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A Practical Guide for EN 61000-4-13: Mains harmonics and interharmonics

Helping you solve your EMC problems

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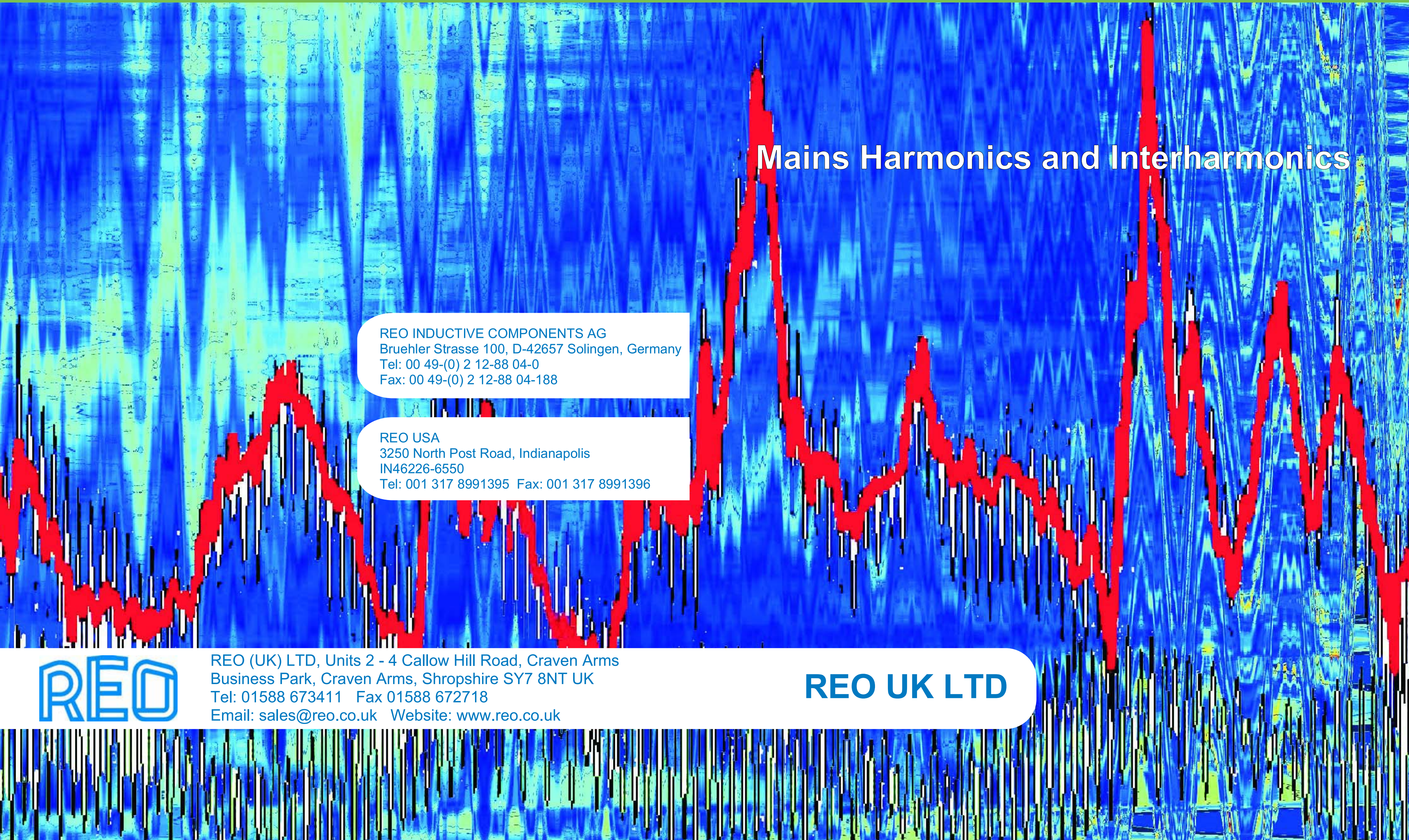
REO **A Practical Guide for EN61000-4-13**



Mains Harmonics and Interharmonics

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EN 61000-4-13 and compliance with the EMC Directive

2

The basic immunity test method for harmonic and interharmonic distortion of 50Hz or 60Hz mains supplies is IEC 61000-4-13 [1], which has been adopted unchanged as the harmonised European standard EN 61000-4-13 [2]. These two standards are available to be called up as basic test methods by immunity standards listed under the Electromagnetic Compatibility (EMC) Directive, 89/336/EEC [3].

The EN version of 61000-4-13 is technically identical to the IEC document, so this booklet is of use where either standard is required. Since many national tests outside the EU or customer contract requirements are based on IEC standards, this booklet may also be of use in such situations.

The ideal mains voltage is a pure sinewave at the fundamental frequency (usually either 16.67, 50, 60 or 400Hz), but non-linear loads and injection of signalling voltages cause the waveform to be distorted. The techniques of Fourier analysis are used to describe the distortion in terms of one or more frequencies superimposed on the pure sinewave fundamental. These added frequencies are classified as harmonic – when they are an integer multiple of the fundamental; and as interharmonic – when they are any other frequency.

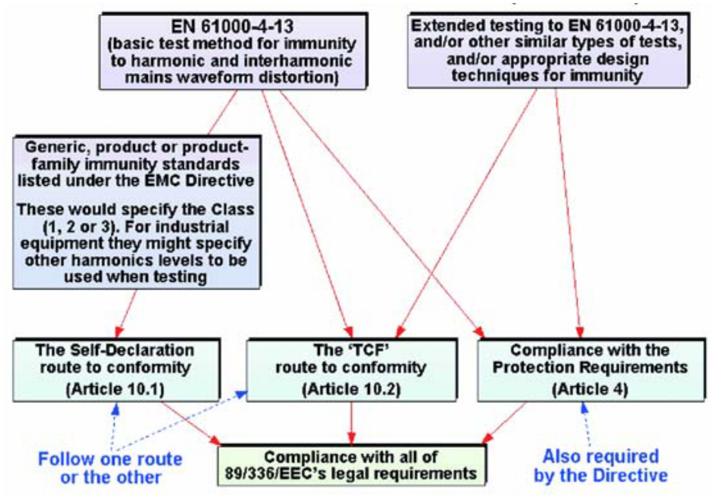
Distorted mains waveforms, and the resulting electrical and magnetic fields and common-mode 'noise' voltages can interfere with almost every kind of electronic device, equipment or system (called 'products' in the rest of this booklet, for convenience). Distorted mains waveforms are ubiquitous in today's world, and in some locations or situations the distortion can be extreme. So it makes good sense to test products for the effects of harmonic and interharmonic distortion of mains supplies to ensure they will work reliably in their intended operating environment. This is especially important in safety-related, high-reliability, mission-critical, or legal metrology electronic applications.

EN 61000-4-13 is a basic test standard, so when following the self-declaration to standards route to conformity (Article 10.1 in [3]), EN 61000-4-13 should *not* be listed on the EMC Declaration of Conformity. Only the relevant generic or product-family harmonised EMC standards should be listed. These can call-up EN or IEC 61000-4-13 as a test *method*, but it is always the generic or product-family standard that sets the minimum test *levels* which allow conformity to be claimed.

At the time of writing no product or generic EMC standards listed under the EMC Directive [3] are known to call up testing to any parts of EN 61000-4-13, but future standards (or versions of them) may well do so, especially for industrial equipment. In any case, testing to this standard may be required to help comply with the EMC Protection Requirements – an essential element in complying with the EMC Directive that is sometimes overlooked.

When using the Technical Construction File route to conformity with the EMC Directive (Article 10.2 in [3]) it is possible to use EN/IEC 61000-4-13 directly, in which case it *should* be listed on the product's EMC Declaration of Conformity. In such cases the product manufacturer should assess the EM environment of the product and ensure that it is designed and/or tested accordingly, so as to comply with the EMC Directive's essential "Protection Requirements" (Article 4 of [3]).

