February 2002
Ref: 2002-2700-0005

Power Quality

in European Electricity Supply Networks - 1st edition

Network of Experts for Standardisation

UNION OF THE ELECTRICITY INDUSTRY
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[2] European Grouping of Electricity Undertakings

Power Quality

in European Electricity Supply Networks

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N-E EMC & Harmonics

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LIST OF CONTENTS

Executive Summary
Introduction
1. General
- Quality related terms
- Electromagnetic compatibility (EMC)
- Electromagnetic compatibility levels
- Co-ordination strategies among the involved parties. Responsibilities
- Structure and object of this Report

2. Standardisation
3. Harmonics
- 3.1 Introduction
- 3.2 Definition of harmonics
- 3.3. Sources of harmonics
- 3.4 Effects of harmonics
- 3.5 Mitigation methods
- 3.6 Considerations on the extra costs due to harmonic pollution
- 3.7 Measurement results
- 3.8 Conclusions

4 Voltage fluctuations/Flicker
- 4.1 Introduction
- 4.2 Definitions
- 4.3 Sources of voltage fluctuations/flicker
- 4.4 Effects of voltage fluctuations/flicker
- 4.5 Mitigation methods
- 4.6 Measurement results
- 4.7 Conclusions

5. Voltage Dips
- 5.1 Definition
- 5.2 Sources of voltage dips
- 5.3 Effects of voltage dips
- 5.4 Mitigation methods
- 5.5 Measurement results
- 5.6 Conclusions

6. Unbalance
- 6.1 Definition
- 6.2 Sources of unbalance
- 6.3 Effects of unbalance
- 6.4 Mitigation methods
- 6.5 Measurement results
- 6.6 Conclusions

7. Transient overvoltages
8. Summary

Annexes
- A. Additional detailed measurements results
- B. Network impedance
- C. Measurement methods
- D. Related Standards
- E. Bibliography
- F. Abbreviations

EXECUTIVE SUMMARY

As one of the most essential bases for today's life – for business as well as for private life – electricity appears as a resource worthwile to enjoy utmost protection in the sense of maintenance of electromagnetic compatibility (EMC).

The measurement results presented in this report show that continuous care for EMC in the supply networks is needed. Although the standardised compatibility levels for the different phenomena within the field of power quality are still not exceeded in general – what correlates with the results from other surveys – this issue is to be considered in a differentiated way. The development of the past years may be summarised in the following recognitions:

- During the past ten years a steady increase of the harmonic levels can be recognised, causing increasing costs which may be counted in hundreds of B$ worldwide. When considering appropriate measures to maintain EMC, the cumulative effect of equipment and systems is to be considered.
- The mean values of flicker are generally quite low compared with the compatibility level; beside the excession of the compatibility levels by maximum flicker levels, some cases of excession have been identified in some networks.
- Voltage dips get an increasing importance for the functionality of electrical equipment, facing an increasing sensitivity against that phenomenon. Appropriate measures on the equipment side allow cost-effective mitigation.
- If considering changes concerning the recent building of standardisation concerning EMC, related to procedures as well as to limits and requirements, careful consideration of the consequences of such changes are indispensable.

INTRODUCTION

Electricity supply represents one of the most essential basic services for the support of an industrial society. From the point of view of electricity consumers this basic service is required

- to be available all the time (i.e. a high level of **continuity**) and also
- to enable all the consumers' electrical equipment to work safely and satisfactorily (i.e. a high level of **power quality**).

Electricity -- nowadays referred to as a product -- is rather a unique product because of its intangible and transient nature. Strictly, it is a product which exists only for an instant at a given point of delivery, and comes into existence at the same instant at which it is being used. It is immediately replaced by a new product with rather different characteristics, and its characteristics are different at each separate point of delivery. Moreover, it is a product whose quality depends not only on the elements which go into its production, but also on the way in which it is being used at any instant by the equipment of multiple users.

The most important characteristics of electricity are described in EN 50160 **[1]**. This European standard gives information on several phenomena which have an effect on the power quality and describes the likely maximum levels of those phenomena under normal operating conditions.

Electrical equipment has become increasingly complex in terms of the functions it fulfils and the way in which it interacts with other electrical equipment. Frequently, that interaction takes place through the medium of the electricity network, which is the common energy source for all the equipment. It arises because the network, intended to be a common energy source, also provides a conducting path interlinking all equipment.

As a result of the increasing complexity, some types of electrical equipment today are more sensitive to deviations from the sinusoidal supply voltage. At the same time there is an increasing tendency for the same or other equipment to cause modifications to the characteristics of the supply voltage. An increasingly important feature is the cumulatively disturbing effect of emissions from equipment connected to the network in large numbers and tending to be in operation simultaneously. So, consideration of this cumulative effect represents an indispensable element of emission limiting standardisation, in order to meet the protection requirements of the EMC Directive of the Commission **[2].**

Thus, there is ample scope, and, indeed, a requirement, for cooperation between electricity suppliers and manufacturers of electricity-using equipment, in the interest of the users who are the common customers of both. That co-operation mainly takes effect in the related standardisation activities (in particular through the development of emission, immunity and compatibility levels) which seek to ensure compatibility of electrical appliances with each other and with the electricity supply system.

It may be recognised as essential to continue this kind of cooperation, since the ever evolving needs of consumers have made the market for electrical appliances highly innovative. Consequently, there is an ongoing challenge to smoothly accommodate new technologies in the electricity system, which consists of the transmission and distribution grid as well as existing appliances (consumers and generators).

Otherwise, unduly high emissions would cause considerable cost in electricity supply networks as well as at equipment level. These supplementary costs are due to factors, such as supplementary losses and heating (Joule losses), premature ageing of components, derating of equipment, malfunction of equipment and industrial processes, etc. There are various utility studies which show extra cost in power systems due to the increase of the various types of disturbances of up to 1.5 % of the Gross Domestic Product (GDP) of the respective countries.

EMC standardisation is the essential tool to achieve the above-mentioned goal without imposing undue limitations on anybody. Since the very beginning of the “electronic age” the electricity industry has fully participated in the standardisation process. A major part of this involvement has been to provide information on the types and levels of various phenomena which appear on public electricity networks.

The purpose of the present report is to provide information on the more important phenomena which are elements of the quality of the electricity, as a further contribution to the standardisation process. It follows also several previous reports **[** e.g. **3, 4, 5, 6, 7, 8]**, and gives an overview of the results of different measurement campaigns, mainly in Europe.

It should be noted that these measurement campaigns were conducted under different network and load conditions, and therefore cannot be regarded as statistically representative of European networks generally. Nevertheless the comparison of the measurement results with the levels that are normally regarded as acceptable and with results from previous measurements in the same areas enables certain trends to be discerned.

EURELECTRIC intends to update this report from time to time as newer information becomes available.

1. GENERAL

Quality related terms

The **quality of the electricity supply** (in some French documents the term is translated as “**Qualité de l’alimentation**”) is a function of its suitability as an energy source for the electrical equipment designed to be connected to the supply network. The two primary components of supply quality are:

- **Continuity** (freedom from interruption): the degree to which the user can rely on its availability at all times
- **Voltage level**: the degree to which the voltage is maintained at all times within a specified range.

Electrical energy is delivered by means of voltage derived from single-phase or three-phase sinusoidal systems and having the following main parameters: magnitude, frequency, waveform and unbalance.

As a load is connected to a supply system, it will affect the before-mentioned parameters unless corrective measures are taken.

There are several mostly short-term and/or frequency related ways in which the supply voltage can vary in such a way as to constitute a particular obstacle to the proper functioning of some utilisation equipment. The term “**Power quality (PQ)"** is frequently used to describe these special characteristics of the supply voltage, particularly in developed countries where discontinuity and ordinary voltage variation have largely been eliminated as matters of frequent concern. The principal phenomena concerned in power quality are:

- Harmonics and other departures from the intended frequency of the alternating supply voltage
- Voltage fluctuations, especially those causing flicker
- Voltage dips and short interruptions
- Unbalanced voltages on three-phase systems
- Transient overvoltages, having some of the characteristics of high-frequency phenomena.

Power quality can be defined as the degree of any deviation from the nominal values of the above-mentioned characteristics. It can be also defined as the degree to which both the utilisation and delivery of electric power affects the performance of electrical equipment. Draft IEC 61000-4-30 **[9]** defines power quality as “The characteristics of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters” (with a Note saying that “these parameters might, in some cases, relate to the compatibility between electricity supplied on a network and the loads connected to that network”).

Security of supply: Technically safe and long term sufficient energy supply in terms of quantity and quality at any time, based on the sufficient availability of energy resources and appropriate low risks in infrastructure, regarding the conditions of international competition and environmental compatibility.

This Report deals only with Power Quality.

Electromagnetic compatibility (EMC)

EMC is defined as "The ability of an equipment or system (or installation) to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment."

Electromagnetic compatibility therefore has two requirements:

- To ensure that emissions of electromagnetic disturbances are limited to a sufficient degree
- To ensure that equipment has a sufficient level of immunity to maintain adequate performance in the presence of the electromagnetic disturbances to which it is subjected.

These requirements concern both high frequency disturbances, affecting especially equipment having telecommunication or information processing functions, and low frequency disturbances, affecting equipment utilising energy drawn from electricity networks in general.

There is a great deal of ground that is common to both the EMC and PQ fields. The phenomena mentioned already in connection with power quality are also electromagnetic disturbances, the emission of which needs to be limited and immunity from which is necessary for the proper functioning of equipment.

Since many of these disturbances are generated as a result of the particular way in which some utilisation equipment makes use of the supplied energy, limitation of emissions from users’ equipment is as vital for PQ as it is for EMC. In fact, it has always been a condition of the contract for electricity supply that the electricity user must avoid disturbing the network and other users. Thus, meeting of the requirements of the EMC Directive and therefore the correct application of EMC standards for emission is very important for power quality.

Equally, given the technical as well as the economic reality that power quality can never be "perfect", it is important that the EMC immunity standards be implemented, so that the equipment utilising the electricity supply can continue to operate satisfactorily in the real conditions of the electromagnetic environment, of which the supply networks are a significant part.

Therefore, the effective implementation of the EMC Directive, the essential requirements of which are focussed on enabling the consumer to be provided with equipment which neither generates disturbance excessively nor is excessively susceptible to disturbance, is very important for power quality. Indeed, the need to protect the electricity networks from disturbance is recognised quite explicitly in the recitals of that Directive.

Electromagnetic compatibility levels

In this report, reference will frequently be made to "compatibility level". This is an EMC term, defined as "the specified electromagnetic disturbance level used as a reference level in a specified environment for co-ordination in the setting of emission and immunity limits". The significance of this level and its relationship to emission and immunity limits are explained in Annex A of the revised IEC 61000-2-2 [**10**] (see also **Fig. 2.1**).

In relation to power quality, the important point is that the compatibility level is intended to represent a measure for the cumulative disturbance level in a given environment, which is expected to be exceeded quite rarely. That is why the measured values mentioned in this report are compared with the compatibility levels for the relevant environment.

From a power quality perspective, any tendency for the actual cumulative disturbance level to exceed the compatibility level would be that electricity users' equipment would be jeopardised to get degraded or hindered in its intended operation by disturbances conducted to it by the electricity networks, and that the networks themselves would be hindered in their function of delivering energy to the utilisation equipment in the form of a voltage with the intended characteristics.

Co-ordination strategies among the involved parties. Responsibilities

The EMC problem usually involves a number of parties with some kinds of interrelationships. Therefore, to properly resolve the problem, cooperating consideration of related problems, in a coordinated way, is of importance.

The costs associated with solving EMC problems, such as the purchase of a conditioning system, must be taken into account.

Thus, when a consumer enquires about the connection of a major load to a low-voltage or medium-voltage public supply network, upon request he shall give the information required to assess the tolerable disturbance emissions caused by the load.

Equally, the electricity supplier will make available relevant information concerning the quality of supply parameters at the point of common coupling when required.

The network operator is responsible for the overall control of disturbance levels under normal operating conditions in accordance with standard requirements.

The consumer is therefore responsible for maintaining his emissions at the PCC (point of common coupling) below the limits specified by the utility.

Utility and consumer should cooperate to achieve an optimum in realizing mitigation, the design and choice of which – maybe on advice by the utility -- being within the responsibility of the consumer.

Structure and object of this Report

In this report, EURELECTRIC presents an overview of the present PQ situation in European electricity supply networks, relating to the main PQ phenomena.

Chapter 2 gives a hint on the position of standardisation in serving customers, manufacturers as well as electricity suppliers at the economic use of electricity and a short overview of the general concept for EMC standardisation having been defined by the International Electrotechnical Commission (IEC) and the European Committee for Electrotechnical Standardisation (CENELEC).

Chapter 3 deals with harmonics,

- presenting results of routine surveys during recent years in different European networks as well as of measurements at points where harmonic problems had been identified at customers' installations.
- analysing the harmonic content and trends over the past twenty years and
- evaluating the expected harmonic distortion in LV as well as in MV and HV networks, taking into account the steadily increasing use of mass marketed distorting equipment

Chapter 4 deals with voltage fluctuations and flicker,

- giving an overview of the main sources of rapid voltage fluctuations and their possible effect via (light) flicker
- highlighting mitigation methods and solutions for specific flicker problems
- presenting measurement results from related surveys in different countries

Chapter 5 deals with voltage dips,

- giving a description of their sources and effects
- presenting measurement results and conclusions

Chapter 6 deals with unbalance,

- giving a description of its sources and effects
- presenting measurement results and conclusions

Chapter 7 gives a short overview of the causes and ranges of values of transient overvoltages.

Chapter 8 summarises the conclusions that may be drawn from the measurement results.

With a comprehensive **Annex** beside others additional examples of results from measurement campaigns performed in different countries are given as well as overviews of the measurement methods and the standards per phenomenon; also the network impedance, that one not representing a component of power quality but an important value in relation to the disturbing effect of some devices that electricity users connect to the network, are dealt with there.

2. STANDARDISATION

For decades – since the early 20th century-- the electricity suppliers have been in a position to 'standardise' their product, electricity. That due to an ever increasing application of this kind of energy within everyday life, leading to a situation when the customer is used to the safe use of electricity in all fields of private as well as of business life, at any time and with a quality level which allows him for operating any kind of electrical equipment with an appropriate reliability.

Having recognised the importance of creating a standardisation building ensuring compatibility between the supply networks and customers' electrical equipment connected thereto, within the responsible standardisation organisations, the International Electrotechnical Commission (IEC), and the European Committee for Electrotechnical Standardisation (CENELEC), a general concept has been defined for EMC standardisation:

- the definition of ***"compatibility levels"*** **per supply network level** (e. g. LV): for a given phenomenon a reference level is defined, which should not be exceeded by 95 % of time and location

- the definition of ***"emission limits"*** **for certain kinds of electrical equipment or systems**: aiming at maintaining the sum of disturbances, being generated by electrical equipment, below a level ensuring that customers' equipment may be operated with a sufficient reliability, limits for the conducted disturbances caused by the single equipment are defined per phenomenon.

- the definition of the ***"immunity level"*** **for certain kinds of electrical equipment or systems**: aiming at ensuring the reliable function of customers' equipment or systems, considering the compatibility level as well as an appropriate functional reliability regarding an economic design, immunity requirements are defined per phenomenon. The design of the margin between immunity level and compatibility level depends on the environment in which the related equipment will be normally operated and on the normally required functional reliability.

The following figure may clarify the role of this concept:

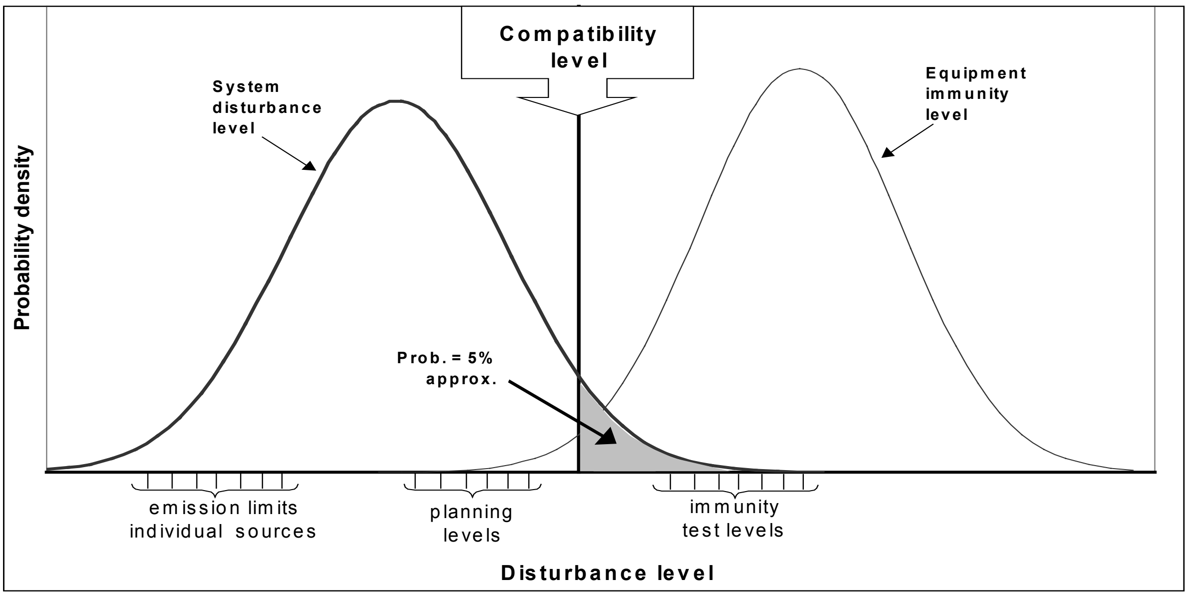

Fig. 2.1 - Relation between compatibility, immunity, planning and emission levels

Manufacturers as well as electricity suppliers are cooperating in this field of standardisation, whose success is the basis of economic manufacturing of equipment on the one side and provision of an economical electricity supply with appropriate power quality.

In **Annex D** an overview of the standards related to the issue of this Report is given.

3. HARMONICS

3.1 INTRODUCTION

Both electricity distribution networks and consumers' equipment are affected by harmonic distortion of the voltage waveform. Harmonic distortion levels have increased rapidly in electric power systems in recent years due primarily to the increasingly widespread application of non-linear semi-conductor devices, which produce the majority of harmonic distortion.

In particular, switched-mode power supplies have over the last twenty years increasingly replaced transformer/rectifier power supplies in electronic equipment. These cause large 5^{th} harmonic emissions, relative to the rated power consumption of the equipment, which are not randomly orientated in-phase and so are strongly additive. Consequently, in Europe, electricity supply systems are experiencing increasing background levels of harmonic voltage distortion at all voltage levels up to 400 kV. As harmonic voltage distortion increases, the risk grows of widespread problems arising from premature ageing of equipment and overloading of neutral conductors.

