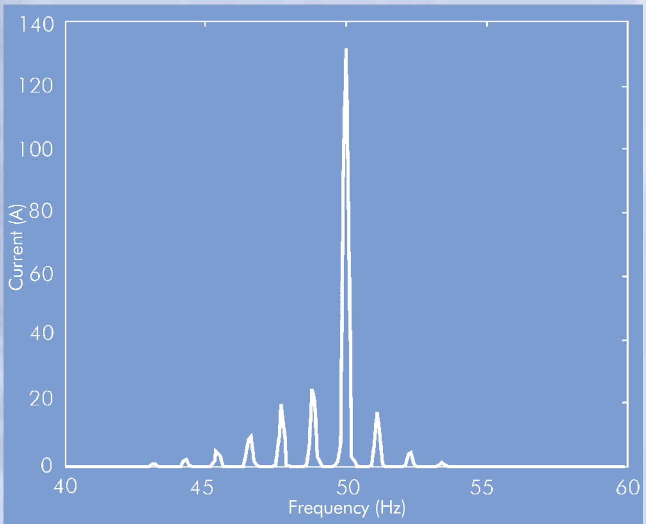
Power Quality Application Guide

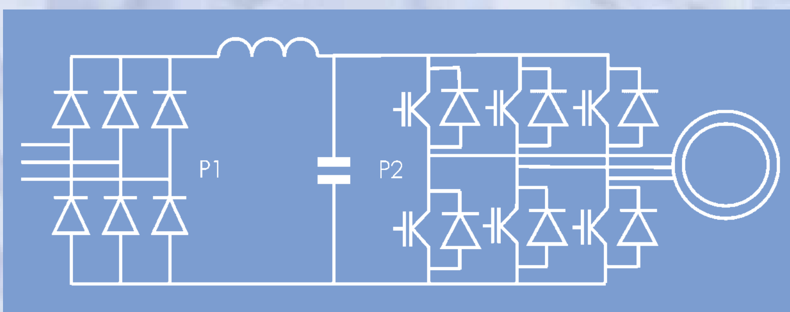
LEONARDO POWER QUALITY INITIATIVE

Harmonics

Interharmonics

3.1.1





Harmonics

Copper Development Association
IEE Endorsed Provider

COPPER

Harmonics

Interharmonics

Zbigniew Hanzelka & Andrzej Bień
AGH University of Science and Technology
July 2004

This Guide has been produced as part of the Leonardo Power Quality Initiative (LPQI), a European education and training programme supported by the European Commission (under the Leonardo da Vinci Programme) and International Copper Association. For further information on LPQI visit **www.lpqi.org**.

Copper Development Association (CDA)

Copper Development Association is a non-trading organisation sponsored by the copper producers and fabricators to encourage the use of copper and copper alloys and to promote their correct and efficient application. Its services, which include the provision of technical advice and information, are available to those interested in the utilisation of copper in all its aspects. The Association also provides a link between research and the user industries and maintains close contact with the other copper development organisations throughout the world.

CDA is an IEE endorsed provider of seminar training and learning resources.

European Copper Institute (ECI)

The European Copper Institute is a joint venture between ICA (International Copper Association) and the European fabricating industry. Through its membership, ECI acts on behalf of the world's largest copper producers and Europe's leading fabricators to promote copper in Europe. Formed in January 1996, ECI is supported by a network of eleven Copper Development Associations ('CDAs') in Benelux, France, Germany, Greece, Hungary, Italy, Poland, Russia, Scandinavia, Spain and the UK.

LPQI is promoted in the UK by members of the Power Quality Partnership:

Fluke (UK) Ltd	*LEM Instruments*	*MGE UPS Systems Ltd*	*Rhopoint Systems Ltd*

Interharmonics

Introduction

Harmonics are voltages or currents with a frequency that is an *integral* multiple of the fundamental supply frequency. Interharmonics are voltages or currents with a frequency that is a *non-integral* multiple of the fundamental supply frequency. The knowledge of electromagnetic disturbance associated interharmonics is still developing and currently there is a great deal of interest in this phenomenon. Interharmonics, always present in the power system, have recently become of more importance since the widespread use of power electronic systems results in an increase of their magnitude.

Definitions

Harmonics and interharmonics of an analysed waveform are defined in terms of the spectral components in a quasi-steady state over a defined range of frequencies. Table 1 provides their mathematical definitions.

The term "subharmonic" does not have any official definition - it is a particular case of interharmonic of a frequency less than the fundamental frequency. However, the term has appeared in numerous references and is in general use in the professional community.

Harmonic	$f = nf_1$ where n is an integer greater than zero
DC component	$f = nf_1$ for $n = 0$
Interharmonic	$f \neq nf_1$ where n is an integer greater than zero
Subharmonic	$f > 0$ Hz and $f < f_1$
f_1 = voltage fundamental frequency (basic harmonic)	

Table 1 - Spectral components of waveforms (of frequency f)

IEC 61000-2-1 standard defines interharmonics as follows:

Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental. They can appear as discrete frequencies or as a wide-band spectrum.

For the purpose of further considerations the following detailed definitions apply:

Interharmonic frequency

Any frequency which is a non-integer multiple of the fundamental frequency. By analogy to the order of a harmonic, the order of interharmonic is given by the ratio of the interharmonic frequency to the fundamental frequency. If its value is less than unity, the frequency is also referred to as a subharmonic frequency. According to the IEC recommendation, the order of interharmonic is denoted by the letter "m" (according to IEC 61000-2-2).

Voltage interharmonic (similarly for current)

A sinusoidal voltage of a frequency between the harmonics, i.e. a frequency which is not an integer of the fundamental component frequency.

Sources

There are two basic mechanisms for the generation of interharmonics.

The first is the generation of components in the sidebands of the supply voltage frequency and its harmonics as a result of changes in their magnitudes and/or phase angles. These are caused by rapid changes of current in equipment and installations, which can also be a source of voltage fluctuations. Disturbances are generated by loads operating in a transient state, either continuously or temporarily, or, in many more cases, when an amplitude modulation of currents and voltages occurs. These disturbances are of largely random nature, depending on the load changes inherent in the processes and equipment in use.

The second mechanism is the asynchronous switching (i.e. not synchronised with the power system frequency) of semiconductor devices in static converters. Typical examples are cycloconverters and pulse width modulation (PWM) converters. Interharmonics generated by them may be located anywhere in the spectrum with respect to the power supply voltage harmonics.

In many kinds of equipment both mechanisms take place at the same time.

Interharmonics may be generated at any voltage level and are transferred between levels, i.e. interharmonics generated in HV and MV systems are injected into the LV system and vice versa. Their magnitude seldom exceeds 0.5% of the voltage fundamental harmonic, although higher levels can occur under resonance conditions.

Basic sources of this disturbance include:

- Arcing loads
- Variable-load electric drives
- Static converters, in particular direct and indirect frequency converters
- Ripple controls.

Interharmonics can also be caused by oscillations occurring in, for example, systems comprising series or parallel capacitors or where transformers are subject to saturation and during switching processes.

The power system voltage contains a background Gaussian noise with a continuous spectrum. Typical levels of this disturbance are in the range (IEC 1000-2-1):

- 40-50 mV (circa 0.02% U_N) when measured with a filter bandwidth 10 Hz
- 20-25 mV (circa 0.01% U_N) when measured with a filter bandwidth 3 Hz

where U_N is the nominal voltage (230 V).

Arcing loads

This group includes arc furnaces and welding machines. Arc furnaces do not normally produce significant interharmonics, except where amplification occurs due to resonance conditions. Transient operation, being a source of interharmonics, occurs most intensively during the initial phase of melting (Figure 1).

Welding machines generate a continuous spectrum associated with a particular process. The duration of individual welding operations ranges from one to over ten seconds, depending on the type of welding machine.

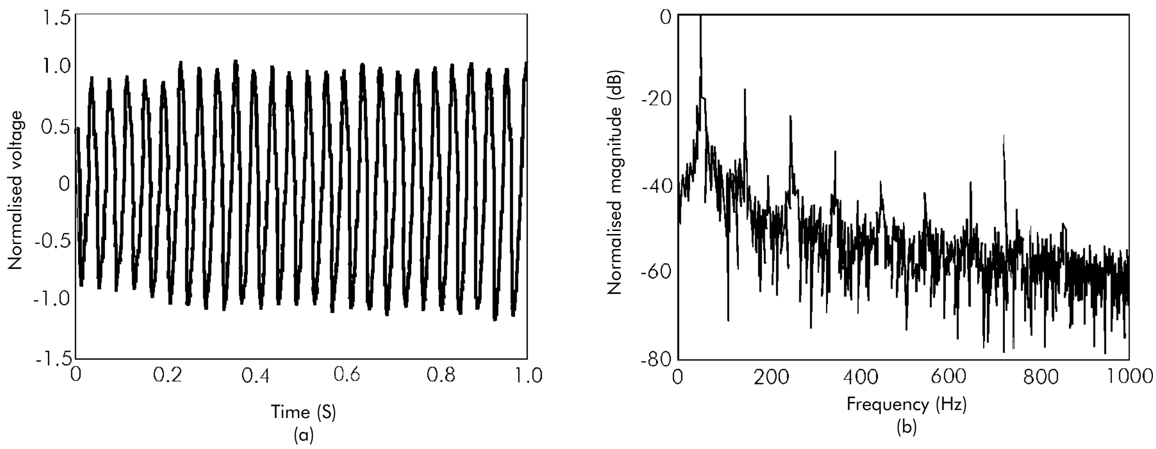


Figure 1 - Typical arc furnace voltage flicker measured at the supply transformer secondary
a) fluctuation of voltage
b) spectrum showing harmonics (spikes) and interharmonics [1]

Electric motors

Induction motors can be sources of interharmonics because of the slots in the stator and rotor iron, particularly in association with saturation of the magnetic circuit (so-called "slot harmonics"). At the steady speed of the motor, the frequencies of the disturbing components are usually in the range of 500 Hz to 2 000 Hz but, during the startup period, this range may expand significantly. Natural asymmetry of the motor (rotor misalignment, etc.) can also be a source of interharmonics – see Figure 2.

