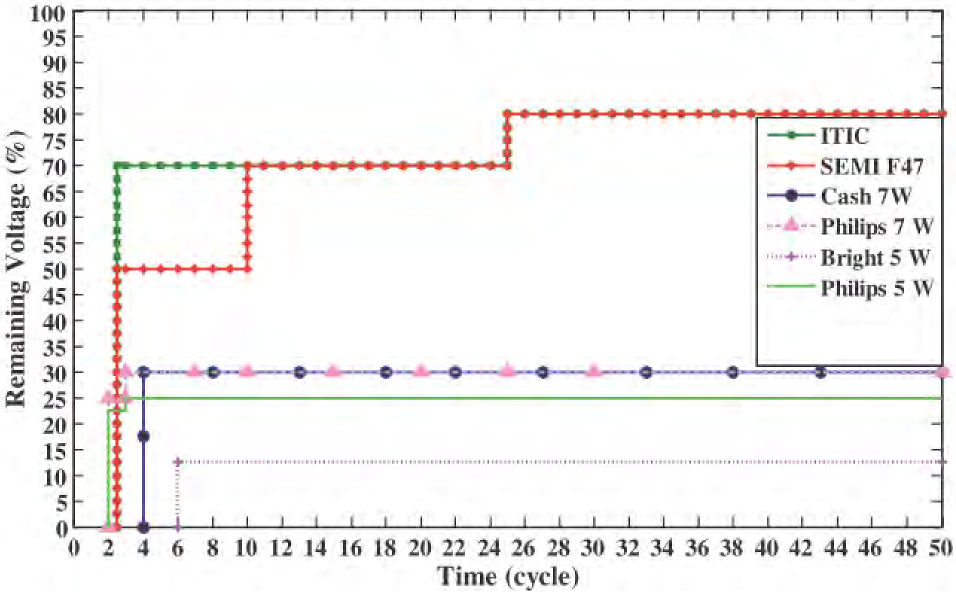


Figure 3.6: Voltage tolerance curves of various LED lamps [11]

Chapter 4

Flicker and waveform distortion

The flicker is the physiological human perception of the variation of illumination intensity usually due to a voltage fluctuation of the power supply. The evaluation of this phenomenon is not simple because the measurement must be weighted by the human response to voltage changes. Flicker is caused by low frequency (especially around 10 Hz) voltage fluctuation of amplitude generally much lower than the threshold of immunity for electrical equipment [10]

4.1 Definitions

A voltage change is defined as a deviation in the r.m.s voltage with respect to a steady-state value averaged over a defined period.
Voltage fluctations are cyclic variations of voltage within the range ±10%. Usually the effect encountered by most of equipment is extremely limited so that the main problem is variation of the illumination intensity of artificial light sources.
flicker is the negative sensation given by the fluctation of luminance or spectral content of the light with time.

Differently by other power quality problems in this case the victim is a generic person whose perception is found with statistical methods [1] so that the immunity level is fixed and not modifiable and the only possibility is to limit the disturbance.

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[1] The perception threshold is given by the level valid for more than the 50% of the population

4.2 Sources of voltage fluctuations

Voltage fluctuations are generally due to load variations. Large industrial loads are the main source of voltage variations. Some examples are arc furnaces, welding machines or electric boilers. Loads that provoke light flicker can be divided into two groups [12]. In the first one, which includes a lot of heating and cooling loads, the cause of fluctuation is the sequence of repetitive events. An example is conditioners and refrigerators where the electrical motor is continuously switched on and off to regulate the temperature and a high inrush current is taken every time it is started. In the second group there are the loads that changes continuously, like arc furnace, arc and resistance welding, traction loads and wind turbines.

4.3 Flicker with other types of lighting

As seen in chapter 2 the IEC standard refers exclusively to incandescent lamps. Nowadays, incandescent lamps are less and less used where a good illumination is required with the progressive substitution with fluorescent or LED lamps so that the reference to only incandescent lamps in the standard seems to be quite limited.

It is theoretically possible to adapt the flickermeter standard to other types of lighting by changing the lamp-eye-brain response. The main problem is that the response of lamps of different manufacturers may vary strongly. Another effect is the electronic dimmer that increases the voltage fluctuation, showing a non linear behavior that, together with effect of voltage distortion on light intensity, not simply proportional to the rms ov the voltage, imply that, if new lamp types are to be included, a complete new lamp model is required.

4.4 Other application of flicker measurements

Flicker measurement is important not only where the consequences of light intensity variation must be evaluated, because there are other loads affected by fluctuation of voltage amplitude. Some examples are : control systems acting on the voltage angle, breaking or accelerating motors, small speed variations in the motor driving with a consequent in the non uniformity of the final product.

4.5 Waveform distortion

Harmonic disturbances are one of the most noticeable power quality issue. They appear anytime a non linear load,such as transformers, rotating electric machines, power electronics components, fluorescent lamps renewable energies and many others, is connected to the power system. In the last years, since electronic equipment is used more and more, the harmonic content of the voltage has strongly increased.

To measure the magnitude of harmonic component is important to find polluting sources and find out critical situations. A digital meter implements the discrete algorithm of the Fourier transform. The analogue signal is sampled, converted by an ADC and the values obtained analyzed.

4.6 Effects

The main effects of harmonics are maloperation of control devices, telephone interferences, additional line losses and equipment (transformer, rotating machines and capacitor banks) losses as well as decreasing of lifetime.

4.7 Harmonics and interharmonics

If a nonsinusoidal waveform is periodic, it can be decomposed in terms of Fourier series, each term of which is an harmonic component with frequency multiple of the fundamental frequency:

$$v(t) = V_0 + \sum_{h=1}^{n} V_h cos(h\omega_0 t + \alpha_h) \tag{4.1}$$

The voltage (or current) can contain also components of frequency not multiple integer of the fundamental components called *interharmonics* as well as components with frequency lower than the fundamental frequency called *subharmonics.*

With the discrete Fourier transform it is possible to find the magnitude and the phase of harmonics and interharmonics with a resolution that depend on the time window: if the time window is n time the fundamental period then the resolution is the fundamental frequency divided by n.

$$T_W = nT \Rightarrow \Delta f = \frac{f}{n}$$

The maximum order of harmonics that can be evaluated depends instead on the number of samples per cycle. Both these enhancement imply a greater number of data that must be elaborated by the algorithm. For this reason the typical choices are 128 sample/cycles that allows the theoretical calculation up to the 63rd in compliance with standards that require at most the 50th and a time window of 10 cycles which allows a resolution in a 50 Hz system of 5 Hz. Therefore the algorithm will be applied to 1280 values.

Chapter 5

Power quality measurement

After the analysis of the main standards useful to undarstand the main characteristics that a Power Quality monitor should have and the most relevant phenomena that lead to disturbances, extremely important to understand the potential markets where this kind of analysis is requested, because there are the conditions that can be origins of power quality problems, it is analysed how to make a new meter considering some innovative possible solutions to analyse power quality and highlighting some issues concerning the measurement strategy in order to understand the main critical aspects and, on the other hand, to understand which non-ideal methods can be applied without any kind of problems because the error or the uncertainty introduced is extremely low.

Depending on the target price we want to get and therefore on the segment of the market to which the new product is addressed it is possible to implement different steps of analysis. Given that this is the first product that will implement advanced power quality analysis some suggestions are given to obtain reliable measurements and useful additional information even if, for complexity or cost reasons, it will be not possible to implement all the features.

5.1 Measurement of voltage dips

To assess the power quality with respect to voltage dips the procedure begins from the sampled voltages, with given sampling rate and resolution. In the IEC 61000-4-30 standard [8] there is not a requirement for sampling rate or resolution for voltage dips, however in cases when also the harmonic analysis is performed a sampling rate of more than 80 samples per cycle (given the calculation up to the 40th harmonic) is required with typical values of 128 or 256 [10] and, having analysed similar products by different manufacturers, these have appeared to be the most frequent values.

The samples are then elaborated to obtain the event characteristic as a function of time; for the IEC 61000-4-30 the characteristic is the sequence of rms values calculated over a cycle and updated every half cycle ($U_{rms_{1/2}}$). The procedure is depicted in figure 3.2a where an ideal short event is considered.

The next step is to obtain the so called single-event indices, for instance duration and depth. From the figure it can be noticed that the behaviour of the rms is delayed in respect to the time-domain signal. However in this case the calculation of the residual voltage (0.85 in p.u) with the algorithm of the IEC 61000-4-30 is correct, the duration, with an hysteris of 2% gives a value of 0.03 (the first rms voltage below 0.9 is at time 0.04 and the first one which goes above 0.92 is at time 0.07) s while the real one is 0.04 with an error of half cycle, though within the accuracy requirements.This effect is given by the fact that the residual voltage is above 0.8; it is smaller than this value it is easy to verify that the value would be greater than the real one. An example is given in figure 3.2b where the duration is calculated half cycle (0.01 s) longer than what it is.

5.2 Park transformation

As we have seen in the previous section the typical method used to detect a voltage dip is to consider r.m.s voltage, updated every half cycle of each channel and to consider each of them independently or the worst channel as the reference. The consequence is that the resolution with which it is possible to establish the duration of the event is not more then half cycle though a huge amount of data are analyzed without permissible interruption. The problem is that, using the r.m.s method, to obtain a number it is always necessary to process all the samples of a cycle. If it were possible to get an indication of an *instantaneous system voltage magnitude* it were possible to detect a voltage dip without the necessity to process a large amount of data. Considering that the industrial plants are the typical application of this kind of measurements it is possible to assume a three phase system where, from the Park theory, it is possible to calculate for each time instant, given only one sample for each phase, the magnitude representative of the whole system so that a variation is instantaneously detected and the duration is perfectly calculated. The algorithm requires to calculate the real and the imaginary part of the vector as illustrated in equations (5.1) and (5.2).

$$V_{re} = \frac{2}{3}\left(V_1 - \frac{1}{2}V_2 - \frac{1}{2}V_3\right) \tag{5.1}$$

$$V_{im} = \frac{2}{3}\left(-\frac{\sqrt{3}}{2}V_2 + \frac{\sqrt{3}}{2}V_3\right) \tag{5.2}$$

Therefore the magnitude is:

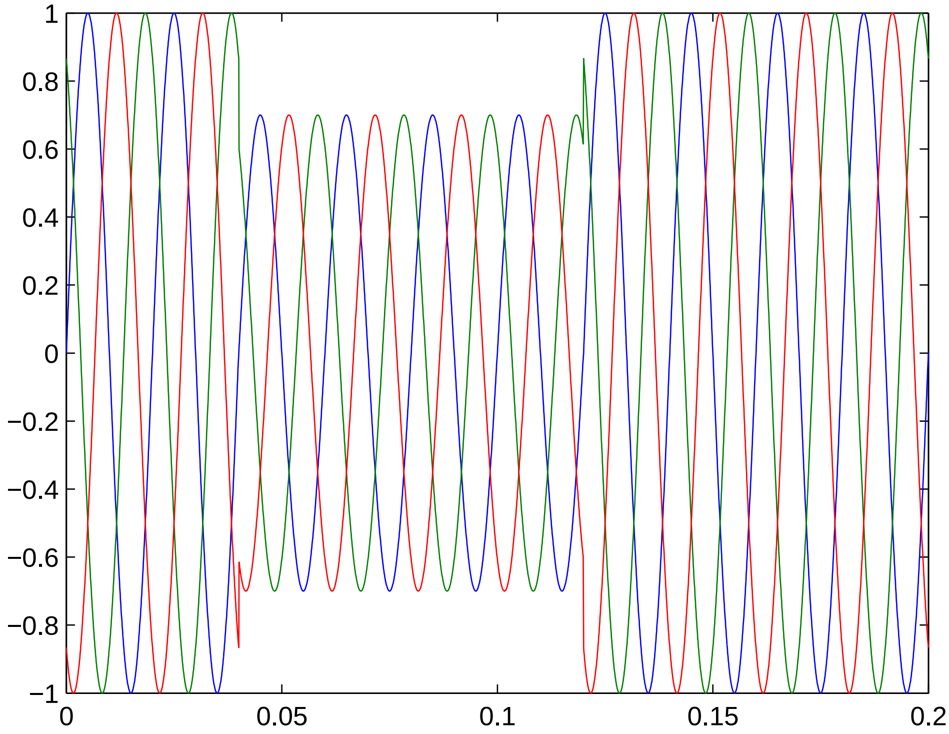
$$V = \sqrt{V_{re}^2 + V_{im}^2} = \sqrt{\frac{\sqrt{3}}{2}V_2 - \left(\frac{\sqrt{3}}{2}V_3\right)^2 + (V_1 - V_2)^2} \tag{5.3}$$

To evaluate if this approach is applicable as a first step consider the case of a three phase symmetrical voltage dip (see fig. 5.1a).