The relationship between EN 61000-4-13 and the first edition of EMC Directive (89/336/EEC)



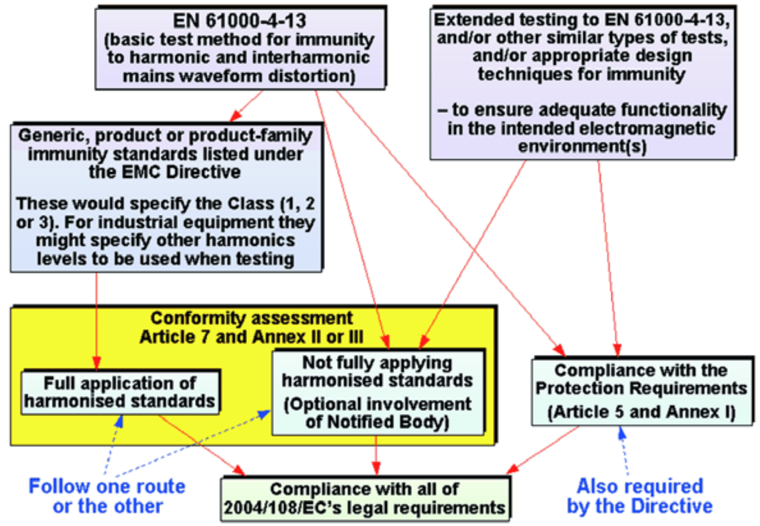
Compliance with the EMC Protection Requirements is a legal requirement that applies *in addition* to the requirement to follow one of the conformity assessment routes (Self-Declaration, Article 10.1; or TCF, Article 10.2). Products that pass tests to all relevant immunity standards listed under the EMC Directive, but nevertheless are unreliable or fail in normal use because they are not immune enough for their real-life EM environment, do not comply with the EMC Directive's Protection Requirements and are therefore illegally CE marked.

Applying EN 61000-4-13 (or similar) immunity tests which go beyond the minimum requirements of the EMC Directive's listed standards can also be a way to help make products more reliable, reduce warranty costs, improve customer satisfaction and reduce exposure to product liability claims – for more on this refer to the section on 'Real-life reliability', later.

The second edition of the EMC Directive, 2004/108/EC [4], replaces 89/336/EEC on 20th July 2007. Products that are already being supplied in conformity with 89/336/EEC will be allowed to be supplied until 20th July 2009, by which date they too must comply with 2004/108/EC. Whereas 89/336/EEC requires the involvement of a Competent Body with all TCFs, 2004/108/EC effectively allows the TCF route to be used with the *optional* involvement of a Notified Body (the new term for Competent Bodies).

Under 2004/108/EC, equipment manufactured specifically for use at a named 'fixed installation' may not have to comply with any EMC requirements when it is supplied. But testing to EN 61000-4-13 at specified levels will generally be a requirement by the customer to help ensure that his fixed installation complies with the EMC Directive's Protection Requirements.

The relationship between EN 61000-4-13 and the first edition of EMC Directive (89/336/EEC)



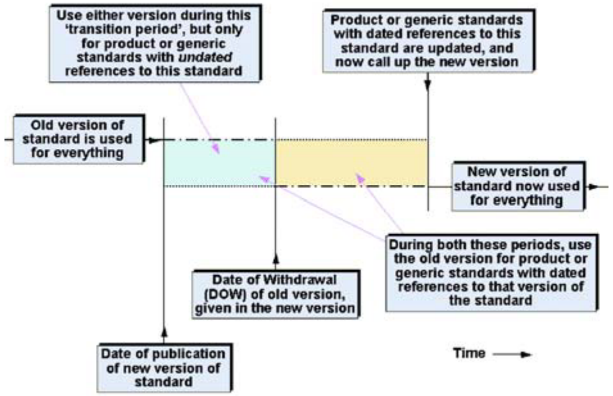
Important Safety Note: As a general rule, people whose health depends on the correct operation of pacemakers or other body-worn or implanted electro-medical devices should never go near any EMC immunity tests or their associated test equipment.

This series of booklets is concerned with testing to the EN standards for typical domestic, commercial, light industrial and industrial environments. But other kinds of immunity tests may be required by the EMC standards for aerospace, rail, marine and military equipment and their environments. Some of these industries may have developed their own harmonics and interharmonics test standards based on their own particular kinds of a.c. power supply networks. For instance, aircraft use 400Hz mains supplies from their engine-driven generators, and some transport systems use 16.67Hz, and these will suffer distortion due to non-linear loads too.

EN 61000-4-13 only applies to 50 or 60Hz mains, but in the absence of standards for areas employing other mains frequencies, tests could be developed based on the approach taken by EN 61000-4-13.

What to do when new versions of basic test standards are issued

What to do when basic test standards are up issued



This booklet describes how to apply EN 61000-4-13:2002. Where a generic or product EMC standard requires the use of the EN/IEC 61000-4-13 basic test method, it will specify either a dated reference (e.g. "EN 61000-4-13:2002") or an undated reference (e.g. "EN 61000-4-13"). If it specifies a dated reference, then this is the version of the basic test method standard that *must* be used. If it specifies an undated reference then the *latest* published version of the standard should be used. (There are no other versions of EN 61000-4-13, yet.)

But it is clearly impractical for manufacturers to rush to test labs to retest all of their products on the very day a new version is issued, so each new version of an IEC standard includes a date on which it supersedes the previous version. This is the "date of withdrawal" (DOW), and provides a transition period during which manufacturers can choose between using the old or the new versions of the standard for declaring compliance. The DOW is preserved in the EN versions of the IEC standards.

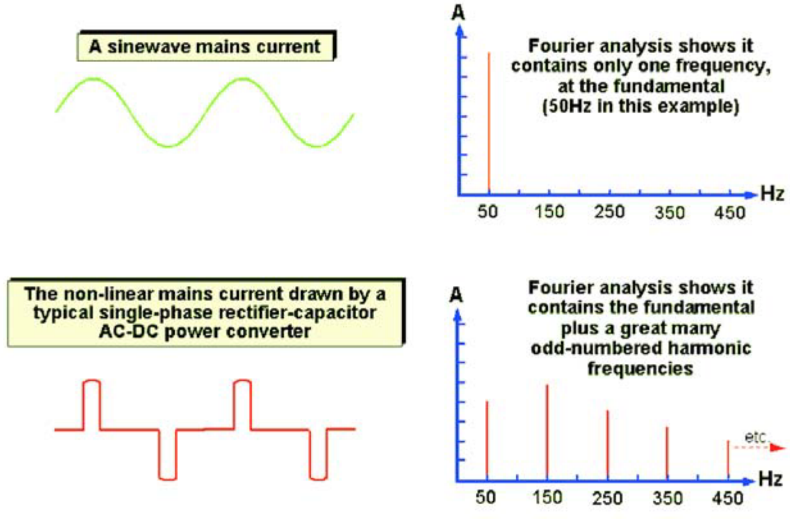
Usually it makes best commercial sense to test new products to the latest version of a standard, retesting older products when they are due for retesting anyway as a result of a design change or upgrade (as long as this happens before the DOW). Some products are sold for such short periods of time that they may never need to be retested to any new versions of standards.

A note of caution: the European Commission (EC) has ruled that where Directive compliance is concerned, only dates that are published in the Official Journal of the EU (OJEU) have any relevance, and not any dates put into standards by their committees. This is not a problem in most cases, but basic EMC test standards such as EN 61000-4-13 are never listed in the OJEU. Since DOW dates in the basic standards are not recognised by the EU, there can be no transition period, which is impractical and silly.

This consequence does not seem to have been foreseen by the EC, and can cause confusion. So it is probably less risky to always use the latest version of a basic test standard, except where the regulatory requirements (for the EU or other markets) specify the exact version to be used.

What are harmonics and interharmonics?

Comparison of waveforms and spectra



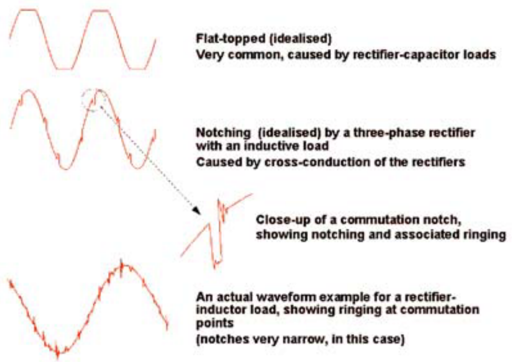
When non-linear loads are connected to a pure sinewave source at the fundamental frequency, they draw non-sinusoidal currents. As these non-sinusoidal currents flow in the inevitable impedance of the power supply network, they cause non-linear voltage drops that distort the waveform of the supply, so it is no longer a pure sinewave. The lower the impedance of the mains power supply, the less will be the voltage distortion created by a given non-linear load.

The ideal mains voltage is a pure sinewave at the fundamental frequency of the mains supply, but pure sinewave mains supplies are now very rare indeed. Fourier analysis is commonly used to describe the distortion of a waveform in terms of one or more frequencies superimposed on a pure sinewave fundamental. Frequencies that are integer multiples of the fundamental are called harmonics, and all the other frequencies are called interharmonics.