Motors with variable-torque loading, i.e. forge drives, forging hammers, stamping machines, saws, compressors, reciprocating pumps, etc, can also be sources of subharmonics. The effect of variable load is also seen in adjustable-speed drives powered by static converters.

In wind power plants the effect of the variation in turbine driving torque, resulting for example from the "shadow effect" of the pylon, can modulate the fundamental voltage component, thus becoming the source of undesirable, low-frequency components.

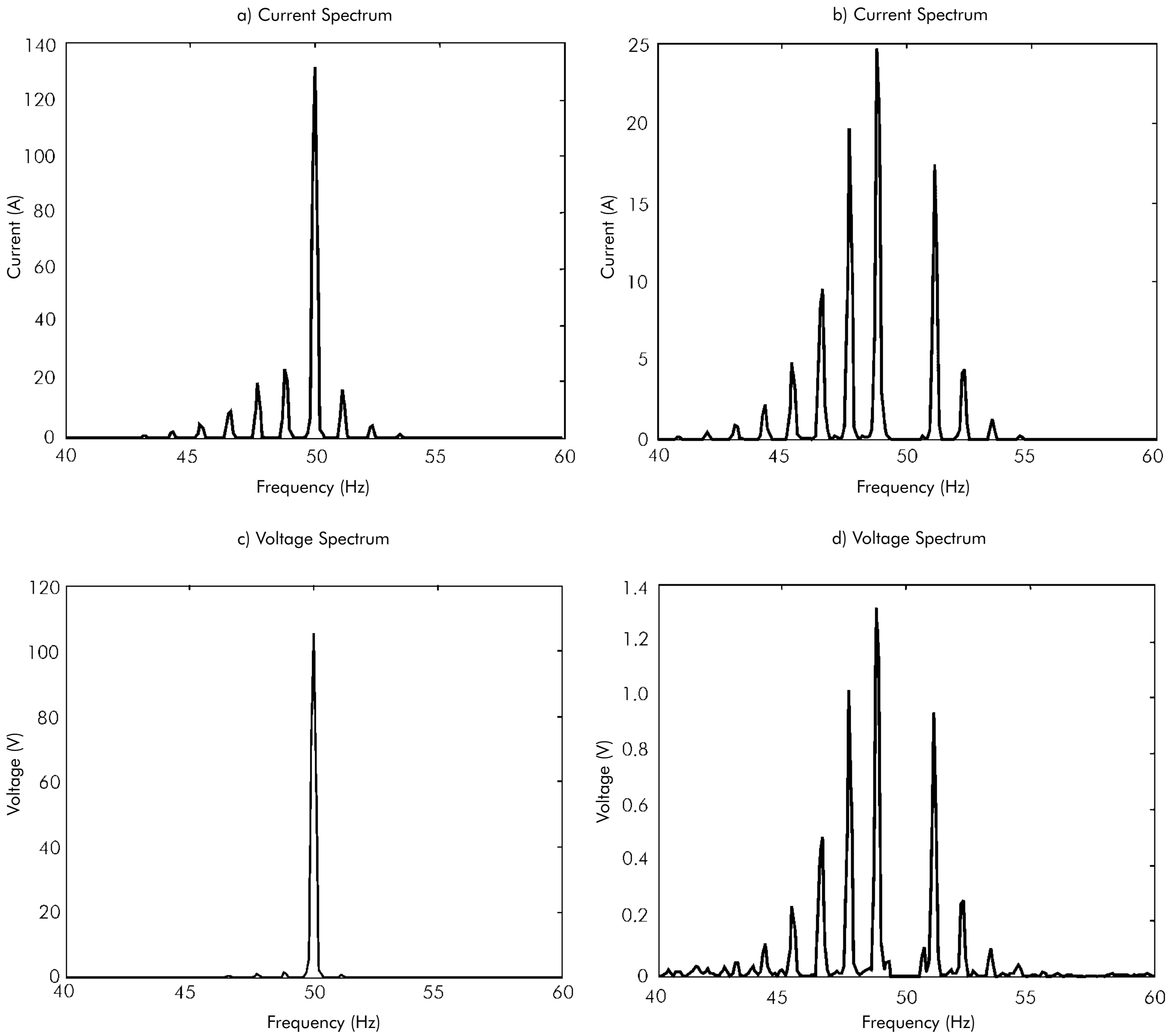


Figure 2 - Results of the spectral analysis of the motor phase current and voltage at the motor terminals

a), c) – full spectra of the signals
b), d) - spectra with the fundamental frequency component eliminated

Static frequency converters

Indirect frequency converters

Indirect frequency converters contain a dc-link circuit with an input converter on the supply network side and an output converter (usually operating as an inverter) on the load side. In either current or voltage configurations the dc-link contains a filter which decouples the current or the voltage of the supply and load systems. For that reason the two fundamental (the supply and the load) frequencies are mutually decoupled. But ideal filtering does not exist, and there is always a certain degree of coupling. As a result, current components associated with the load are present in the dc-link, and components of these are present on the supply side. These components are subharmonic and interharmonic with respect to the power system frequency.

Current-source load commutated inverters

Due to the semiconductor devices switching technique, these are classified as line commutated indirect frequency converters. A frequency converter consists of two three-phase bridges *P1* and *P2* and a dc-link with reactor (of inductance L_d – Figure 3). One of the bridges operates in the rectifier mode and the other in the inverter mode, although their functions could be interchangeable.

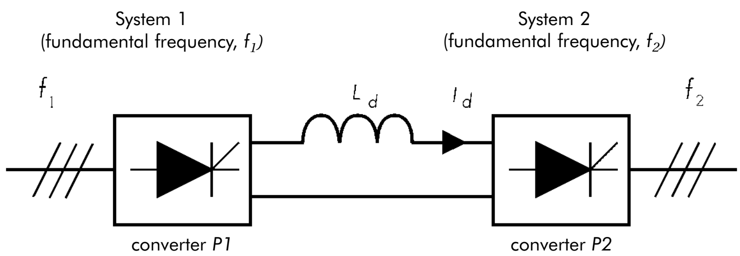


Figure 3 - Indirect frequency converter with a load commutated inverter

The presence of two rectifier bridges supplied from two systems of different frequencies results in the dc-link current being modulated by two frequencies – f_1 and f_2. Each of the converters will impose non-characteristic components on the dc-link, which will appear as non-characteristic harmonics on the ac side, both in the load and in the power supply system.

Components in the dc-link:

from system 1: $f_{d1} = p_1 k f_1$ $\quad k = 0, 1, 2, ...$

from system 2: $f_{d2} = p_2 n f_2$ $\quad n = 0, 1, 2, ...$

where:

p_1, p_2 = pulse number, respectively of the converters *P1* and *P2*

f_1 = fundamental frequency of the system 1 (supply network) [Hz]

f_2 = fundamental frequency of the system 2 (load) [Hz].

The operation of converter *P1* will cause characteristic current harmonics to occur in the supply network, with the following frequencies:

$$f_{hh,char} = (p_1 k \pm 1) f_1 \qquad k = 1, 2, ...$$

In addition, components associated with the *P2*-generated dc-link components will occur.

A complete set of frequencies of the supply network current components could be expressed in general form by:

frequencies in the supply network current (system 1) = $(kp_1 \pm 1) f_1 \pm p_2 n f_2$

where:

$k = 0, 1, 2, ...$ and $n = 0, 1, 2, ...$

Assuming $n = 0$, for $k = 0, 1, 2,...$ we obtain orders of characteristic harmonics for a given configuration of the converter *P1*. Components determined for k = const and $n \neq 0$, are the sidebands adjacent to the inverter characteristic frequencies. Thus each characteristic harmonic, e.g. for a six-pulse bridge, of order $n_1 = 1, 5, 7,...$ has its own sidebands, as illustratively shown for the 5^{th} harmonic in Figure 4.

The first pair of interharmonics, occurring in the vicinity of the fundamental component, i.e. with frequencies $f_1 \pm p_2 f_2$ has the largest amplitude. The inductance of the reactor in the dc-link has significant influence on the interharmonics level. An example of the electric drive configuration containing a current-source inverter is the static slip recovery drive.

Voltage-source inverters

For voltage-source converters (Figure 5) also, the characteristic harmonics of converter *P1* are predominant. Sidebands, with frequencies determined by the number of pulses of converter *P2*, occur around the characteristic *P1* frequencies, i.e.:

$$(kp_1 \pm 1) f_1 \pm n\, p_2 f_2$$

for $k = 0, 1, 2, 3,... n = 0, 1, 2,...$ In most cases non-characteristic harmonics are a very small portion of the supply current.

Numerical determination of the supply current harmonics and interharmonics values requires precise analysis of a particular frequency converter including the load, or information from the manufacturer.

Some converters comprise an active input rectifier operating at a switching frequency that is not an integer of the line frequency. This frequency may be constant or variable, depending on the design of the converter control.