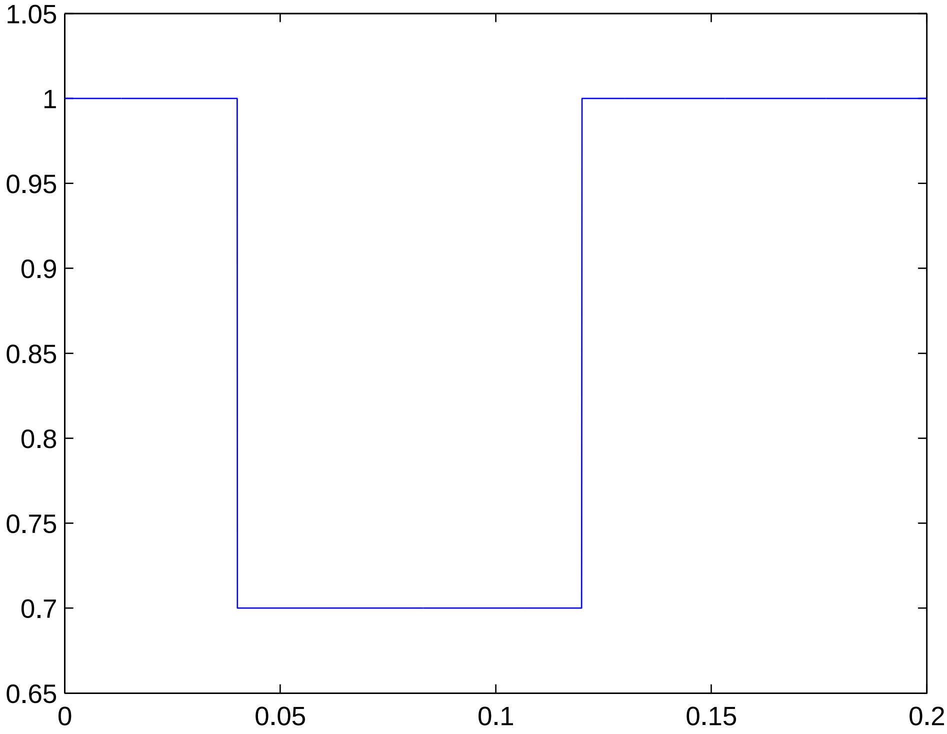
Considering the magnitude of the spatial vector resulting by the application of the transform the result is depicted in figure 5.1b.

If only one phase is affected by the voltage dip, as a consequence of a monophase fault, a complication appears because the magnitude calculated is no longer constant during the phenomenon as it can be seen in figure 5.2

In this case the result is not so immediate so that the method proposed is not generally applicable, but in any case it can be used to detect an event, as a trigger. A possible solution could be, in order to reduce the computational effort, to apply this algorithm a few times during a cycle with a low sampling ratio. This is extremely cheap because only three values have to be elaborated. Simultaneously

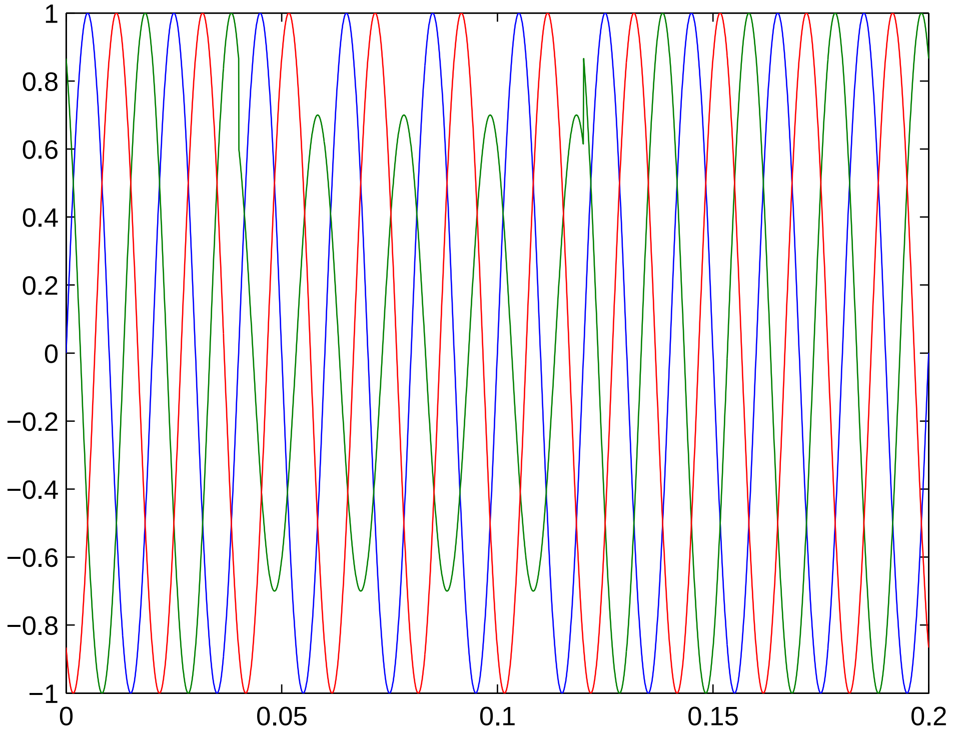


(a) Time domain voltage and current

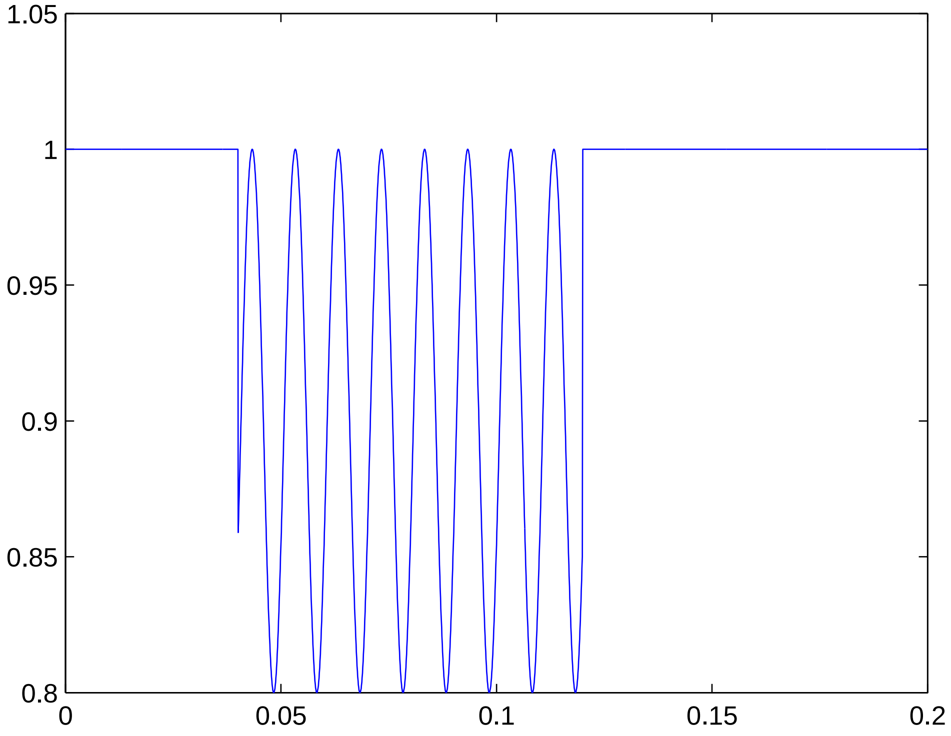


(b) r.m.s voltage and current

Figure 5.1: Symmetrical three-phase voltage dip



(a) Time domain voltage and current



(b) r.m.s voltage and current

Figure 5.2: Non-symmetrical three-phase voltage dip

and in parallel an higher sampling ratio sampling can be used to save in a FIFO memory all the values that, in case a voltage dip is detected can be saved in a non volatile memory and eventually further analysed to get depth, duration and all other requested information about the event.

5.3 Sources of voltage dips

When a power quality disturbances occurs, the most important thing, maybe even more than the exact value of the disturbance, is to know the cause or the location of the problem.As we have seen power quality is often referred to as voltage quality and the consequence is that for what regards power quality measurement only voltage signals are taken into account. In the IEC 61000-4-30 there is never the requirements to measure the current, because the current is dependent only on the user so there is no sense in talking about current quality.

Anyhow, bearing in mind the main scope of this work, that is to define what a new power quality meter, in a combination of performance and economical feasibility, should do, the identification of the source of problems would be a great added value in respect with other similar devices. In the literature advanced techniques of signal processing are proposed to analyse voltage signal, but most of them are extremely expensive from a computational point of view. This means that if we want to implement these algorithms in a power quality meter, the cost of the device will inevitably grow significantly.

In the harmonic analysis it is possible to obtain the direction of the disturbance from the knowledge of the displacement between the phases of the harmonics.

In case of a voltage dip there is a phase angle shift, in fact, from equation (3.5) it is clear that in addition to the magnitude variation there is also a phase angle shift due to changing of the X/R ratio. From this value it is possible to find some information about the voltage dip, but the most important thing to know is the location of the origin of the problem. A quite easy observation is this: as a first step we want to know if it is upstream or downstream the meter because, if we put the meter at the PCC of the user we are able to find if the responsibility of the voltage dip is of the user or not. In another case, if the meter is put at the beginning of a dedicated line we can check if the problem is there or elsewhere.

If the voltage dip source is upstream the meter, the load is not not responsible, there is no change in the equivalent impedance of the load that will see a reduction of the voltage applied: the consequence will be a reduction of the current absorption or the same current if this is the case. If the problem is downstream then the load is responsible of great current absorption. The idea is therefore to apply a simple algorithm but considering also the current.

- If the current is below or at the same level of the voltage between the event, then the source is elsewhere,
- if the current is much above the previous value the source of the disturbance is the load itself.

This method is quite simple to implement because, it is enough to consider the rms of the current when the event is detected. Anyhow, because the event duration might be extremely short, then not only the rms of voltage but also the rms of the current should be update with high frequency, for instance every half cycle in a FIFO memory.

To explain how this method works a single-phase system is considered (see fig.5.3) and a simulation is done with simulink. A power quality meter is supposed to be connected downstream the point of common coupling. Two situation are considered:

- At a certain time the user connects an heavy load
- At a certain time there is a short circuit on another feeder connected to the same PCC.

The measurement of voltage and current is done with a sampling rate of 128 sample/cycle. The sampled values are then processed using Matlab in order to simulate the power quality meter.

The waveform of the current and the voltage obtained are represented in figure 5.4a shows what happens for the case of a short circuit on another feeder. The behaviour of voltage and current is clear by observing the rms values (fig. 5.4b): current follows the path of the voltage.