In response to that, many network operators are implementing monitoring systems to obtain a better overview of the present status of harmonic loads and of the related development.

In this section the harmonic voltage distortion in LV, MV and HV networks measured over the past twenty years is analysed and trends are identified, which reflect the steadily increasing use of mass marketed equipment, in particular IT equipment (ITE) and TV receivers which have created the harmonic distortion.

Results are presented of

- recent routine measurement surveys in different European networks,
- measurements made at points where harmonic problems had been identified at customers' installations

Measurements are also included from a selection of household and commercial areas to verify compliance with the harmonic voltage compatibility levels adopted in the present EMC standards and to assess the present situation in relation to the voltage characteristics specified in the product electricity standard EN 50160 **[1]**.

Some data from countries outside Europe are also included.

To obtain an understanding of the generation of harmonic distortion, actual data have been classified by countries and voltage levels, taking into account different distribution systems structures.

3.2 DEFINITION OF HARMONICS

Harmonics are sinusoidal voltages or currents having frequencies that are multiples of the fundamental frequency -- at which the supply system is designed to operate (e.g. 50 Hz in Europe).

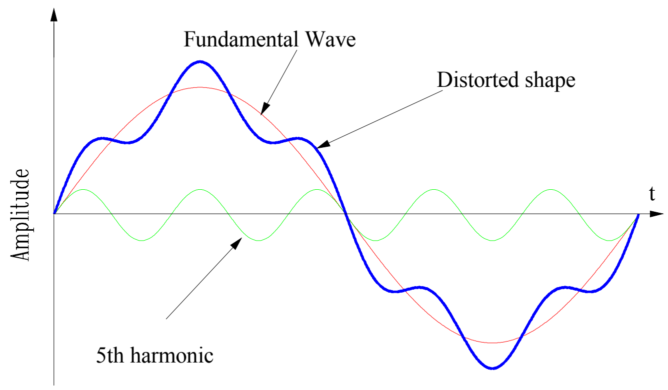

Fig. 3.1 – Fundamental, 5th harmonic

An electric power supply system is inherently very passive and the generator outputs and voltages measured on the system would be nearly sinusoidal at the declared frequency if no load was connected to the system.

For a pure sinusoidal voltage wave, with 50 Hz frequency and 230 V amplitude, the spectrum is equal to zero for all frequencies except 50 Hz, for which the value is 230 V.

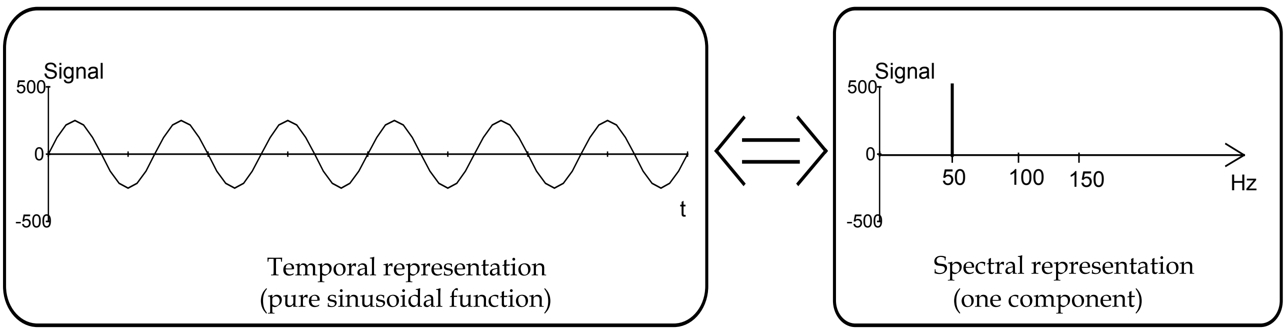

Fig. 3.2 - Time / spectral function

For a distorted voltage wave, the spectrum contains harmonic frequencies which are characteristic of the nature of distortion.

The fundamental is the component of the spectrum at which the network is designed to work. It is normally the first and greatest component of the spectrum. The term Total Harmonic Distortion (THD) is used to describe the r.m.s. sum of the voltages of all harmonic frequencies that are present relative to the fundamental.

3.3 SOURCES OF HARMONICS

Harmonic currents are mainly generated by industrial and residential loads with non-linear characteristics. Sources may produce harmonics at a constant or varying level, depending on the method of operation.

Industrial loads which are a source of significant levels of harmonic distortion include power converters (rectifiers), variable speed drives, induction furnaces, arc furnaces, etc.

Studies published during the past 10 years show the origin of harmonic distortion as being given by:

- harmonic currents injected by industrial and commercial installations. In general, the harmonic currents produced by industrial installations are high, and very often, for mitigation purposes, a filter is needed to get installed. High levels of harmonic currents stemming from commercial areas are usually associated with large installations of ITE.

- harmonic currents injected by residential equipment connected to LV public network as for example TVs, PCs, self-ballast lamps, air conditioners. In general, the single equipment has a low rated power and produces only a low harmonic current, but because they are very often applied at the same time by customers and because there is no self-cancelling effect, the cumulative effect of all these small contributions of harmonic emission is not insignificant (► *see also sub-clause 3.4*).

3.4 EFFECTS OF HARMONICS

The main effects of harmonic distortion in networks are the following:

- Destruction of capacitors in consumers' installations due to the amplification of the normal operating current, by resonance. In particular this effect has been observed
    - in industrial installations containing static converters,
    - in commercial areas with large amounts of fluorescent lighting equipment comprising power factor capacitors, and
    - in areas with significant computer load.
- increasingly, overheating of transformers and neutral conductors caused by harmonic currents, particularly of the third order. Fires may result from excessive third order harmonic currents because these harmonic currents add in the neutral whereas the fundamental frequency currents cancel each other out so that neutral conductors in three-phase circuits have not in the past needed to be separately protected against overload.
- Consumers and distribution systems are sometimes forced to derate their transformers because of the heating effects of harmonic currents. Transformer manufacturers recommend derating by 10 % when a transformer supplies more than 30 % of its nominal capacity to non-linear load, and the same recommendation applies to generating plant.
- Neutral conductors of supply systems and installations have the same cross-sectional area as phase conductors. There is already evidence of the use of neutral conductors of larger cross-section in newer commercial installations to take account of the increased third harmonic currents. The retrospective installation of such larger neutral conductors in existing networks would result in astronomical costs, including significant increase in demand for copper and aluminium, which cannot be realistically contemplated.
- The flow of harmonic currents in power supply systems, caused by non-linear loads of customers, may affect telephone communication.
- Poor power factors associated with non-linear loads are responsible for a substantial increase in the currents flowing in power supply systems and consumer installations, and hence in the cost of losses.

The following indicates how problems with consumers' equipment and network components **[8]** increase as Total Harmonic Voltage Distortion, THD, measured on public networks increases:

THD up to 5 % …………………………….small and infrequent problems

THD between 5 % and 7 % …………….. problems begin to become more common

THD between 7 % and 10 % …………... increasing probability of getting problems

THD > 10% ………………………………. high probability of getting problems.

Harmonic voltages in excess of the compatibility levels, would cause distributors to replace their transformers, switchgear and lines at prohibitive cost. The resulting networks would be inefficient as harmonic distortion represents reactive power flow.

There is no doubt that at such levels many consumers would begin to experience significant difficulties and early failure of components and machines could be expected to increase.

Cumulative effect of harmonics

As mentioned above (*► sub-clause 3.3*) – the cumulative effect of harmonic distortion can be of great significance in relation to conducted low frequency disturbances when considering mass produced equipment. In specifying emission limits, the need is to ensure that the limit applicable to equipment groups is in proportion to their contribution to the cumulative disturbance level. Harmonised standards in the framework of the EMC Directive **[2]**, which specify limits and requirements to meet the requirements of Article 4 of the Directive, need therefore take into account the characteristics, use and the expected number and dispersion of equipment to ensure a fair balance between appropriately manufactured equipment and appropriately designed electricity supply systems.

This implies that some limits might need only to be applied to certain categories of products. Therefore equipment groups could be defined and indications given in a matrix which limits would apply to which equipment group.

3.5 MITIGATION METHODS

There are several reasons why harmonic distortion has to be limited. Firstly in the industrial plant itself in order to prevent interference, malfunctions, overloading etc of the equipment in the installation itself. The second is to limit the emission of harmonic currents out to the supplying network and fulfil the regulation on harmonic distortion applied by the electricity company.

The timeframe is important when considering the different methods to reduce harmonic distortion. At the planning stage of a new plant or when new equipment shall be installed certain tools are available. If harmonic distortion in an existing plant has to be reduced, the tools are partly different.

Harmonic sources generally behave as current generators. Harmonic voltages appear as a consequence of the flow of currents through the frequency dependent network impedance. To reduce the harmonic distortion, usually to a specified limit, at a bus where sensitive load is connected, several measures can be taken:

- separation of disturbing and sensitive loads, i.e., having separate busses
- reduction of the generation of harmonic currents by increasing the pulse number of converters. If several sources are involved, connecting them through transformers with different phase shifts such that the vectorial summation of harmonic currents will have favourable diversity
- installation of a filter at the bus with the disturbing source. A similar method is to install reactors in series with existing shunt capacitors so as to make the impedance inductive for the characteristic harmonics. Care has to be taken with parallel (anti-) resonances which may occur below the tuning frequency or between tuning frequencies if several filters are installed.

Passive mitigation consists of a low impedance filter for one or several harmonic orders. They are based on series resonant filters. Passive filters at the point where the loads are connected to the public distribution systems are technically difficult to be applied due to continuous change of system conditions. In fact, it is technically impossible to install a passive filter at each point of connection for each residential installation because connection of a large number of identical filters on the same network would create other serious problems.

Active mitigation may be applied at equipment, site or system level. It consists of filters that -- by electronic techniques -- may continuously adapt to changing conditions in the network. Active mitigation is more expensive but technical improvements made these filters more cost effective now. Mitigation measures at equipment level are less costly to be implemented in general.

It is generally less costly to apply mitigation measures at individual equipment level.

3.6 CONSIDERATIONS ON THE EXTRA COSTS DUE TO HARMONIC POLLUTION

Harmonics can cause considerable cost in electricity supply networks as well as at equipment level. These supplementary costs are due to [**11**]

- supplementary losses and heating (Joule losses);
- iron losses (Eddy currents);
- insulation ageing (capacitors, motors, cables, transformers);
- resonance phenomena;
- derating of network equipment, mainly of transformers;
- malfunction of equipment and industrial processes;
- account of customer's complaints.

Some previous analysis have been performed by utilities regarding the extra cost in power systems due to harmonic pollution. Evaluation methods are based on the calculation of harmonic levels, increase of cost growing with the square of the growth of the harmonic voltage, calculation of ageing according to operation duty cycle of equipment and other factors as above-mentioned.

The main hypothesis is based on a constant increase of harmonic voltage level in networks, extrapolating from the development during the past twenty years.

As a first conclusion, based on a five-year global cost estimation and adopting different hypotheses for calculation of these extra costs, the following estimations can be shown:

1) France: Basic data: Gross Domestic Product (GDP) = 1400 B€; overall consumption [GWh} = 450;. Population = 60 M. EDF has performed an analysis based on the hypothesis of incorporating active filters in HV/MV substations and reinforcing the neutral wire in LV networks A total extra cost of roughly 25 B€ has been estimated.

2) Quebec (Canada): GDP = 150 B€; GWh = 120; Population = 7,5 M. Hydro-Quebec has performed a study based on the calculation of Joule losses and ageing of equipment. A total extra-cost of 650 M$ has been estimated.

3) Germany: Basic data: GDP = 2300 B€; GWh = 500; Population = 85 M. An approximate estimation based on reinforcement of all network installations throughout the country would lead to an extra cost of 20 – 25 B€.

4) Spain: Basic data: GDP = 560 B€; GWh = 180; Population = 40 M. An approximate calculation based on the application of a combination of the above several hypothesis would lead to an extra cost of 6 – 7 B€.

Data taken from EUROSTAT 1999

A gross extrapolation to the entire world would lead to quite high numbers.

3.7 MEASUREMENT RESULTS

Anyone with a basic technical background in electricity and an understanding of rational troubleshooting techniques can monitor conducted disturbances, but often the interpretation of the information about the power quality can seriously be undertaken only by experts.

It is important to note that the measurement criteria necessarily refer to the compatibility levels. However, the compatibility levels are only reference values for coordination purposes, which enable definition of, with appropriate methods and margins, emission limits and immunity tests levels for equipment connected to the supply. They are supposed to cover 95 % of the cases, allowing for the fact that the network operator, or an industrial customer, cannot control 100 % of a power system for 100 % of the time.

3.7.1 Harmonic levels in European networks. General survey over the past 20 years. Trends of the 5th harmonic in the past 20 years

In recent years, measurements in different countries showed increasing harmonic voltage distortions in public networks.

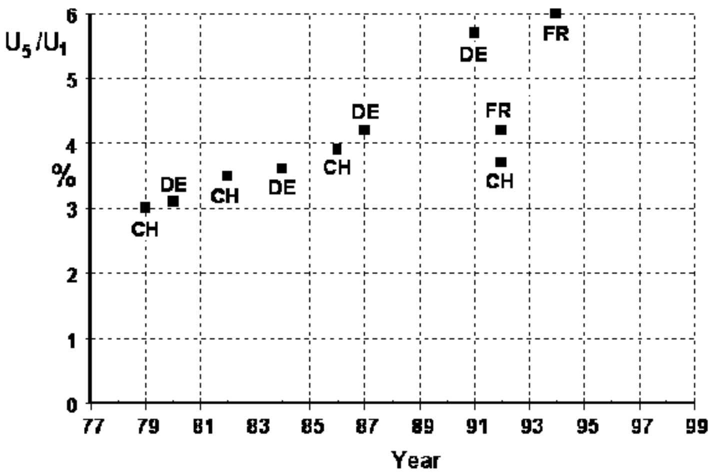

Fig.3.3 - Trends of the 5th harmonic in different countries

A general survey within UNIPEDE (**Fig.3.3**) shows a mainly significant increase of the 5th harmonic, with a constant slope, during the last twenty years.

In fact, the 5th harmonic is the most significant one and, consequently, directly affects the Total harmonic distortion factor (TDH) in the same manner.

In **Annex A.1.2**, examples from several surveys, conducted in several countries, can be found.

3.7.2 Harmonic levels in European networks. Further results from surveys

General surveys made throughout different European countries, show results based on statistical treatment of measurement in multitude test sites, and so are considered reasonably representative.

The following figure shows the results in the three voltage levels, concerning the 5th harmonic, of a general survey made in Austria in June 2000 and January 2001 by about 15 utilities, elaborated within the Austrian Association of Electricity Companies.

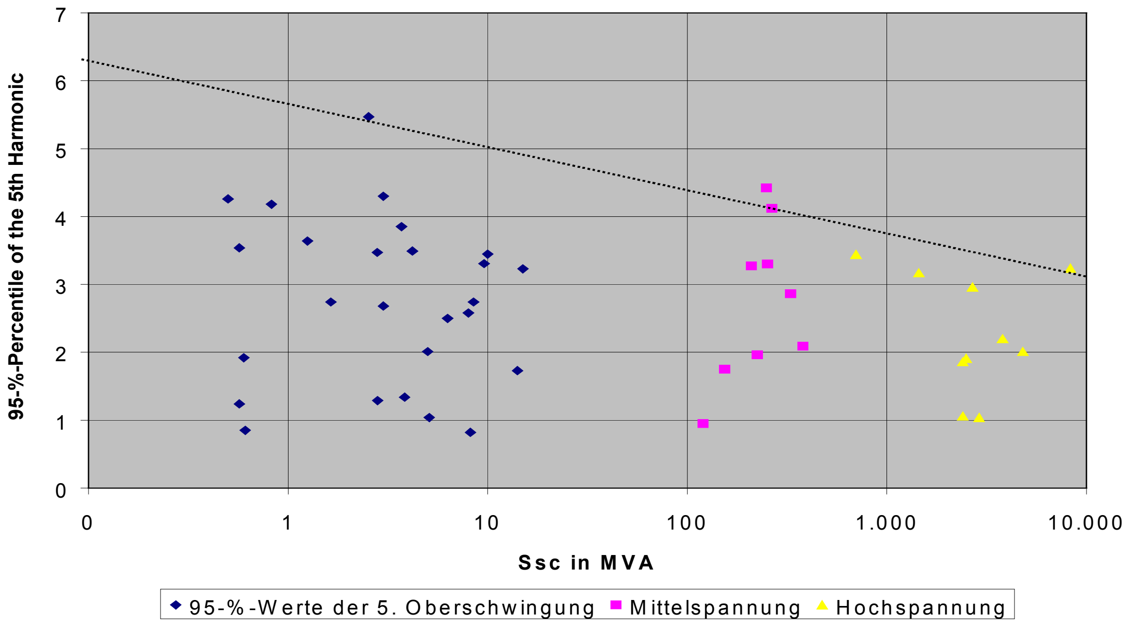

Fig. 3.4 - Maximum values of the 5th harmonic vs. fault level in Austrian LV, MV and HV systems

At certain sites in LV networks, the maximum value of the 5th harmonic exceeds or is just below the compatibility levels.

Evaluation of the results concerning the 95-%-value shows a similar behaviour, with somehow lower values compared with the maximum levels, by nature.

A correlation between the measurement results in LV, MV and HV networks can be recognised.

Further examples from several surveys, conducted in several countries, can be found in **Annex A.1.3**.

3.7.3 Harmonic load distribution over the week

Weekly and daily diagrams show the cumulative effect produced by harmonic generating equipment, like TVs.

As an example, the following describes higher harmonic levels as having been measured on French LV supply systems. Related measurement results have been obtained during a survey carried out for the period of about 12 days in a winter sports resort. The 95-%-value of the 5th harmonic voltage was equal to 11,2 %.