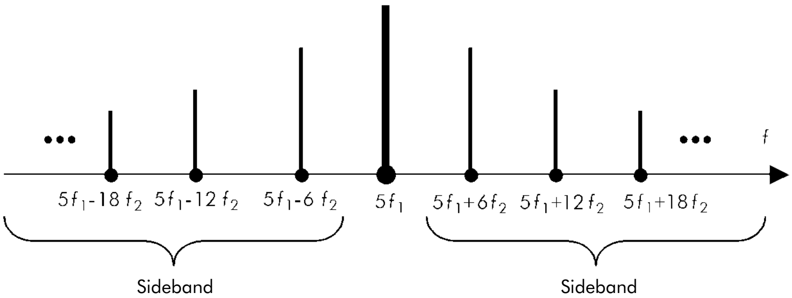


Figure 4 - Sidebands adjacent to the characteristic 5^{th} harmonic of a six-pulse converter P1 and P2

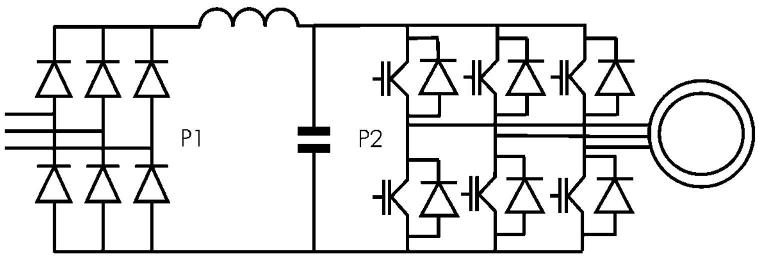


Figure 5 - Schematic diagram of a frequency converter with the voltage source dc-link

Voltage-source frequency converters with a PWM modulated input rectifier emit current components at the semiconductor device switching frequency and their harmonics, which are not synchronised with the line frequency. Normally they are within the range from several hundred Hertz to several tens kHz.

Integral cycle control of thyristor switch

This kind of control allows a full cycle of current to flow through a semiconductor switch. Thus the current is not distorted as a result of the control – it is either sinusoidal (for a linear load) or it is zero.

Figure 6 shows an example of controlled semiconductor switches in a three-phase configuration. Switching a three-phase load at zero-crossing of phase voltages results in a current flow in the neutral conductor in a four-wire system. For simultaneous switching in phases and a resistive load there is no current flow in the neutral conductor (Figure 6) but, in the case of an inductive load, transients associated with switching processes occur.

The analysis for a configuration as in Figure 7a (with neutral conductor) can be restricted to a single-phase circuit (Figure 7b). A single-phase, resistive load, as the most common practical application, will be further considered.

A full control cycle comprises *N*-cycles of conduction within an integer number of cycles *M* (Figure 8). The average power supplied to a load is controlled by means of controlling the value of the ratio *N/M*. As a basis for Fourier analysis, the period of the current waveform repeatability should be assumed to be Mf_1^{-1}, where f_1 is the frequency of the supply voltage and *M* is the number of cycles.

The first component is the interharmonic at a frequency of $(1/M)f_1$, which is the lowest frequency component of the current. In the example from Figure 8, where $N = 2$, $M = 3$, the value of this subharmonic is one third of the supply voltage frequency. Frequencies of the other components are multiples of it.

This kind of control is a source of subharmonics and interharmonics, but it is not a source of higher harmonics of the fundamental component. When $N = 2$, $M = 3$, as in Figure 8, amplitudes of the harmonics are zero for $n = 6, 9, 12...$ The spectrum of the current for this case is shown in Figure 9. As seen from the figure, major components are harmonic of the supply voltage frequency and subharmonic of frequency $(2f)/3$. Amplitudes of harmonics are equal to zero.

Mains signalling voltage in power systems

The public power network is intended primarily for supplying electric power to customers. However, the supplier often uses it for transmitting system management signals, e.g. for controlling certain categories of loads (street lighting, changing tariffs, remote loads switching, etc.) or data transmission.

From the technical point of view these signals are a source of interharmonics occurring with a duration of 0.5-2 s (up to 7 s in earlier systems) repeated over a period of 6-180 s. In the majority of cases the pulse duration is 0.5 s, and the time of the whole sequence is circa 30 s. The voltage and frequency of the signal are pre-agreed and the signal is transmitted at specified times.

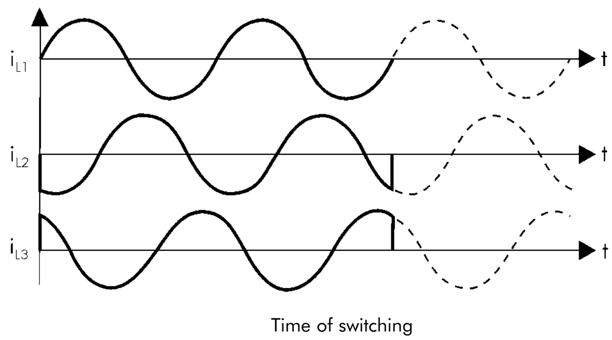


Figure 6 - Waveforms of currents in a three-phase configuration with a neutral conductor for integral cycle control

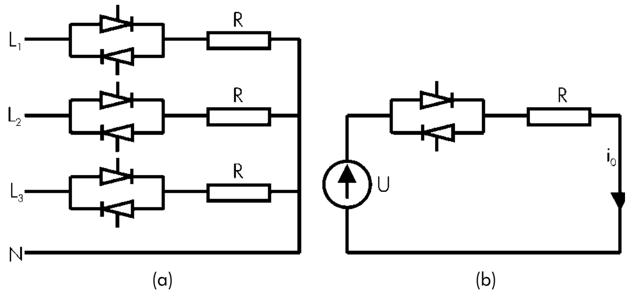


Figure 7 - Alternating current controller in
a) a three-phase and
b) a single-phase configuration

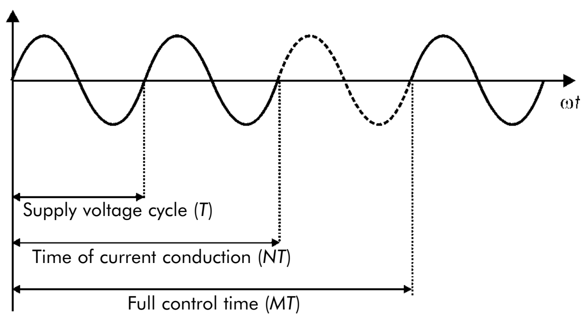


Figure 8 - Waveform of a load current in the integral cycle controlled system: N = 2, M = 3

Four basic categories of these signals are specified in Standard IEC 61000-2-1:

- *Ripple control signals:* Sinusoidal signals in the range 110-2 200 (3 000) Hz with 110-500 Hz preference in new systems. Mainly used in professional power systems (sometimes also in industrial power systems) at LV, MV and HV levels. Magnitude of the sinusoidal voltage signal is in the range 2-5% of the nominal voltage (depending on local practices). Under resonance conditions it may increase to 9%.
- *Medium frequency power-line-carrier signals:* Sinusoidal signals in the range 3-20 kHz, preferably 6-8 kHz. Mainly used in professional power systems. Signal magnitude up to 2% U_N.
- *Radio-frequency power-line-carrier signals:* 20-150 (148.5) kHz (up to 500 kHz in some countries). Used in professional, industrial and communal power systems, also for commercial applications (equipment remote control, etc.).
- *Mains-mark systems:* Non-sinusoidal masks on the voltage waveform in the form of:
  - long pulses (voltage notch of duration 1.5-2 ms, preferably at the voltage zero-crossing point)
  - short pulses, duration 20-50 µs
  - pulses with 50 Hz frequency and duration equal to one or a half of the mains voltage cycle.

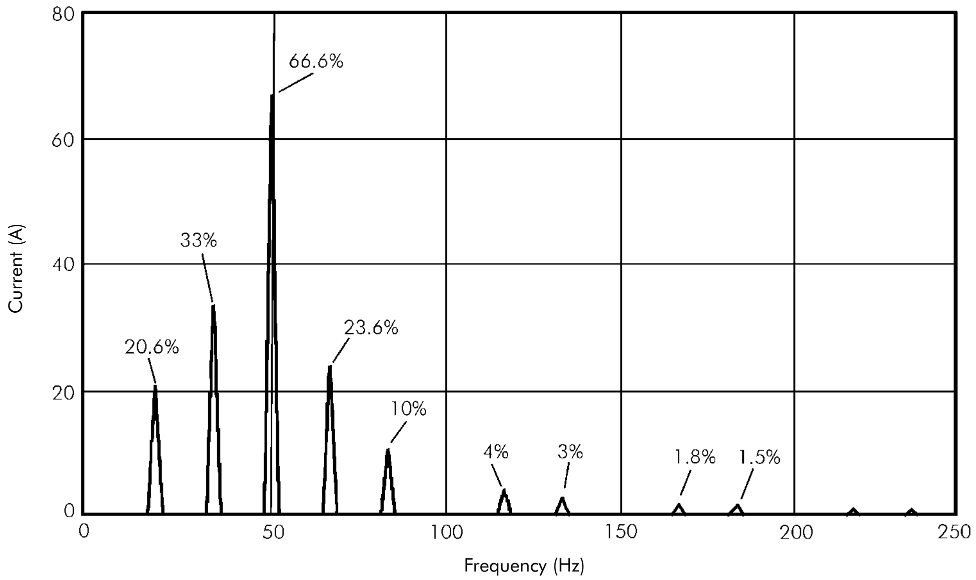


Figure 9 - Spectrum of the current for N = 2, M = 3

Figure 10 shows an example of the voltage spectrum for a system using data transmission at a frequency 175 Hz (U_{ih} = 1.35 %). In the example, there are other interharmonics generated by interaction with harmonic frequencies. Components above the second harmonic are unimportant (they will not disturb loads), while interharmonics below 200 Hz may cause problems.