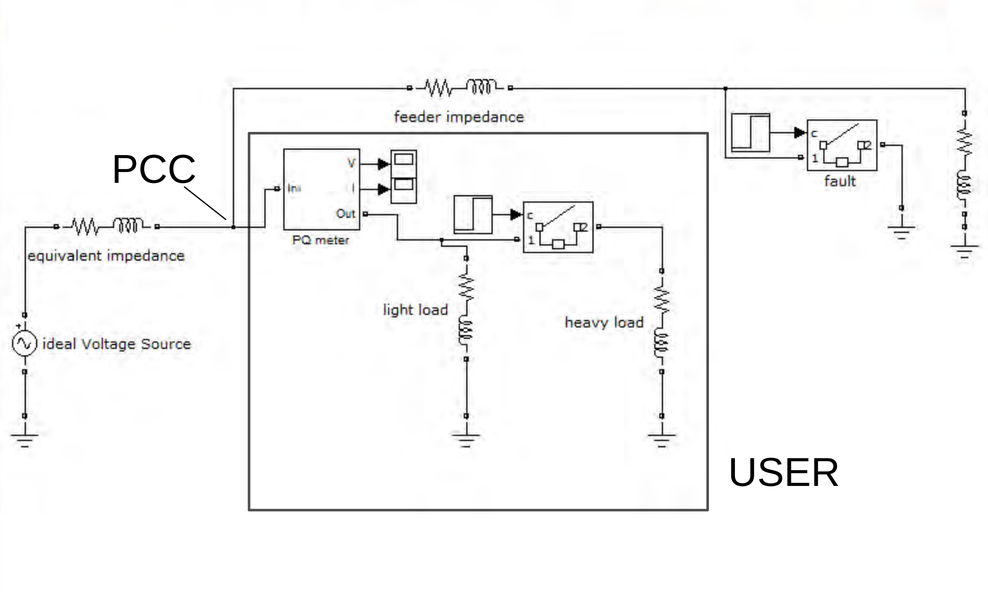
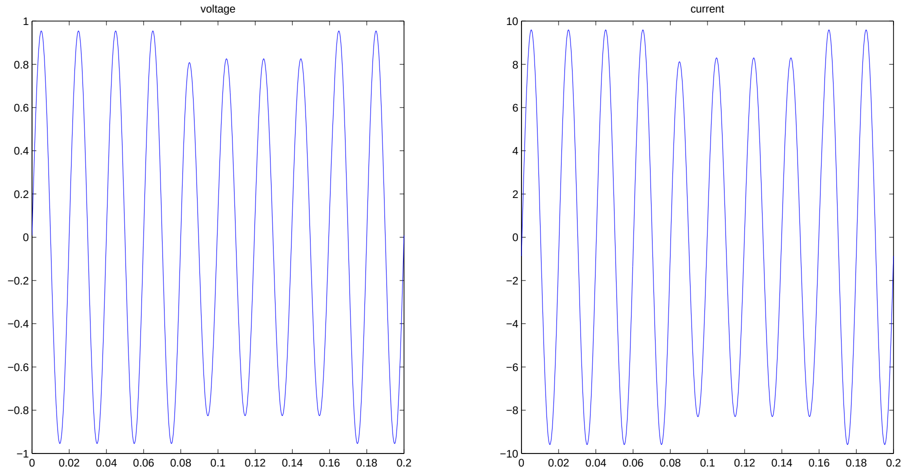


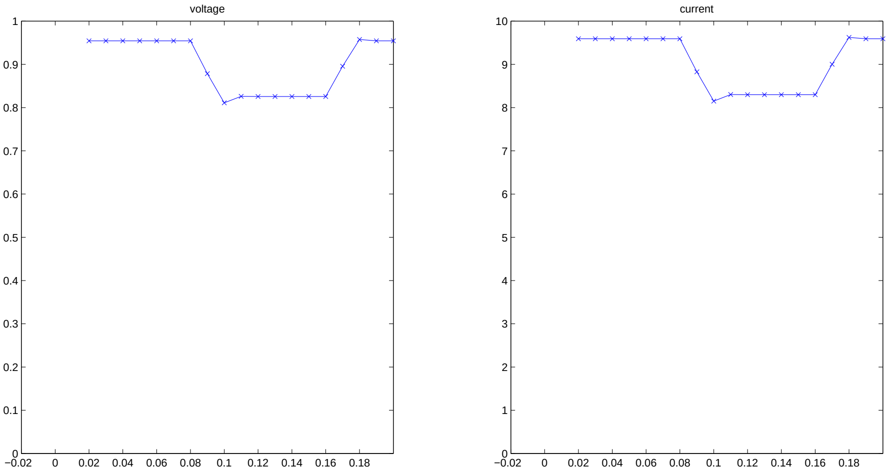
Figure 5.3: Single-phase model of a system used to simulate a voltage dip

In the case where the voltage dip is due to a large load connected by the user (downstream the meter) from figure 5.5a and 5.5b it is clear that the situation is completely different because to the voltage dip correspond an increase in the current absorption.

An algorithm very simple to be implemented can be produced on the basis of the observations done above. If all the point collected could be memorized the analysis could be done on the basis of the waveform analysis but, considering that the monitoring time is often very long, to have enough information to study the statistical behaviour of the system, the amount of data, even if collected only when an event is triggered could be too much big. This is the reason because in the standard it is suggested to save only duration and magnitude. Adding the information of the location of the source of disturbance is quite inexpensive. Comparing the average rms of the current during the voltage dip, with the average before the event seems to be enough to decide the source of the problem.

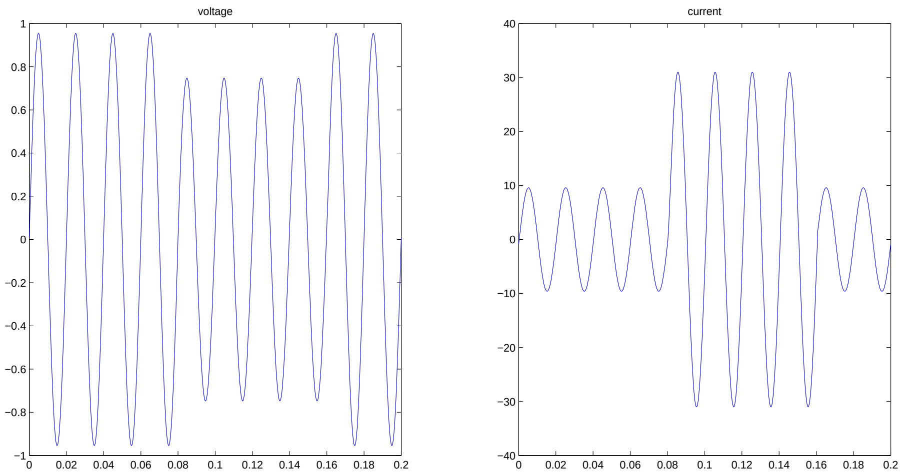


(a) Time domain voltage and current

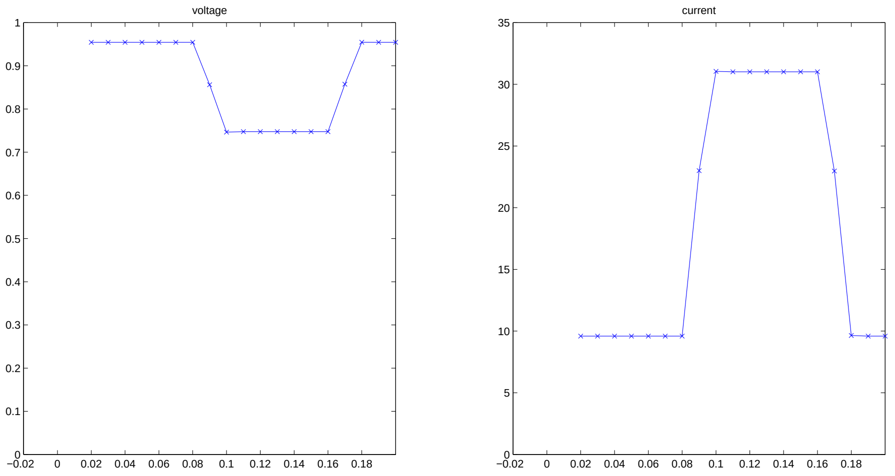


(b) r.m.s voltage and current

Figure 5.4: Voltage dip due to a short circuit on another feeder



(a) Time domain voltage and current



(b) r.m.s voltage and current

Figure 5.5: Voltage dip due to the connection of a large load of the user

Table 5.1: Network parameters

Source	10 MVA, 33 kV, X/R=10
Transformer T1	5MVA, 33/11 kV, %Z 7.15, X/R=10, DYn11
Transformer T2	750kVA, 11/0.433 kV, %Z 5, X/R=6, DYn11
Line	0.6748+j0.372 Ω/km, 2km
Load	190 kW, 130 kvar
Frequency	50 Hz

5.4 Three phase voltage dip: a case study

In order to better understand the impact on the network of a fault and the generation of voltage dips a simulation is performed starting from the system under study in [16] in which the feeder of Bajaj hospital is considered. The main characteristics are summarized in the table 5.1.

To analyse with the *PowerSystem block* tool of *Simulink*the three-phase system, the source is modelized by the series of an ideal voltage source and an equivalent impedance composed by the series of a resistance R_{eq} and a reactance X_{eq}. From available data the equivalent impedance is calculated

$$Z_{eq} = \frac{V^2}{S} = \frac{(3310^3)^2}{1010^6} = 108.9\Omega \tag{5.4}$$

and then the resistance and inductance:

$$R_{eq} = \sqrt{\frac{Z_{eq}^2}{1+(X/R)^2}} = 10.836\,\Omega \tag{5.5}$$

$$L_{eq} = \frac{\sqrt{Z_{eq}^2} - R_{eq}^2}{2\pi\, f} = 344.9\,mH \tag{5.6}$$

The same procedure is applied to the transformers for which a simplified model is considered with resistance and reactance put to the secondary.

As a first step, considering the transformer T1, the nominal current at the secondary is calculated:

$$I_{n2} = \frac{S}{\sqrt{3}V_{n2}} = \frac{5 \cdot 10^6}{\sqrt{3}V_{n2}} = 262.43\,A \tag{5.7}$$

Then the short-circuit impedance Z_{sc}:

$$Z_{sc} = \frac{Z_{\%} \cdot V_{2n}}{\sqrt{3}I_{n2}} = 1.73\,\Omega \tag{5.8}$$

from which, as done in (5.5) and (5.6) it is possible to calculate

$$R_{sc} = 0.172\,\Omega$$

and

$$L_{sc} = 5.5\,mH$$

.

The same procedure can be applied to transformer T2 for which the result is:

$$R_{sc} = 2.1\,m\Omega$$

$$L_{sc} = 0.039\,mH$$

Built up the model with all relevant elements is possible to simulate some typical events in order to test the monitoring procedure.

It is clear that it is not always possible to storage all the relevant waveforms. Then, as stated above, different algorithms can be applied to summarize information. The measurement block (see fig. 5.7) implemented in *Simulink* calculate the RMS value of each voltage and current updated continuously and at the same time compares the results with the magnitude of the space vector (see fig. 5.8).

In case of a short circuit on the phase A, the consequences at the point of common coupling are depicted in figure 5.9 and 5.10 It can be seen that, how it is expected from the theory, there is a drop in the voltage magnitude that depends on the ratio between the PCC and the short circuit location and the total impedance