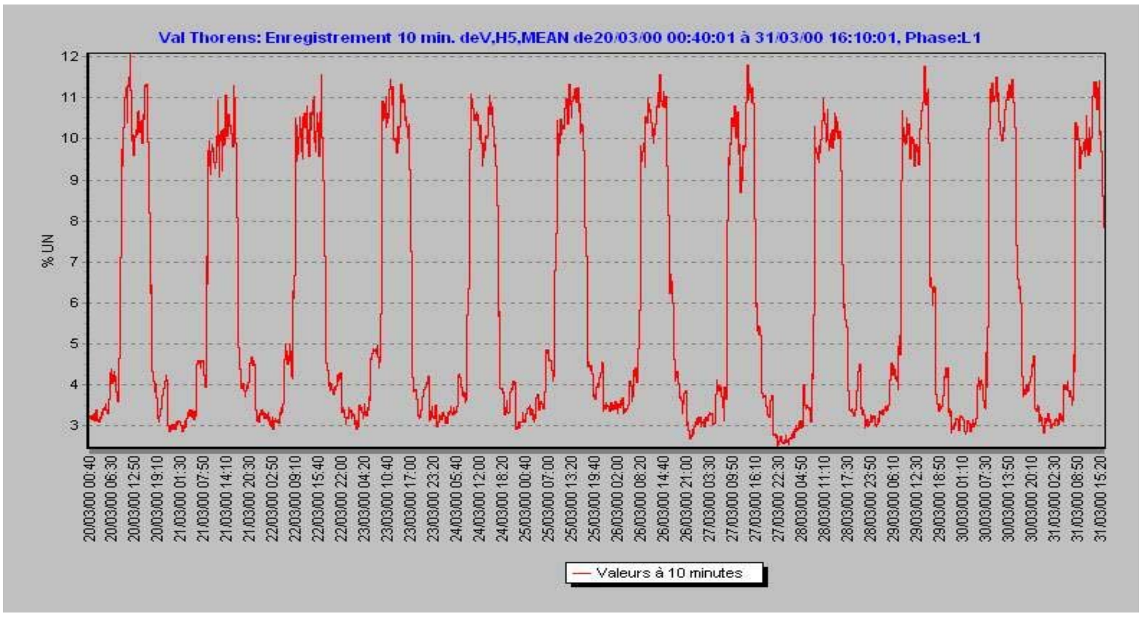

Fig. 3.5 - Distribution of the 5th harmonic during 12 consecutive days in a substation (France)

The 5th harmonic level is very high between 9 am and 5 pm. This is due to ski-lifts with variable speed drives which are in service at that time. When the first customers complained, the operator of the system measured a 95-%-value for the 5th harmonic of more than 15 %. After modifying the use of the compensation capacitor banks installed in the HV/MV substation, the operator managed a decrease of this 95-%-value to 11 %; no further improvement could be achieved.

In a similar situation, for the 5th harmonic there was measured a 95-%-value of 7,6 %. This case high-lights problems due to harmonic emissions on public LV systems.

In **Annex A.1.4**, further examples from several surveys, conducted in several countries, can be found.

3.8 CONCLUSIONS

3.8.1. Abstract of results

In this report, most surveys show a constant increase of the THD voltage as well as the predominance of the 5th harmonic in LV, MV and HV networks. Only in a few countries, there has been a quite stable situation during the last years.

According to results corresponding to large sample measurements, systematically performed in several countries during the past twenty years, there can be summarised:

1) There has been a constant increase of 1 % of the THD voltage as well as of the harmonic of 5th order, with respect to the fundamental, every 10 years.

2) A significant percentage of 5th harmonic values is around the compatibility levels established in IEC 61000-2-2 **[12]** and Draft IEC 61000-2-12 **[13]**. In some surveys, around 5 % and even more of the 5th harmonic values exceed the compatibility levels .

3) The rising number of ITE equipment, particularly PCs and TVs, results in a considerable total non-linear load in residential areas that causes a continued considerable rise in the THD and harmonic levels, in particular of 5th order. In consequence, compatibility levels can be expected to be widely exceeded leading to more frequent damages to existing equipment.

4) Future dispersed generation will also contribute to harmonic distortion in public distribution networks.

5) Further voltage components with frequencies up to some tens of kHz are likely to occur in distribution networks, due to the increasing application of, for example, switched mode power supplies and adjustable speed drives.

6) The use of non-linear loads over a day may be observed by the distribution of harmonic values along the 24-hours profile, showing peak hours.

7) In MV, the impact of low order harmonics is also significant. In several large MV systems, the harmonics exceed the compatibility levels in around 5 % of the cases. Taking into consideration that harmonics can transfer from low to higher voltage levels, it may be expected that harmonic pollution in MV and even in HV networks could dangerously increase.

8) In general, in MV networks, the annual increase of the THD and 5^{th} harmonic is similar to that in LV networks.

3.8.2 Main conclusions

The connection of a wide range of non-linear devices to supply networks needs to be considered in relation to the cumulative effect of disturbances emitted into these networks.

The number of problems caused by harmonics is not yet a significant widespread problem, but the potential for such problems is much greater today than it was 10 years ago.

Monitoring of harmonic pollution of public electricity networks has shown a steady increase in voltage waveform distortion over the past twenty years. Particular harmonics that are characteristic for the power supplies used in televisions, personal computers and similar equipment have increased by a factor of 3 and have been shown to follow patterns of usage of such equipment.

The principal harmonics are now found at levels of several percent on distribution networks, and of about 2 % on many transmission networks. Some decades ago the related levels were only a fraction of these present levels. The difference mainly stems from electronic products, as e.g. TV sets, the peak harmonic levels closely corresponding to times of peak television viewing.

4. VOLTAGE FLUCTUATIONS / FLICKER

4.1 INTRODUCTION

The voltage of an electrical network varies all the time under the influence of various switching on and off operations of electrical equipment connected to the supply network.

The voltage variation can be slow or fast, depending on whether it is a progressive variation of the total load supplied by the grid, or it is an abrupt variation of a large load.

The level of voltage variations emitted by an electrical equipment into the supply network to which it is connected depends on the network impedance. With increasing impedance, the level of voltage variations will increase.

4.2 DEFINITIONS

Voltage variations

Due to the influence of the variations of the load, the voltage of an electrical network, which is subject to various switching on and off operations of the connected electrical equipment, varies all the time.

The voltage variation can be slow or fast, depending on whether it is a progressive variation of the total load supplied by the grid, or it is an abrupt variation of a large load.

Voltage fluctuation

A series of voltage changes or a cyclic variation of the voltage envelope.

Note: The boundary between slow and rapid variations is very fuzzy and can be assumed to be situated between a few seconds and a minute. The slow variations are evaluated as an average over consecutive intervals of ten minutes.

Sudden variations of voltage can be individual or repetitive.

The amplitude of these sudden variations does not in general exceed 6 % to 8 % of the nominal voltage. The electrical equipment does not, in principle, malfunction for these types of sudden voltage variations (which are usually corrected by the voltage regulating equipment such as on-line tap-changers) except in cases when the initial voltage is very low.

Sudden voltage variations are called voltage fluctuations. These types of variations are caused by the fluctuating loads such as welding machines, arc furnaces, and crushers.

The rapid variations of voltage can be described as cyclic variations of the r.m.s. value or random series of sudden voltage changes.

The voltage steps of more than 10 % amplitude, whatever being their duration, are considered as voltage dips (or swells).

Flicker

Impression of insteadiness of visual sensation induced by a light stimulus whose luminance and spectral distribution fluctuates with time.

Note: Repetitive type voltage variations cause the flicker phenomenon in lighting equipment. The amplitude of these variations are usually small and within 10 %. The operation of the electrical equipment connected to this network is not much affected; but a physiological uneasiness in vision occurs due to electrical lighting, particularly with incandescent lamps.

*Flicker is the perturbation affected to lighting equipment by voltage fluctuations. Very small variations are sufficient to provoke variations of illumination that are unbearable (irritating) to the human eye. This sensitivity varies according to the frequency of occurrence of this phenomenon. The strongest human response to light flicker occurs between 800 and 1200 changes per minute (7 Hz-10 Hz). In this range human perception thresholds when viewing at an incandescent lamp are as low as a 0.3 % r.m.s. voltage change. However, it is well known that the threshold light flicker perception and irritation are significantly dependent on the observer **[14]**.*

Flicker can be caused not only due to repetitive variations of illumination but also due to more complex phenomenon linked to low frequency noise superimposed to the fundamental wave: this is the case for flicker with the use of arc furnaces.

When pulsating or intermittent electrical loads are large enough, they may affect the supply voltage by causing it to fluctuate. Even slight voltage fluctuations with an order of less than one percent may cause changes in the light output from most types of electric lighting. Most people perceive these slight changes in variations of luminance and get irritated by the repeated fluctuations. The degree to which flicker is annoying is not as straightforward to a measurement as other power quality characters.

Flicker is described by the following units of measurement **[15, 16]**:

- P_{st} : Short term value (observation time: 10 minutes)
- P_{lt} : Long term value (observation time: 2 hours according to **[1]**)

The compatibility level for P_{st} is 1.

The compatibility level for P_{lt} is 0,8. As a P_{lt} value is obtained over an observation time of 2 hours, a flicker with P_{st} = 1 over such a long period of time may be annoying.

The indicators P_{st} and P_{lt} take into account:

- the characteristic of the source of flicker by the form of the deformation of the sine wave,
- the characteristics of the human eyes by the frequency response of the eye,
- the probability of occurrence.

4.3 SOURCES OF VOLTAGE FLUCTUATIONS / FLICKER

The main sources of rapid voltage fluctuations are industrial loads like

- Resistance welding machines
- Rolling mills
- Large industrial motors with variable loads
- Arc furnaces
- Arc welders
- Saw mills
- Switching on of power factor correction capacitors
- Large capacity electric boilers or large capacity loads that are connected to low voltage distribution network of independent craftsmen or liberal professionals
- X-ray machines
- Lasers
- Large capacity photocopying machines or copying machines in offices
- Motors in heat-pumps in homes or air-conditioning equipment for cold chambers in meat shops

Switching on or off of large capacity electrical equipment cause sudden voltage changes. Some kinds of residential low voltage equipment also provoke flicker.

It is important to note that voltage fluctuations caused by large industrial loads could affect a large number of other consumers connected to the same electrical network. Since the impedance of the public power supply networks differs from place to place, the voltage fluctuations produced by a particular piece of equipment vary considerably depending on the point of the public supply network at which the equipment is connected, for example, whether it is situated near the source or far distant from the source.

From the point of view of their effect on incandescent lamps, voltage dips can be considered as extremely severe voltage fluctuations. Faults cleared by complex cycles of opening and reclosing of a circuit breaker are at the origin of series of voltage dips, which appear on incandescent lamps. This phenomenon, which is real light flicker, is therefore not due to voltage fluctuation of the common definition, because the voltage variation in the case of voltage dips is greater than 10 %. The original phenomenon of a voltage dip is completely different from voltage fluctuations, and the effect of voltage dips is generally more severe than that of flicker. Voltage dips are not dealt with in this part, but in **chapter 5**.

4.4 EFFECTS OF VOLTAGE FLUCTUATIONS / FLICKER

Generally, voltage fluctuations do not exceed 10 %. Most electrical equipment is not affected by such rapid voltage variations.

The major effect of rapid voltage variations is light flicker (fluctuation of illumination of an electric light source). The physiological effect caused by this phenomenon depends on the amplitude of the fluctuations, sequence of repetitive voltage variations, and the frequency spectrum and the duration of the disturbance.

Everybody has experienced a similar feeling in an office building that is lit by a defective fluorescent tube lamp, causing excessive variations in luminance. However, a similar situation can occur in a building due to excessive voltage variations.

Note: The flashing in a defective fluorescent lamp, although similar to the effect of flicker, is not due to voltage fluctuations. This condition is not the subject for discussion in this report.

In high doses, flicker can cause problems to epileptics. It has been shown that video games, due to the frequency of images which is below that one used in cinema can cause epileptic seizures to some people prone to this disease. In the armed forces, a flicker frequency of 10 Hz is used to test future combat pilot candidates for nervous disorders. The flicker levels which are normally encountered in an electrical network are generally very low. Nevertheless the malaise caused by them is not negligible particularly for two important domestic leisure activities, namely, reading and watching TV.

Due to their small amplitude, voltage fluctuations generally do not affect the image as produced on the screen of a TV set. However, in case of an electrical lighting of the room where TV is watched, the TV viewer may feel disturbed by the flicker of the light source, especially if the light source is at the periphery of the visual field.

The perceptible visual sensitivity of a human being to light intensity variations caused by an incandescent lamp varies with the frequency and presents a maximum spectral response between 8 Hz and 10 Hz at 0,3 % voltage variations. The upper frequency limit is 35 Hz (any frequency higher than this limit does not cause luminance variations due to the thermal inertia of the tungsten filament). There are, however, special cases where higher frequency voltage components can cause flicker.

The luminance fluctuation caused by voltage variations depends upon the type and power of the lamp and its nominal voltage. In addition, there is a perceptible threshold level below which flicker is not perceptible. In the case where the waveform of the voltage is periodic such as sinusoidal, rectangular, sawtooth, etc., the threshold level is a function of the frequency of fluctuation.

The theory of flicker is based on the most commonly used lamp: the incandescent 60 W bulb with a nominal voltage of 230 V. The choice of a particular bulb as reference is mandatory in the standardising process. The bulbs of higher power ratings have thicker filaments; therefore, they have higher thermal inertia. For this reason, the flicker caused by these lamps is less for the same amount of voltage variations. Such is the case for fluorescent lamps. In some situations, replacement of existing lighting system showing flicker by another type of lighting equipment could be an acceptable and economical alternative for mitigation.

To complete this theory, an amendment to the existing standards concerning bulb lamps for 110 V systems is in progress.

4.5 MITIGATION METHODS

A perfect compensation of flicker is not possible. Mitigation is therefore defined by the attenuation of the flicker:

The amplitude of voltage fluctuations causing flicker can be decreased by:

- Increasing the short-circuit power level of the network

  That can be achieved by increasing the short-circuit power of the exterior (outside) network, installation of a series of capacitors or by moving the PCC to a higher voltage level.

- Decreasing the reactive power flow from the network (which causes voltage dips).

  That can be achieved either by introducing a self-inductance in series with the disturbing appliance (arc furnace) or by connecting a static var compensator (SVC) in parallel to it.

- Progressive addition of capacitor banks. Moreover, a large number of groupings of capacitor banks with smaller reactive power per group lead to a fine compensation of reactive power.

Solutions for specific flicker problems:

- Motor starting problem: The most simple and economical method of starting is direct starting. The motor is designed for normal operation with delta-connected stator windings, rated for the line voltage.

- Star-Delta resistance-delta starter. In order to reduce the in-rush current during starting, one can introduce an intermediate stage in a star-delta starter by inserting resistors in series with the delta-connected windings.

- *Insertion of series resistance (metallic or electrolytic) or series inductor with stator windings.* This method consists of reducing the applied voltage to the stator winding while starting, by inserting series resistor or inductor in each phase.

- *Autotransformer.* An autotransformer, is specifically matched to the motor and has special construction. At the time of starting, the stator voltage is reduced by a factor k; the in-rush current is reduced by a factor k^2. Autotransformer method of starting is used for large capacity motors that are fed by a MV network.

- *Thyristor AC controller.* Thyristor AC controllers are used for drives that require low torque at low speeds. They are used if the drives require frequent starting and small speed variations (5 % to 10 %) of the nominal speed (motor must be of high resistance cage type).

- *Power electronic frequency converter systems.* In general, power electronic frequency converter systems are used in applications where an adjustable speed control is required or in drives when the speed requirement is above 3000 rpm or if a number of motors must be started in succession.

4.6 MEASUREMENT RESULTS

As can be recognized from several surveys, the compatibility level for long-term flicker P_{lt} is exceeded in some rare cases. As an example the results from a measurement campaign in Denmark may be taken, where P_{st} and P_{lt} values were measured at approximately 200 points in the LV network from November 1996 to May 1998.

The results show that the P_{lt} values are around a mean value of 0,45 in urban and 0,5 in rural areas (**Fig. 4.1**). These mean values are relatively low compared to the compatibility level. Nevertheless, the maximum values exceeded the compatibility level in approximately 50% of the points of measurement, at about every tenth delivery point.

Generally the maximum flicker level is higher in urban areas than in rural areas **[17].**

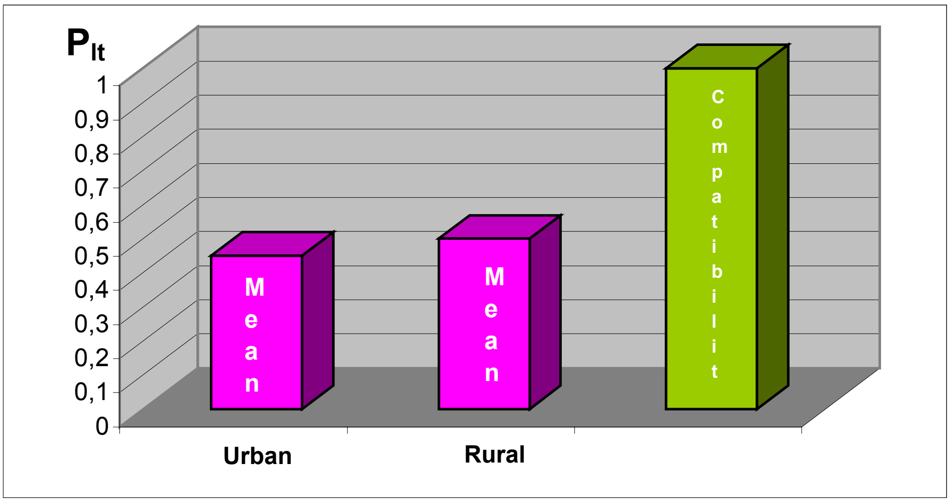

Fig. 4.1 – Mean P_{lt} levels obtained in measurements in Denmark

4.7 CONCLUSION

The above figure shows that flicker is not a general problem in public supply networks. Problems associated with flicker usually remain localised. However, implications may be quite severe in terms of human discomfort. Owing to the subjective aspect of flicker the perception of what is an acceptable level can vary from person to person. At the extreme there are some rare cases of supply networks operating in excess of the compatibility levels without any customers complaints; equally there are rare cases of customers complaining of unacceptable flicker when in fact the supply is operating well within the compatibility levels.

Mean values are generally below 0,7 and therefore below the susceptibility threshold. However, the actually quite high maximum values, which are being experienced in some single locations, demonstrate, that careful consideration should be given to the proper management of flicker sources.

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5. VOLTAGE DIPS

The following paragraphs are mainly taken from **[18].**

5.1 DEFINITION

A voltage dip is a two dimensional electromagnetic disturbance, the level of which is determined by both voltage level and time (duration). Typically, a dip is associated with the occurrence and termination of a short circuit or other extreme increases in current on the system or installations connected to it.

The definition of a voltage dip is a convention, derived from practical experience, but also depending on the context in which the phenomenon is discussed.

Draft IEC 61000-2-8 **[18]** describes a voltage dip as a sudden reduction of the voltage at a particular point on an electricity supply system below a dip threshold followed by its recovery after a brief interval.

The **duration** of a voltage dip is the time between the instant at which the voltage at a particular point on an electricity supply system decreases at least to a value below the start threshold and the instant at which it rises to the end threshold.

The **depth** of a voltage dip is the difference between the reference voltage and the residual voltage. It is determined by the location of the observation point in relation to the site of the short circuit respectively large current variation and the source of supply.

The **reference voltage** is either a fixed value, such as the nominal or declared voltage, or a sliding value (in case of HV networks), representing the voltage immediately before the start of the voltage dip.