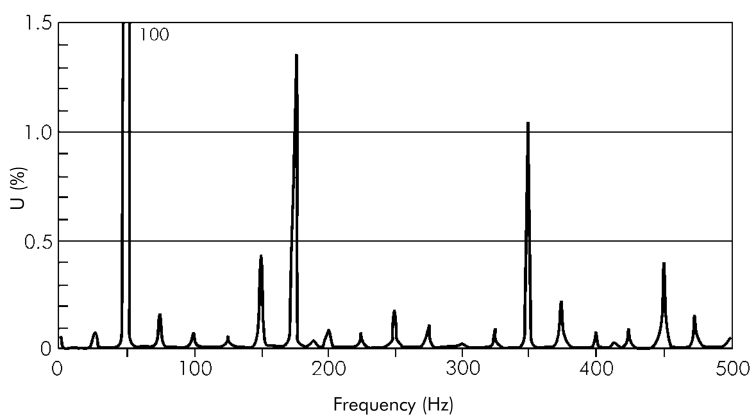


Figure 10 - FFT results for the voltage during emission of data transmission signal (U_{ih} = 1.35%, $f(U_{ih})$ = 175 Hz)

Effects of the presence of interharmonics

Interharmonic currents cause interharmonic distortion of the voltage depending on magnitudes of the current components and the supply system impedance at that frequency. The greater the range of the current components' frequencies, the greater is the risk of the occurrence of unwanted resonant phenomena, which can increase the voltage distortion and cause overloading or disturbances in the operation of customers' equipment and installations. Among the most common, direct, effects of interharmonics are:

- Thermal effects
- Low-frequency oscillations in mechanical systems
- Disturbances in fluorescent lamps and electronic equipment operation. In practice, the operation of any equipment that is synchronised with respect to the supply voltage zero-crossing or crest voltage can be disturbed (Figure 11)
- Interference with control and protection signals in power supply lines. This is now the main harmful effect of interharmonics
- Overloading passive parallel filters for high order harmonics
- Telecommunication interference
- Acoustic disturbance
- Saturation of current transformers.

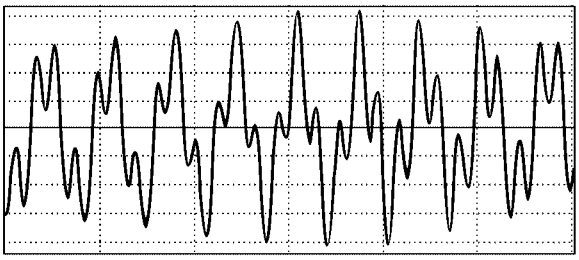


Figure 11 - Multiple zero-crossing of the voltage waveform as a result of distortion

The most common effects of the presence of interharmonics are variations in rms voltage magnitude and flicker.

Voltage fluctuations and flicker

The supply voltage can be expressed as:

$$u(t) = U_1 \sin(\omega_1 t)[1 + m\sin(\omega_i t)] + \sum_h U_h \sin(\omega_h t) \qquad (1)$$

$$u(t) = U_1 \sin(\omega_1 t) + \left[\sum_h U_h \sin(\omega_h t)\right][1 + m\sin(\omega_i t)] \qquad (2)$$

where $\omega_1 = 2\pi f_1$ and m is the index of modulation signal with frequency $\omega_i = 2\pi f_i$.

The above equations represent possible sources of voltage fluctuations caused by modulation of the fundamental component with integer harmonics. The second case is of small practical significance.

With only the fundamental component taken into account, the equation becomes:

$$u(t) = U_1 \sin(\omega_1 t)[1 + m\sin(\omega_i t)] = U_1 \sin\omega_1 t + \frac{mU_1}{2}\left[\cos(\omega_1 - \omega_i)t - \cos(\omega_1 + \omega_i)t\right] \qquad (3)$$

In this equation, besides the fundamental component, there are two components with frequencies associated with the modulating signal frequency located symmetrically on each side of the fundamental frequency component. Periodic variations of the voltage could be considered as variations of the rms (or peak) value, or as a result of the presence of the sideband interharmonics, which modulate the supply voltage.

For instance, for $u(t) = \sin(2\pi ft) + m\sin(2\pi f_i t)$ (assumed $U_1 = 1$), the maximum variation of voltage amplitude is equal to the amplitude of the interharmonic, whereas the variation of the rms value depends on both the amplitude and frequency of the interharmonic. Figure 12 shows maximum percentage variation of the voltage rms value, determined over several cycles of the fundamental waveform, caused by interharmonics of different frequencies but of a constant amplitude m = 0.2% of the fundamental component voltage.

As seen from Figure 12, the influence of interharmonics of frequencies higher than twice the power supply frequency is small compared to the influence of components of frequencies lower than the second harmonic frequency (100 Hz). In the case of interharmonics there is a risk of voltage fluctuations causing flicker if the level exceeds, for a given frequency, a certain limit value. Hence, if $f_i \leq f_1$, and particularly for f_i near to the fundamental frequency - (f_1 ± 15 Hz), modulation of the fundamental component causes fluctuations of rms voltage magnitude and therefore it is a source of flicker. This phenomenon can be observed both for incandescent and fluorescent lamps, however the mechanism and frequency range, and also permissible amplitudes of disturbing components, are entirely different.

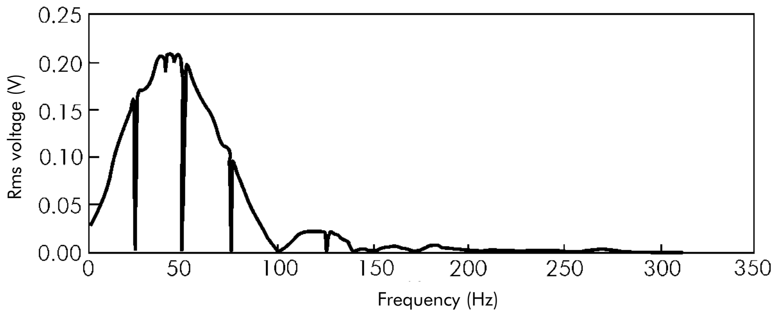


Figure 12 - Dependence of maximum rms voltage variation on the frequency of interharmonic of a constant amplitude (0.2% of the fundamental component amplitude)[10]

A particular source of flicker can be the power line signalling systems discussed earlier. Despite their small magnitude, these signals can sometimes give rise to flicker in the case of very sensitive lighting devices such as energy-saving compact fluorescent lamps, particularly with inductive ballasts. This kind of disturbance seldom occurs for light sources with electronic ballasts.

Measurement

Most instruments that perform measurements in the frequency domain work correctly when only harmonics are present in the measured signal. These instruments employ a phase locked loop to synchronise the measurement with the fundamental component frequency and sample the signal during one or several cycles in order to analyse it using Fast Fourier Transformation (FFT). Due to the phase locked loop, the “single-cycle” samples can give an accurate representation of the waveform spectrum only when it does not contain interharmonics. If other non-harmonic frequencies (in relation to the measuring period) are present and/or the sampled waveform is not periodic in this time interval, difficulties with interpretation of results arise.

The fundamental analysis tool is the Fourier Transformation (FT). In practice the signal is analysed in a limited time interval (measuring window of time T_w) using a limited number of samples (M) of the actual signal. Results of Discrete Fourier Transformation (DFT) depend on the choice of the T_w and M values. The inverse of T_w is the fundamental Fourier frequency – f_F. DFT is applied to the actual signal within the time-window; the signal outside the window is not processed but is assumed to be identical to the waveform inside the window. In this way, the actual signal is substituted with a virtual one, which is periodical with a period equal to the window width.

In the analysis of periodic waveforms there is no problem synchronising the analysis time with the fundamental waveform period (also with harmonics). However, with interharmonics analysis the problem becomes more difficult. The frequencies of interharmonic components are non-integer multiples of the fundamental frequency, and often they are time-varying, which makes the measurement additionally difficult.

Because of the presence of both harmonic and interharmonic components the Fourier frequency, which is the greatest common devisor of all component frequencies contained in the signal, is different from the supply voltage fundamental frequency and is usually very small. There are two problems:

- Minimum sampling time can be long and the number of samples large
- It is difficult to predict the fundamental Fourier frequency because not all the component frequencies of the signal are known *a priori*.

This can be illustrated by the following examples:

The signal to be analysed is a sum of the fundamental component (50 Hz), interharmonic (71.2 Hz) and harmonic (2 500 Hz). The fundamental Fourier frequency is 0.2 Hz and is much lower than the frequency of the fundamental component. The corresponding period is 5 s and consequently the permissible minimum sampling time is also 5 s. Assuming the sampling frequency is 10 kHz, which is practically the minimum applicable value resulting from the Nyquist criterion (Appendix 2), the minimum required number of samples M is 50 000. If there were no interharmonic component (71.2 Hz), the minimum time measurement would be 20 ms and the number of samples would be 200.

The signal to be analysed is a sum of the fundamental component (50 Hz) and harmonic (2 500 Hz), the amplitude of each of them sinusoidally varying with frequency 0.1 Hz and 5 Hz respectively. The effect of these modulations is four interharmonics at frequencies of 49.9 Hz, 50.1 Hz, 2 495 Hz and 2 505 Hz. The fundamental Fourier frequency is 0.1 Hz, and the minimum sampling time 10 s and M = 100 000.

In practical applications, due to the equipment and software limitations, the number of samples M cannot be greater than a certain maximum number, and consequently the measurement time is limited. Use of a measurement time different from the fundamental Fourier period results in a discontinuity between the signal at the beginning and the end of the measuring window. This gives rise to errors in identification of the components known as spectrum leakage. A possible solution to this problem is the use of the “weighted” time-window to a time-varying signal before FFT analysis. In practice two kinds of measuring windows are applied: the rectangular and Hanning window (Appendix 1).

Standardisation

Standardised factors

Table 2 below gives some numerical factors of interharmonics content used in various standardisation documents.