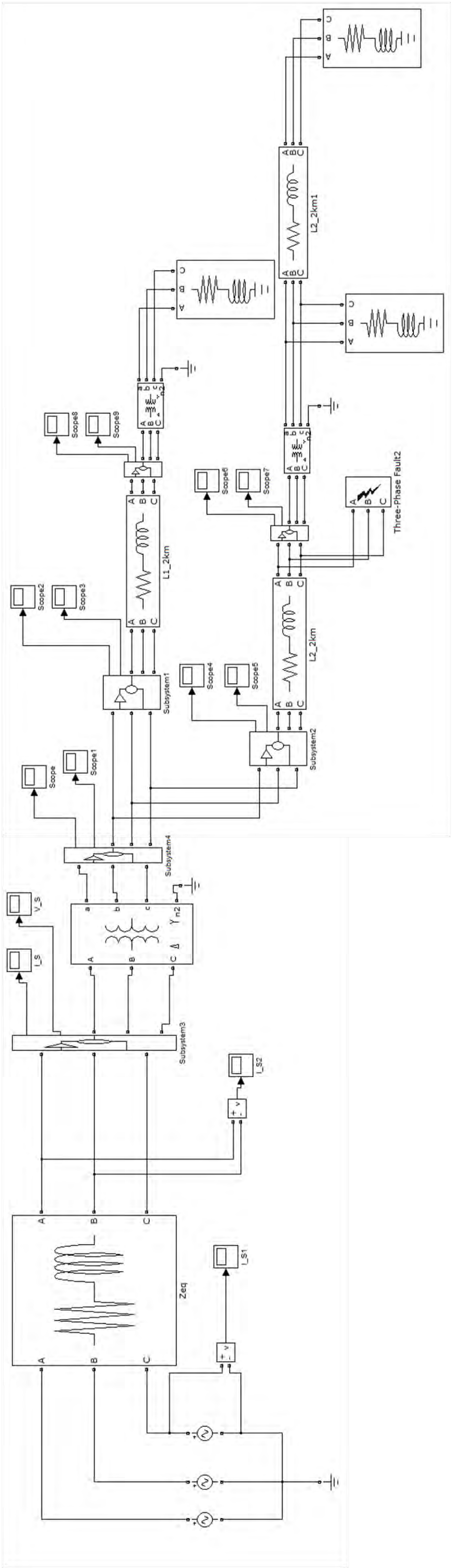


Figure 5.6: Simulink (PowerSystem library) model of Bajaj hospital feeder

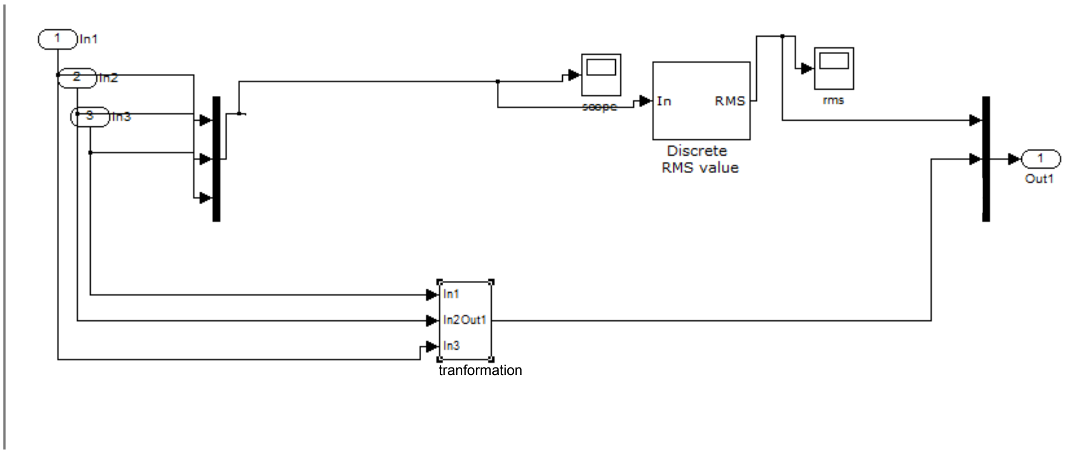


Figure 5.7: Measurement subsystem block in Simulink model

between that point and the ideal voltage source. The magnitude of the voltage dip is therefore dependent on the distance between the PCC and the fault location. In figure 5.9 are represented the measurements of the monitor *meas1* in which it is possible to understand that, given that the behaviour of the current follows the voltage then the line 1 is not responsible of the voltage dip. On the other hand, in figure 5.10 is clear that the cause of the power quality event is a short circuit on phasese A.

The same calculation can be repeated for different types of faults as done in figure 5.11 and 5.12 and different types of connection of the transformer T1.

If a discrete time intervals calculation only a few points of the curves are calculated (for instance every half cycle).

From these examples is possible to understand the strength and weakness points of the method proposed with the Park transformation. If the short circuit is due to a three phase symmetrical fault the method proposed appears absolutely as the best solution because both the duration and the magnitude can be perfectly calculated as well the exact detection of the starting and ending point.

If the fault is a two-phase things change and the method proposed gives only partial information. Finally if the fault is a one pase fault there is an oscillation. Then the method, as seen above, can be used only to give an indication that

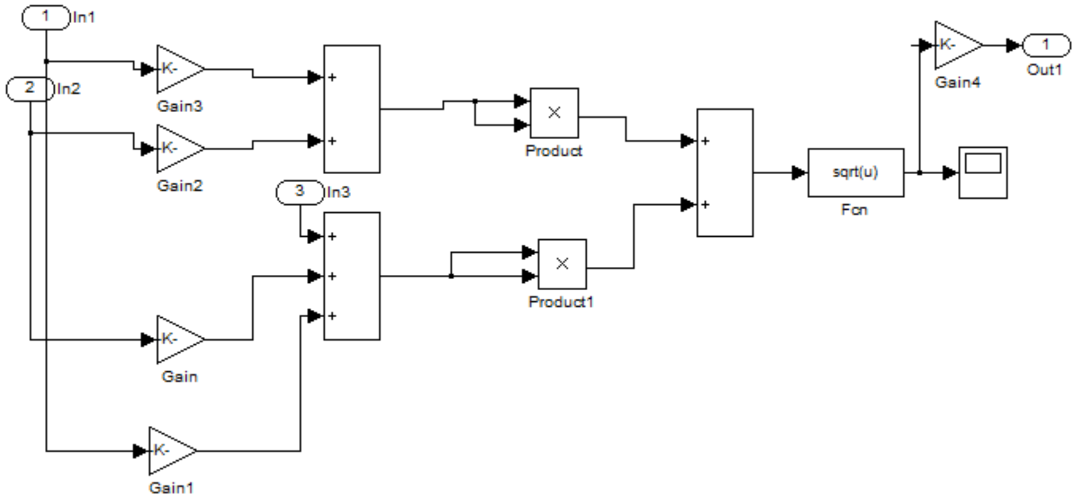


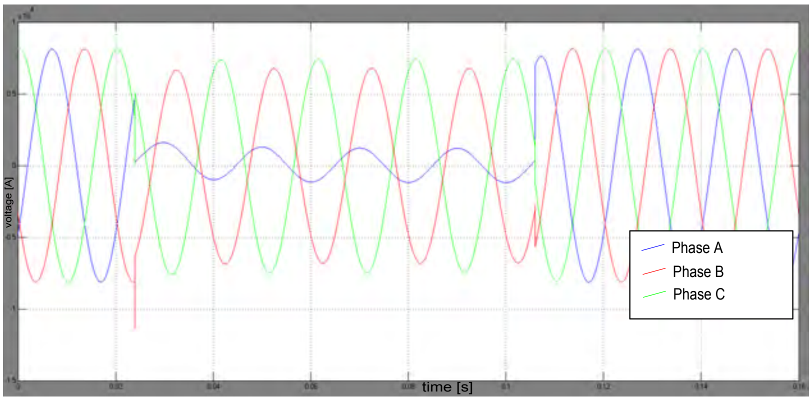
Figure 5.8: *Transformation* subsystem block in figure 5.7

something wrong is happening but not to describe in a quantitative way the event.

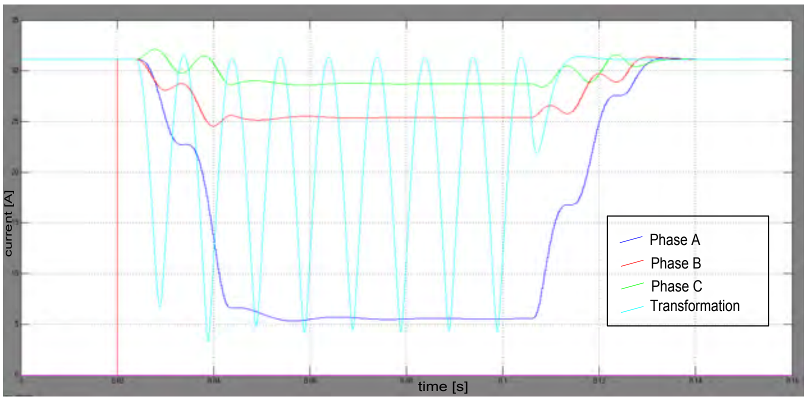
Another method that could be applied is the following: the transform applies only to three phase systems. If we want to analyze a one-phase system it can be virtually imagined as part of a symmetrical three phase system obtained shifting the waveforms. In this case, taking only three sampled values is possible to get the behaviour of the signal with an extremely reduced computational effort. Furthermore an additional advantage is obtained: the value representative of the r.m.s. value is obtained in a time interval shorter than a cycle and can be freely updated.

5.5 Harmonic analysis

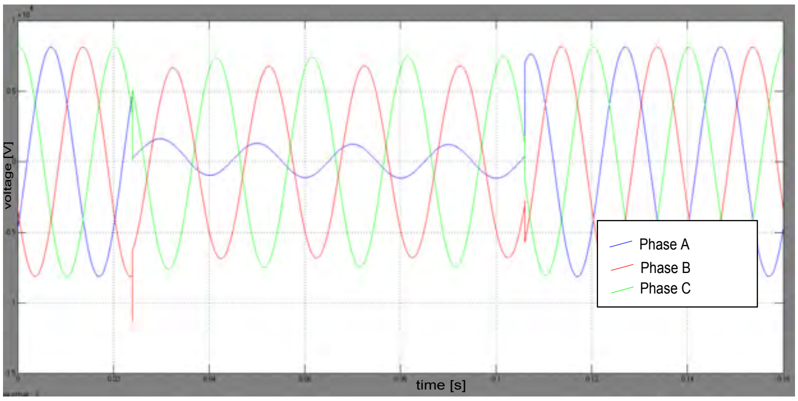
Differently from voltage dips, as seen in the previous chapters, voltage distortion is a power quality phenomenon that can't be considered an event but simply a *variation* from the ideal sinusoidal waveform. The consequence is that, if it is licit to assume that the voltage distortion is quite constant, or at least that its changes are slow, compared with the time interval of the measurement refresh, it is no longer necessary to have a continuous sampling of each channel and a full



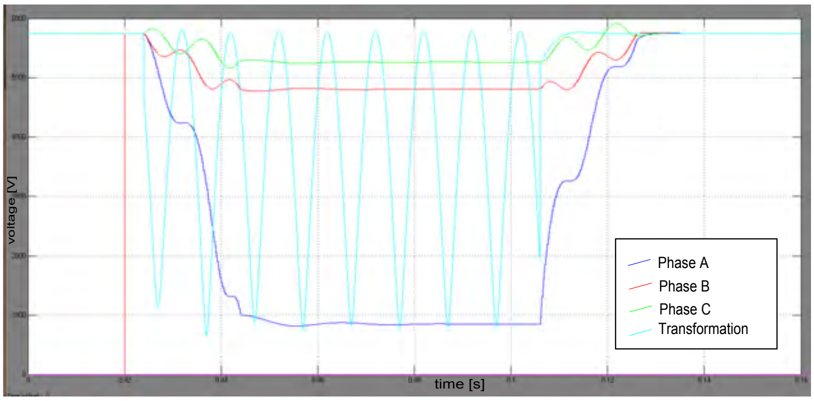
(a) Current waveforms



(b) Current magnitude

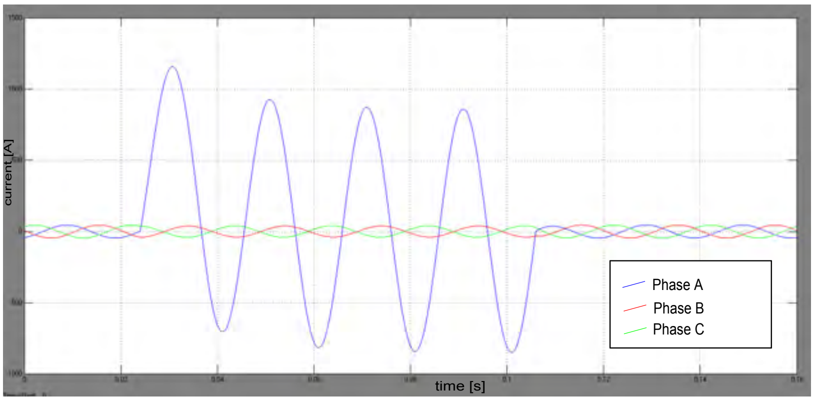


(c) Voltage waveforms

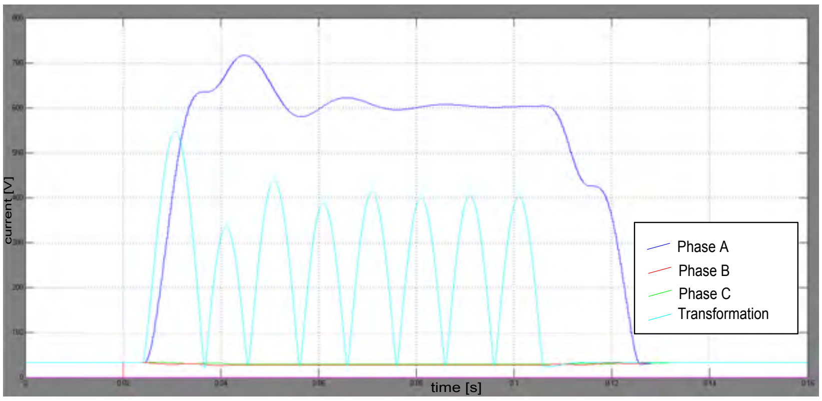


(d) Voltage magnitude

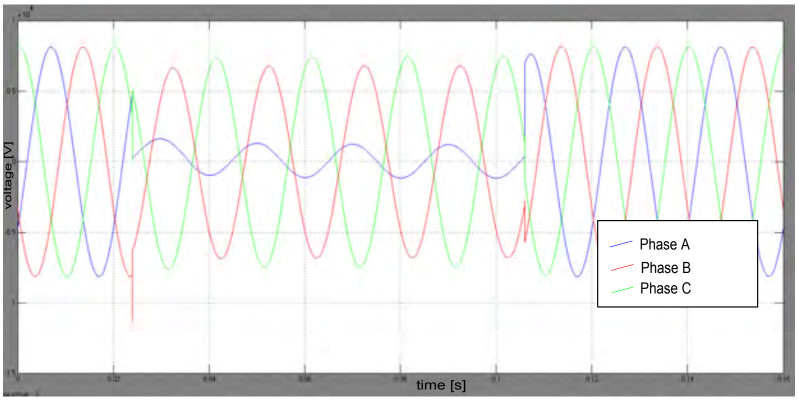
Figure 5.9: Consequences on line 1 voltages and currents of a short circuit between fase A and ground at node F.