Generally, the threshold corresponds to the minimum value of the voltage tolerance band.
The **start threshold** is an r.m.s. value of the voltage on an electricity supply system specified for the purpose of defining the start of a voltage dip. The start threshold can be either the lower limit of the bandwidth of normal variation or a value at a specified margin below that limit. No specified threshold has been defined, the choice of the threshold depends on the local conditions but typically values between 0.85 and 0.90 of the reference voltage have been used for this threshold. For example, EN 50160 **[1]** uses the value 0.90 of the declared voltage as the threshold.

The **end threshold** is an r.m.s. value of the voltage on an electricity supply system specified for the purpose of defining the end of a voltage dip. The end threshold is equal to the start threshold plus a hysteresis voltage for measurement reason. Typically, a value of 0 or 0.01 of the reference voltage above the start threshold has been used for this threshold.

5.2 SOURCES OF VOLTAGE DIPS

The primary source of voltage dips is the electrical **short circuit** occurring at any point on the electricity supply system. The short circuit causes a very large increase in current, and this, in turn, gives rise to large voltage drops in the impedances of the supply system. Short circuit faults are an unavoidable occurrence on electricity systems. They have many causes, but basically they involve a breakdown in the dielectric between two structures which are intended to be insulated from each other and which normally are maintained at different potentials.

Many short circuits are caused by overvoltages, which stress the insulation beyond its capacity. Atmospheric lightning is a notable cause of such overvoltages. Alternatively, the insulation can be weakened, damaged or bridged as a result of other weather effects (wind, snow, ice, salt spray, etc.), by the impact of or contact by animals, vehicles, excavating equipment, etc., and as a result of deterioration with age.

Supply systems are equipped with **protective devices** to disconnect the short circuit from the source of energy. As soon as that disconnection takes place, there is an immediate recovery of the voltage, approximately to its previous value, at every point except those disconnected. Some faults are self-clearing: the short circuit disappears and the voltage recovers before disconnection can take place.

The sudden reduction of the supply voltage, followed by voltage recovery as just described, represents the phenomenon known as voltage dip (also known as "voltage sag").

Switching of large loads like of large motors or fluctuations of great magnitude that are characteristic of some loads may cause **large current variations**, similar in effect to a short circuit current. Although the effect is generally less severe at the point where the event happens, the resulting voltage changes observed at remote locations can be indistinguishable from those arising from short circuits. So they are also evaluated as voltage dips. (Therefore the connection conditions for public networks, give maximum permissible voltage fluctuations).

5.3 EFFECTS OF VOLTAGE DIPS

The energy delivery capacity of the network decreases as the voltage decreases. Voltage dips and short interruptions, therefore, cause a temporary diminution or stoppage of the energy flow to the equipment. This leads to a degradation of performance in a manner that varies with the type of equipment involved, possibly extending to a complete cessation of operation.

As with all disturbance phenomena, the gravity of the effects of voltage dips and short interruptions depends not only on the direct effects on the equipment concerned, but also on how important and critical there is the function carried out by that equipment.

5.4 MITIGATION METHODS

On the supply network side:

Network design affects the network quality. But excessive network improvements are not justified by too sensitive customer. So the use of underground cable, adequate protection, arrester, increasing short-circuit power and separating disturbed busbar to the not perturbed one decrease the number or the severity of the voltage dips.

On the customer side:

Some remedial measures use an energy storage capability to supply, for a limited time, the energy that is missing from the system supply. This can compensate for voltage dips of any residual voltage and even short interruptions. The capability of equipment to ride through voltage dips and interruptions over a certain time depends on the relationship between the energy stored and the power requirement of the process concerned. In many cases, a certain reaction time must be taken into account (several milliseconds). Since the storage of energy is very costly, the protection of a process tends to be directed at parts that are especially sensitive.

Examples of remedial measures:

- Rotating machine with additional inertia
- Rotating machine with flywheel and engine or emergency power system
- Uninterruptible power supply (UPS)
- Superconducting magnetic energy storage (SMES)
- Static var compensator (SVC)
- Dynamic voltage restorer (DVR)

5.5 MEASUREMENT RESULTS

Taken from **[18], Table 5.1** shows results obtained of one of the measurement campaigns, with details as follows:

- measurements using 45 dip recorders at 109 measurement sites on an MV overhead line network
- carried out for three years from 1996
- recording the results at each selected site for one full year
- taken phase-ground in general, but phase-phase where necessitated by the available voltage transformer
- using voltage dip thresholds of 90 % (start) and 91 % (end) of the nominal voltage

Residual voltage u % of ref. Voltage	Duration t						
	20≤t<100 (ms)	100≤t<500 (ms)	0,5≤t<1 (s)	1≤t<3 (s)	3≤t<20 (s)	20≤t<60 (s)	60≤t<180 (s)
90 > u ≥ 85	150	37	9	6	3	2	1
85 > u ≥ 70	238	93	14	5	1	0	0
70 > u ≥ 40	141	128	15	5	1	0	0
40 > u ≥ 1	55	113	12	4	1	0	0
1 > u ≥ 0	0	4	1	6	7	2	3

Table 5.1 - MV overhead networks: voltage dip incidence – 95^{th} percentile

5.6 CONCLUSIONS

Voltage dips and short interruptions can be expected at any place and at any time. The voltage may drop down to virtually zero; the reduced voltage may last up to and above one second. The frequency of their occurrence and the probability of their occurrence at any level are highly variable both from place to place and from one year to another.

Voltage dips cannot be predicted or eliminated. Although their incidence may be generally reduced by appropriate measures without large costs, this phenomenon will still exist. Depending on the application of and the therefrom resulting requirements for equipment performance, equipment will have to be correspondingly designed and customers will have to take special attention if necessary.

It is clear that quite high annual rates of voltage dips are possible on overhead networks reflecting the exposure of these networks to fault causes, especially severe climatic conditions, that are additional to the range of causes that affect all networks.

Voltage dips have been an intrinsic feature of a public electricity supply system since the earliest times. Yet in recent decades they have become an increasingly troublesome phenomenon giving rise to inconvenience and even considerable economic loss. The reason is that some modern electricity utilisation equipment, either in its own design or because of control features incorporated in it, has become more sensitive to voltage dips.

There is therefore a need for an increased awareness of the phenomenon among electricity users and the manufacturers of electrical equipment.

In rural areas supplied by overhead MV lines the number of voltage dips can reach hundreds of even several hundreds per years, depending in particular on the number of lightning strokes and other meteorological conditions in the area. On cable MV networks, an individual user of electricity connected at low voltage may be subjected to voltage dips occurring at a rate which extends from around ten per year to about a hundred per year, depending on local conditions.

6. UNBALANCE

6.1 DEFINITION

Voltage unbalance is a condition in a polyphase system in which the r. m. s. values of the line-to-line voltages (fundamental component), or the phase angles between consecutive line-to-line voltages, are not all equal. The degree of the inequality is usually expressed as the ratios of the negative and zero sequence components to the positive sequence component. The negative sequence (or zero sequence) voltages in a network mainly result from the negative sequence (or zero sequence) currents of unbalanced loads flowing in the network.

To define the unbalance, the symmetrical components V_+, V_- and V_o are used, where **[19]**

V_+ is the positive sequence voltage,

V_- the negative sequence voltage

V_o the zero-sequence voltage

with:

$$V_+ = (V_1+aV_2+a^2V_3)/3$$

$$V_- = (V_1+a^2V_2+aV_3)/3$$

$$V_o =(V_1+V_2+V_3)/3$$

where $a = \exp(j2\pi /3)$ and V_1, V_2 and V_3 are the line-to-neutral voltages.

Very often the unbalance is defined by the unbalance $\tau = V_-/V_+$

6.2 SOURCES OF UNBALANCE

The sources of unbalance are the single or two-phased loads like

- trains, arc furnaces on the HV and MV system, induction furnaces …
- differently distributed customer loads on the single-phase LV system.

The predominant cause of unbalance is unbalanced single-phase load. In low voltage networks single-phase loads are almost exclusively connected phase-to-neutral but they are distributed more or less equally over the three phases. In medium-voltage and high-voltage networks single-phase loads can be connected either phase-to-phase or phase-to-neutral. Important single-phase loads include a.c. railway supplies and single-phase furnaces.

The propagation of negative sequence voltages from lower to higher voltage networks occurs with high attenuation. In the direction from higher to lower level any attenuation depends on the presence of three-phase rotating machines, which have a balancing effect.

6.3 EFFECTS OF UNBALANCE

The negative sequence impedance of a three-phase induction machine is similar to its impedance during starting. Consequently, a machine operating on an unbalanced supply will draw a current with a degree of unbalance several times that of the supply voltage. As a result, the three-phase currents may differ considerably and the increased heating in the phase(s) with the higher current will be only partly offset by reduced heating in the other phases and the temperature rise of the machine will be increased. The most extreme form of unbalanced supply is the disconnection of one phase, a condition that can quickly lead to destruction of the machine.

Motors and generators, particularly larger and more expensive ones, may be fitted with protection to detect this condition and disconnect the machine: if the supply unbalance is sufficient, the "single phasing" protection may respond to the unbalanced currents and trip the machine. Polyphase converters, in which the individual input phase voltages contribute in turn to the d.c. output, are also affected by an unbalanced supply, which causes an undesirable ripple component on the d.c. side, and non-characteristic harmonics on the a.c. side. Since the main effect of unbalance is heating of machine windings, higher short-term levels of unbalance may be acceptable, for a few seconds or even a few minutes.

6.4 MITIGATION METHODS

Concerning planning of a reduction of voltage unbalance, different technical solutions are available. The most common options are:

- rearrangement of phase connections
- change of the load's configuration or its operating conditions
- increase of the fault level at the PCC
- special transformers
- static var compensators.

For more information see **[19]**.

6.5 MEASUREMENT RESULTS

Belgium

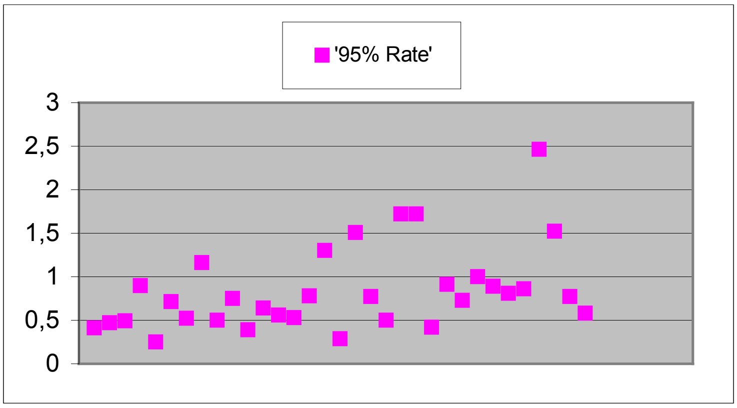


Fig. 6.1 - Unbalance rates measured in 1994 in 33 Belgian LV networks

A dot = one measurement result

6.6 CONCLUSIONS

The unbalance is found generally at all network levels to be below the 2 % and therefore satisfy the related compatibility levels **[12].** Exceptions may occur in certain places e.g. where arc furnaces with a 2-phase-connection to the supply network are installed.

7. TRANSIENT OVERVOLTAGES

The following description is taken from **[10]:**

Several phenomena, including the operation of switches and fuses and the occurrence of lightning strokes in proximity to the supply networks, give rise to transient overvoltages in low-voltage power supply systems and in the installations connected to them. The overvoltages may be either oscillatory or non-oscillatory, are usually highly damped, and have rise times ranging from less than one microsecond to a few milliseconds. Their levels and durations can sometimes be limited by the use of surge arrestors throughout the system, and not only at the point of common coupling.

The magnitude, duration, and energy-content of transient overvoltages vary with their origin. Generally, those of atmospheric origin have the higher amplitude, and those due to switching are longer in duration and usually contain the greater energy. Critical equipment needs to be protected by individual surge protective devices, and these should generally be selected to cater for the greater energy content of the switching overvoltages.

Switching of capacitor banks is a common cause of transient overvoltages. Typically, their value at the point of incidence is less than twice the nominal voltage. However, wave reflections and voltage magnification can occur as the transient is propagated along a line, amplifying the overvoltage incident on connected equipment. This needs to be taken into account if immunity is being considered for particular equipment or installations.

Synchronised switching is a possible mitigation technique to minimise capacitor, reactor and transformer switching transients, more often applied at medium and higher voltages.

Magnitudes up to 2 kV are generally regarded as typical of transients of atmospheric origin, but values up to 6 kV and even higher have been recorded.

No measurement results are available for the present report. However, there is no reason to believe that there has been any increase in the level of this phenomenon, which is an intrinsic feature of public electricity networks. There is some anecdotal evidence that modern electronic devices are not always provided with sufficient immunity from this phenomenon.

8. SUMMARY

The measurement results presented by this report show that essential tasks there are given for ensuring electromagnetic compatibility between the electricity supply networks on the one side and the electric and electronic equipment connected thereto. A task which the electricity industry is ready to carefully manage in cooperation with the manufacturing industry, both areas working in a competitive environment.

Power quality seems to get an increasingly strategic status, for the competing electricity industry as well as for the manufacturers. Due to the increasing economic pressure on the electricity industry within a liberalised electricity market, a decrease of the power quality is feared to take place in future. Such a decrease could cause high costs e.g. considering production losses, so power quality could have an impact on the choice of locations of industries in the future.

The results of different surveys reported about within this report demonstrate that

- any change in standardisation would carefully to be considered, due to a presently quite comprehensive construction of the present EMC standardisation and the mutual dependability of different areas (e.g.:
    - reference network impedance – emission limits;
    - compatibility levels – immunity requirements;
    - Basic standards – Generic & Product (family) standards;
    - definition of a phenomenon – PQ requirements).
- PQ levels in the supply networks show a different behaviour related to the margin remaining to the compatibility levels for LV networks, phenomenon by phenomenon. Concerning harmonics the measurement results show that there is still some small margin remaining whenever in some cases the compatibility levels appear as getting exceeded. In any case a tendency of steady increase of harmonic levels is to be recognised. Due to the cumulative effect and the transfer of harmonics from the LV to MV and HV networks, the harmonic levels in the HV networks do already exceed the design (planning) levels.

  The fact that in most cases the power quality levels continue to be lower than the compatibility levels may be acknowledged thanks to improvements of the supply networks. Due to the now increasing connection of harmonics generating equipment this management becomes an increasingly pretentious task and therefore reliance on appropriate limits in related standards gets an increasing weight

In other cases – like concerning flicker – the results demonstrate that the recently given compatibility levels are exceeded in some cases and should be reconsidered for possible relaxation, considering the low percentage of related complaints.

Referring to the different phenomena dealt with within this report, it can be summarised:

Harmonics:

Harmonic pollution, its effect growing with the growth of the harmonic voltages, can cause considerable cost in power networks, which – regarding the steady increase of harmonic voltage levels during the past twenty years -- may be counted in hundreds of B$ worldwide.

In regard to known practical or operational problems caused by harmonics, these are not yet widespread, but the potential for such problems is much greater today than it was 10 years ago, and the effects of non-linear loads are becoming a steadily increasing concern.

Monitoring of harmonic pollution of public electricity networks has shown that over the past twenty years, there has been a significant increase in the distortion of the voltage waveform. Particular harmonics that are characteristic for the power supplies used in televisions, personal computers and similar equipment have increased by a factor of 3 and have been shown to follow patterns of usage of such equipment. Most surveys given in this report show a constant increase of the THD voltage, as well as the predominance of the 5^{th} harmonic in LV, MV and HV networks. Only in a few countries a relatively stable situation can be observed during the past years.

The principal harmonics are now found at levels of several percent on distribution networks, and at about 2 % on many transmission networks. Some decades ago the levels were only a fraction of these levels now present. A constant increase of 1 % of the THD voltage as well as of the 5^{th} order harmonic can be observed over each 10-year period.

On LV networks, a significant percentage of the 5^{th} harmonic values are already around the compatibility levels established in IEC 61000-2-2 **[12]** and 61000-2-12 **[13]**. In some cases, 5 % to 20 % of the values exceed these compatibility levels.

To ensure electromagnetic compatibility also in the future, it can't be assumed to be managed by simply enhancing the compatibility levels; besides, that would cause the need to enhance also the immunity requirements and endanger the functionality of equipment already applied.

In general, in MV networks, the annual increase of the THD and 5^{th} harmonic grows at a similar scale than that in LV networks. Also in MV networks, the impact of the 5^{th} harmonic is significant, also that one of the harmonic of 3^{rd} order. In several large MV systems both harmonic orders exceed the compatibility levels in around 5 % of the cases. Taking into consideration that harmonics can circulate between the voltage levels low, medium and high, there is a risk that harmonic pollution in MV, and even in HV networks could dangerously increase.

There is an urgent need for the effective application of EMC, taking due account of the cumulative effect of multiple devices emitting harmonics simultaneously, that considering also the economic impact of related emissions from equipment.

Voltage fluctuations/Flicker:

Measurement results in different countries show that flicker levels are relatively low, in general. In some cases P_{lt} values are found to exceed the compatibility level. The frequency distribution of P_{lt} shows maxima within the range of from 0,2 and 0,6.

Generally the flicker level is higher in urban areas than in rural areas.

Voltage dips:

Voltage dips have been an intrinsic feature of public electricity supply since the earliest times, but some modern electrical equipment, either in its own design or because of control features incorporated in it, has become more sensitive to voltage dips, giving rise to inconvenience and even considerable economic loss. There is therefore a need for an increased awareness of the phenomenon among the suppliers and users of electricity and the manufacturers of equipment using electricity.

Voltage dips are unpredictable in place and time of occurrence as well as in levels, involving voltages down virtually to zero and durations up to and above one second. The frequency of their occurrence and the probability of their occurrence at any level are highly variable both from place to place and from one year to another.

Voltage dips cannot be eliminated, although their incidence may be reduced by appropriate measures, in general without affording high costs.

In addition to the range of causes that affect all networks, higher annual rates of occurrence are possible on overhead networks reflecting the exposure of these networks to fault causes, especially severe climatic conditions.

In rural areas supplied by overhead MV lines the number of voltage dips can reach hundreds of even several hundreds per years, depending in particular on the number of lightning strokes and other meteorological conditions in the area. On cable MV networks, an individual user of electricity connected at low voltage may be subjected to voltage dips occurring at a rate which extends from around ten per year to about a hundred per year, depending on local conditions.

Unbalance:

The levels of unbalance found are generally below 2 % at all network levels and therefore continue to be reflected by the related compatibility levels **[12].** Exceptions may occur in certain places where, for example, arc furnaces with a 2-phase-connection to the supply network are installed or where significant segments of the local load are on a single phase.

Transient overvoltages:

Due to several phenomena giving rise to transient overvoltages in low-voltage power supply systems and in the installations connected to them, such overvoltages typically will reach magnitudes up to 2 kV in case of atmospheric origin, but values up to 6 kV and even higher have been recorded; its rise times are ranging from less than 1 ms to a few milliseconds.