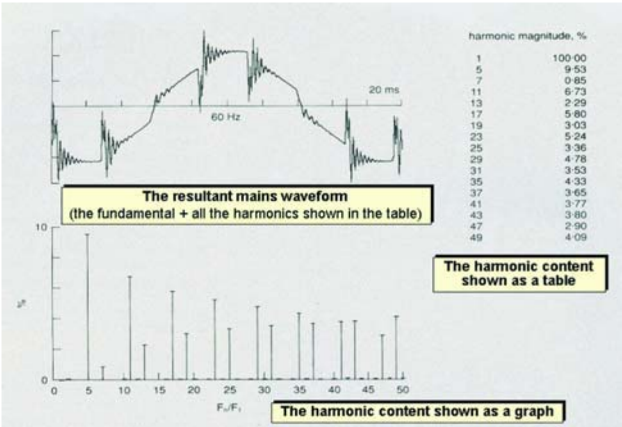
Harmonics are split into two main types odd-numbered (3, 5, 7, 9, …..39, etc.) and even-numbered (2, 4, 6, 8, …..40, etc.), because they can cause different problems (see later) and as a result may need to be treated differently. Odd-numbered harmonics are often called odd-order harmonics, and even-numbered are often called even-order harmonics. Odd-order harmonics are further divided into those that are a multiple of 3 times the fundamental, called triplens (or 'triples' or 'tripled harmonics'), and the rest. This is because in three-phase power systems, triplens can be cancelled out whereas other odd-order harmonics cannot be. This segregation of types of harmonics is evident in table 1, 2 and 3 in EN 61000-4-13.

Distorted mains waveforms range from clipped and/or notched and/or ringing, and examples of each are provided in the figures in this booklet. [5] and [6] provide much more detailed information and mathematical analyses.

Some examples of harmonically distorted mains waveforms (copied from various figures in [5] [6] and [13]



Constructing a distorted waveform from harmonics (from Figure 5 of [6])



Actual mains waveforms can be 'decomposed' into a list of frequencies (with their individual levels and phase relationships) – usually by means of a mains harmonic analyser (although some commercial instruments might not measure the phase information).

And individual frequencies can be generated and added together in an electronic device (in hardware or software) to produce distorted waveforms that can be used for testing products.

It is commonplace to measure the quality of a mains supply using the single figure of its total harmonic distortion (THD), but this is a meaningless figure. What matters is the mains waveshape, and how the product reacts to that, as should become clear during the rest of this booklet. THD does not correlate with interference.

It was mentioned earlier that non-linear loads draw non-sinusoidal currents when supplied from a pure sinewave, and that as these currents flow in the inevitable impedances in the mains supply network they produce non-linear voltage drops that distort the mains voltage waveform.

The mains systems in most developed nations have a very low impedance and so maintain reasonable waveform quality, but many products are supplied from mains supplies that have higher impedances and hence suffer more waveform distortion for a given amount of non-linear loading.

Products sold globally may have to deal with mains supplies that have higher impedances than their European equivalents. Also, even in developed nations products may be expected to operate on locally generated mains, with a higher impedance, e.g. from a stand-by generator in the event of a power failure. And we must not forget remote locations and vehicles, where there is no mains supply network available and local generation is all that is available. So-called 'green power' is starting to become a serious force, with local generation augmenting or replacing the national mains supply network, but these power sources also have high impedances. All these are discussed in more detail below.

Global markets

These days, many types of electrical or electronic equipment are sold to many different countries around the world. But when developing equipment in a developed nation it is easy to take the high-quality mains power supply for granted, and assume that mains power around the world is just as good. This assumption can be very wrong, and could lead to great expense. For example, refer to [7], which describes the very poor quality of the mains waveform in a residential area of Israel in 2000.

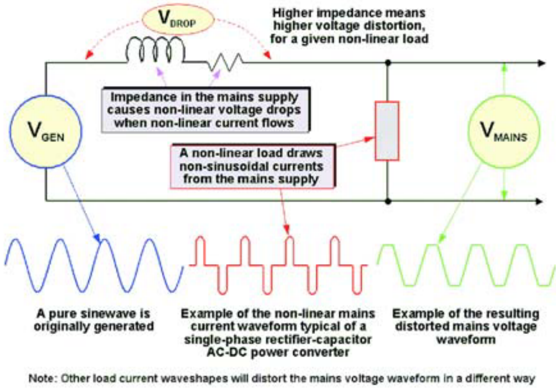
Example of domestic mains waveform in Israel, in 2000
From Nick Maroudas PhD, 2nd October 2000, [12]

Also around 2000, a company having domestic appliances intended for the UK market made in China had to use a portable generator to power them during testing, since the mains provided to the factory was "a pretty good square wave, although at least it measured 230Vrms". And a company supplying a large textile machine to a new town in China had a problem with the mains supply that burnt out the brush leads in several of the electric motors – the time it took to solve the problem left the manufacturer with a bill for half a million pounds in penalty charges, 10% of their annual turnover, causing their accountants to recommend winding up the company.

Local generation

Local generation of power usually has higher source impedances than are provided by a connection to LV, MV or HV power networks forming part of a national grid. A consequence of their higher impedance is that they will suffer more waveform distortion for a given loading of harmonic and interharmonic currents.

How mains waveform distortion is caused by non-linear loads



Many types of products may be required to operate from local generation from time to time, such as…

- All hospital equipment, telephone exchanges and internet hotels when the emergency generators are tested (typically once per week) or when running on emergency power due to loss of the normal mains supply.

- All domestic and commercial equipment when run on emergency power due to a loss of the normal mains supply (for example, all the equipment in the authors office building usually has to run from a small standby generator for several hours, several times each year).

- Equipment installed on vehicles (marine, inland waterways, road vehicles, aircraft, diesel trains, etc.) and offshore oil and gas platforms which, of necessity, have to generate their own mains power locally. As more and more high-power electronic power converters are used in such vehicles (e.g. marine thrusters, and even main propeller drives at several MW) the distortion in their relatively high-impedance mains networks is increasing.

In some oil and gas drilling platforms it is not uncommon to find that 80% of the load is non-linear [5]. Total distortion levels of up to 22% are known to exist on some marine power supplies [8].

- Equipment used in open-air concerts, travelling fairgrounds, etc., supplied by portable generators.

Green power

Premises powered by 'green' energy sources, e.g. photovoltaic, wind, wave or water power, are usually connected to the public mains supply via a two-way electronic power converter that can export surplus electricity to the public mains supply, and import public mains power when the green energy can't keep up with the demand of the premises.

These electronic converters have higher output impedance than a 'normal' mains connection; so will create more waveform distortion for a given harmonic and interharmonic current loading. The number of such premises is set to rise, as products for domestic and commercial CHP (combined heat and power) become more affordable, and also due to numerous initiatives intended to help stave off global warming.

There are very many different types of non-linear loads, consuming harmonic and/or interharmonic currents. Transformers and motors are weakly non-linear due to the saturation characteristics of the magnetic materials in their cores. But if run into saturation (which can be caused by even-order distortion of the mains waveform) they can become very non-linear indeed. Fluorescent lamps with standard 50 or 60Hz magnetic ballasts are moderately non-linear. Arc welding and arc furnaces are extremely non-linear loads, creating very large amounts of interharmonics. Electronic power converters (rectifiers) are very non-linear loads and are an increasing proportion of the load on most modern mains power systems.

DC motors powered by rectifiers

For many years it has been traditional to run d.c. motors directly from the mains, through a rectifier, to obtain speed control through such means as field weakening. Smaller motors would use a single-phase rectifier, but larger motors (up to several MW) used for heating, ventilating and air-conditioning (HVAC) fans and pumps in larger buildings, and for numerous purposes in industry, would use three-phase rectifiers, sometimes called 6-pulse rectifiers. The d.c. load on these rectifiers is inductive, and the rectifiers are slower to turn off than they are to turn on, so there are periods during each mains cycle when the rectifiers short out the supply for a short while, three times in each cycle.

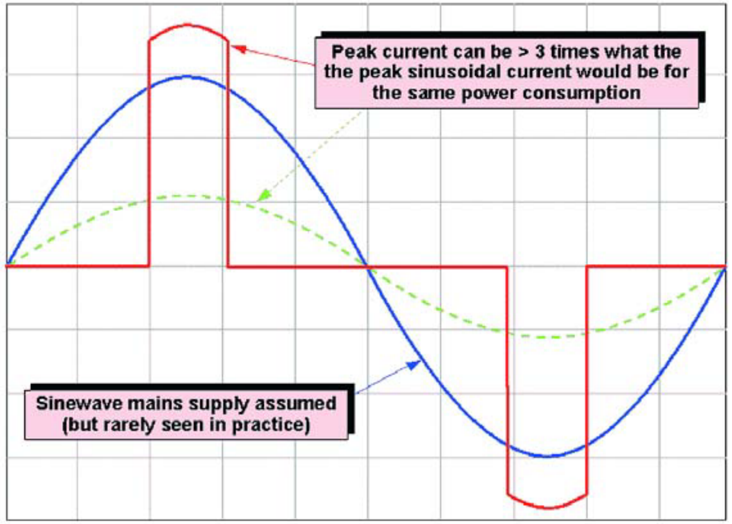
Inductance in the supply limits the currents and (hopefully) prevents the rectifiers from damage, but the resulting 'commutation notch' in the waveform goes down to 0V, when measured at the rectifier's mains input. The steepness of the notch edges consist of many very high frequency components that often excite resonances due to the various inductances and capacitances in the network (due to devices and 'strays'). These notches and their associated resonances can cause spurious zero-crossings in the waveform.