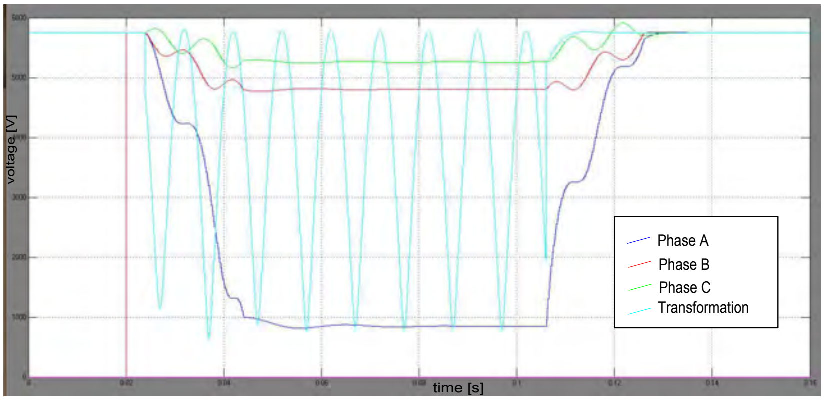
(a) Current waveforms



(b) Current magnitude

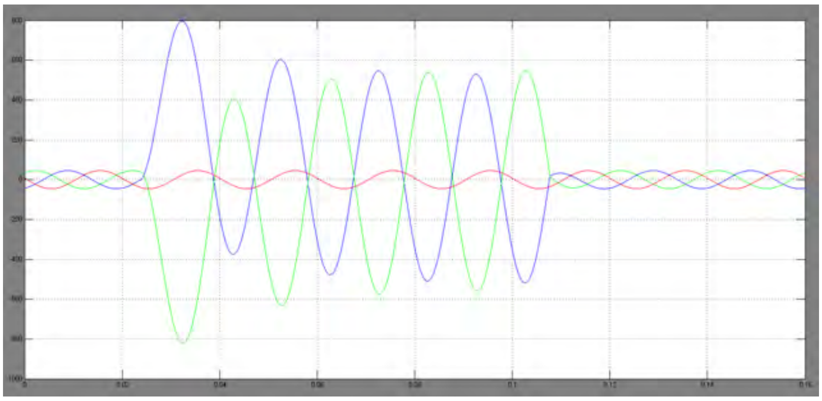


(c) Voltage waveforms

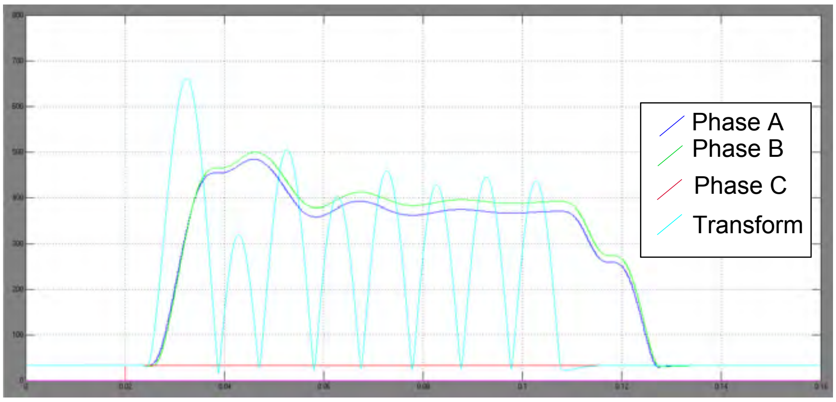


(d) Voltage magnitude

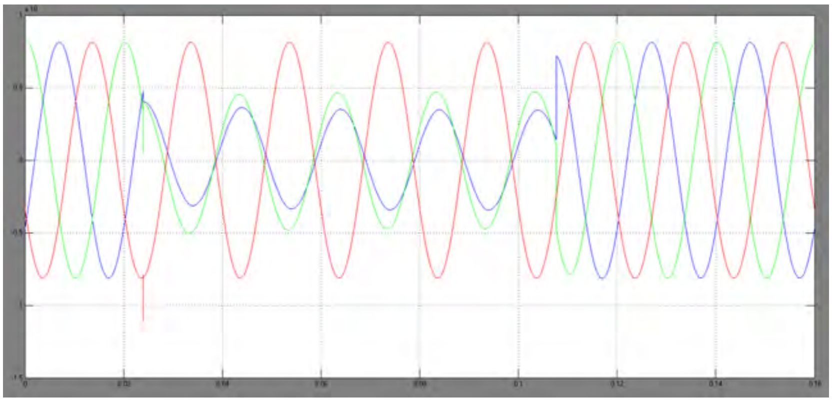
Figure 5.10: Consequences on line 2 voltages and currents of a short circuit between fase A and ground at node F.



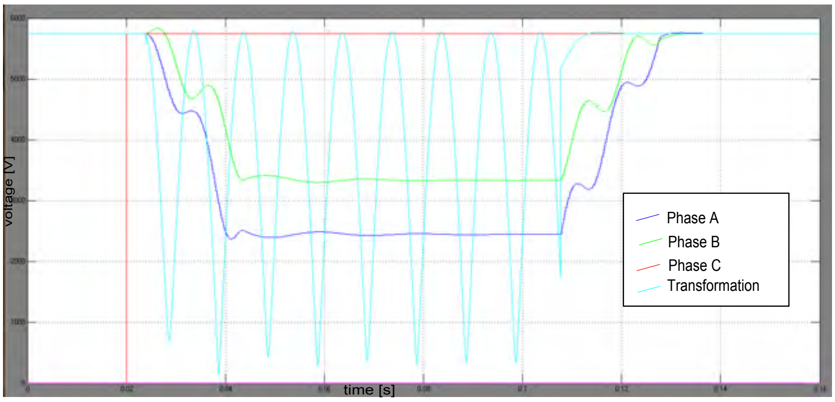
(a) Current waveforms



(b) Current magnitude

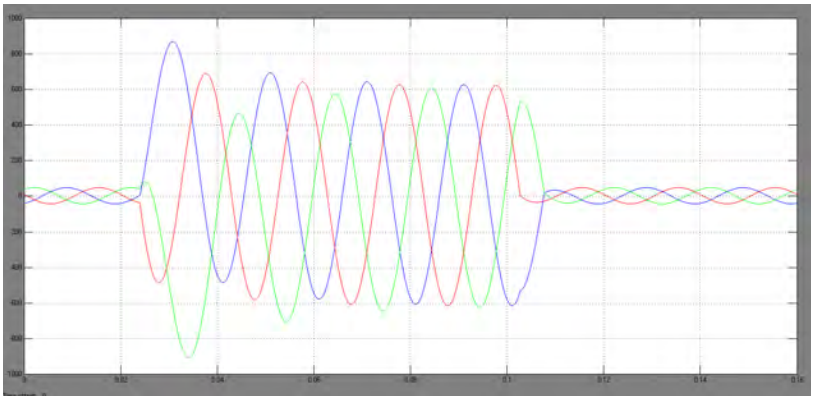


(c) Voltage waveforms

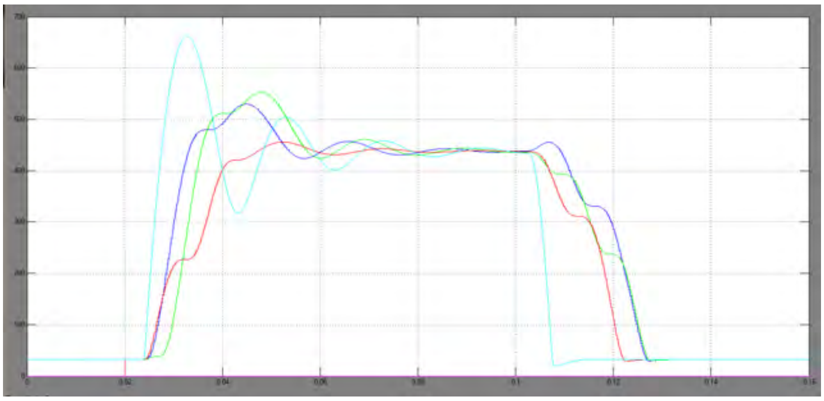


(d) Voltage magnitude

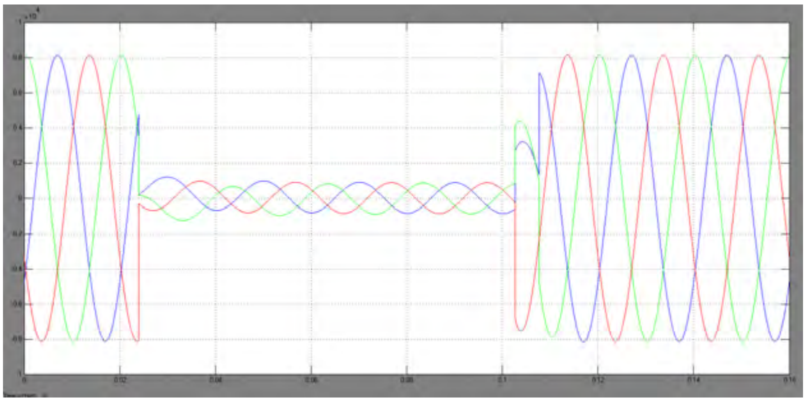
Figure 5.11: Voltages and currents of line 2 at PCC consequence of a short circuit between fase A and B at node F.



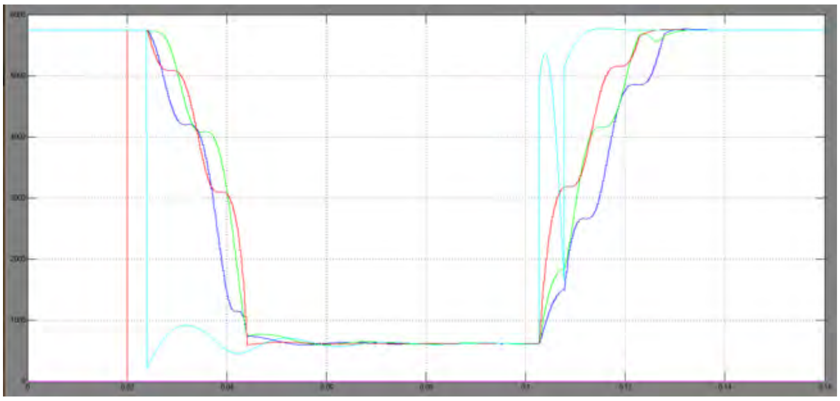
(a) Current waveforms



(b) Current magnitude



(c) Voltage waveforms



(d) Voltage magnitude

Figure 5.12: Voltages and currents of line 2 at PCC consequence of a short circuit between fase A and B at node F.

data processing. Therefore, an extremely simpler to implement *batch method* with which a few cycle are sampled and then, during a time interval in which the meter is blind to the eventual variations of the signal (this is the reasons for which we need to assume a constant behaviour), the collected data are processed and then the measurements are displayed or stored.