(Reference) Network impedance (see **Annex B**)**:**

For Europe, the related IEC Standard gives values which – still – appear as appropriate for the given impedance situation. At present no reasons seem to be given for modification of these values. In future, any consideration of modifications should be done considering the comprehensive impact of the reference network impedance on the construction of EMC standards and the limits and requirements contained.

ANNEX A : ADDITIONAL DETAILED MEASUREMENT RESULTS

A.1 HARMONICS: EXTRACT OF MEASUREMENTS ON LV, MV AND HV NETWORKS IN DIFFERENT COUNTRIES

A.1.1 INDEX

A.1.1.1 Harmonic levels in European networks. General survey over the past 20 years. Trends.

1 UK Survey 1979 – 1999 in residential areas

2 UK LV Survey 1979 – 1999 in residential areas

3 UK 1980 – 1995

4 UK Survey 1979 – 1999 in residential areas.

5 Switzerland 1979 – 1997

6 Austria 1997 - 1999

A.1.1.2 Harmonic levels in European networks. Further results from surveys

7 France: survey on 20 public LV systems. 2000

8 France: survey on 20 public LV systems. 1991

9 Denmark:

10 Spain

11 Czech republic

12 France – EDF HV networks

A.1.1.3 Harmonic load distribution over the week

13 Austria

14 UK: Residential environment

15 UK: IT Office

16 UK: Plastic extrusion factory

17 UK: Residential housing estate

18 UK: IT (Insurance) office

19 UK: IT office

A.1.2 HARMONIC LEVELS IN EUROPEAN NETWORKS. GENERAL SURVEY OVER THE PAST 20 YEARS. TRENDS.

1 UK Survey 1979 – 1999 in residential areas [20]

Results from measurements taken from 1979 to 1999 at a typical distribution substation in a residential area, the last survey having been carried out in April 1999.

The most prevalent harmonic voltages of 3rd, 5th and 7th order as well as the THD are represented in as the following graphic.

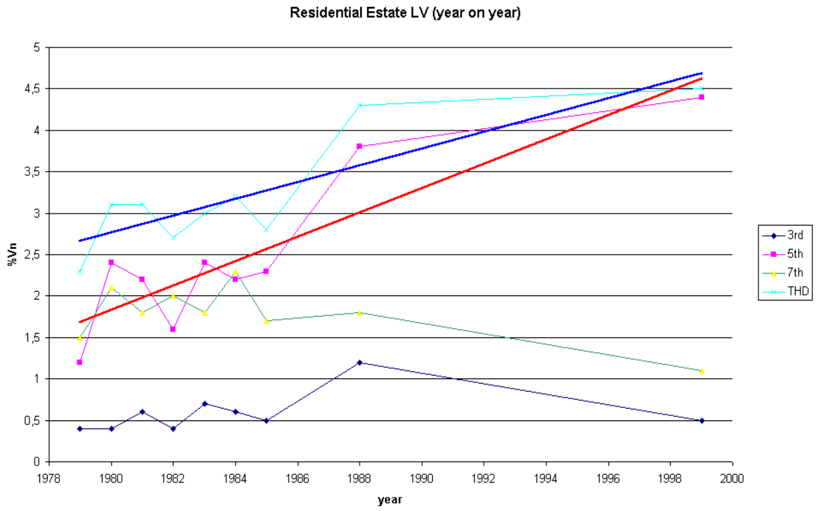


Fig. A.1 - Development of 3rd, 5th and 7th harmonic and THD in a UK distribution substation in a residential area, 1979 – 1999

The THD increases at an average of 1 % U_1 every 10 years, and the 5th harmonic at 1,45 % U_1 (≈ 1,5 % U_1 / 10 years). The conclusion is that in the year 2008, U_5 will reach 6 % C.L. This hypothesis is even not correct, taking into account that the annual increase of ITE + TV products is expected to be higher than linear.

2 UK LV Survey 1979 – 1999 in residential estate [20]

Residential Estate (Year on Year) 1979 -1999

Supply Voltage	415 V
Type of service	Distribution Substation
Maximum Demand	380 kVA
Type of Load	Domestic dwellings
Duration of survey	One week
THD Maximum	4.52 % (1999)
U_3 Maximum	2.3 % (1984)
V5 Maximum	4.4 % (1999)
V7 Maximum	1.2 % (1988)
Analyser Used	Robinson 555
Sample Interval	15 minutes
Reason for Survey	Routine monitoring

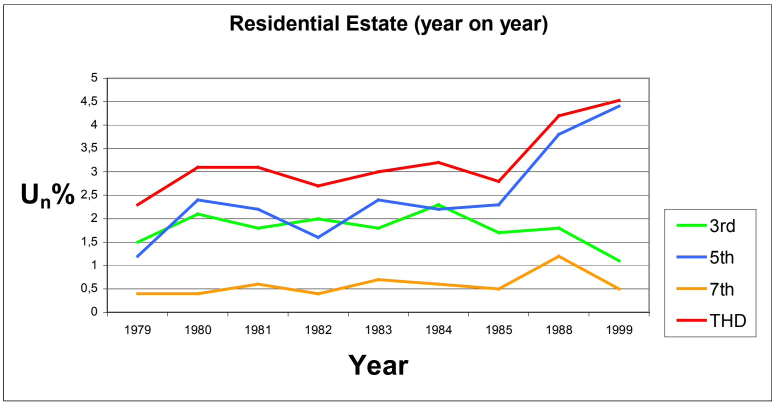


Fig. A.2 - Development of 3rd, 5th and 7th harmonic and THD in a UK distribution substation in a residential estate, 1979 – 1999

Summary: This survey is part of an ongoing harmonic monitoring programme, initiated by the Electricity Council, in 1979, to assess the growth of harmonic voltage distortion seen at a typical distribution substation. The last survey was carried out in April 1999.

Conclusions: There is a clear indication in the rise of the 5th harmonic, and therefore of the THD, over the years. This is most probably due to the rise in application of colour television equipment and other electronically controlled domestic appliances over this period. Future measurements need to be taken at the same time each year to allow more accurate comparison of results.

3 UK 1980 – 1995 [20]

Measurements taken since 1980 at a typical MV side of a substation feeding to a residential area; the last survey was carried out in 1995.

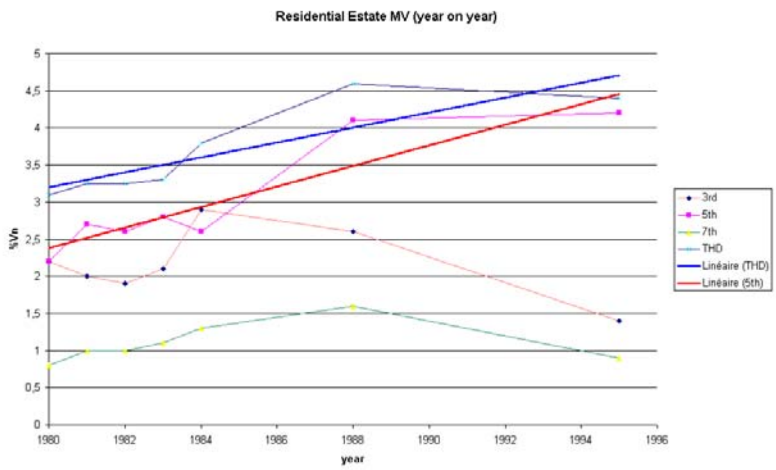


Fig. A.3 - 3rd, 5th and 7th harmonic and THD at a substation, MV side, in UK

Comment: The THD increases at an average of 1 % U_1 every 10 years, and the 5th harmonic at 1,4 % U_1 (≈ 1,5 % U_1 / 10 years). The conclusion is that in the year 2004, U_5 will reach the 6 % compatibility level.

4 UK survey 1979 – 1999 in residential areas [20]

Residential Estate (MV) 1980 – 1999

Supply Voltage	11 kV
Type of service	Primary Substation
PCC	33 kV
Type of Load	Residential
Duration of survey	1 week
THD Maximum	4.58 % (1988)
U_3 Maximum	2.9 % (1984)
U_5 Maximum	4.2 % (1995)
U_7 Maximum	1.6 % (1988)
Analyser Used	Robinson 555
Sample Interval	15 minutes
Reason for Survey	Routine monitoring programme

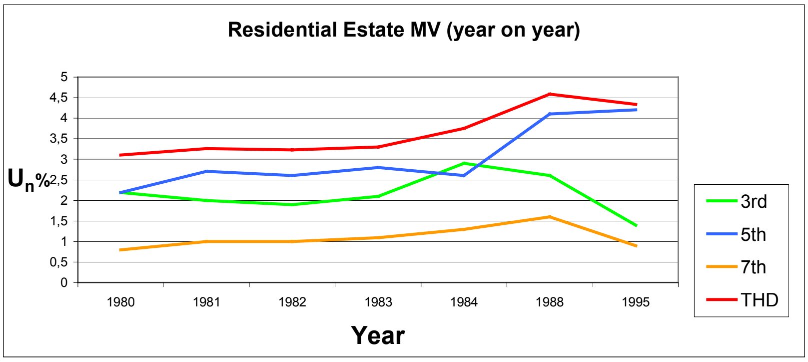


Fig. A.4 - 3rd, 5th and 7th harmonic and THD in a UK residential area, MV

Summary: This survey is part of an ongoing harmonic monitoring programme, initiated by the Electricity Council, in 1979, to assess the growth of harmonic voltage distortion seen at a typical distribution primary substation. The last survey was carried out in September 1995. Since privatisation of the UK Electricity Industry in 1990, this programme has suffered from a lack of co-ordination, hence the recording surveys have not been carried out every year, and not always at the same time of year, hence comparison of year on year results is not straightforward.

Conclusions: There is a clear indication in the rise the 5^{th} harmonic, and therefore THD, over the years. This is most probably due to the rise in application of colour television equipment and other electronically controlled domestic appliances over this period. Future measurements need to be taken at the same time each year to allow more accurate comparison of results.

5 Switzerland 1979 – 1997 [21]

In Switzerland, in the area of Zurich, the evolution of harmonics seems to remain stable. Nevertheless the 5th harmonic is the prevalent one.

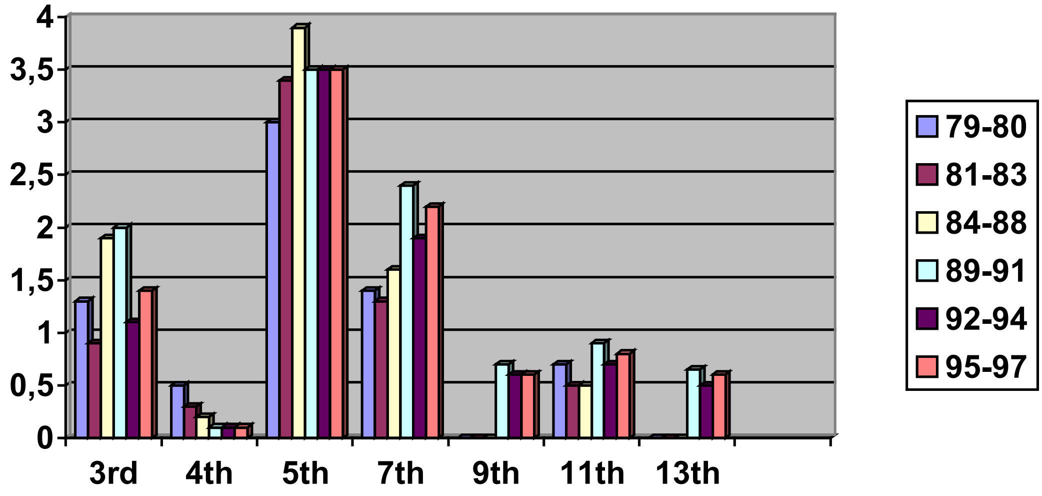


Fig. A.5 - Development of the 5th harmonic in Switzerland 1979 - 1997

6 Austria 1997 – 1999 [22, 23]

The following graph shows the evolution of the 95-%-values for different harmonics measured in a substation from 1997 to 1999.

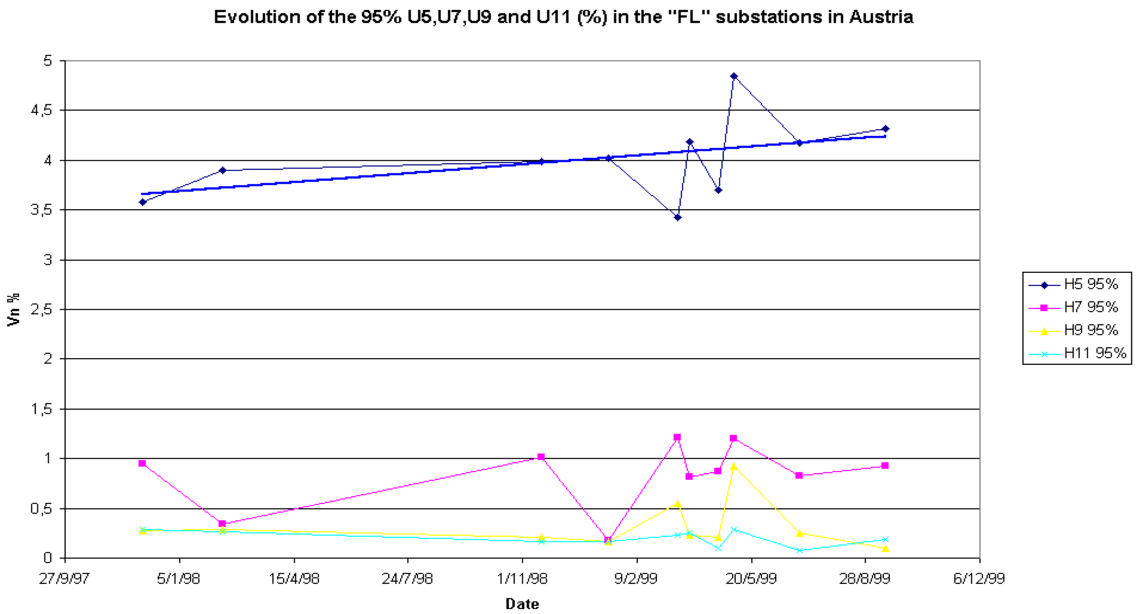


Fig. A.6: Evolution of the 95% 5th, 7th, 9th and 11th harmonic 1997 - 1999

Comment: The 5th harmonic increases at an average of 0,6 % U_1 during 5 four-month periods (≈ 3,6 % U_1 / 10 years). However, the period of measurement is not representative.

A.1.3 HARMONIC LEVELS IN EUROPEAN NETWORKS. FURTHER RESULTS FROM SURVEYS

Extract of measurements of harmonics on LV, MV and HV networks in different countries

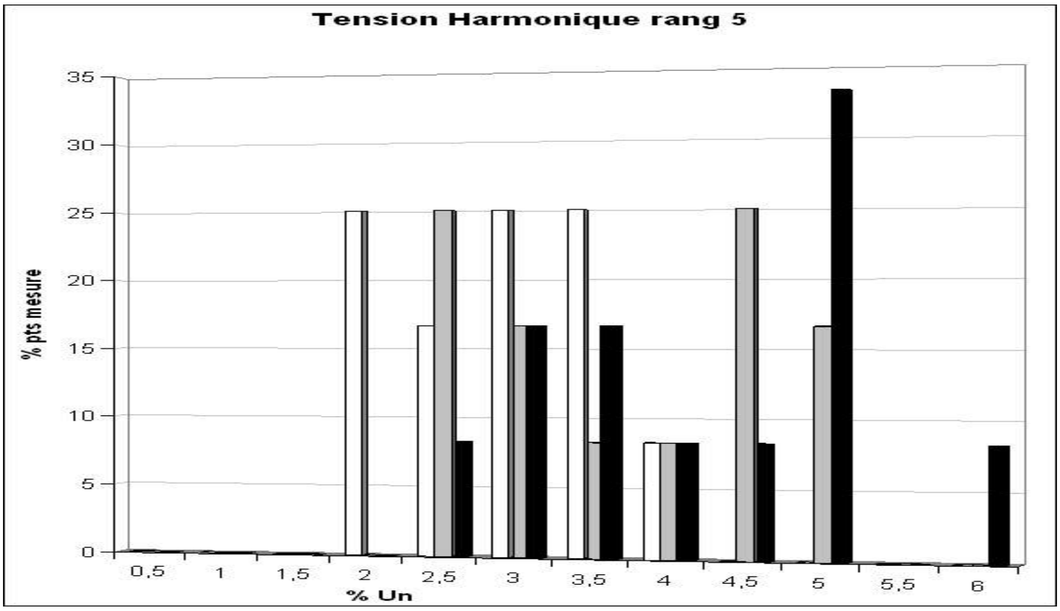
7 France: survey on 20 public LV systems. 2000 [24]

20 public LV systems, including 16 typical systems and 4 special ones, having been involved.

For the 16 typical LV systems, the only criterion of choice was that each LV system only supplies one type of customers (residential, industrial or tertiary). Next, for each type of customers, the choice of LV systems was practically made randomly.

For the 4 special LV systems, the criterion of choice was to have LV systems with a high value for THD.

The results obtained on the whole sample for the 5th harmonic were as follows:



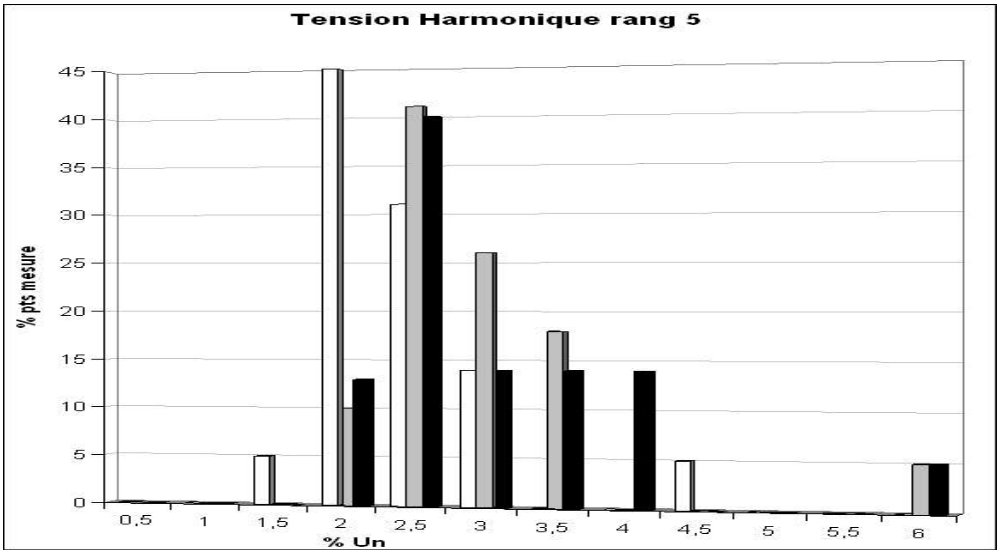
50-%-values
95-%-values
maximum values

Fig. A.7 - 5th harmonic in French LV systems, 2000

Comment: For nearly a half of the considered sample, the measured 5th harmonic voltage levels were high compared with the compatibility level.