Such motor rectifiers have balanced three-phase currents and generate very low levels of triplen harmonics. And because they use bridge rectifiers their currents have low levels of even-order harmonic currents. But they do have high levels of odd-order harmonic currents at the 5^{th} and above (except triplens). To comply with mains network planning requirements in most countries, such as G5/4 in the UK [9], phase shifting transformers are used to generate six-phase or even twelve-phase supplies for use with 12-pulse or even 24-pulse rectifiers. Six-phase (twelve pulse) rectifiers have low levels of 5^{th} and 7^{th} harmonics, so their mains current only contains reasonable levels of odd-order harmonics at the 11^{th} and above (but low triplens).

Rectifiers followed by capacitors

It is the development of loads that use rectifiers followed by a storage capacitor that is causing mains distortion headaches these days. The rectifier only conducts when the mains voltage is two 'diode drops' higher than the d.c. voltage on the storage capacitor, so the mains current drawn is discontinuous. This pulsating current has a peak level that is a lot higher than would occur with a sinewave current, for the same power consumption.

Non-linear currents in a rectifier-capacitor type AC-DC converter



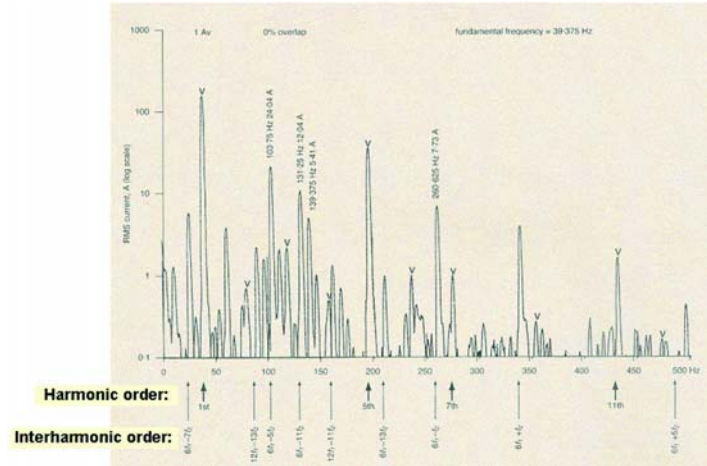
In recent years a vast number of electronic devices have been connected to the mains supply in developed countries, most of them using rectifier-capacitor a.c. - d.c. power converters, including…

- Televisions (TVs), video cassette recorders (VCRs), hi-fi amplifiers and DVD players.
- Microwave cookers.
- Personal computers (PCs), video monitors, printers and photocopiers.
- Low-energy lamps, high-frequency ballasts for fluorescent lighting, low voltage lighting using 'electronic transformers'.
- Hordes of low-power products using 'wall-wart' plug-top power supplies.
- Variable-speed a.c. motor drives using frequency changers (often called inverters) based on pulse-width modulation (PWM), for HVAC in commercial buildings and for replacing variable-speed d.c. motors in industry (a.c. motors are more rugged and require less maintenance than d.c. types).

The low current consumption of many of the domestic and commercial products (e.g. TVs and PCs) has been balanced by the very high numbers of them connected to the mains supply, so that they are now often more important for mains waveform quality than high-power d.c. motor drives in factories. For example, some office buildings contain as many as 3,000 PCs and their 3,000 VDU monitors, plus several thousand fluorescent lamps with magnetic or high-frequency ballasts – a very large very non-linear load by anybody's reckoning. Apartment buildings and hotels can present similar loads, as can areas of domestic housing (although more spread out geographically).

Example of real harmonic and interharmonic currents produced by a large inverter-fed motor

(from Figure 13 of [14], inverter output frequency is 39.4Hz)



The desire to save money (and hopefully help save the planet too) by improving energy efficiency, uptime and maintenance costs has led to heavy power users embracing electronic power control devices that begin by converting the mains to d.c. using rectifier-capacitor converters. Variable speed inverter motor drives are now used for pumps, fans, and traction in a variety of sizes from 1kW to 10MW, mostly supplied with three-phase mains.

Now that semiconductor manufacturers have managed to produce the necessary low-cost devices, the next major change will be the use of variable speed motor drives in all domestic appliances, to save energy, replacing many more fairly linear loads with very non-linear ones. In a typical domestic house in 2015 that does not use electrical space heating, the only linear loads remaining will probably be the few remaining tungsten filament or halogen lamps that operate directly from the mains.

Rectifier-capacitor loads generate harmonic currents, but any ripple on their storage capacitor's d.c. voltage modulates the mains current. So, where the d.c. load has a current consumption that varies with time, the d.c. ripple it generates will modulate the mains current, leading to interharmonic distortion of the mains waveshape.

This is most easily seen by a typical inverter drive for an AC motor – the mains current will contain harmonics related to the input frequency (the mains) and interharmonics related to the output frequency (which is variable). In fact, the odd-numbered harmonics of the output frequency appear in the mains side as sidebands on both sides of each of the even-numbered harmonics of the mains.

Thyristor power control

Another source of non-linear currents is the use of thyristors and triacs for a.c. power control – for heaters, ovens and lighting of many sorts, ranging from low power (e.g. domestic lamp dimmers) to very high power. Where these use phase-angle control the harmonic distortion frequencies they generate depend on their conduction phase angle. Where they use 'burst firing' they tend to create very low frequency interharmonics related to their firing rate.

Power and frequency conversion in mains power systems themselves

The same rectifier techniques as described above are increasingly used in the mains networks themselves, to convert between a.c. and high-voltage d.c. (HVDC) transmission lines, and to convert from one frequency to another (e.g. from 60 to 50Hz or vice-versa). These are usually very high-powered equipment, and they are fitted with harmonic filters to help them preserve a good waveshape.

Just as was described earlier, ripple on the 'DC links' in such converters appears as interharmonic currents, leading to interharmonic distortion of the mains supply.

Mains signalling (ripple control)

Signal frequencies from 110Hz to 3kHz are used in some mains networks (or parts of them) to transfer data from one part of the network to another, or to control equipment in parts of the network. The frequencies used are interharmonics, and unlike the other sources described above they are not caused by the interaction of non-linear currents with supply impedance – they are actually placed on the mains as voltage signals and cause distortion directly.

This is called 'ripple control' because when seen on an oscilloscope it appears as a ripple in the peak level of the mains voltage. It is mostly used in national power systems, and sometimes in industrial power systems too, at low-voltage (LV), medium-voltage (MV) and high-voltage (HV). The level of the added signalling frequencies are between 2 and 5% of the nominal mains voltage. Resonances can increase the levels of this voltage distortion component to as much as 9%. More detail will be found in [10].

Other sources of interharmonics

[10] describes interharmonics caused by resonances occurring in systems that contain series or parallel capacitors (e.g. switched capacitors used for power factor correction and voltage control). All mains conductors have series inductance, so the addition of capacitors cannot help but create resonant circuits. These resonant circuits cause great problems when they happen to resonate at the same frequency as a harmonic or interharmonic component (see later) – but they can also cause interharmonics in their own right, when they are excited by a transient event or a distortion component that is nearby in frequency.

Standards that limit emissions of harmonic currents are not a panacea

Some might assume that because EN 61000-3-2 now limits the harmonic currents produced by products supplied in the EU, and because we will soon have EN 61000-3-12 to do the same for products that consume more than 16A/phase – all harmonic problems will go away. Unfortunately, this is not the case, because the limits applied by these standards still allow significant amounts of harmonic currents to be created (they do not limit interharmonic currents at all).

There was a recent example of this in the lighting scheme for a new road tunnel in the UK. A total of 1MW of lighting was installed, powered by a 1MVA distribution transformer, via switchgear that permitted the lamps to be powered in various combinations suitable for every situation from night time to mid-day in the summer.

But power levels greater than 75% could not be achieved without the main circuit breaker tripping out to (correctly) protect the 1MVA transformer from overheating. And as the power level was increased the buzzing and vibration of the switchgear increased too, until at 75% power setting it was necessary to shout in order to be heard in the distribution room. Investigation showed that all of the lamps met the limits set by EN 61000-3-2:1995, yet the total harmonic current load was still high enough to cause the problems described.