Anyhow, this method is to be implemented when cost reasons are predominant with respect to the reliability of the measurement and it is clear that it is not in compliance with standards on power quality measurement. Anyhow, when cost reduction is the driving force, this method can be applied but bearing in mind that it shows the real behaviour only for reduced portions of time.

To understand how the the harmonic analysis can be performed on a real system a simulation with Matlab has been used in order to understand the behaviour of the algorithm as a function of sampling rate or non perfectly synchronized sampling or unaccuracy of sampled values.

The harmonic analysis is usually performed applying the discrete Fourier transform using the FFT (fast Fourier transform) algorithm. Different signals are analysed with the built in Matlab FFT function and an original function that implement the DFT algorithm that practically gives the same results.

First of all a rectangular waveshaped signal is considered (see fig. 5.13)

for which the total harmonic distortion, knowing its Fourier series expansion can be analytically calculated from the equation:

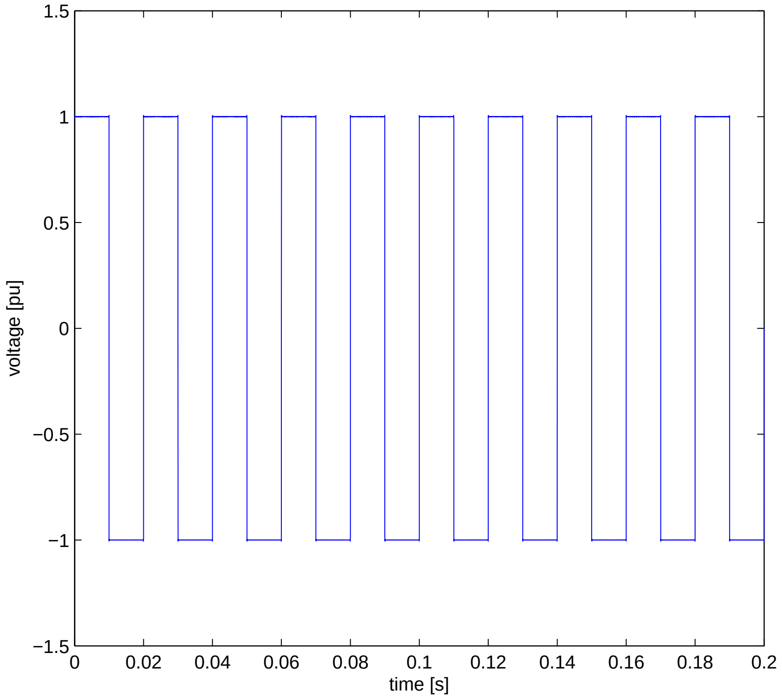
$$THD_V = \sqrt{\frac{\pi^2}{8} - 1} \simeq 48.34\% \tag{5.9}$$

The calculated THD as a function of the sampling per cycle is depicted in figure 5.14.

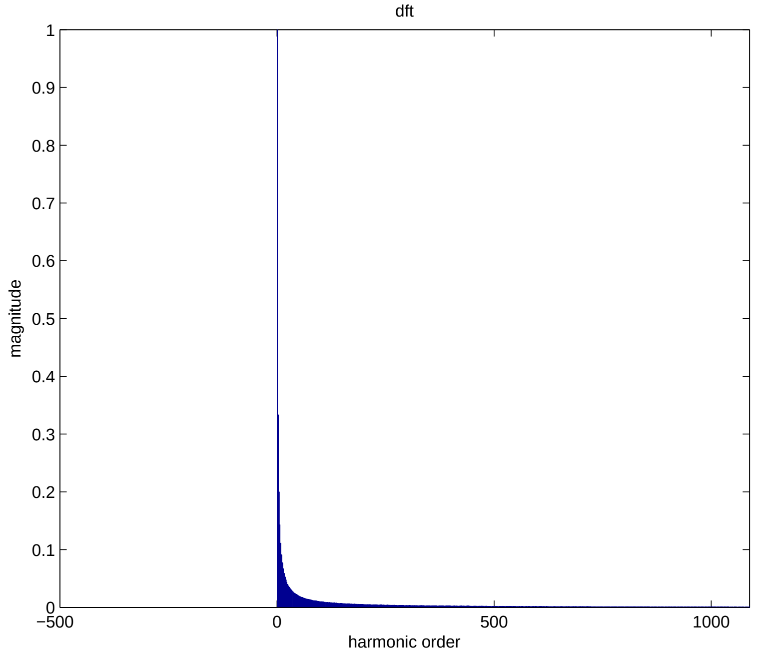
If a sampling ratio of 4096 (2^{12}) sample/cycle is applied and the THD is calculated summing up all contributes of harmonics the result is:

$$THD_{4096} = 48.28\%$$

with an error of 0.1%. From this simple example it can be seen that even with an



(a) Signal in p.u.



(b) Harmonic spectrum

Figure 5.13: Rectangular voltage analysed with 4096 samples per cycle

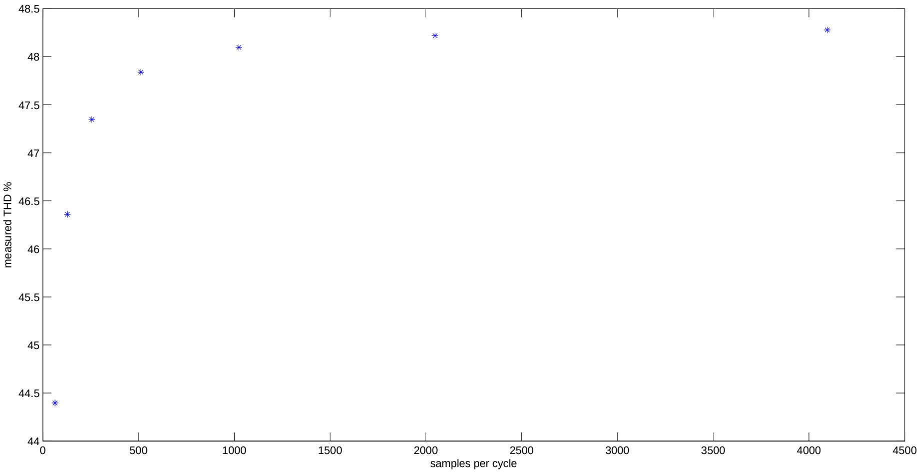


Figure 5.14: Calculated THD of a square waveform signal as a function of the number of samples per cycle.

ideal sampling a perfect calculation of the THD is not so easy. If a more realistic sampling of 512 sample per cycle is applied the result is

$$THD_{512} = 47.84\%$$

that is an error of 1%. If the lower sampling rate power of 2 requested to be in compliance with Power Quality standards (128 samples/cycles) is applied the result is

$$THD_{128} = 46.3\%$$

with an error of the 4%; the THD calculated is 44.4% if it is applied a 64 point/cycle sampling.

Another test is performed with an hypothetical current with harmonics of order 60 and 120. The results with 64, 128 and 256 samples per cycle are depicted in figure 5.15

Even if the THD is calculated correctly in all the three cases the single harmonics calculation is wrong because components with frequency higher than half of the sampling frequency, as expected from aliasing theory, appear as low frequency

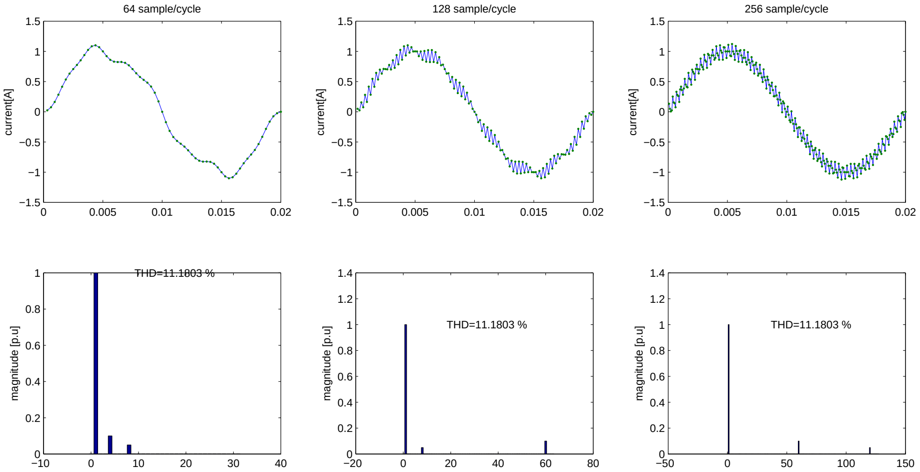


Figure 5.15: Harmonics analysis of a distorted signal

component.

5.6 A case study

To evaluate with deeper details the behaviour of the algorithm it is applied to study a real triad of voltages and currents measured upstream of an AC/DC converter (see fig. 5.16) measured with a 256 point/cycle sampling.

It is possible to recognize the typical waveforms given by a three-phase diode rectifier bridge. From the given samples it is possible to simulate a lower frequency sampling through a process of decimation.

The results obtained are represented in figure 5.17 for one of the voltages and in figure 5.18 for one of the currents.

In this case it is not possible to say *a priori* if the THD calculated with a reduced sampling ratio is more or less than the real one because real components and fictious components given by aliasing are summed with positive or negative components.

The figure 5.19 is important because it a shows the effect of aliasing in a real application. It's clear that the worst results are obtained with the lower resolution