Comparison with results obtained in 1991. In 1991, EDF already conducted a survey on 20 public LV systems for one week. These LV systems were situated in the Paris region and mainly supplied residential customers. The measured harmonic voltages were mean values over time intervals of 5 minutes. The results obtained for the 5th harmonic voltage are given in **Fig. A.8** below.

8 France: survey on 20 public LV systems. 1991 [24]



50-%-values,
95-%-values,
maximum values.

Fig. A.8 - 5th harmonic in French LV systems, 1991

Comparing these results obtained in 1991 with those obtained in 2000, the average of the 95-%-values for the 5th harmonic voltage may be found between 2,5 % and 3 % in 1991, and between 3,5 % and 4 % in 2000. So, in 10 years, a mean increase of about 1 % for the 5th harmonic voltage on public LV systems can be recognised.

9 Denmark [17]

The THD and the individual harmonics of order 3, 5, 7, 9, 11, 13 and 15 were measured in urban and rural areas involving 200 delivery points in LV.

The THD is shown in **Fig. A.9** below. It may be noticed that the harmonic level is higher in urban than in rural areas.

For the 3rd harmonic, values of 3-4 % were found at several points.

With respect to the 5th harmonic, in urban areas higher values exceeding the compatibility level of 6 % were found during some periods of the observation time of a week.

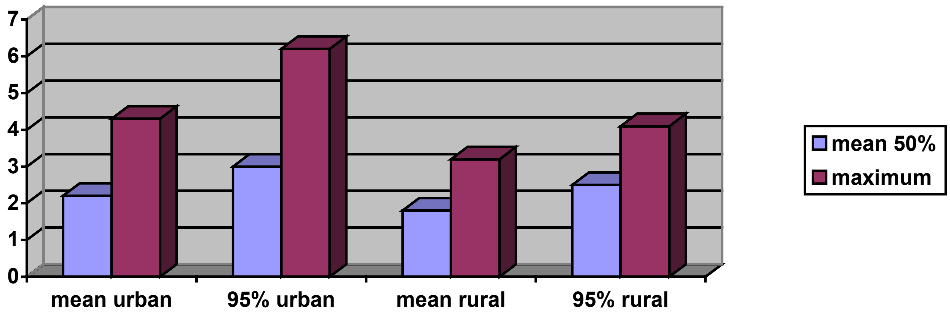


Fig. A.9 - Distribution of THD values in urban and rural areas in Denmark

10 Spain [25]

Average of measurements in 79 MV substations during 1987 to 1989.

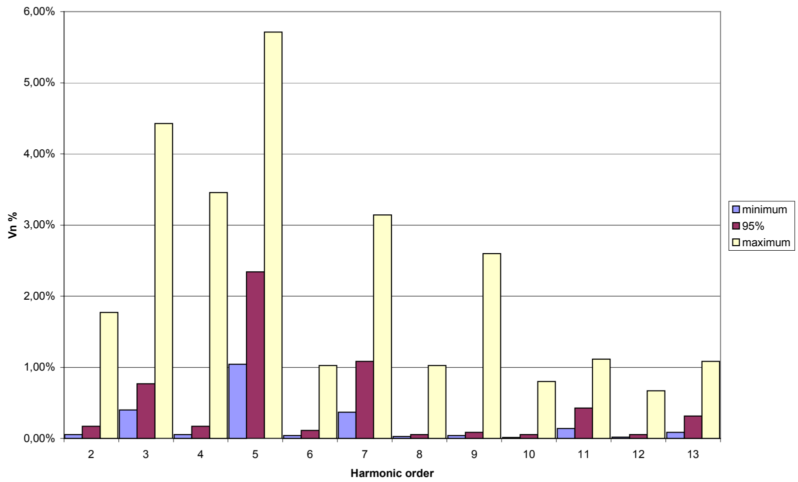


Fig. A.10 - Harmonics up to order 14 in 79 MV substations in Spain, 1987 - 1989

Comment: Due to the higher increase of the Spanish GPD and electricity consumption as well during the nineties with respect to the European rate, a higher increase of the 5th harmonic and the THD per year is to be expected. Consequently, the tendency is to reach the compatibility level in a similar way as in other European countries.

11 Czech Republic [26]

These measurements were performed in different locations of Prague

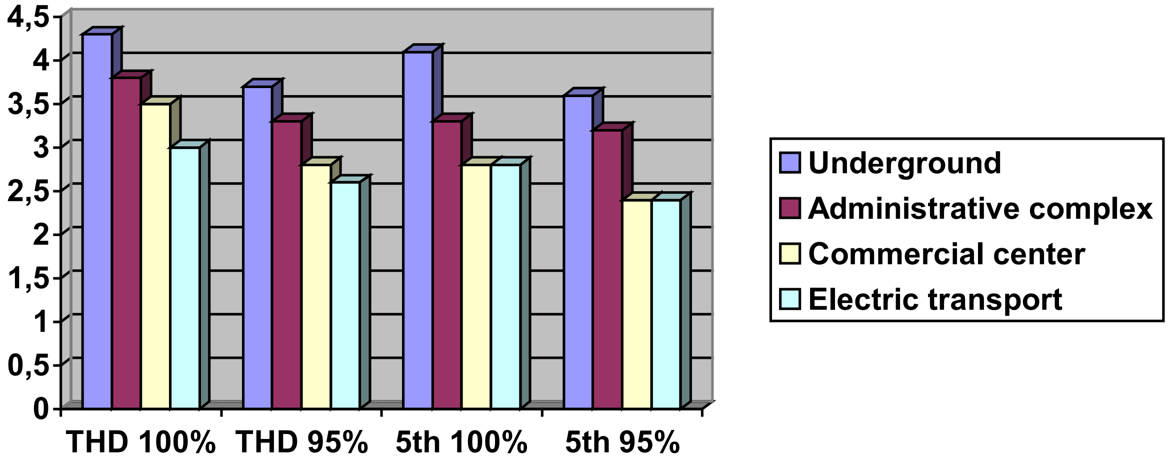


Fig. A.11 - THD and 5th harmonic in different locations with specific type of loads

12 France – EDF HV networks

5th harmonic measurements made in 1990 and 1994 at the HV bus bars at 22 most disturbed substations.

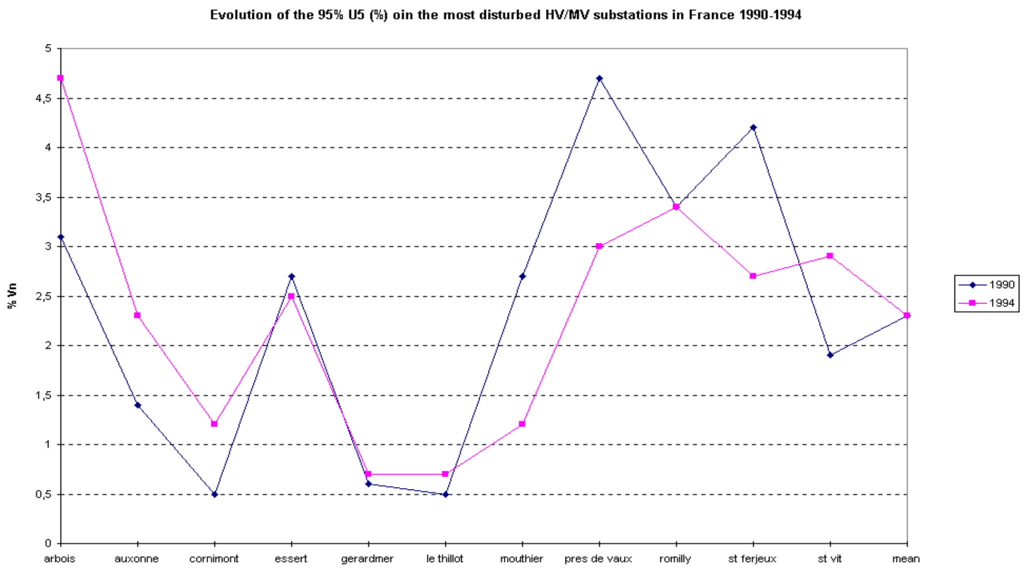


Fig. A.12 - 5th harmonic on French HV busbars 1990, 1994

For 5 substations, the level of harmonic increased between 1990 and 1994. For 4 substations, the levels remained unchanged. For three of them, the levels decreased due to the fact that the Short Circuit Power has been increased.

A.1.4 HARMONIC LOAD DISTRIBUTION OVER THE WEEK / DAY

Extract of measurements of harmonics on LV, MV and HV networks in different countries

13 Austria [22, 23]

The graph shows the results of a survey concerning the 5th harmonic, carried out at the 110-kV-busbar and the 30-kV-busbar of a substation as well as at the 0,4-kV-bar of a transformer station connected to this substation via a mixed 30-kV-network (overhead line/cable), The 5th harmonic is shown at the three levels, with the significant rise in the early evening and a rapid decrease at about 10 pm.

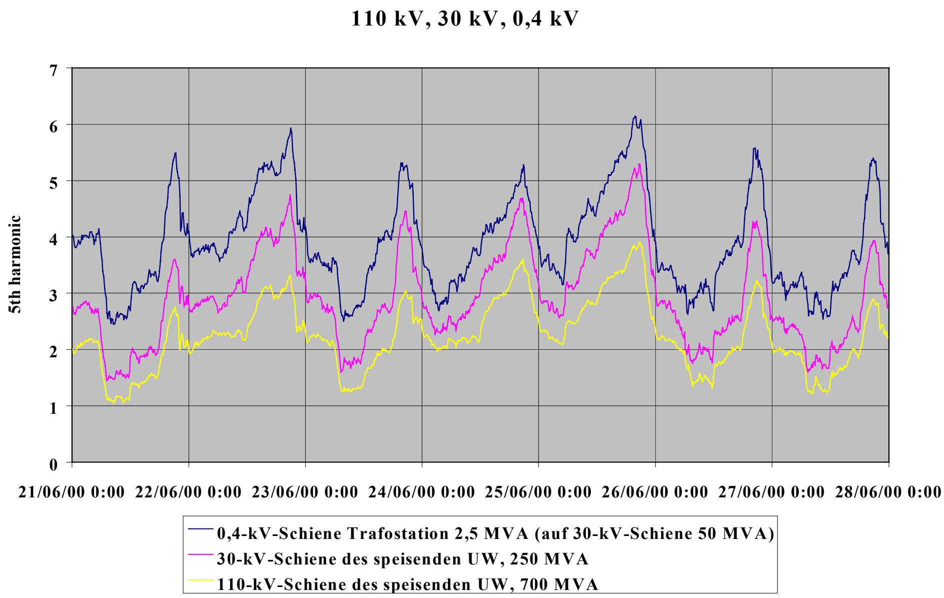


Fig. A.13 - 5th harmonic at 400V-, 30-kV and 110-kV busbar over a week, in Austria, 2000

It may be assumed that this evening peak of the 5th harmonic results from the decrease of the load in conjunction with an increase of the share of equipment with a significant 5th harmonic current (e.g. TV sets). The rapid decrease of the 5th harmonic at 10 pm may be assumed to be caused by the switch-off of a large number of equipment with a significant 5th harmonic current on the one side and by the switch-on of ohmic heating equipment by ripple control as e.g. heating radiators and water boilers.

14 UK: Residential environment [20]

Residential housing estate (number of houses 252, maximum demand 380 kVA, date of measurements April 1999) LV

Supply Voltage	415 V
Type of service	N/A
Number of Houses	252
Maximum Demand	380 kVA
Duration of survey	1 week
THD Maximum	4.52 %
U_3 Maximum	1.4 %
U_5 Maximum	4.4 %

Analyser Used	Robinson 555
Sample Interval	15 minutes
Reason for Survey	Routine monitoring

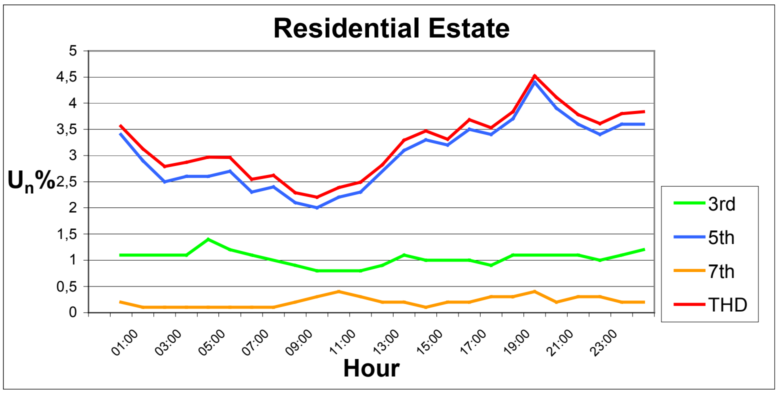


Fig. A.14 - 3rd, 5th and 7th harmonic and THD in UK residential estate over 24 hours

Summary: This monitoring survey is part of an ongoing survey at this particular substation. The survey programme was initiated by the Electricity Council to provide details on the background level of harmonic distortion present on a typical distribution substation serving a residential environment. This particular survey was carried out over one week in April 1999. The graph shown represents a typical set of results over one day of the survey.

Conclusions: As expected the dominant harmonic is the 5th harmonic, this follows the typical daily load pattern. It has its peak of 4.4 % at 19:00 (THD = 4.52 %). There is no coincident rise in the 3rd and the 7th harmonics, indicating that the source of the rise in the 5th harmonic might be on an adjacent section of the network. The most likely cause for the rise in the 5th harmonic would be TV load.

The 5th harmonic reaches 4,4 % at "TV peak" hours. According to an averaged increase of 1,5 % / 10 years, U_5 would reach the compatibility level of 6 % in 2009.

15 UK: IT Office [20]

Supply Voltage	415 V
Type of service	Direct from local 11000/415 transformer
PCC	415 V terminals of local transformer
Fault Level	10 MVA
Type of Load	Office equipment – particularly PCs, Monitors, Fluorescent Lamps and Printers. 24 Hour operation
Duration of survey	5 days
THD Maximum	7.87 %
U_3 Maximum	2.46 %
U_5 Maximum	7.56 %
Analyser Used	Robinson 555
Sample Interval	15 minutes

Reason for Survey	Interference to VDU screens and hot neutral conductor.

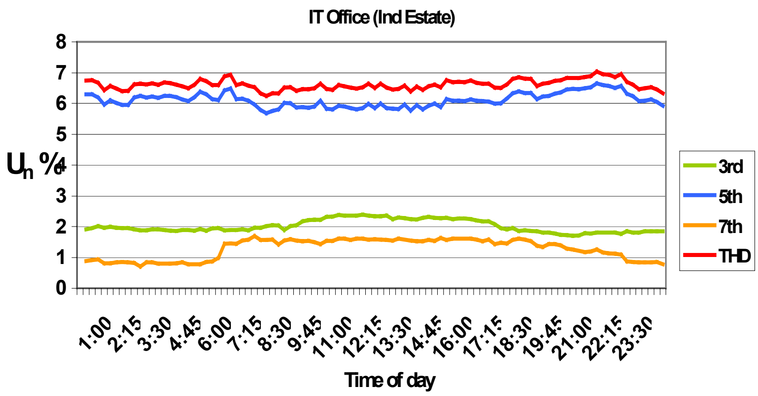


Fig. A.15 - 3rd, 5th and 7th harmonic and THD in UK residential area over 24 hours

This office is an international IT support centre, that operates 24 hours per day seven days per week and is located on an industrial estate. The load is mainly comprised of IT equipment and fluorescent lighting. The survey was prompted by a complaint from the consumer to the local Electricity Supply Company of "VDU screen 'wobble' and excessively hot neutral conductor". The neutral current was approximately 150 % of the highest phase current; this was due to third harmonic current and severe out of balance loading. The VDU interference was caused by stray neutral current returning to earth via the structure of the building; producing local EM fields around the building supports.

Conclusions: The level of the 5th harmonic and hence THD, is high throughout the day, and often exceeds the 6 % compatibility limit for that harmonic order. In this instance the consumer paid for neutral uprating, load balancing and anti EMF hoods for affected VDUs.

16 UK Plastic extrusion factory [20]

Supply Voltage	11kV
Type of service	11 kV cable network
Fault Level	100 MVA
Duration of survey	1 week
THD Maximum	3.3 %
U_3 Maximum	0.68 %
U_5 Maximum	3.19 %
Analyser Used	Robinson 555
Sample Interval	15 minutes
Reason for Survey	New load enquiry

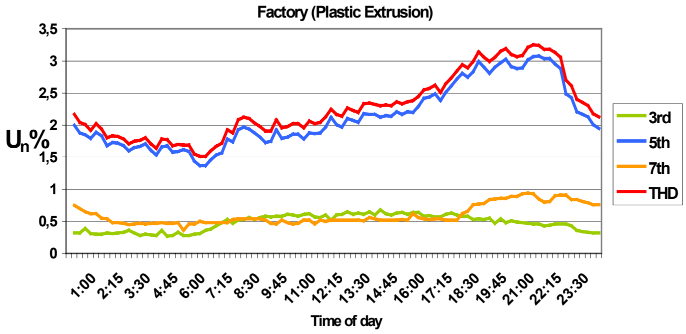


Fig. A.16 - 3rd, 5th and 7th harmonic and THD in a UK plastic extrusion factory over 24 hours

Summary: This factory is located within a large housing estate. The site load is comprised of several extrusion machines that are driven by dc motors, supplied via six pulse drives. The prompt for this survey came from the consumer applying to the local Electricity Supply Company for permission to connect a new dc drive. The monitoring instrumentation was connected to the metering VT and CTs.

Conclusions: The factory starts production at 07:00, this is characterised by the rise in the 5th harmonic at about this time. The 5th harmonic continues to rise throughout the day, reaching a peak of 3.19 %, at about 21:00, this is most likely due to TV load within the surrounding residential houses. The planning limit used at 11 kV in the UK is 3 % THD. Therefore it was agreed to allow the connection of the new drive on the basis that a system monitoring survey is to be completed after the installation, and if deemed necessary the consumer will install filters to reduce the harmonic emissions.