Low-voltage mains distribution networks consist of lots of long conductors, which have inductance; transformers, which have even more inductance; power factor correction devices (usually capacitors, sometimes very large; harmonic filters, consisting of capacitors and inductors; and a large variety of electrical and electronic products powered by the network, many of which connect radio-frequency interference (RFI) filters consisting of inductors and capacitors to their mains supply. The radio-frequency (RF) filters might be small in value, but in a large building or vessel there can be many thousands of them, totalling a very significant amount of inductance and capacitance.

Whenever we have inductance and capacitance in the same circuit, we always have one or more resonant frequencies. The amplitude of a resonance – the amount by which it amplifies the signal or noise occurring at that frequency – is limited by the resistance in the circuit. Unfortunately, resistance in a mains network is kept low to minimise losses, improve energy efficiency and save money, so the mains network resonances can have dramatic effects.

Parallel resonances tend to amplify any frequencies present in the mains waveform, that match their resonant frequencies, causing much higher than expected peak voltages and/or waveform distortion on the mains network. Series resonances have a similar effect, but tend to amplify the harmonic or interharmonic currents at their resonant frequencies. Either of these can reduce the life or cause damage to the equipment concerned. In either case the unwanted harmonic or interharmonic voltage or current can be at least doubled in amplitude.

The problems that can be caused by harmonics and interharmonics

It is usually the case that a network's resonances do not coincide with the harmonics or interharmonics that are present in significant levels in that network. But *resonances are always present*, and it can happen that the addition of new equipment, or an attempt to reduce distortion by adding harmonic filters, or a number of other modifications to the network, can cause an existing resonance frequency to shift and coincide with a significant harmonic or interharmonic. The resulting effects can be quite dramatic.

[11] describes a case where an intermittent failure was caused when the pulse driven motor of a 'lifting crane' went into resonance with the power factor correction capacitors in a nearby lighting system. All manner of costly and time-wasting investigations were carried out and sources of blame sought, before the real culprit – the resonance – was found.

Mains harmonic distortion has been a problem ever since the AC mains was first widely employed. It was more of a problem in some industries than others, for example: mains harmonic immunity testing equipment was being used to test products for use in power generating stations around 1968.

Early TV sets used to use single-phase rectifiers and on a Saturday afternoon in the UK in the 1980s, when most factories and offices were closed and many people sat down in front of their TVs to watch the football, the even-order distortion of the mains supply could increase to such high levels that some AC motors would synchronise to the second harmonic (at 100Hz) and (try to) run at twice normal speed [12].

[13], [14] and [15] contain a great deal of useful information on this topic, summarised below.

List of equipment that can be affected by distorted mains waveforms

Problems caused by harmonic distortion of the mains include (from [16] and [17]):

- Capacitors: reduced life, increased likelihood of damage, fuse disconnection, damage to any switching contacts.

  [18] describes a situation that existed in a London office building where power factor correction capacitors in the fluorescent lamps all failed, even when replaced, forcing the site to pay extra for its electricity because of its poor power factor. The same problem has occurred in the much larger power factor correction capacitors in some electricity distribution rooms.

- Rotating machines (motors and generators): reduction in efficiency, increased temperatures, overheating, reduced life, increased acoustic noise emissions, pulsating or reduced torque, shaft fatigue, reduced bearing life, damaged products.
- Cables: increased temperatures, inability to provide full current rating without overheating, reduced life, increased likelihood of damage.
- Transformers: increased temperatures, overheating, reduced life, increased likelihood of damage, increased acoustic noise emissions.
- Fuses and circuit-breakers: reduced life, increased 'nuisance tripping' when the power consumed by the loads is still within the current trip rating.
- Surge suppressors: reduced life, increased likelihood of damage.
- Electricity meters: increased errors.
- Residential equipment: increased emissions of acoustic noise, incandescent lamp flicker.
- Electronic equipment: defective operation of circuits that rely on the zero-crossing of the mains waveform; noise coupling from mains cables and devices into analogue and digital circuits causing interference with radio and TV sets, digital clocks and timers, hi-fi and other audio systems; unreliable operation of computers.
- Telephones: increased levels of audible noise (even to the point of making conversations impossible [19], which can cause health and safety problem in some circumstances).
- Power distribution networks: excitation of system resonances leading to increased levels of voltage distortion – exacerbating many of the above problems.

Much more information on mains harmonics can be found in [5] [6] [9] [13] [15] and [20].

Problems caused by interharmonic distortion of the mains include most of the above plus low-frequency effects due to beating between interharmonics and the fundamental frequency when they are close together. These low frequency effects include lighting flicker, and low frequency oscillations in electrically-powered mechanical systems [14].

[10] says that the most common effect of interharmonics is now interference with control and protection signals in power lines. Experience in the USA indicates that TV sets are likely to be disturbed by interharmonic levels of 0.5% [9]. More information on mains interharmonics, their causes and effects, can be found in [14].

Skin effect and heating

As frequency increases from d.c., the current in the cross-section of a conductor tends to travel more towards its circumference (its skin – hence the name). Since less of the cross sectional area is carrying the current, the resistance of the conductor increases, and so do its power losses for a given current. At 160Hz one skin depth (the depth below the surface of a conductor by which the current has decreased to 36.8% of its value at the surface) is about 5mm. At 1.6kHz it is about 1.6mm. Every skin depth further into the conductor the current decreases by another 36.8%. Skin effect is only usually considered to be significant, given the diameter of typical mains conductors, at frequencies above 350Hz (the 7^{th} harmonic of 50Hz).

So, supplying loads with distorted mains waveforms causes conductors to experience higher losses than might be expected based on the losses at the fundamental frequency. Conductors are (of course) used in all cables, but they are also used in capacitors and the windings of transformers and motors, so all of these types of linear components tend to run hotter when supplied with distorted mains voltages.

Non-linear currents consumed by linear loads

When a distorted sinewave is supplied to a *linear* load (such as a resistor, capacitor or inductor) it will consume *non-linear* currents, and these usually need to be taken into account when specifying the ratings of the load. The impedance of capacitors decreases as frequency increases, so harmonics and interharmonics at a higher frequency than the fundamental result in higher currents. For example, a distortion component of 1% of the nominal mains voltage at the 11^{th} harmonic, would cause a current in a capacitor that was 11% of the current at the fundamental frequency. So high frequency waveform distortion in the mains can overheat capacitors or damage them in other ways, due to their high currents.

Resistors have no significant problems with harmonics or interharmonics, but inductors do. More specifically, inductors used in transformers and motors are usually designed to make very cost-effective use of their magnetic materials – which means running them as close to saturation as can be achieved without shortening their life through overheating caused by excessive magnetising currents. But distorted waveforms (especially those that increase the peak voltages, or even-order harmonics) can cause the magnetic materials to be more heavily saturated, causing currents to increase and temperatures to rise, possibly shortening the life of the inductive device, maybe even damaging it.

Even-numbered harmonics cause d.c. currents to flow in transformers and motors, increasing the saturation of their magnetic cores and thereby increasing their magnetising current and their 'copper losses'. This makes them less efficient and causes overheating that can lead to the tripping of protective devices, reduced life and even damage. As a result, even-order harmonics are now tightly controlled by limiting the use of half-wave rectification in products.

Eddy current losses ('core losses') in magnetic materials are proportional to the square of the frequency; another cause of overheating when applying distorted mains waveforms to transformers and motors.

And because triplen currents add constructively in the neutral cables, supplying single-phase loads with distorted waveforms tends to increase the heating in the neutral cables, possibly helping to cause smoke or fire hazards in building which don't have over-sized neutrals and which are already suffering from high levels of triplen currents.

Rotating fields and torques

The harmonic and interharmonic components of distorted mains waveforms in three-phase systems create magnetic fields in transformers and motors that rotate faster than those caused by the fundamental. Some of them rotate in the same direction as the fundamental fields ('positive sequence'), but some rotate in the *opposite* direction ('negative sequence'). Triplens do not give rise to a rotating field, but they do create a pulsating 'zero phase' magnetic flux that can help drive the magnetic material into saturation (see above).

Such unwanted rotating fields in motors have a direct effect on their rotors, which try to follow all of the fields they are subjected to at the same time. The result is a so-called 'ripple torque' – a mechanical vibration or oscillation of the motor shaft. This can be a cause of excessive bearing wear and annoying acoustic noise, but serious problems can arise when the frequencies of the vibration come near to, or coincide with, a natural resonant frequency of the shaft and the mechanical load it is driving. Machines can literally shake themselves to pieces very quickly, or snap their drive shafts through exceeding their expected lifetime's metal fatigue in just a few weeks or months.

Acoustic noises

Even very well-made transformers and motors emit acoustic noise as their core material changes shape due to the magnetostrictive effect. When they are fed with pure sinewave fundamental frequencies they merely hum at 50 or 60Hz, usually a fairly tolerable noise. But when fed with distorted waveforms the hum turns into a much more objectionable buzz because the human ear is more sensitive to frequencies above 50Hz.