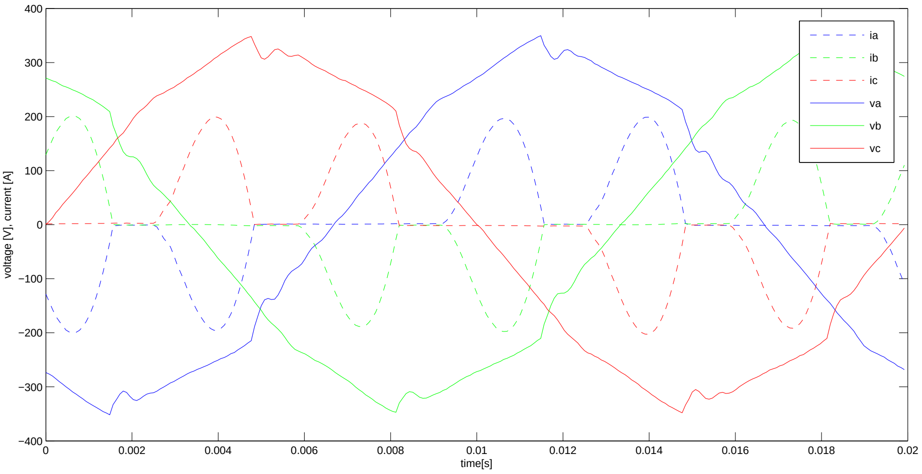


Figure 5.16: Measured voltages and currents upstream of an AC/DC converter

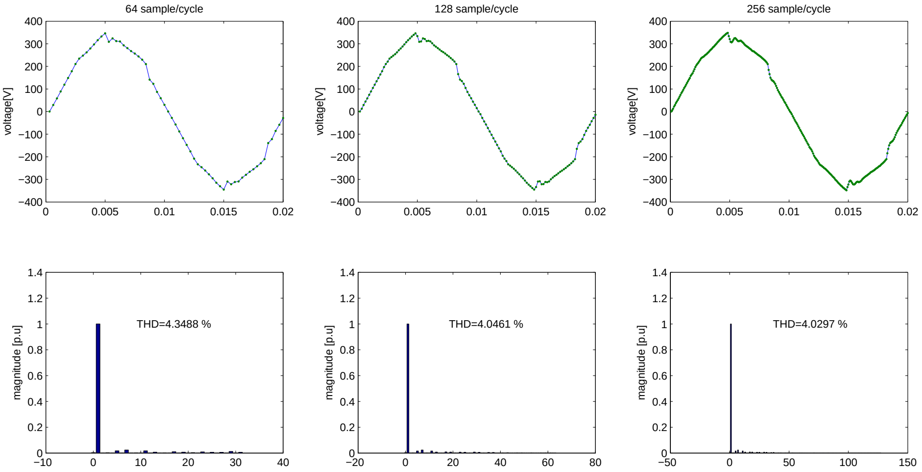


Figure 5.17: Harmonic analysis of one of the sampled voltages

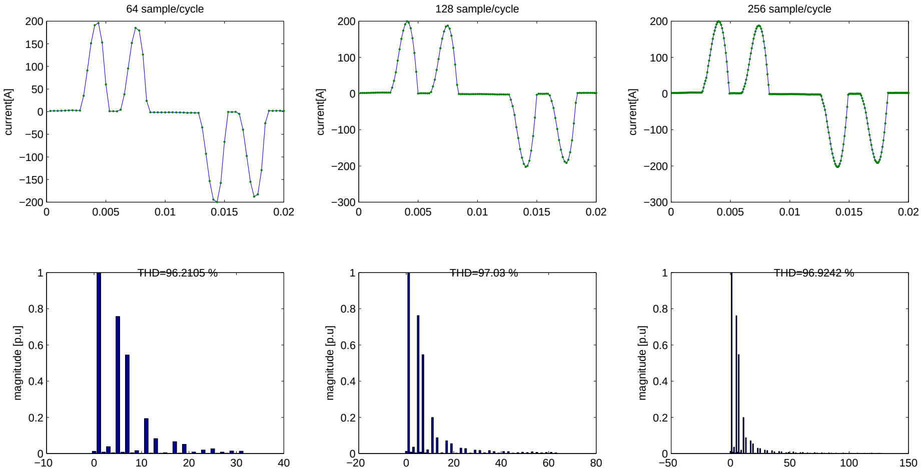
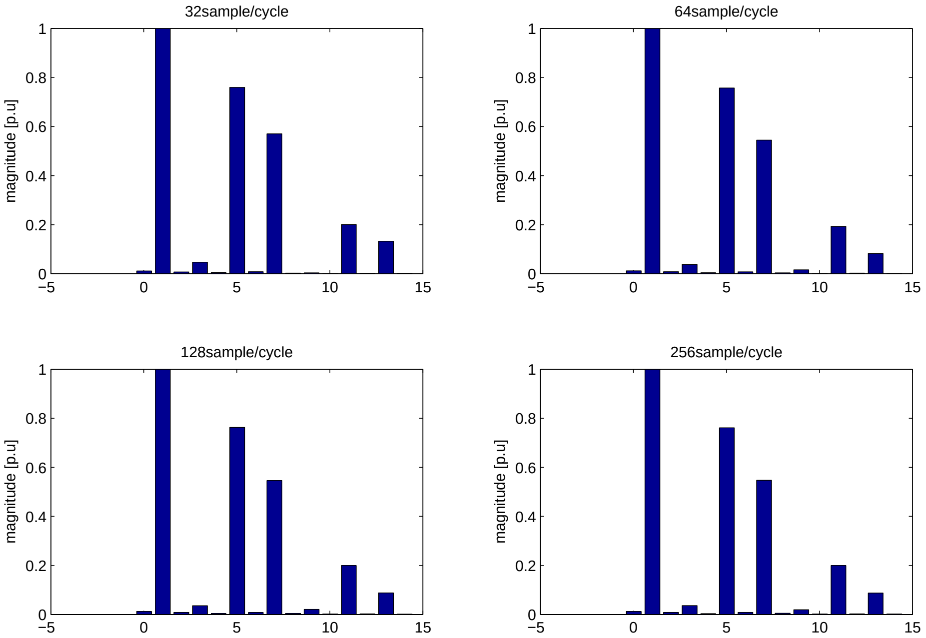


Figure 5.18: Harmonic analysis of one of the sampled currents

and, even if 32 samples/cycle seems to be an extremely poor resolution, it is not difficult to find low cost product of this kind. The conclusion is that, if an anti-aliasing filter is not applied, results given by the harmonic analysis are not reliable.



harmonic component	32 s/c	64 s/c	128 s/c	256 s/c
3	4.73%	3.84%	3.58 %	3.59%
5	76%	75.7%	76.3 %	76.1%
7	57.1%	54.5%	54.6 %	54.7%
9	0.3%	1.63%	2.08 %	1.9%
11	20.1%	19.3%	20 %	19.9%
13	13.3%	8.24%	8.79 %	8.7%

Figure 5.19: Comparison of calculated harmonic components magnitudes with different sampling ratios

Chapter 6

Measurement techniques

In this chapter the measurements algorithms are analyzed in order to obtain an evaluation of their reliability of the measurement process as a function of different parameters that makes the measure different from the ideal case. The results will permit the definition of the specification of an instrument that will be able to measure not only the typical electric parameters, but also power quality indexes.

6.1 Measurement chain

The measure of all electric parameters and power quality indexes derives from the post-elaboration of the measured values of the currents and the voltages of the three phases. The power signal (voltage or current) is transduced into a signal of magnitude suited for the ADC converter and conditioned through a filter. This signal is then processed by a sample and hold circuit and finally converted into a digital signal by the ADC converter.

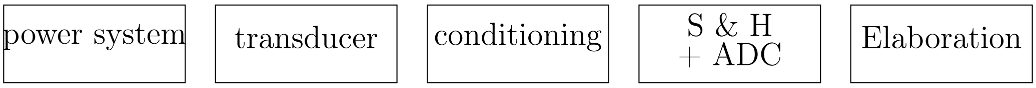


Figure 6.1: Measurement chain

6.2 Sampling

Sampling is the base of all digital measurement devices. It is a key step because it substitutes a continuous signal in time and magnitude with a finite number of values each of them is the rounded amplitude of the signal in given times (discretization and quantization). The values obtained are suited to be elaborated by a microprocessor to get the parameters of interest. What the instrument does is take the continuos signal, convert it in a discrete signal (a vector) and then analyze the vector to obtain information of the continous signal. It is very important to understand that when a real meter is considered there are some practical limitation to power quality analysis accuracy. When the power system analyst wants to check higher frequency components, considerations about the reliability of the meter become extremely important.

The analog-to-digital converter (ADC) is usually 12 or 16 bit. Assuming a range of 0-10 V the smallest detectable voltage change is

$$\frac{10}{2^{12}} = \frac{10}{4096} = 2.441mV$$

or

$$\frac{10}{2^{16}} = \frac{10}{65536} = 0.153mV$$

At first glance the second option seems to be more accurate but the higher resolution in practical power systems will probably be into the noise band so that the lower significant bits are given by the noise, they should be neglected and the final result is not more accurate than the one obtainable by the 12-bit ADC. From this moment suppose to have a 12 bit ADC (the choice is given also by present hardware in the model to be enhanced).

The sampling frequency is very important, first of all because the Shannon Theorem assess that to have a good representation of a signal it is necessary that the sampling frequency is at least twice the upper frequency component of the signal. As we have seen above,a practical power system investigation require information up to the 40th or to the 50th harmonic component. In a 50 Hz power system the sampling frequency is therefore at least

$$f_s = 50 * 100 = 5kHz$$

if it is required to measure up to the 50^{th} harmonic component (IEC 61000-4-30 class A) or $4kHz$ if the higher component is the $40th$ (IEC 61000-4-30 class S, EN 50160).

If the FFT (fast fourier transform) algorithm is used, the number of samples required is a power of 2. In a 50 Hz system the number of sample per second could be $2^7 * 50 = 128 * 50 = 6.40kHz$ or $2^8 * 50 = 12.80kHz$ that is 128 or 256 sample/cycle.

A sampling frequency not synchronized with the fundamental frequency causes errors in the determination of the phase and amplitude of harmonic components but also in the simple determination of rms values. An important issue is how the sampling frequency is determined in order to follow the frequency variations that are always present in a practical application. If the sampling frequency is determined by the last value measured of the frequency, typically updated every 10 cycles (200 ms in a 50 Hz system) and the system is perfectly in steady state, or at least the frequency does not change, the result is correct. Otherwise, if the frequency is changing or the measure is not exact, an error in the measure of the parameters, also the rms values of voltages and currents, occurs.

Suppose that the voltage is evaluated as:

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} V_i^2} \tag{6.1}$$

the rms of the current as:

$$I_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} I_i^2} \tag{6.2}$$

and the active power as:

$$P = \frac{1}{N}\sum_{i=1}^{N} V_i I_i \tag{6.3}$$

The utilization of a 12 bit A/D conversion is supposed. Let v(t) be a sinusoidal

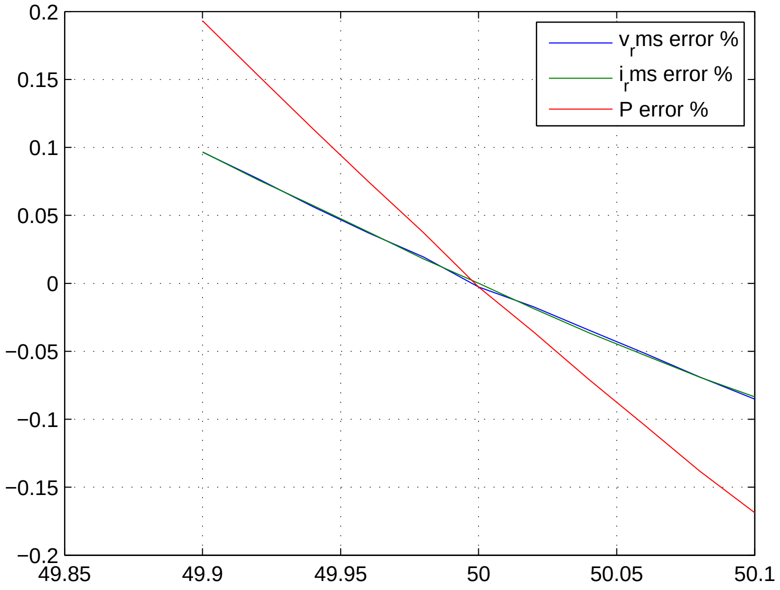


Figure 6.2: Errors in the evaluation of V_{rms},I_{rms} and P due to non synchronized sampling with a 10 cycles window

voltage, 50 Hz and i(t) a sinusoidal current in phase with the voltage. As it is possible to see from figure 6.2 an error of 0.01 Hz, within the typical accuracy of these types of instruments, leads to an error of 0.01% on voltage and current and 0,02% on active power if a 10 cycle window is used but also if a 1 cycle window is used (e.g for the calculation of the $U_{rms_{1/2}}$ for voltage dips detection)

In the case considered the first sample is coincident with a zero cross of both voltage and current. But in a real case it could also happen that the current is not in phase with the voltage ($cos\phi \neq 1$). There are two parameter that can change in respect with the previous case: the angle between voltage and current and the angle between the zero cross of the voltage and the first sample. To see the influence of the $cos\phi$ suppose to have the same sinusoidal waveforms for voltage and current, 50 Hz, and that the frequency used in the algorithm is 49.99 Hz for different angles.