17 UK Residential housing estate [20]

Supply Voltage	415 V
Type of service	N/A
Number of Houses	135
Maximum Demand	230 kVA
Duration of survey	1 week
THD Maximum	4.76 %
U_3 Maximum	1.4 %
U_5 Maximum	4.4 %
Analyser Used	Robinson 555
Sample Interval	15 minutes
Reason for Survey	Routine survey

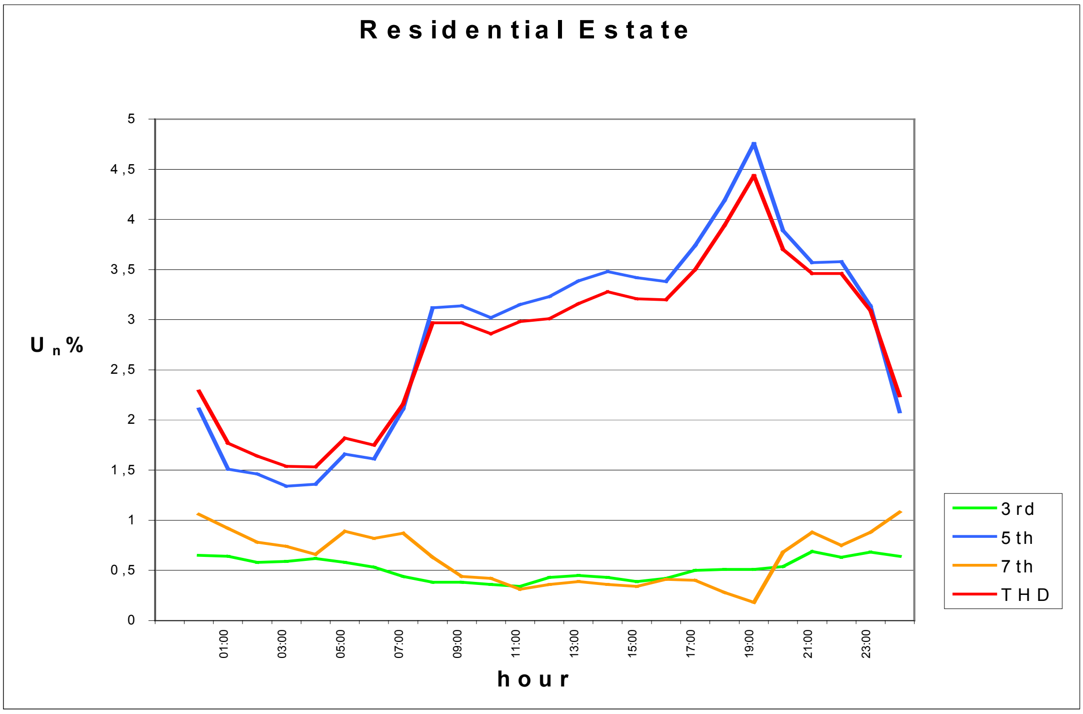


Fig. A.17 - 3rd, 5th and 7th harmonic and THD in UK residential housing estate over 24 hours

Summary: This monitoring survey is part of an ongoing survey at this particular substation. The survey programme was initiated by the then Electricity Council to provide details on the background level of harmonic distortion present on a typical distribution substation serving a residential environment. This particular survey was carried out over one week in June 1999. The graph shown represents a typical set of results over one day of the survey.

Conclusions: As expected, the dominant harmonic is the 5th harmonic, this follows the typical daily load pattern. It has its peak of 4.4 % at 19:00 (THD = 4.76 %). There is no coincident rise in the 3rd and the 7th harmonics, indicating that the source of the rise in the 5th harmonic might be on an adjacent section of the network. The most likely cause for the rise in the 5th harmonic would be TV load.

18 UK IT (insurance) office [20]

Supply Voltage	415 V
Type of service	Direct from local 11000/415 transformer (2 x 500 kVA)
PCC	415 V terminals of local transformer
Fault Level	20 MVA
Maximum Demand	610 kVA
Type of Load	Office equipment – particularly PCs, Monitors, Fluorescent Lamps, Printers and some domestic load.
Duration of survey	1 week
THD Maximum	7.88 %
U_3 Maximum	2.32 %
U_5 Maximum	7.49 %
Analyser Used	Toshiba – EATL
Sample Interval	10 minutes
Reason for Survey	Routine survey

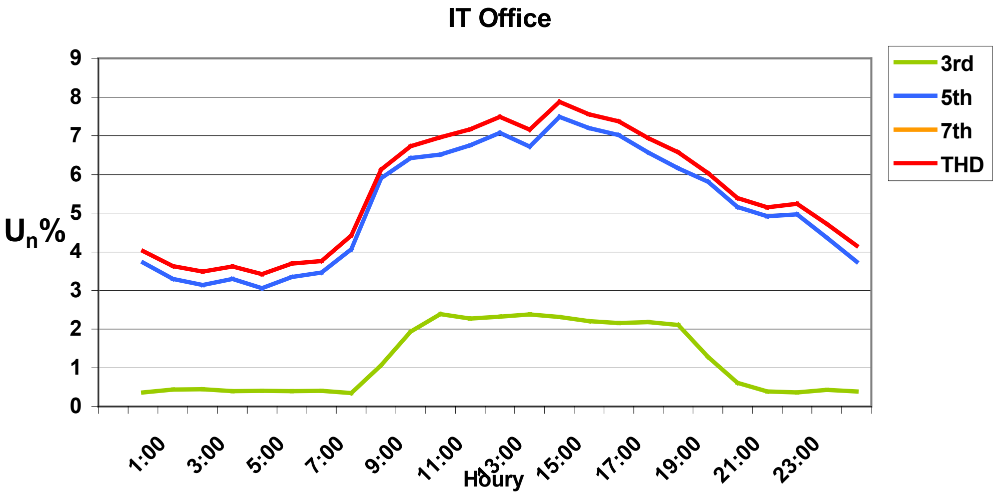


Fig. A.18 - 3rd, 5th and 7th harmonic and THD in a UK IT insurance office over 24 hours

Summary: This survey was carried out by the local Electricity Company for the reason of identifying the level of harmonic distortion that is present on a typical distribution substation. The main load on this substation is an insurance office, within which there is a large amount of IT equipment and fluorescent lighting. The duration of the survey was one week, and it was carried out during February 2000.

Conclusions: The office starts work at 08:00, this is characterised by the rise in harmonic distortion seen at this time. The coincident rise in the 3rd and 5th harmonics indicates that the source of the distortion is connected to the LV network of this substation, the daily peak is reached at approximately 14:00. The office continues working until about 7 p.m., again this aligns with the recordings of the 3rd and 5th harmonics. However the 5th harmonic continues to remain high as a result of domestic load connected to this and adjacent substations. The level of the 5th harmonic is high throughout the working day, and often exceeds the 6 % compatibility level. However the nature of harmonic distortion is such that it could be some time before a high level of distortion manifests itself in equipment failure or other problems occur.

19 UK IT office [20]

Supply Voltage	415 V
Type of service	Direct from local 11000/415 transformer
PCC	11 kV Cable network
Fault Level	4 MVA
Maximum Demand	70 kVA
Type of Load	Office equipment – particularly PCs, Monitors, Fluorescent Lamps and Printers.
Duration of survey	1 week

THD Maximum	5.67 %
U_3 Maximum	1.29 %
U_5 Maximum	5.23 %
Analyser Used	Robinson 555
Sample Interval	15 minutes
Reason for Survey	Telephone interference

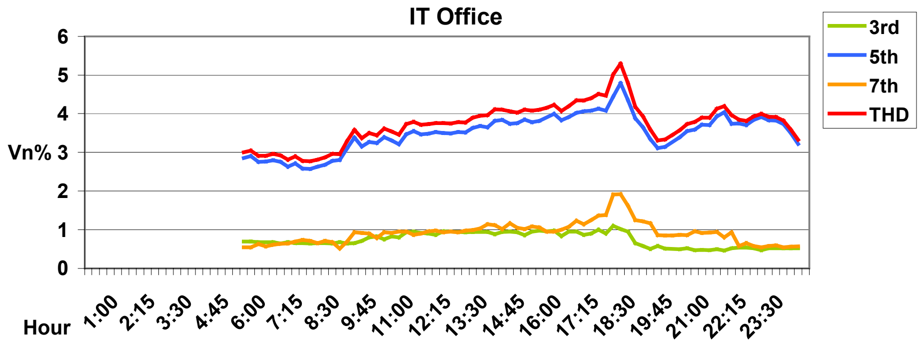


Fig. A.19 - 3rd, 5th and 7th harmonic and THD in a UK IT office over 24 hours

Summary: This office is supplied via a discrete pole mounted transformer rated at 200 kVA, hence the low fault level. The office is situated in residential housing estate in a semi-urban area. The survey was prompted by the consumer complaining to the local Electricity Company of interference on their telephone lines. The office is the head office of a national and international equipment supplier. The load is mainly composed of IT equipment and fluorescent lighting. This survey was carried out during one week in early March 1995.

Conclusions: The office starts work at about 08:00 and this is characterised by the rise in the 5th and 7th harmonics. Throughout the day the 5th harmonic continues to increase until the office closes for the day at about 18:00. The sudden rise at around 18:00 is thought to be due to additional lighting being switched on and the work of cleaning staff. The back- ground level of the 5th harmonic increases in the evening as a result of the surrounding residential TV load. Replacing the PABX system by one with a higher immunity rating, cured the problem of telephone interference.

A.2 VOLTAGE FLUCTUATIONS / FLICKER: EXTRACT OF MEASUREMENTS ON LV AND MV NETWORKS

Belgium [27]

10 measurements in LV networks during ± two weeks in 1994

	Flicker $P_{st\ 99\%}$	P_{lt}	$P_{lt\ 95\%}$
A	0.39	0.32	0.22
B	0.53	0.46	0.37
C	0.62	0.53	0.48
D	2.55	2.03	1.67
	0.37	0.32	0.27
F	0.84	0.63	0.55
G	0.22	0.32	0.18
H	0.99	0.78	0.51
I	0.94	0.8	0.62
J	2.28	1.66	0.93

Tab. A.1 - Flicker values from Belgian measurements 1994

Austria

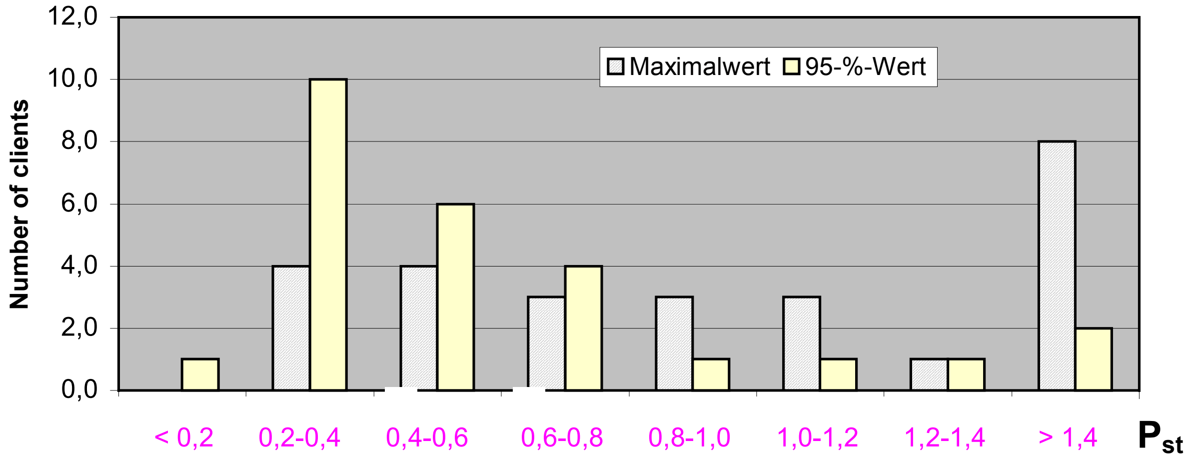


Fig. A.20 - Number of clients per P_{st} range

A.3 UNBALANCE: EXTRACT OF MEASUREMENTS ON MV AND HV NETWORKS

Czech Republic [26]

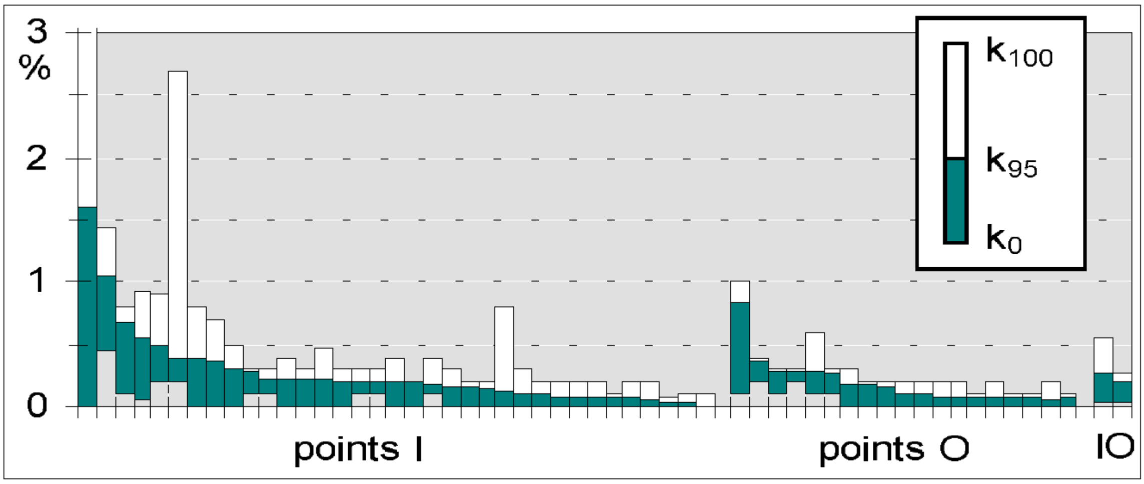


Fig. A.21 - Unbalance *k* in Czech MV networks

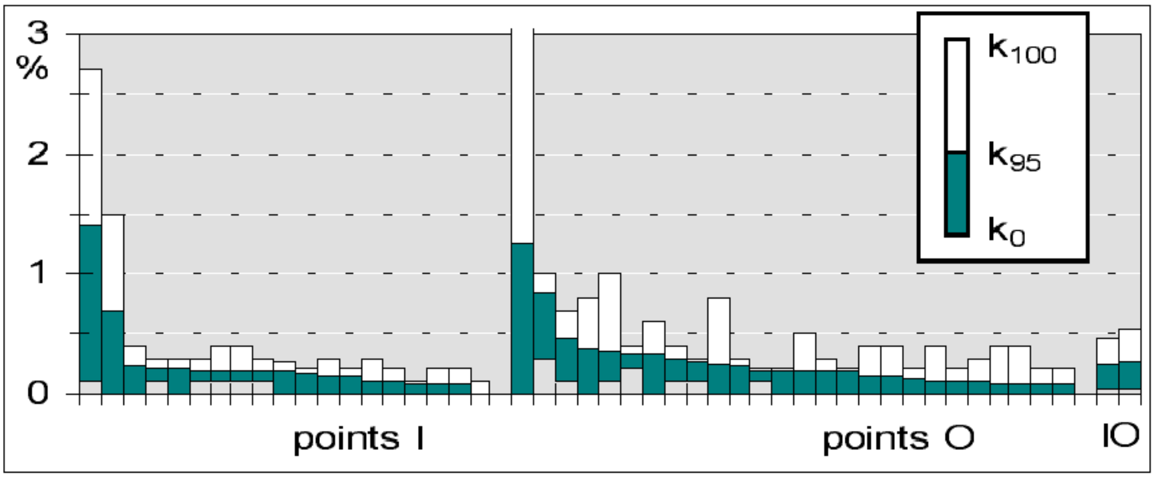


Fig. A.22 - Unbalance *k* in Czech 110-kV-networks

Comment: The unbalance in MV and in 110 kV networks is low. The magnitude of unbalance k95 always satisfies the criteria of EN 50160 despite of the fact that in individual cases (see diagrams) the unbalance k95 amounts up to 1.6 % (22 kV) or 1.4 % (110 kV). These exceptional cases concern the points of the network situated in the vicinity of supplying the a.c. single-phase railway traction or, maybe, also when combined with a small short-circuit power or a non-standard scheme of the network. However, the unbalance is even higher - up to 3.6 % or 3.3 % respectively for the rest 5 % of the week interval but these values are being tolerated by EN 50160 **[1]**.

ANNEX B : NETWORK IMPEDANCE

B.1 INTRODUCTION

The level of some disturbances emitted by an electrical equipment into the supply network to which it is connected depends on the network impedance. With decreasing impedance, the level of voltage fluctuations will decrease.

Therefore, in 1981 IEC published a report on a reference network impedance [**28**]. This was necessary for the definition of the emission limits, in particular for mass product equipment whose final conditions of application are not foreseeable (neither for manufacturers nor for network operators), especially for flicker and voltage variations. For industrial or large commercial installations, the reference network impedance is not appropriate; if problems occur, these are usually treated on a case by case basis taking into account the real network impedance - measured or assessed - at the PCC.

B.2 DEFINITION

The value recommended by IEC 60725 **[28]** was as follows for three-phase four-wire 230/400 V supplies:

Phase conductor	(0,24 + j 0,15) Ω
Neutral conductor	(0,16 + j 0,10) Ω
Phase to neutral	(0,40 + j 0,25) Ω

For harmonics of order below 40, the reference impedance can be considered as equal to (0,4+j n 0,25) Ω, where n is the harmonic order.

B.3 MEASUREMENT AND ASSESSMENT METHODS

The assessment can be simply done by calculation of the impedance point by point on the basis of the impedance characteristics of the network components. The reference impedance is the statistical value deduced from a statistic. Also, measurements can be made to determine the impedance at a specific point.

B.4 MEASUREMENT RESULTS

Table B.1 presents the measurement or assessment results which were considered in proposing the value of the reference impedance. When updating these data the progress made within the supply networks may be evaluated.

Country	**Percentage of consumers with less than stated impedance**			
	98%	**95%**	**90%**	**85%**
Australia	-	0,43 + j 0,33	-	_
Belgium	-	0,63 + j 0,33	0,32 + j 0,17	0,28 + j 0,15
France	-	0,55 + j 0,34	0,45 +j 0,25	0,34 + j 0,21

Germany	-	0,45 + j 0,25	0,36 +j 0,21	0,31 + j 0,17
Ireland	1.47 + j 0.64	1,26 + j 0,60	1,03 + j 0,55	0,94 + j 0,43
Italy	-	0,59 + j 0,32	0,48 + j 0,26	0,44 + j 0,24
The Netherlands	-	0,70 + j 0,25	0,41 + j 0,21	0,32 + j 0,17
Switzerland	-	0,60 + j 0,36	0,42 + j 0,25	0,30 + j 0,18
United Kingdom	0,46 + j 0,45	-	0,25 + j 0,23	_
Union of Soviet Socialist Republics	_	0,63 + j 0,30	0,50 + j 0,26	_

Tab. B.1 - Percentage of consumers with less than the stated impedance in Ohms at 50 Hz

A more recent study was made in **Spain** at 1440 LV PCCs, of which 1301 were mainly situated in a citizen area (A) and 139 were mainly situated in rural areas (B). The choice of PCCs was made randomly.