Also, products are often of a size that makes them more efficient radiators of acoustic noise at harmonic and interharmonic frequencies, especially because audio resonances commonly occur in the range 200Hz – 2.4kHz.

Nuisance tripping of fuses and circuit breakers

Distorted mains waveforms will give rise to distorted currents even in linear loads. It was shown earlier that capacitors to which distorted voltages are applied consume higher levels of higher-frequency currents. Transformers and motors can also consume more high-frequency currents if the waveform causes their magnetic materials to saturate more.

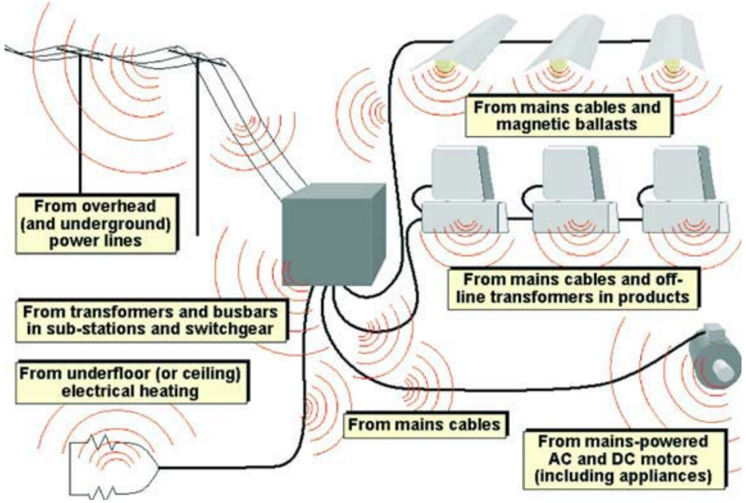
So distorted waveforms can cause fuses, circuit breakers or other overcurrent protection devices to (correctly) trip to protect from overheating, despite that fact that the load – calculated on the assumption of a pure sinewave supply – would seem to be well within the rating of the device. This can lead some people to fit fuses with larger ratings, risking damage, smoke and even fire.

A particular problem here is the use by site electricians of average responding meters, that are only accurate when measuring a sinewave fundamental. All such meters should immediately be sent for recycling, and replaced with meters that measure true-RMS for frequencies up to at least 2kHz, preferably 10kHz or more.

Noise induction from magnetic fields

Distorted mains waveforms lead to the flow of non-linear currents, and these currents create magnetic fields at the distortion frequencies. These magnetic fields can induce noise voltages into circuits in nearby (unrelated, unconnected) products and possibly interfere with their operation.

Magnetic and electric field emissions at the mains' fundamental frequency, plus its harmonic and interharmonics



This can be a problem for all circuits, analogue or digital – but analogue circuits with a high signal-to-noise specification, or that are especially sensitive, are more likely to be affected.

Magnetic field noise induction is more likely where phase and neutral conductors are separated, for example near overhead LV, MV or HV transmission lines; switchyards; busbars in sub-stations, mains distribution cabinets and rooms; high-power electrical cubicles; 'risers' in tall buildings; electric blankets; underfloor heating; and anywhere in an electricity generating plant.

Significant magnetic fields can also be generated near metal structures forming part of a building, site or vehicle, due to stray or accidental 'earth leakage' currents (see later).

Audio frequency induction loops are often fitted in public buildings (banks, theatres, cinemas, courtrooms, churches, etc.). These systems create magnetic fields directly corresponding to the audio signals to be communicated, which are then picked up sensitive magnetic pickups ('T' coils) in the hearing aids. Hearing aid wearers switch to their T-coil setting to pick up the signal.

50 or 60Hz sinewave 'hum' is too low in frequency for most hearing aids to reproduce or most people to notice if they did. But unfortunately, mains harmonics and interharmonics lie in the audio frequency spectrum, and the peak sensitivity of the human ear is in the region around 1kHz (the 20th harmonic of 50Hz).

Manufacturers of audio frequency induction loops often have problems in achieving adequate audio signal quality in the hearing aid, because of the stray magnetic fields in the audio range created by mains cables carrying distorted voltages and currents [21]. Telephone cables can also pick up significant amounts of noise form nearby mains cables, through magnetic field coupling.

Magnetic field coupling increases in effectiveness in linear proportion to the frequency, so higher frequency harmonics or interharmonics couple more strongly than lower frequencies of the same magnitude. For example, a 17th harmonic (850Hz in a 50Hz system) with a level of 1% of the fundamental, would magnetically couple into a cable or circuit with a level of 17% with respect to the coupling at 50Hz.

EN 61000-4-13 does not test for magnetic field coupling (but see later).

Noise induction from electric fields

Electric fields created by distorted mains waveforms can induce noise currents into sensitive or high-impedance circuits, or into long cable runs (e.g. for telephones, industrial transducers, etc.).

As for magnetic fields (above), electric fields are more likely to induce noise currents in nearby (unrelated, unconnected) products where phase and neutral conductors are widely separated. Typical situations include the proximity of overhead LV, MV or HV transmission lines; switchyards; busbars in sub-stations, mains distribution cabinets, rooms and high-power electrical cubicles; electric blankets; and anywhere in an electricity generating plant.

Electric field coupling increases in effectiveness in linear proportion to the frequency, so higher frequency harmonics or interharmonics couple more strongly than lower frequencies of the same magnitude. For example, an 11th harmonic (550Hz in a 50Hz system) with a level of 1% of the fundamental, would electrically couple into a circuit with a level of 11% with respect to the coupling at 50Hz.

EN 61000-4-13 does not test for electric field coupling (but see later).

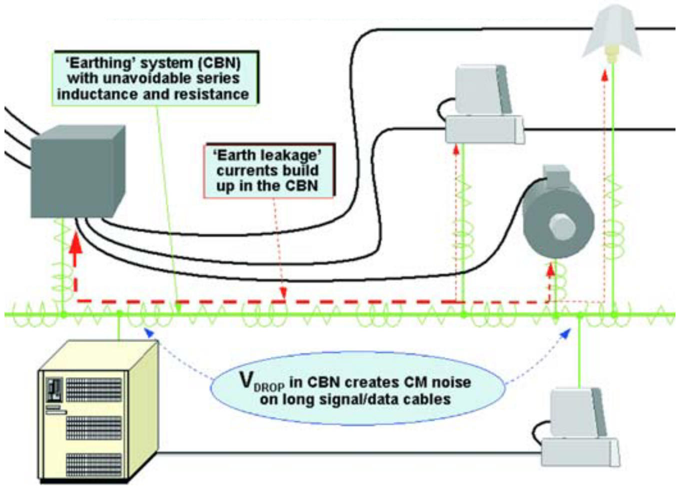
Earth/ground noise voltages on external signal and data cables

Within a building, vehicle or other structure

Currents flow in the protective earth conductors – often mainly due to leakage from RFI filters. Currents of up to 70A due to filter leakage have been measured in the main protective earth terminals of large office buildings – due to the thousands of PCs and VDUs installed there, each one with a few milliamps of 'earth leakage' from its RFI filter. Industrial and military installations, and EMC test laboratories often use filters with much greater leakage, maybe even amps. Also, it is not unknown for there to be accidental neutral-to-earth short-circuits in a building, so part of the neutral current flows in the common bonding network (CBN), often referred to as the 'earth' or 'ground' system.

As these currents flow in the inevitable impedances in the CBN, they give rise to voltage drops between different locations, and the products situated in them. Harmonic and interharmonic distortion of the mains waveforms means that CBN currents also contain harmonic and interharmonic frequency components, so the earth/ground potential differences (noise voltage) between products also contain these frequencies.

Common-mode signal and data noise voltages caused by mains harmonics and interharmonics



But the harmonics and interharmonics currents in the CBN are worse than might be expected, because most of the earth leakage current is created by mains filter capacitors that have lower impedance at higher frequencies, so their leakage current doubles for every doubling in frequency. This means that the earth/ground potential differences between products have the proportion of their higher frequency components amplified, compared with their proportions in the distorted mains waveform.

For example, a 13th harmonic (650Hz in a 50Hz system) with a level of 1% of the fundamental, would be likely to cause earth/ground noise between items of equipment with a level of 13% with respect to the noise created at the fundamental frequency.

Another issue is that as frequencies rise above 1kHz the impedance of most cables begins to be dominated by inductance, not resistance, so the earth/ground noise voltage between products in a building rises even faster as the noise frequencies increase above 1kHz.

The earth/ground noise voltage between products becomes important when signal or data cables connect the products. The noise appears as a common-mode voltage on the signal or data conductors, and can cause interference. EN 61000-4-1 [22] states that this problem may occur due to waveform distortion, but EN 61000-4-13 does not test for this (see later).