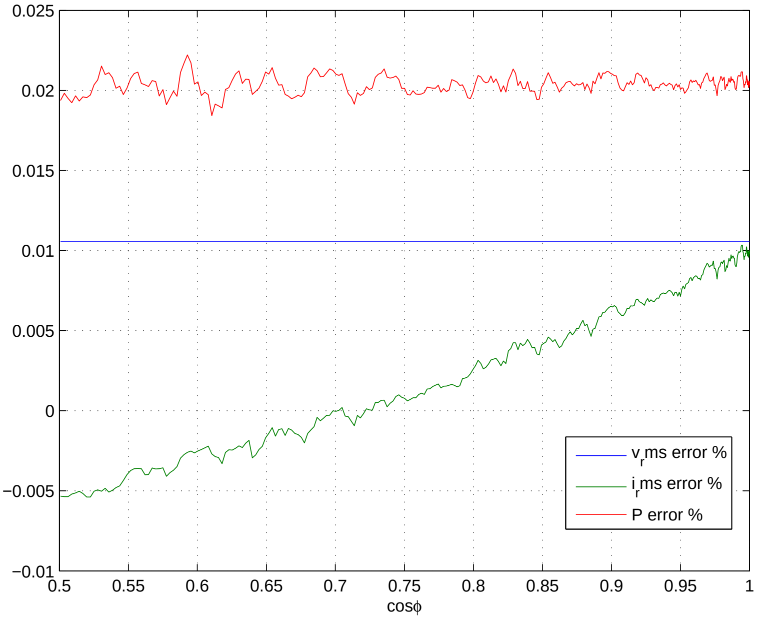


Figure 6.3: Errors in the evaluation of V_{rms},I_{rms} and P due to non synchronized sampling (49.99 Hz instead of 50 Hz) as a function of the power factor with a sampling rate of 128 samples/cycle

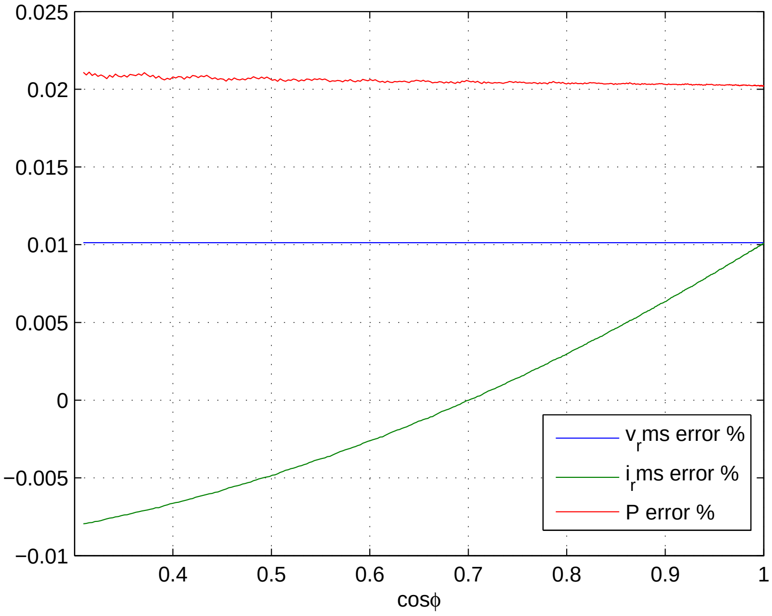


Figure 6.4: Errors in the evaluation of V_{rms},I_{rms} and P due to non synchronized sampling as a function of power factor (sampling ratio: 8192 sample/cycle)

As it is possible to see in figure 6.3 there is a variation in the accuracy of the current measurement but the error on the power remains more or less the same. The variation between near values is given by the finite number of samples per cycles, in fact increasing the number is a smoother behaviour (fig. 6.4).

To see what happens with the first sample not synchronized with the zero crossing let's consider the same waveforms with $cos\phi = 0.995$. The as a function of the delay between the zero-crossing and the first sample is depicted in figure 6.5.

The error on p varies between 0,02% and 0%. Because the initial angle is random it is interesting to see the average error as the standard deviation:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N} P_i^2} = 0.015\% \tag{6.4}$$

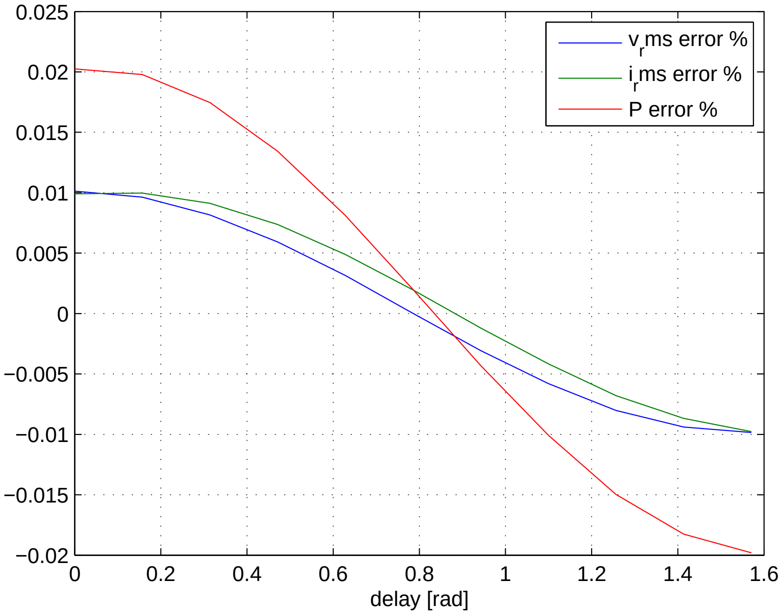


Figure 6.5: Errors in the evaluation of V_{rms},I_{rms} and P due to non synchronized sampling as a function of the delay between the zero-crossing and the first sample

6.3 Quantization and non symultaneous sampling

Up to now values of signals equal to the full scale have been considered so that the error introduced by the discrete number of steps of the ADC was negligible. But in a real case, while in the normal operation the voltage is expected to remain near rated values, the current can vary a lot. If the current is 10% of the full scale and voltage 90% of the full scale, the error, as can be seen in figure 6.6 in respect with figure 6.2 is greater and also for a perfect synchronous sampling the result is not correct.

Another issue related to the practical implementation is that sometimes it is not possible to sample the different channels simultaneously and a small time difference will result between samples on different channels with a consequent phase error. A realistic value for the complete conversion of a sample is $15\mu s$ that in a 50 Hz

Figure 6.6: Errors in the evaluation of V_{rms},I_{rms} and P due to non synchronized sampling with a 10 cycles window and a current of 10% of the full scale

system means a phase shift, if no correction is applied, of

$$\frac{15\mu s}{20ms}2\pi = 0.047rad$$

as can be seen in figure 6.7 with a negligible consequent error on the power evaluation of

$$cos(0.0047) = 0.0011\%$$

as confirmed by the simulation (fig 6.8) for the case with $cos\phi = 1$ but with a relevant error if the power factor is far from unity. For instance if the power factor is 0.7 the error, without considering any other source of uncertainty always present, is 0.5% that is critical if the meter is class 0.5 or higher.

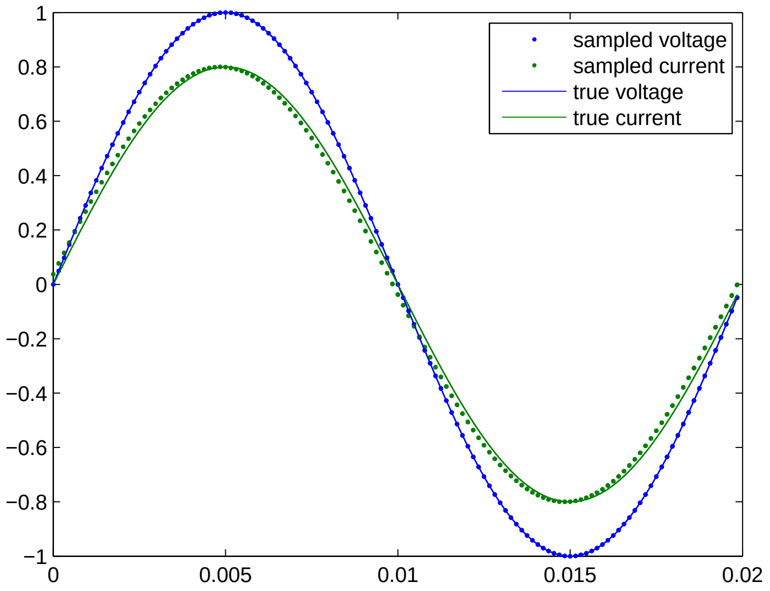


Figure 6.7: True and sampled voltage and current due to delay between voltage and current sampling

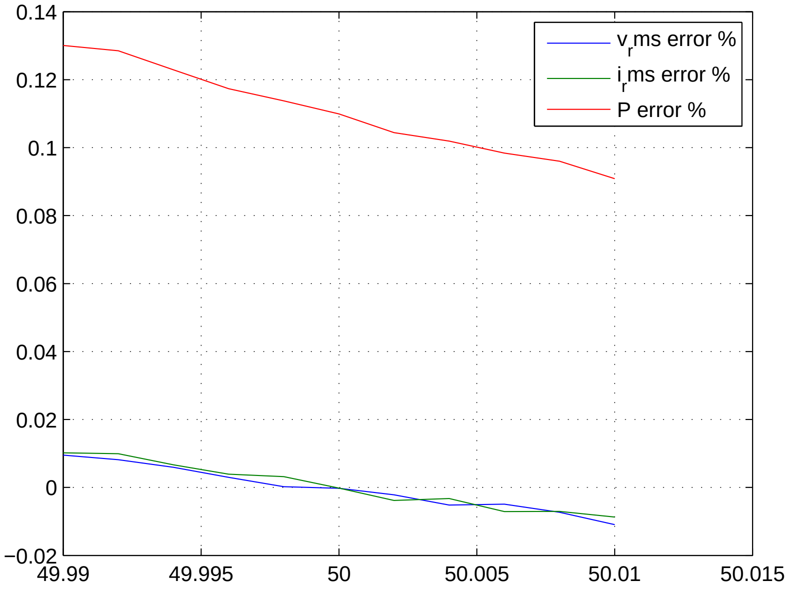


Figure 6.8: Errors in the evaluation of V_{rms},I_{rms} and P due delay between voltage and current sampling with $cos\phi = 1$

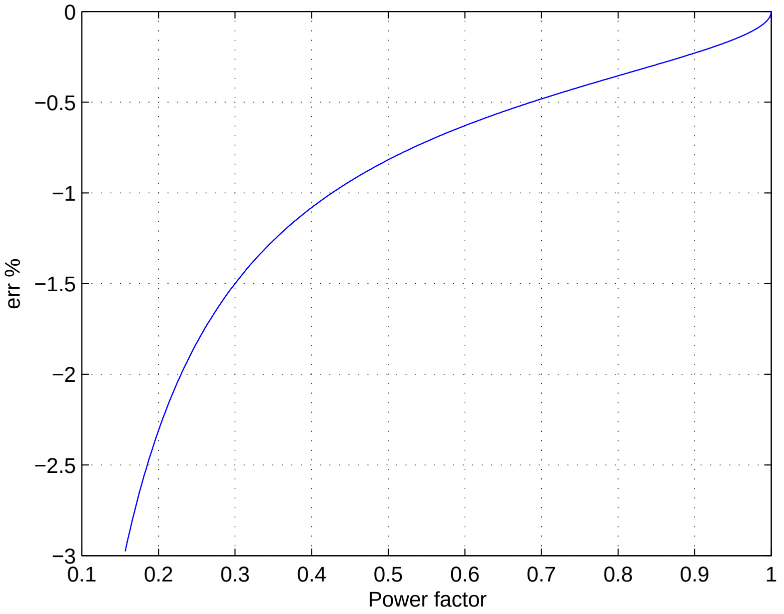


Figure 6.9: Errors in the evaluation of power due delay between voltage and current sampling of 15 μs as a function of the power factor

6.4 Peculiarity of power quality monitoring

As observed in [12] from a measurement point of view there is no difference between power quality measurements and measurement of voltages or currents for other purposes like control or protection. The results are not used for an automatic intervention but are processed and memorized for a later analysis or used to generate alarms. The further analysis can lead to the detection of the cause of equipment malfunction, first step in solving and mitigating the problem and when permanent monitoring is chosen it is possible to get reliable information on the performance of the power supply. The main difference in respect with other meters (e.g multimeters) is that is not possible to consider the system in steady state so the importance to not lose any event or any variation implies that implementations with alternation between sampling and elaboration during which the signal is not sampled so that what happens is unseen and therefore not admissible for a high quality instrument.

Conclusions

The basis of the path on which, in the next future, a new power quality meter will be developed, have been traced. The application field have been deeply analysed and starting from the state of the art some innovative methods to face the problem have been proposed. In particular, the possibility to find out the origin of the problems seems to be extremely valuable because it gives the required information without prohibitive hardware requirements.

The proposed methods have been implemented in *Matlab* and *Simulink* giving good results that seems to have the possibility to be easily implemented in a real instrument. In addition, all the information to choose the best way to reach the desired objective as o trade off between functionalities and economical reasons are given.

Possible errors originating from non-ideal signal elaboration have been considered in order to highlight the most critical stages in contrast with problems that can be normally neglected. The main differences with other measurement devices have been explained to ensure a guaranteed and fast development of the new product understanding what can be kept of the existing analysis procedure and what has to be modified.

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