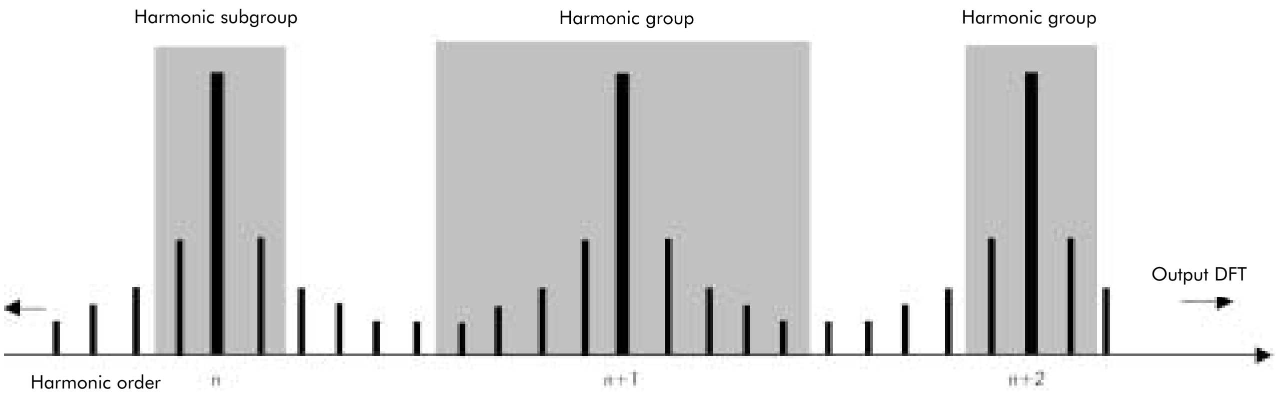
Factor	Definition
Magnitude of the interharmonic with respect to the fundamental component (current or voltage)	$\frac{Q_i}{Q_1}$
Total Distortion Content	$TDC = \sqrt{Q^2 - Q_1^2}$
Total Distortion Ratio	$TDR = \frac{TDC}{Q_1} = \frac{\sqrt{Q^2 - Q_1^2}}{Q_1}$
Total Interharmonic Distortion Factor	$TIHD = \frac{\sqrt{\sum_{i=1}^{n} Q_i^2}}{Q_1}$
Total Subharmonic Distortion	$TSHD = \frac{\sqrt{\sum_{i=1}^{S} Q_i^2}}{Q_1}$
Q = total rms value representing either current or voltage	
Q_1 = rms value of the fundamental component	
Q_i = rms value of the interharmonic	
i = running number of interharmonic	
n = total number of considered interharmonics	
S = total number of considered subharmonics	

Table 2 - Harmonic distortion factors applied in Standards

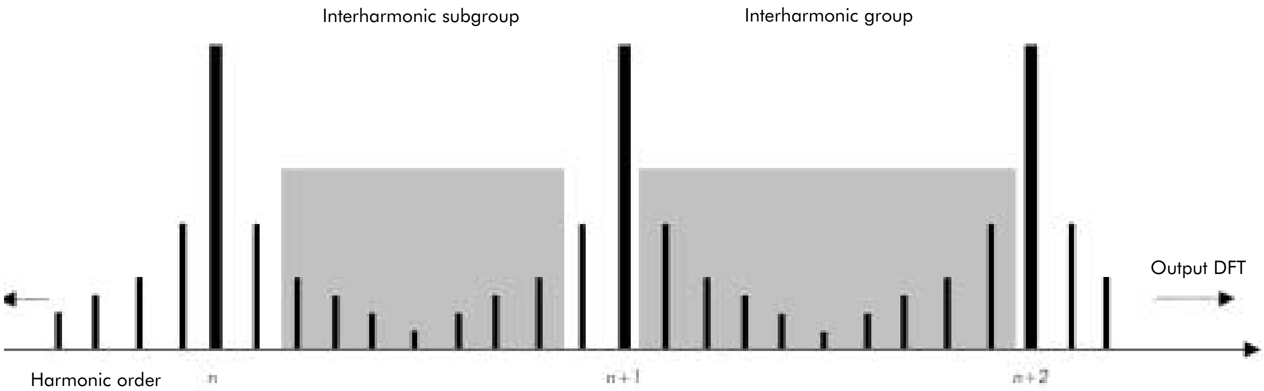
Standardised method of measurement

The measurement of interharmonics is difficult with results depending on many factors, hence the attempts to develop a "measurement" method to simplify the measurement process and produce repeatable results. Standard [6] suggests a method of interharmonics measurement based on the concept of the so-called "grouping". Its basis is Fourier analysis performed in a time-window equal to 10 cycles of the fundamental frequency (50 Hz), i.e. approximately 200 ms. Sampling is synchronised with the power supply frequency by means of a phase-locked loop. The result is a spectrum with 5 Hz resolution. The standard defines the method of processing individual 5 Hz lines in order to determine so-called harmonic or interharmonic groups, to which recommendations of standards and technical reports are referred.

Groups of harmonics and interharmonics are calculated according to equations in Figure 13.



$$G_{sg,n}^2 = \sum_{k=-1}^{1} C_{k+i}^2 \qquad G_{g,n+1}^2 = \frac{C_{k-5}^2}{2} + \sum_{k=-4}^{4} C_{k+i}^2 + \frac{C_{k+5}^2}{2} \qquad G_{sg,n+2}^2 = \sum_{k=-1}^{1} C_{k+i}^2$$



$$C_{isg,n}^2 = \sum_{i=2}^{8} C_{k+i}^2 \qquad C_{ig,n+1}^2 = \sum_{i=1}^{9} C_{k+i}^2$$

Figure 13 - Illustration of the principle of the harmonics and interharmonics groups

Definitions related to the concept of grouping:

Rms value of a harmonic group

The square root of the sum of the squares of the amplitudes of a harmonic and the spectral components adjacent to it within the observation window, thus summing the energy contents of the neighbouring lines with that of the harmonic proper.

Rms value of a harmonic subgroup

The square root of the sum of the squares of the amplitudes of a harmonic and the two spectral components immediately adjacent to it, for the purpose of including the effect of voltage fluctuation during voltage surveys. A subgroup of output components of the DFT is obtained by summing the energy contents of the frequency component directly adjacent to a harmonic on the harmonic proper.

Rms value of an interharmonic group

The rms value of all interharmonics components in the interval between two consecutive harmonic frequencies (see Figure 13).

Rms value of an interharmonic centred subgroup

The rms value of all interharmonic components in the interval between two consecutive harmonic frequencies, excluding frequency components directly adjacent to the harmonic frequencies (see Figure 13).

More detailed information concerning this concept of measurement can be found in the standard [6]. On the basis of these definitions, measurements can be performed for any interharmonic group, as well as for total interharmonic distortion, and referred to the fundamental component, total rms value or other reference value. These values are the basis for determining limit values.

This method is attractive for monitoring purposes in the event of complaints and for compatibility tests, because the limit levels can be defined on the basis of total distortion and they do not refer to the measurement of particular frequencies. This method is not adequate for diagnostic purposes.

Compatibility limits

The interharmonics standardisation process is in its infancy, with knowledge and measured data still being accumulated.

The limit level 0.2% for interharmonic voltages is widely applied, chiefly because of the lack of a better suggestion. It has been introduced with regard to load sensitivity in the mains signalling systems but its application to other cases, not taking into account the possible physical effects, may lead to very costly solutions e.g. expensive passive filters. Provisions of several example documents are quoted below, but inconsistency and significant variations are apparent.

Provisions of International Electrotechnical Commission (IEC)

According to the IEC recommendations the voltage interharmonics are limited to 0.2% for the frequency range from dc component to 2 kHz.

The Standard [7] gives immunity test levels for interharmonics in various frequency ranges. Depending on the equipment class the voltage levels are contained within 1.5% U_1 (1 000-2 000 Hz). Test levels for interharmonics above 100 Hz are within 2-9%.

In the document [5] compatibility levels are formulated only for the case of the voltage interharmonics with frequencies near to the fundamental component, which result in modulation of supply voltage and flicker. Figure 14 shows the compatibility level for a single interharmonic voltage, expressed as a percentage of the fundamental component amplitude, as a function of

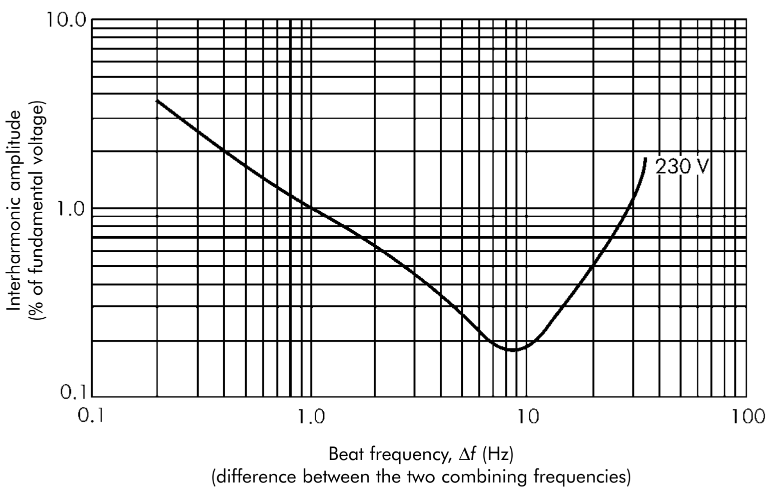


Figure 14 - Compatibility levels for interharmonics relating to flicker (beat effect) [5]

beat frequency of two combining components whose interaction results in the interharmonic. The characteristic is referred to as the flicker severity $P_{st} = 1$ for 230 V incandescent lamps.

More detailed recommendations with regard to limit values of the mains signalling voltage in power systems are given below:

- *Ripple control signals:* The level of these signals shall not exceed values of the odd harmonics being a non-multiple of 3 for the same frequency band ([5], (Table 3). For practical systems this value is contained in the range 2-5% $U_{N.}$
- *Medium frequency power-line-carrier signals:* Signal value up to 2% U_N.
- *Radio-frequency power-line-carrier signals:* Compatibility levels under consideration; should not exceed 0.3%.