Between buildings or other structures

Low voltage power distribution connects the neutral to the earth at each building. As a result a portion of the neutral current flows in the earth connection (usually the protective metal jacket of an underground cable) and in the soil between the buildings. The result is similar to what was discussed above, but this time with intentional neutral-to-earth connections, and long distances – so there can be very significant common-mode earth/ground 'noise' voltages between buildings, a problem for any signal or data cables that interconnect them.

On a larger scale, MV and HV distribution interconnect the more numerous LV networks, and they also generate earth/ground noise voltages on a geographical scale. The waveforms of MV and HV transmission lines tend to suffer less waveform distortion than the LV networks, but their electric and magnetic fields tend to couple with the soil under the lines – another source of earth/ground noise voltages.

A few signal or data cables are routed over such large distances – the most common example being telephone wires. Depending on the type of circuits they use, the telephones may be more or less susceptible to the common-mode earth/ground noise caused by harmonic and interharmonic distortion of the mains voltage waveform. And they may also be susceptible to the magnetic and electric fields from nearby overhead cables – after all, they often use the same poles. [13] describes the problems of telephones in more detail, and gives a useful reference.

As was mentioned above, the earth/ground noise voltages as well as the magnetic and electric fields coupling all increase as the frequency increases, so even low levels of high-order harmonic distortion frequencies can cause high levels of common-mode noise and/or field coupling.

Problems for electronic products

Many industrial, commercial and domestic products, particularly those controlled by electronic controllers, use the zero-crossings of the mains waveform to measure the fundamental frequency or to control power converters [13]. Mains waveform distortion can cause frequency measurement problems in timers, clocks (including domestic clocks) and uninterruptible power supplies (UPSs) – not forgetting the rapidly increasing number of 'green power' converters that interconnect an alternative source of energy (such as domestic CHP, see earlier) to the public mains supply.

Power converters that can suffer from distortion around the zero-crossing point include phase-angle controlled thyristors or triacs used in a variety of domestic, commercial and industrial products, from very low to very high powers. But many other types of power electronic controllers exist and can be upset by spurious zero crossings, including all d.c. motor drives supplied via three-phase rectifiers.

Bridges that use inverse cosine control circuits are particularly susceptible to zero-crossing distortion. An example is the automatic voltage regulator (AVR) on synchronous electricity generators. There have been reports of loss of generator voltage control where there was significant distortion of the mains voltage [13].

Electronic products that do not measure the frequency of the mains, and which also do not rely upon detecting the zero-crossings or any other characteristics of their mains waveform, can be quite resistant to harmonic and interharmonic distortion of the voltage at their mains

inputs. But most such electronic products use rectifier-capacitor mains input circuits, and they can have some problems.

The major problem with distorted mains waveforms occurs when the 'crest factor' (the ratio of peak to RMS) is too low. (The crest factor for a sinewave is 1.414.) Their mains input circuits charge their capacitors up to the peak mains voltage, and couldn't care less about the RMS voltage. But 'clipped' (or 'flat-topped') mains waveforms are a standard feature of mains networks heavily loaded by rectifier-capacitor loads, and in some places the mains waveshape is closer to a square wave than to a sine.

Products are rated by the RMS value of the mains voltages (for example 220-240Vac) – but when the peak value is depressed by flat-topping, a product can find its unregulated voltage rail a lot lower than its designers were expecting. As a result, it might not function near the bottom end of its input voltage range.

This is usually less of a problem for products designed for global markets with switch-mode power supplies that will operate with mains voltages from 100-240Vac (or, better still, 90-270Vac to cope with supply tolerances in both Japan and the UK).

Apart from low crest factors (flat-topping), the remaining harmonic or interharmonic problem with rectifier-capacitor loads is due to overvoltages. Overvoltages (called 'over swing' in EN 61000-4-13) are most likely to occur when network resonances happen to coincide with a significant harmonic or interharmonic. The result can be peak voltages that exceed the maximum ratings of the rectifiers, capacitors, mains filters, or other components connected to the primary circuit (e.g. the primary switcher in an off-line switch-mode power supply). It is also possible for high levels of high frequencies (usually due to system resonance) to overheat the RF filters or pass through the power supply to interfere with the circuitry.

The author has experienced an industrial plant where switching currents from a new inverter drive happened to excite a resonance in another branch of the factory network, causing 15 Volts peak-to-peak at 20kHz that caused a microprocessor controlling a packaging machine to crash. A low-frequency differential-mode filter quickly solved the problem, but suppression of the motor drive emissions would have been a better solution.

It is a problem that there are (as yet) no standards listed under the EMC Directive that place limits on emissions between 2 and 150kHz. As a result, many manufacturers simply ignore their product's emissions in this frequency range – which also happens to be a range in which mains network resonances can arise.

All electronic products can also suffer from interference due to electric and magnetic field coupling from distorted mains voltage and current waveforms, especially sensitive circuits – including many types of audio product (even loudspeakers with nothing connected to them) and control circuits (e.g. for switching thyristors). Field coupling was discussed earlier.

Common-mode earth/ground noise voltages can also interfere with a product's external signal or data connections. This was discussed earlier.

A big problem with warranty claims and field service is the 'no-fault-found' customer return. Many manufacturers spend considerable amounts of money to try to keep their customers happy, despite not knowing what the cause of the problem is. Many no-fault-found problems appear to be caused by inadequate immunity, but interference events can be hard to repeat, and not many people know enough about EMC to even think of this possible cause, much less correctly identify such problems.

The financial rewards of producing products with adequate immunity can be very great indeed, as one UK manufacturer discovered when they spent £100,000 on redesigning their products to comply with the new issues of the EMC Directive's immunity standards around mid-2001, and found to their complete surprise that their products' new designs saved them £2.7 million in warranty costs *per year*.

But complying with any immunity test standards does not necessarily guarantee sufficient real-world reliability. This can be a problem for safety-related equipment and systems, or for equipment and systems that require very high reliability (such as speed cameras and 'internet hotels'). Mere compliance with the EMC Directive is often insufficient for ensuring that products have been designed and tested well enough for these issues – additional and/or tougher immunity requirements may need to be applied. This is too large a subject to discuss here – for more, refer to [23] [24] [25] and the IEE's training course on 'EMC for functional safety, high reliability and legal metrology' [26].

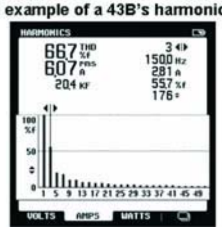
If it is suspected that mains waveform distortion is a cause of failures in the field, a survey with appropriate power quality measuring instruments can discover what events are occurring and where they are being generated. An oscilloscope is a very powerful tool, and there are digital multimeters made by Fluke and others that will give a visual display of the mains waveform and/or a graph of its spectrum. There are also portable oscilloscopes made by Tektronix and others for power engineers, which provide spectrum analyses and digital multimeter functions too.

Mains distortion analysers can be used instead, and where accurate and traceable measurements are required they should comply with EN 61000-4-7 and be regularly calibrated. However, instruments designed for measuring harmonics may well not detect interharmonics. On an oscilloscope, harmonic distortion shows as a distorted waveform – not a pure sinewave – although it is difficult to detect low-order harmonic distortions of less than 3% by looking at a 'scope screen. But interharmonics show up as a ripple or flicker, or even a slow fluctuation in the level of the waveform, and maybe as an unstable waveshape instead/as well.

Safety Note: When measuring mains voltages or currents, only use probes and equipment that are proven to comply with the appropriate parts of EN 61010 for the appropriate 'Measurement Category' (previously known as 'Overvoltage Category' or 'Installation Category'). Measurement Category II is the *minimum* requirement, and Category III or even IV may be required for safety.

Examples of some low-cost mains distortion analysers

Fluke 43B and 41B
and an example of a 43B's harmonics display



A TekScope® THS720P

If you don't understand exactly what this means, have someone who is qualified and competent in this area sort it out for you. In some installations, special working procedures may be required. Electrical and electronic engineers are killed every year by mains electricity – don't let it be you!

Sometimes the problems are intermittent, and automatic monitoring equipment will need to be left to monitor the mains quality for days, weeks, even months. A problem with any automatic power quality monitoring equipment is that if it is not set up correctly, it will soon fill its memory (or use up all of its paper) recording useless data.

If you are not skilled in these matters, and if you don't want to spend time and money going through a learning curve – instead of hiring power quality monitoring equipment from one of the many companies that provide it – hire a power quality consultant instead and have him/her do the work using their own equipment, analyse the results and produce a report.

AVO-Megger PA9plus, a mains harmonics and power quality test instrument

Introduction

This booklet is not a complete recital of everything that is in EN 61000-4-13, only a general guide. Anyone performing tests to this standard must have a copy of its relevant version (including any amendments), and follow it exactly.