Spain	**98 %**	**95 %**	**90 %**	**85 %**
A 1301 PCCs	1,58 + j 0,45	0,86 + j 0,31	0,58 + j 0,23	0,44 + j 0,20
B 139 PCCs	2,12 + j 0,61	1,59 + j 0,40	1,22 + j 0,23	1,03 + j 0,19
A+B 1440 PCCs	**1,75 + j 0,46**	**1,05 + j 0,32**	**0,67 + j 0,23**	**0,51 + j 0,20**

Tab. B.2 - Percentage of consumers with less than the stated impedance in Ohms

A study made in **France** in 1987 shows a different situation for overhead networks, cables networks and twisted networks. The following main results were obtained:

% of customers for which Z is lower than Z given in this table	**Overhead**	**Twisted**	**Cable**
95%	-	0,80+ j 0,315	0,450+ j 0,135
90%	-	0,72+ j 0,225	0,270+ j 0,135
85%	1,12+ j 0,36	0,63+ j 0,190	0,270+ j 0,100

Tab. B.3 - System impedance in Ohms in overhead, cable and twisted networks

ANNEX C: MEASUREMENT METHODS

Over all, the future Section 30 of IEC 61000-4 **[9]** will define the methods for measurement and interpretation of results for power quality parameters in 50/60 Hz a. c. power supply systems.

C.1 HARMONICS

IEC 61000-4-7 **[29]** defines the measurement instrumentation intended for testing individual items of equipment related to emission limits given in product standards as well as for the measurement of harmonic currents and voltages in supply systems.

Harmonic measurements can be performed only on a stationary signal. Nevertheless, fluctuating harmonics can be evaluated by inter-comparation by using a simplified approach.

Two classes of accuracy (I and II) are considered, to permit the use of simple and low-cost instruments.

The general structure of the instrument is based on the use of the Discrete Fourier Transform DFT technique. It comprises an input circuitry with anti-aliasing filter, A/D-converter including sample and hold-unit, synchronisation and window-shaping-unit if necessary, DFT-processor providing the Fourier coefficients and it is complemented by the special parts devoted to current assessment and/or voltage assessment.

Assessment of compliance with emission limits is performed by statistical handling of the data according to the conditions given in the relevant standards, such as IEC 61000-3-2 **[30]**.

C.2 VOLTAGE FLUCTUATIONS / FLICKER

Related measurement is described in IEC 61000-4-15 **[15]** and IEC 60868 **[16]**.

C.3 VOLTAGE DIPS

All voltage values relating to voltage dips are r.m.s. values, obtained at least during one half of the period of the voltage at the supply frequency, 10 ms, for 50 Hz.

The measurement of voltage dips involves recording the value of the voltage during the dip, of the duration of the event, and of the number of events within the measurement period. In order to record these values and to enable results to be compared, it is necessary to adopt certain rather arbitrary conventions concerning reference voltage and threshold.

In case of multi-phase measurements, voltage dips whose durations overlap in time have conventionally been counted as a single event. In some cases the practice has been to measure the duration from the instant at which the first phase or line voltage falls below the start threshold to the instant at which the last phase or line voltage rises to or above the end threshold.

In order to deal with the complexity of non-rectangular dips it would be possible to designate several gradations on the voltage scale and to record the duration for which the voltage is at or below each such mark. This would result in the recording of several residual data pairs of voltage level and duration for describing each voltage dip.

When collecting or presenting results of a measurement campaign for voltage dips, it is necessary to have regard to the two-dimensional nature of the phenomenon. This suggests a two-dimensional matrix or tabular approach, with the rows containing the classification of depths or residual voltages and the columns containing the duration classifications.

Table C.1 shows the tabulation developed by UNIPEDE. For a given measurement site, each cell is intended to contain the number of voltage dips of the corresponding depth and duration occurring within a specified period, usually one year.

Residual Voltage u% of U_{ref}	**Duration (seconds)**							
	0.01 < Δt ≤ 0.02	*0.02 < Δt ≤ 0.1*	*0.1 < Δt ≤ 0.5*	*0.5 < Δt ≤ 1*	*1 < Δt ≤ 3*	*3 < Δt ≤ 20*	*20 < Δt ≤ 60*	*60 < Δt ≤ 180*
90 > u ≥ 85								
85 > u ≥ 70								
70 > u ≥ 40								
40 > u ≥ 10								
10 > u ≥ 0								
Measurement results in the first column and first row are likely to be inflated by transients and load fluctuations, respectively.								

Tab. C.1 - Classification of measurement results according to UNIPEDE

A similar table is used to compile the results from all the sites in the measurement campaign. In this case each cell can contain

- a percentile (typically 95) of the number of dips recorded in that cell for all sites
- the maximum number recorded in the cell
- the average number for the cell for all sites
- or other statistic.

If several types of networks are involved, it is appropriate to produce a separate table for each type. For example, measurement results from overhead lines should be distinguished from underground networks.

C.4 UNBALANCE

To apply the symmetrical component method.

Specified in IEC 61000-4-27 **[31]**

ANNEX D : RELATED STANDARDS

D.1 HARMONICS

Compatibility levels are given in

- IEC respectively ENV 61000-2-2 for LV networks **[12]** and
- IEC 61000-2-12 for MV networks **[13]**
- IEC 61000-2-4 **[32],** which specifies compatibility levels for harmonic voltages at the IPC (in-plant point of coupling) for industrial installations, establishing three classes according to required immunity of equipment.

These are set by experience in order to give guidance for setting appropriate emission limits and immunity requirements, also aiming at reduction of complaints about mal-operation (both of loads and of system components) to a minimum. By definition, compatibility levels do not represent rigid limits, but are expected to be exceeded with a low probability and only to a small percentage of places.

Compatibility levels for the 3^{rd} respectively 5^{th} order of harmonic voltage are 5 % respectively 6 % and 8 % for the Total Harmonic Distortion Factor (THD).

Note: Additionally to the compatibility levels, so-called planning levels have been defined; they represent levels, set by the network operator for their single supply network, which is aimed at not getting exceeded, being lower than the standardised compatibility level.

*IEC 61000-3-6 **[33]** establishes planning levels for HV and EHV networks as well as the conditions for connecting disturbing loads producing harmonics.*

Emission limits are given in:

- IEC 61000-3-2 **[30],** which specifies limits for harmonic current emissions applicable to electrical and electronic equipment having an input current up to and including 16 A per phase, and intended to be connected to public low-voltage distribution systems. The tests according to this standard are type tests.
- IEC 61000-3-12 **[34]**: the recommendations of this -- at present -- draft standard, are applicable to electrical and electronic equipment with a rated input current exceeding 16 A, up to 75 A per phase and intended to be connected to public low-voltage ac distribution systems.
- IEEE 519 **[35]**: establishes limits on harmonic currents and voltages at the point of common coupling (PCC) or at the point of metering.

Immunity levels are defined in:

- IEC 61000-4-13 **[36]**, which proposes different immunity levels in accordance with different performance criteria.

D.2 VOLTAGE FLUCTUATIONS / FLICKER

Compatibility levels are given in

- IEC respectively ENV 61000-2-2 for LV networks **[12]** and
- IEC 61000-2-12 for MV networks **[13]**

A flicker value is also given in EN 50160 **[1]**, with P_{lt} lower or equal to 1 during 95 % of the time.

For **emission**, the **limits** for equipment connected to the LV supply network are given in:

- IEC 61000-3-3 **[37]**

- IEC 61000-3-11 **[38]**

The **immunity levels** as well as the performance criteria and the immunity **measurement method** are specified in:

- IEC 61000-4-14 **[39]**.

D.3 VOLTAGE DIPS

CENELEC EN 50160 “Voltage characteristics of electricity supplied by public distribution systems” **[1]** gives some indications including indicative values.

> *“Voltage dips are generally caused by faults occurring in the customers’ installations or in the public distribution system. They are unpredictable, largely random events. The annual frequency varies greatly depending on the type of supply system and on the point of observation. Moreover, the distribution over the year can be very irregular.*
>
> *Indicative values: Under normal operating conditions the expected number of voltage dips in a year may be from up to a few tens to up to one thousand. The majority of voltage dips have a duration less than 1 s and a depth less than 60 %. However, voltage dips with greater depth % of U_n can occur very frequently as a result of the switching of loads in customers’ installations.”*

Also IEC 61000-2-2 “Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems” **[12]** deals with the voltage dip issue.

As far as voltage dips are concerned, this standard will be completed by the future standard IEC 61000-2-8 “Voltage dips and short interruptions on public electric supply with statistical results” **[18]**. The present report reflects mainly this future standard.

EN 61000-6-1 “Generic immunity standard: Residential, commercial and light industry” **[40]** and EN 61000-6-2 “Generic standard – Immunity for industrial environments” **[41]** specify minimum immunity requirements:

- For a 10 ms duration and 30 % depth of a dip, the apparatus shall continue to operate as intended after the test. No degradation of performance or loss of function is allowed below a performance level specified by the manufacturer. During the test, degradation of performance is however allowed. No change of actual operating state or stored data is allowed. This is called performance criterion B.

- For a 100 ms duration and 60 % depth, temporary loss function is allowed, provided the function is self-recoverable or can be restored by the operation of the controls. This is called performance criterion C.

D.4 UNBALANCE

EN 50160 **[1]** gives values for unbalance in LV and MV supply networks.

IEC 61000-2-2 **[12]** and 61000-2-12 **[13].**

> Due to these three standards, for LV and MV systems, in normal operating conditions, 95% of the 10 minutes values of τ (over the week) shall be less than 2%. In some areas where single or bi-phase lines are existing, the limits could be 3 %.

IEC 61000-4-27 **[31]** defines the immunity levels of equipment from unbalance as well as the measurement method.

D.5 NETWORK IMPEDANCE

IEC 60 725: 1981 **[28]**

Note: This standard was submitted for enquiry concerning a possibly given need for revision. As at present, available experience does not seem to justify any modification, it has been decided to leave that standard unmodified.

ANNEX E: BIBLIOGRAPHY

[1] EN 50160:11-1999 “Voltage characteristics of electricity supplied by public distribution systems”

[2] EMC Directive 89/336/EEC on the approximation of the laws of the Member States relating to electromagnetic compatibility, amended by the Directives, amended by Directives 91/263/EEC, 92/31/EEC, 93/68/EEC, 93/97/EEC

see also:

Guidelines on the application of Council Directive 89/336/EEC of 3 May 1989, European Commission DG III – Industry, 23 May 1997

[3] UNIPEDE DISNORM 12, “Definitions of the Physical Characteristics of Electrical Energy Supplied by Low and Medium Voltage Public Systems”, NORMCOMP, September 1989

[4] UNIPEDE Application Guide to the European Standard EN 50160 on “Voltage Characteristics of Electricity Supplied by Public Distribution Systems”, 230.02 NORMCOMP, Ref.: 23002Ren9530, July 1995

[5] UNIPEDE Report “Measurement Guide for Voltage Characteristics”, NORMCOMP, 1995

[6] UNIPEDE Report “Voltage Dips and Short Interruptions in Electricity Supply Systems”, (50.DISDIP), Ref.: 91 en 50.02

[7] UNIPEDE Report on “Expected Harmonic Distortion in LV Networks”, NORMCOMP, October 1995

[8] UNIPEDE: “Harmonic Distortion in Public Electricity Distribution Systems: Contribution of Class D Equipment,” February 1997

[9] Draft IEC 61000-4-30 Ed. 1.0): “Electromagnetic compatibility (EMC) – Part 4-30: Testing and measurement techniques -- Power quality measurement methods” (77A/356/CDV)

[10] IEC 77A/367/FDIS (revision of 61000-2-2)

[11] Study of the extra cost due to harmonics in HQ networks and equipment. R. Bergeron. 1998.

[12] IEC/ENV 61000-2-2:1990-05: “Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems” (second edition under way (RDIS))

[13] Draft IEC 61000-2-12 Ed. 1.0: “Compatibility levels for low-frequency conducted disturbances and signalling in public medium-voltage power supply systems” (77A/321/NP, Approved new work)

[14] UIE - Guide to Quality of Electrical Supply for Industrial Installations. Part 5 : Flicker and Voltage Fluctuations

[15] IEC 61000-4-15 (1997-11): “Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 15: Flickermeter – Functional and design specifications”, superseding IEC 60868 and IEC 60868-0 [see 17]

Draft Amd. 1 Ed. 1.0 under way „Amendment to add specifications for flickermeters for 120 V systems and more closely define the specification of a filter in the instrument according to standard IEC 61000-4-15” (77A/341/CVD)

[16] IEC/TR2 60868 (1986-09): “Flickermeter – Functional and design specifications” (see also [16]) +
IEC/TR2 60868-am1 (1990-06), IEC/TR2 60868-0 (1991-05) “Flickermeter – Part 0: Evaluation of flicker severity”

[17] The Power Quality in Denmark. P. Jorgensen et al. CIRED 1999

[18] Draft IEC 61000-2-8 TR3 Ed. 1.0: “Voltage dips and short interruptions on public electric power supply system with statistical measurement results” IEC 77A/329/CD (future

[19] UIE-Guide to the quality of electrical supply for industrial installations. Part 4: Voltage unbalance.

[20] Harmonic Distortion Levels in UK Distribution Networks. EA, May 2000. Ref. 77AWG1-000518Sinclair01.

[21] PQ in Switzerland. M. Levet, UCS, 1998

[22] „Spannungsqualität. Koordinierte Messungen österreichischer EVU", VEÖ-Journal 11/2000

[23] „Spannungsqualität. Koordinierte Messungen österreichischer EVU II", VEÖ-Journal 7-8/2001

[24] Harmonics measurements on French public LV systems. EDF. Luc Berthet. October 2000. Ref. 77AWG1-001026Berthet01.

[25] Plan de Medidas de Perturbaciones de UNESA

[26] CIRED 1999: Some Problems of Power Quality in the Czech Distribution Networks (K. Procházka, P. Santarius, M. Schneider, Z. Hejpetr, P. Vašenka)

[27] Measurements ELECTRABEL / LABORELEC

[28] IEC/TR3 60725 (1981-01): "Considerations on reference impedances for use in determining the disturbance characteristics of household appliances and similar electrical equipment"

[29] IEC 61000-4-7 (1991-08) "Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 7: General guide on harmonics and inter-harmonics measurements and instrumentation, for power supply systems and equipment connected thereto"

Revision under way (77A/317/CDV)

[30] IEC 61000-3-2 (1995) Ed. 2.1 (Consolidated Edition 2001-10): Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)

Revision under way (Ed. 3.0, 77A/242/NP, Approved new work)

[31] IEC 61000-4-27 (2000-08): "Electromagnetic compatibility (EMC) – Part 4-27: Testing and measurement techniques – Unbalance, immunity test"

[32] IEC 61000-2-4 (1994-02): "Electromagnetic compatibility (EMC) – Part 2: Environment – Compatibility levels in industrial plants for low-frequency conducted disturbances"
+
IEC 61000-2-4 Corr.1 (1994-08)

[33] IEC/TR3 61000-3-6 (1996-10): "Electromagnetic compatibility (EMC) – Part 3:Limits –Section 6: Assessment of emission limits for distorting loads in MV and HV power systems"

[34] Draft IEC 61000-3-12 Ed. 1.0: "Electromagnetic compatibility (EMC) – Part 3-12: Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current < 75 A per phase and subject to restricted connection" (77A/325/CD)

[35] IEEE 519 "Recommended Practices and Requirements for Harmonic Control in Electric Power Systems"

[36] Draft IEC 61000-4-13 Ed. 1.0 "Electromagnetic compatibility (EMC) – Part 4-13: Testing and measurement techniques – Harmonics and interharmonics including mains signalling at a.c. power port, low frequency immunity tests " (77A/323/CDV)

[37] IEC 61000-3-3 (1994-12): "Electromagnetic compatibility (EMC) – Part 3: Limits –Section 3: Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current ≤ 16A"
+
IEC 61000-3-3-am1 (2001-01)

[38] IEC 61000-3-11 (2000-08): "Electromagnetic compatibility (EMC) – Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current ≤ 75 A and subject to conditional connection"

[39] IEC 61000-4-14 (1999-02) + IEC 61000-4-14-am1 (2001-07): „Electromagnetic compatibility (EMC) – Part 4-14: Testing and measurement techniques – Voltage fluctuation immunity test"

[40] IEC 61000-6-1 (1997-07): "Electromagnetic compatibility (EMC) – Part 6: Generic standards – Section 1: Immunity for residential, commercial and light-industrial environments"

[41] IEC 61000-6-2 (1999-01): “Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity for industrial environments”

- Phase 1 Report on European Residential Harmonics, 2001, The Low Frequency Emission Industry (LFEIC)
- “Why it is necessary to control harmonic and flicker emission”. E.A. G. Finlay. July 1999. Ref. TF5a-9925
- Indices for Assessing Harmonic Distortion from Power Quality Measurements: Definitions and Benchmark Data. D.D. Sabin et al. CC02-9821 (1998).
- Results of EEI Harmonic Survey for IEC
- Draft IEC 61000-1-4 Ed. 1.0: „Electromagnetic compatibility (EMC) – Part 1-4: Rationale for limiting power-frequency conducted harmonic and inter-harmonic current emissions from equipment, in the frequency range up to 9 kHz” (77A/339/CD)
- Draft IEC 61000-3-1 TR Ed. 1.0): „Electromagnetic compatibility (EMC) – Part 3-1: Overview of emission standards and guides” (Approved new work)
- „Empfindlichkeit von elektrischen Geräten gegenüber Spannungseinbrüchen und Kurzzeit-Unterbrechungen“, Studie, im Auftrage des Verbandes der Elektrizitätsunternehmen Österreichs (VEÖ) durchgeführt an der TU Wien, Institut für Elektrische Anlagen und Energiewirtschaft, November 2001
- ERA Technology “How to improve Voltage Dip Immunity in Industrial and Commercial Power Distribution System”. ERA Report 99-0632R, August 1999

ANNEX F : ABBREVIATIONS

CENELEC	European Committee for Electrotechnical Standardisation
DFT	Digital Fourier Transform
DPQ	EPRI System Power Quality Monitoring Project
EHV	Extra High Voltage
EMC	Electromagnetic Compatibility
EN	European Standard
EPRI	Electric Power Research Institute, USA
EURELECTRIC	Union of the Electricity Industry
GDP	Gross Domestic Product
HV	High Voltage
IEC	International Electrotechnical Commission
IEEE	The Institute of Electrical and Electronic Engineers, USA
IPC	In-plant point of coupling
ITE	Information Technology Equipment
LV	Low Voltage
MV	Medium Voltage
PCC	Point of Common Coupling
PQ	Power Quality
SVC	Static var Compensator
THD	Total Harmonic Distortion (Factor)
UIE	International Union for Electroheat
UNIPEDE	International Union of Producers and Distributors of Electric Energy