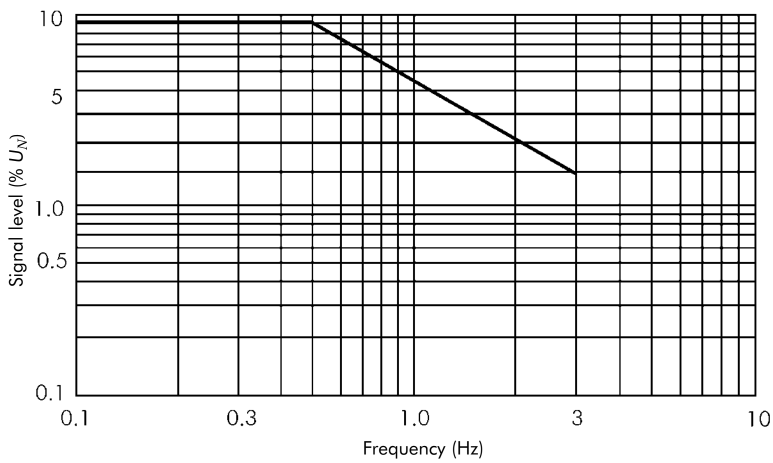


Figure 15 - Meister curve for ripple control systems in public networks (100 Hz to 3 000 Hz) [5]

- *Mains-mark systems:* The equipment manufacturers shall guarantee compatibility with the working environment.

In some countries the so-called *Meister curve*, shown in Figure 15, is officially recognised.

Harmonic order	5	7	11	13	$17 \le h \le 49$
Rms harmonic value (% of fundamental component)	6	5	3.5	3	$2.27 * (17/h) - 0.27$

Table 3 - Values of harmonics as the basis for determining the interharmonics compatibility levels [5]

CENELEC (Standard EN 50160)

Over 99% of a day, the three-second mean of signal voltages shall be less than or equal to the values given in Figure 16.

Sub-harmonic and interharmonic emission limits [13]

In the United Kingdom, for example, it is assumed that ripple control systems are not used and therefore a customer's load may be connected without assessment if the individual interharmonic emissions are less than the limit values in Table 4. Limits for particular interharmonic frequencies between 80 and 90 Hz may be interpolated linearly from the limits given in Table 4.

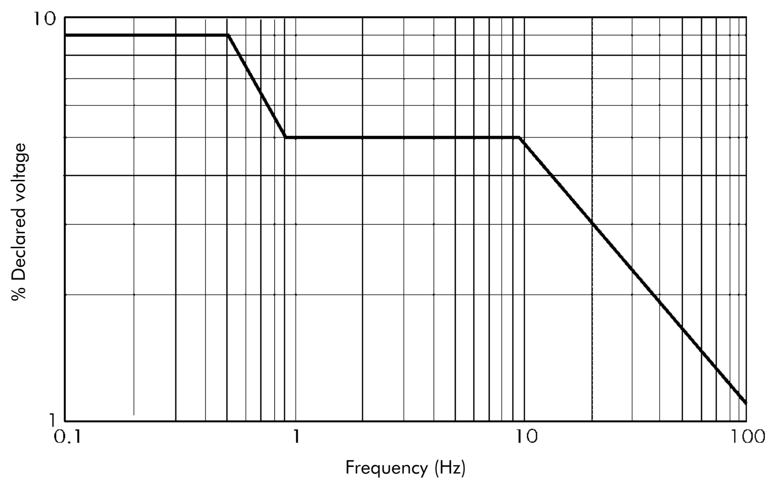


Figure 16 - Voltage levels of signals used in public MV distribution systems [11]

Sub-harmonic or interharmonic frequency in Hz	< 80	80	90	> 90 and < 500
Voltage distortion as % of the fundamental	0.2	0.2	0.5	0.5

Table 4 - Sub-harmonic and interharmonic emission limits

Methods for mitigation of interharmonics and reduction of their effects

Methods of eliminating the effects of interharmonics include:

- reducing the emission level
- reducing the sensitivity of loads and
- reducing coupling between power generating equipment and loads.

The methods used are the same as for harmonics.

Additional factors should be taken into account in the design of passive filters. For example, resonance between filters and the power system interharmonics can be amplified and cause significant voltage distortion and fluctuations. Filters need to be designed with a higher damping factor.

Figure 17 shows an example of the source impedance characteristics of a passive filter (3, 5, 7 and 12 harmonics) seen from input terminals of the converter supplying a large dc arc furnace installation. The dotted line corresponds to undamped filters. There was a real risk of resonance for the interharmonics adjacent to 120 and 170 Hz. Damped 3rd and 7th harmonics filters reduced the danger of resonance occurring. The filter design process sometimes requires a compromise between the accuracy of tuning and power losses, which involves choosing the filter quality factor.

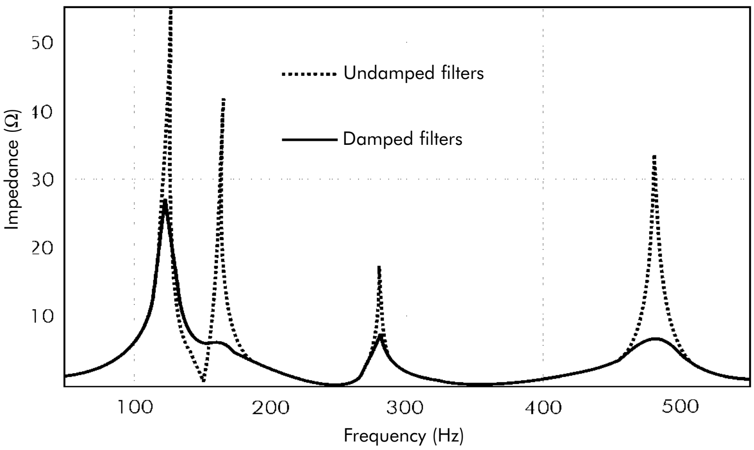


Figure 17 - Example of impedance seen from converters' terminals [10]

The design of a narrow pass-band filter presents several problems. The normal power system frequency deviation may be important, especially when combined with changes in tuning frequency due to component tolerance, ageing and temperature variation and changes in the impedance of the supply.

The resulting variation in the filter resonant frequency, considering the very narrow pass-band of the filter, can significantly reduce the efficiency of the filtering, even if the change is small. It sometimes requires the choice of a reduced quality factor, which widens the bandwidth and so is also advantageous in terms of filtering interharmonics.

Disturbances caused by the mains signalling systems can be eliminated by applying series filters, tuned to desired frequencies and correctly located in the system. Other solutions involve increasing the immunity level of the equipment in use or using active filters.

Conclusions

The above review of the presence of interharmonics, their basic sources and the characteristic features of the continuous and discrete spectrum, allows the formulation of several conclusions of a general nature.

Firstly, in the vast majority of cases the values and frequencies of interharmonic currents and voltages are stochastic quantities, which depend on numerous complex parameters of transient processes.

Secondly, assessment of the value and frequency of an interharmonic is possible for a particular, considered process.

Thirdly, there are no coherent standardisation regulations concerning the interharmonics, yet there is a practical need for them.

References and Bibliography

[1] *Arrillaga J, Watson N R, Chen S: Power system quality assessment, Wiley, 2000*

[2] *Gunther E W: Interharmonics in power systems, UIEPQ-9727*

[3] *Interharmonic Task Force Working Document – IH0101 20001, IEEE*

[4] *IEC 61000-2-1: 1990 - Electromagnetic compatibility (EMC) Part 2: Environment – Section 1: Description of the environment – Electromagnetic environment for low-frequency conducted disturbances and signalling in public power supply systems*

[5] *IEC 61000-2-2: 2002 - Electromagnetic compatibility (EMC) Part 2: Environment – Section 2: Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems. (also materials used in preparation of the standard, obtained from the authors)*

[6] *IEC 61000-4-7: 2002 Electromagnetic compatibility (EMC) Part 4: Testing and measurement techniques Section 7: General guide on harmonics and interharmonics measurements and instrumentation for power supply systems and equipment connected thereto*

[7] *IEC 61000-4-13: 2002 Electromagnetic compatibility (EMC) Part 4: Testing and measurement techniques Section 13: Harmonics and interharmonics including mains signalling at ac power port, low frequency immunity tests (also materials used in preparation of the standard, obtained from the authors)*

[8] *Kloss A: Oberschwingungen, vde Verlag, ISBN 3-8007-1541-4*

[9] *Materials used in preparation of standard IEC 61000-2-4 (obtained from the authors)*

[10] *Mattaveli P, Fellin L, Bordignon P, Perna M: Analysis of interharmonics in dc arc furnace installations, 8th International Conference on Harmonics and Quality of Power, Athens, Greece, October 14-16, 1998*

[11] *EN 50160: 1999 - Voltage characteristics of electricity supplied in public distribution systems*

[12] *Staudt V: Effects of window functions explained by signals typical to power electronics, 8th International Conference on Harmonics and Quality of Power, Athens, Greece, October 14-16, 1998*

[13] *Engineering Recommendation G5/4, Electricity Association, Feb. 2001.*

Appendix 1

Fourier transformation is the most popular method of spectral analysis of a signal. The fundamental theory of spectral analysis assumes that the analysis is performed over a time interval from - ∞ to + ∞. Discrete Fourier Transformation (DFT), or its variant Fast Fourier Transformation (FFT), may introduce unexpected spectral components of the analysed signal. This effect occurs because DFT and FFT operate over a finite number of samples, i.e. on a portion of the real signal. The determined and actual spectrum will be identical only when the signal is periodic, and the time over which it is analysed contains an integer number of the signal cycles. This condition is very difficult to satisfy in practical implementations.

Results presented in Figures A.1.1 and A.1.2 illustrate how the actual spectrum may look. Different spectra have been obtained for the same signal while the observation time in Figure A.1.2 was 2.5% longer. In the bibliography this effect is called spectral leakage. It could be said that part of the energy from the main spectral line is transferred to the side lines. The following interpretation of this phenomenon has been proposed. Sampling for DFT analysis can be compared to multiplication of the actual signal of infinite duration by a rectangular window corresponding to the time of observation, Figure A.1.3.

To limit the spectrum leakage it is necessary that values of the analysed signal do not change rapidly at the origin and the end of the sampling interval.

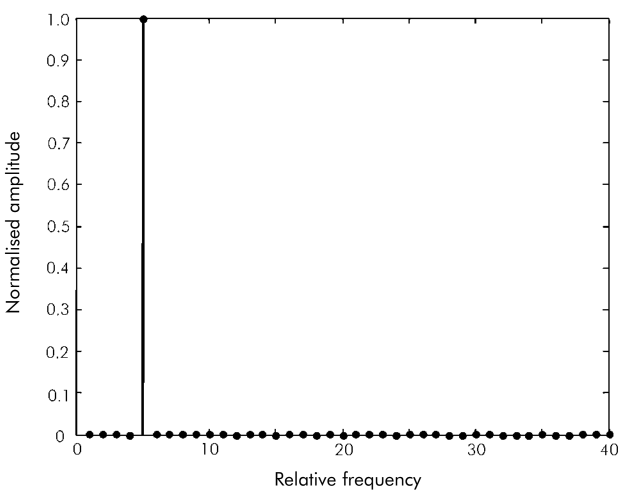


Figure A.1.1 - Modula of the signal spectrum, exactly 4 cycles have been used for analysis

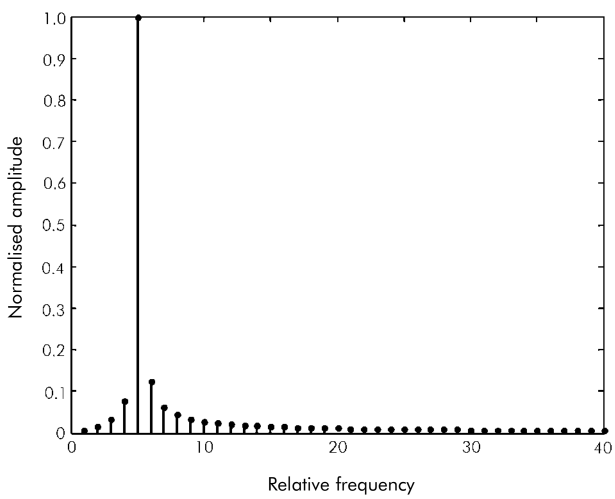


Figure A.1.2 - Modula of the signal spectrum, 4.1 cycles have been used for analysis

Figure A.1.3 - Acquisition of samples for DFT analysis

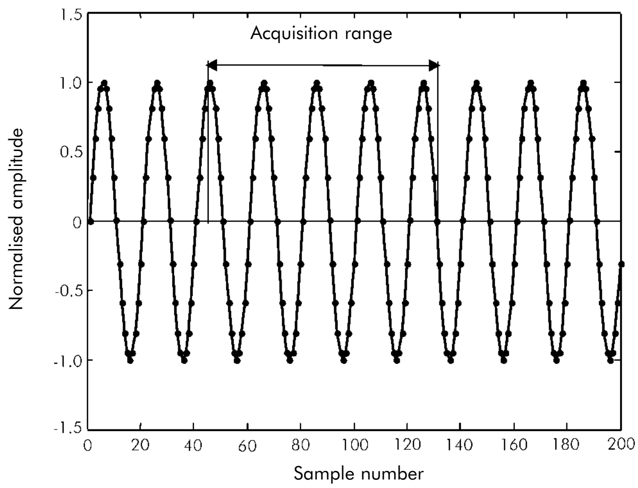


Figure A.1.4 shows how the time window should be used for signal analysis.

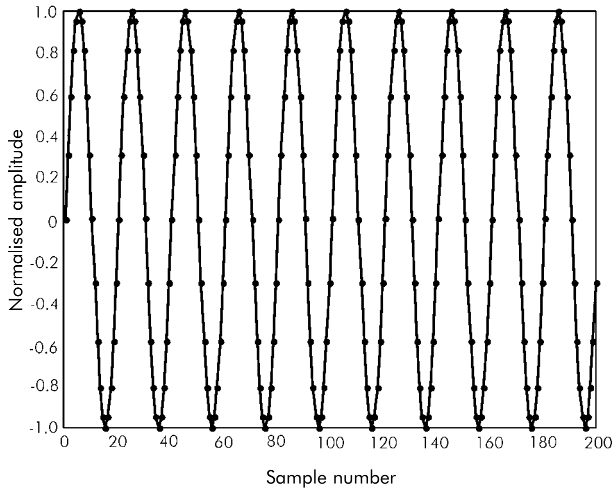


Figure A.1.4a - Drawing of samples for analysis

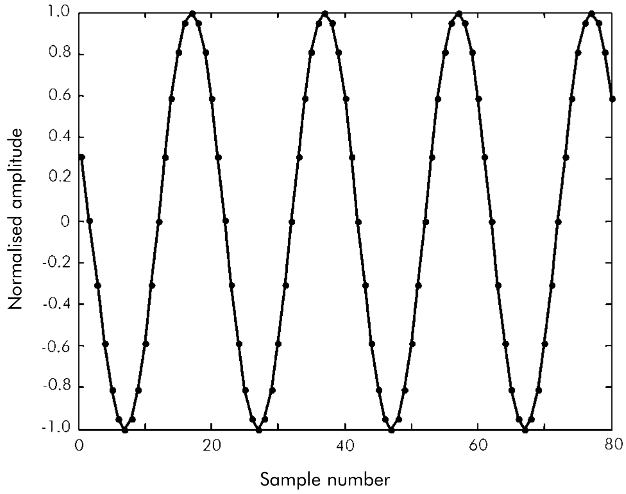


Figure A.1.4b - operation of the time window imposing $y_i = w_i * x_i$

where: y_i *= signal with imposed window*
x_i *= measured samples*
w_i *= window function on i changes from 1 to N (samples number)*

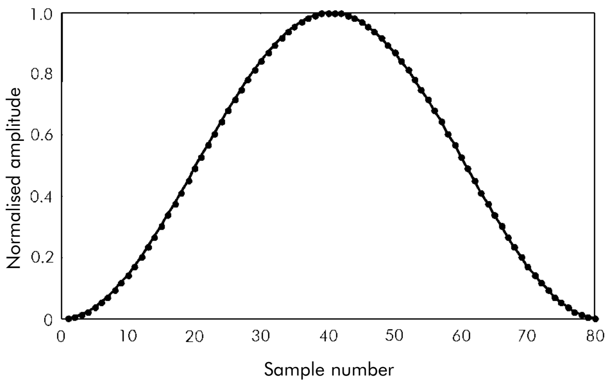


Figure A.1.4c - DFT spectrum analysis

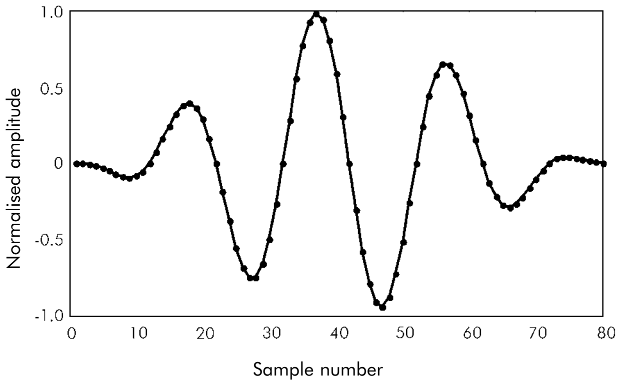


Figure A.1.4d - FFT spectrum analysis

Figure A.1.4e. - Time windows used for the signal spectrum analysis

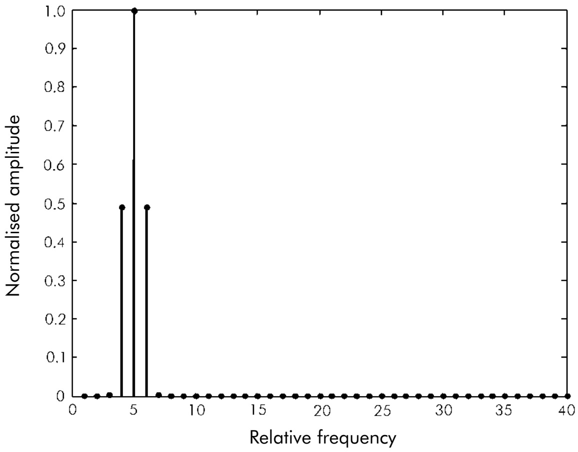


Figure A.1.5 shows how the presented methods have influenced the spectrum from the Figure A.1.2 example. The Hanning window has been used for the purpose of this example. The effect is a reduction in the number of non-zero spectral lines, and the spectrum approaches the correct one, as shown in the Figure A.1.1.

A number of DFT analysis windows are known in the current bibliography. The most popular are (Figure A.1.6):

- Triangular window similar to Barlett window
- Hanning window
- Window lifted cosine or Hann, or Hamming window.

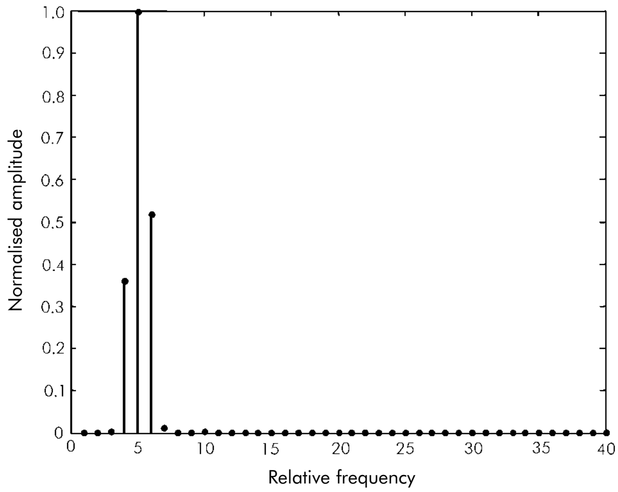


Figure A.1.5 - An example of Hamming window application to DFT analysis

These windows are the most often used in measuring instruments. Their use does not eliminate spectral leakage problems but limits significantly the effect of finite observation time. This is particularly evident as an improvement of the spectrum resolution.

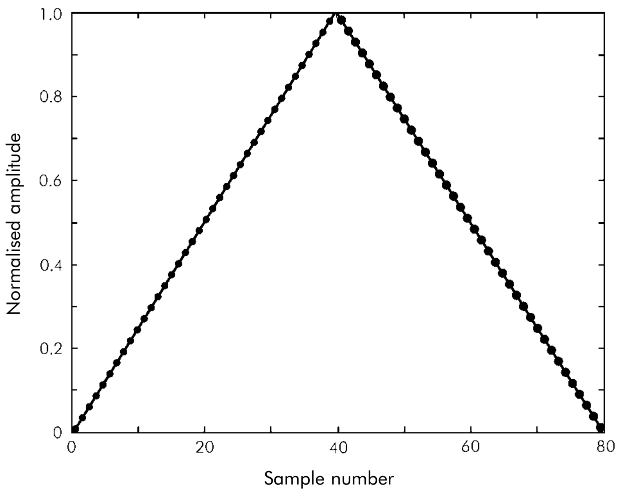


Figure A.1.6a - Triangular window

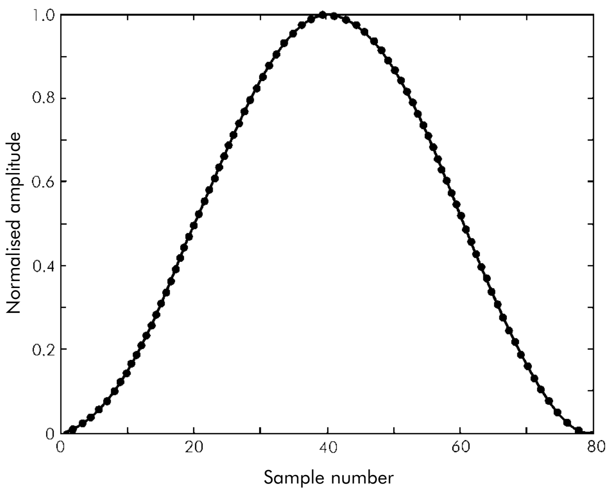


Figure A.1.6b - Hanning window

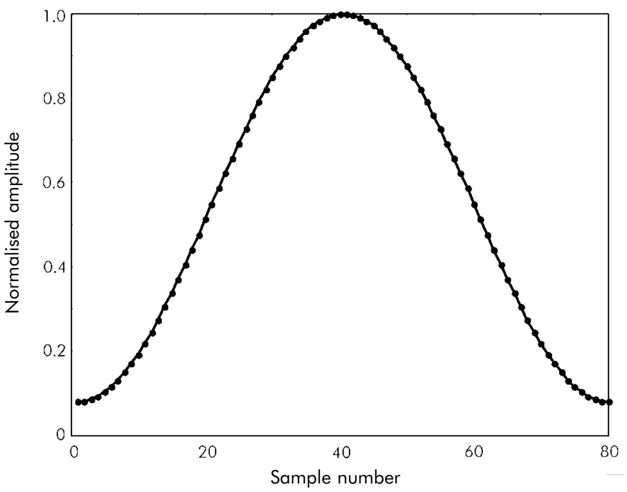


Figure A.1.6c - Hamming window

Appendix 2

The greatest difficulty associated with sampling a continuous signal is the problem of ambiguity. The essence of the problem is illustrated in Figure A.2.1. It follows from the figure that the same set of sampled data may describe several waveforms, indistinguishable by measuring equipment.

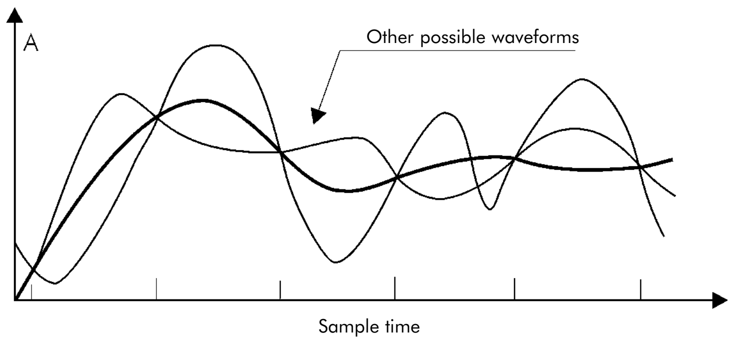


Figure A.2.1 - Ambiguity

The principle of frequency analysis is the representation of an arbitrary waveform by the sum of a series of sinusoidal signals. Such a method of presentation allows the analysis of the problem of ambiguity quantitatively. For this purpose, consider the waveform shown in Figure A.2.2.

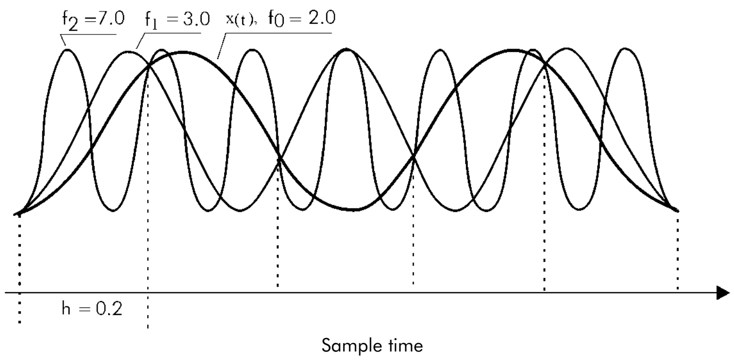


Figure A.2.2 - Analysis of ambiguity

A signal *x(t)* is sampled in equal intervals of time *h*, determining the instants of sampling, for which values of the measured signal are indicated in the figure. Assume that the function *x(t)* is sinusoidal with frequency f_0. The same points could also represent sinusoids with frequencies f_1 or f_2, which are multiples (not necessarily integer multiples) of frequency f_0. These various frequencies are obviously associated with the sampling period. The frequency f_0 is referred to as the fundamental frequency.

It could be stated, without presentation of the mathematical proof, that the range of frequencies for which the effect of ambiguity does not occur extends from $f_0 = 0$ to $f_0 = f_N$, where f_N, the maximum frequency, is referred to as the Nyquist frequency. It determines the limit frequency of data sampling, the so-called Shannon limit, beyond which a unique reconstruction of a continuous signal is not possible. Thus, if the signal being analysed does not contain any component frequencies greater than f_N, then the minimum sampling frequency necessary to allow the sampled signal to represent the real signal is given as:

$$f_S \geq 2 f_N, \text{ or because } f_S \geq \frac{1}{h}, \text{ then } f_N \geq \frac{1}{2h}$$

This is the so-called sampling theorem. It follows that, for a given spectrum of frequencies, the components situated between $f_0 = 0$ and $f_0 = f_N$ can be considered separately. If the signal contains components of frequencies $f > f_N$, these components will not be distinguished.

Therefore it is necessary to limit the bandwidth of the measured signal to reduce a direct consequence of the ambiguity during its sampling. That implies the need to filter the signal to be measured through a low-pass filter before sampling, in order to eliminate all frequencies greater than f_N.

Notes

Reference & Founding* Partners

European Copper Institute* (ECI) *www.eurocopper.org*	ETSII - Universidad Politécnica de Madrid *www.etsii.upm.es*	LEM Instruments *www.lem.com*
Akademia Gorniczo-Hutnicza (AGH) *www.agh.edu.pl*	Fluke Europe *www.fluke.com*	MGE UPS Systems *www.mgeups.com*
Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA) *www-citcea.upc.es*	Hochschule für Technik und Wirtschaft* (HTW) *www.htw-saarland.de*	Otto-von-Guericke-Universität Magdeburg *www.uni-magdeburg.de*
Comitato Elettrotecnico Italiano (CEI) *www.ceiuni.it*	Hogeschool West-Vlaanderen Departement PIH *www.pih.be*	Polish Copper Promotion Centre* (PCPC) *www.miedz.org.pl*
Copper Benelux* *www.copperbenelux.org*	International Union for Electricity Applications (UIE) *www.uie.org*	Università di Bergamo* www.unibg.it
Copper Development Association* (CDA UK) *www.cda.org.uk*	ISR - Universidade de Coimbra *www.isr.uc.pt*	University of Bath *www.bath.ac.uk*
Deutsches Kupferinstitut* (DKI) *www.kupferinstitut.de*	Istituto Italiano del Rame* (IIR) *www.iir.it*	University of Manchester Institute of Science and Technology (UMIST) *www.umist.ac.uk*
Engineering Consulting & Design* (ECD) *www.ecd.it*	Katholieke Universiteit Leuven* (KU Leuven) *www.kuleuven.ac.be*	Wroclaw University of Technology* *www.pwr.wroc.pl*
EPRI PEAC Corporation *www.epri-peac.com*	Laborelec *www.laborelec.com*	

Editorial Board

Prof Zbigniew Hanzelka

AGH-UST
Al. Mickiewicza 30
30-059 Kraków
Poland

Tel: (012) 617 28 78
Fax: (012) 633 22 84
Email: hanzel@uci.agh.edu.pl
Web: www.agh.edu.pl

Dr eng Andrzej Bień

AGH-UST
Al. Mickiewicza 30
30-059 Kraków
Poland

Tel: (012) 617 28 73
Fax: (012) 633 22 84
Email: abien@uci.agh.edu.pl
Web: www.agh.edu.pl

Copper Development Association

Copper Development Association
5 Grovelands Business Centre
Boundary Way
Hemel Hempstead
HP2 7TE

Tel: 00 44 1442 275700
Fax: 00 44 1442 275716
Email: helpline@copperdev.co.uk
Websites: www.cda.org.uk and www.brass.org

European Copper Institute
168 Avenue de Tervueren
B-1150 Brussels
Belgium

Tel: 00 32 2 777 70 70
Fax: 00 32 2 777 70 79
Email: eci@eurocopper.org
Website: www.eurocopper.org