The test generator

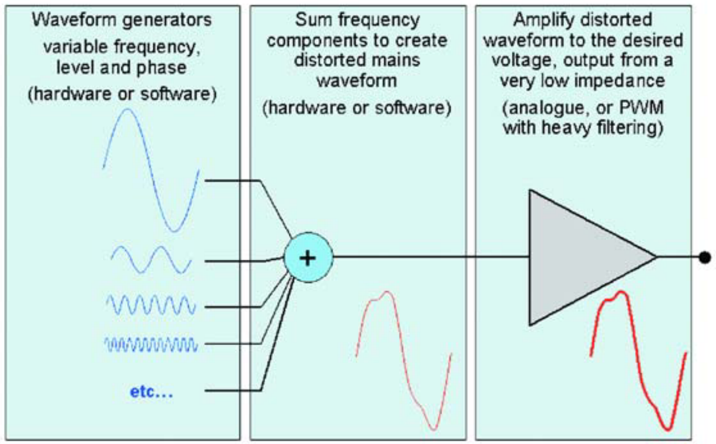
Clause 6 and tables 5 and 6 of EN 61000-4-13 specify the characteristics of the test signal generator, and these specifications will not be repeated here. Basically, the test signal generator consists of a waveform generator amplified by a power amplifier to synthesise a mains waveform. When the waveform generator outputs a 50Hz sinewave, the power amplifier outputs up to 16A at 50Hz at the nominal mains voltage (e.g. 230V rms), for powering the Equipment Under Test (EUT).

A common term for a power amplifier intended for providing mains power is 'mains synthesiser', but EN 61000-4-13 calls it an "AC Source". The term 'power amplifier' is used in this booklet as being more uniquely descriptive of the function provided.

The waveform generator can be controlled to produce fundamental frequency sinewaves with various amounts of distortion, by adding specified amounts of harmonic voltages, at specified phase angles, to the fundamental signal. The resulting distorted fundamental waveform is in turn amplified by the power amplifier and used as the mains source to power the EUT.

An early (1968) mains harmonic immunity tester consisted of a bank of 40 transistor oscillators producing individual frequencies from the 50Hz fundamental through all of the odd and even harmonics up to 2kHz. These 40 signals were mixed together in various proportions using an array of linear potentiometers (looking much like an audio mixing desk) to produce a single distorted waveform that was fed to a1kW linear amplifier that used thermionic valves operating in Class A.

The essentials of a test signal generator (analogue or digital)



These days the oscillators are more likely to be created in software running on a microprocessor, with the resulting 'distorted mains waveform' signal supplied in pulse-width-modulated (PWM) format to the switch-mode power converter that provides the 16A output at up to 250V rms phase-to-neutral (for example). The software will most likely be under computer control, so that individual harmonics or combinations or them can be added in various proportions, using mouse or keyboard controls, and so that sequences of pre-set distorted waveforms can be run in real time.

It is easy to set-up a suitable test generator using laboratory bench equipment: for example an arbitrary waveform generator feeding a suitably-rated power amplifier, but some test equipment manufacturers supply single-box solutions with all the pre-programmed test waveforms and on-screen user interfaces to make them easy to use for EN 61000-4-13 testing.

Please note: power amplifiers intended for audio use are usually not suitable as mains power sources for equipment, even if they have apparently suitable ratings, as the author can attest from bitter experience. Always check that the power amplifier is actually designed to be used as a mains power supply.

Where three-phase equipment is to be tested, the waveform generator outputs three identical distorted waveforms with 120° phase angles between their fundamentals, and three power amplifiers provide the power to the EUTs.

The test generator should be filtered or otherwise prevented from distorting its 'clean' mains supply, so that it does not affect the auxiliary equipment and test gear used during the testing.

An example of a test generator for EN 61000-4-13, from California Instruments

But clause 6.1 and Table 5 of EN 61000-4-3 do not specify the amount of RF noise that is permitted on the generator's output(s). These should have low levels of RF noise so that they do not interfere with any type of EUT and confuse the results of the test. But modern test generators almost always use pulse-width-modulated switch-mode techniques in their power amplifiers to generate their output signals, and as a direct result their outputs contain huge levels of RF energy. Very effective RF suppression will be required at the outputs (and inputs) of such generators.

Verifying the test signal generator

Clause 6.2 and Table 6 in EN 61000-4-13 specify how the generator's characteristics should be verified, at the output terminals of its power amplifier(s) when driving the EUT with the fundamental frequency (no added distortion) *before* testing an EUT. The harmonic distortion limits of Table 6 should be checked by a harmonic analyser that complies with IEC 61000-4-7, accuracy class A.

An oscilloscope and a true-rms meter should be used to check that the peak voltages are within 1.40 and 1.42 times the rms value of the waveform, and they occur between 87° and 93° after each zero crossing. The maximum output voltage change between no load (EUT disconnected) and the EUT at maximum load should be less than 2% of the nominal voltage.

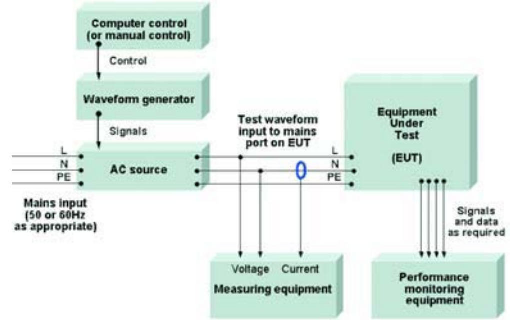
The test set-up

The test set-up is specified in clause 7 and figures 2 and 3 of EN 61000-4-13. Basically, the outputs from the test generator are simply connected to the mains input of the EUT.

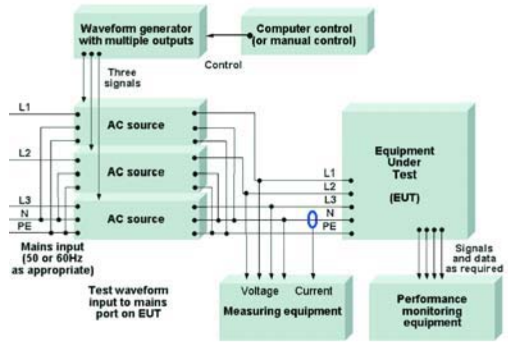
Because this test does not use RF it is possible to perform it anywhere, with almost any variety of physical arrangements, and still achieve correct results. This makes it a test that it is easy and low-cost for a manufacturer to perform, since it does not need shielded rooms, anechoic chambers, costly RF test gear, or test engineers who have RF skills.

For example, the length of the cable from the power amplifier (mains synthesiser) to the EUT is not specified. In practice, to accurately control the levels of harmonics applied to an EUT it would be wise to keep this cable length to less than one-fiftieth of the wavelength of 2.4kHz in a PVC mains cable – about 1500m. So mains cable lengths of up to 1km between power amplifier and are perfectly acceptable – few manufacturers or test laboratories will need to use longer cables!

Example of test set-up for single-phase equipment



Example of test set-up for' three-phase + neutral' equipment



The EUT should be connected in the normal manner and operated in accordance with the appropriate product or generic standard. Where no product or generic standard applies, the EUT should be operated in the mode that causes the greatest susceptibility to distorted mains waveforms. For flat-topped waveforms (Test A1) this will probably be the mode that consumes the most power, with the nominal mains voltage set to the minimum rated operating voltage. For over-swing waveforms (Test A2) it will probably be the mode that consumes the least power, with the nominal mains voltage set to the maximum rated voltage. For tests B, C1, C2 and D – if Test A2 was done using light load and maximum rated voltage – maximum load and lowest rated input voltage are probably the most susceptible.

Operational modes in which the mains supply is used for timing or control should also be employed. It may be necessary to repeat all of the tests with the EUT in its different operational modes, to be sure that all the potential susceptibilities of the EUT have been tested.

REO can create custom loads to meet any requirements

Test conditions and test plan

Clause 8.1.1 of EN 61000-4-13 states that tests can be carried out under any climatic conditions, as long as there is no condensation on the EUT and the conditions are within the manufacturers specifications for the EUT and the test equipment. Product and generic standards committees can impose climatic conditions when they call up this basic test standard, if they believe they can affect the test results.

EN 61000-4-13 does not mention a rather obvious fact – the electromagnetic (EM) environment in which the test is being conducted should not be so severe as to interfere with the EUT. Such situations make it difficult to tell whether it is the environment or the test that is causing its functional performance to go out of specification (see later).

Clause 8.1.2 requires a test plan to be prepared before starting to test an EUT. It is always a good idea to create a test plan well beforehand anyway, to help identify testing requirements ahead of time, to avoid wasting time sorting out unforeseen problems whilst paying premium test laboratory rates.

A list of test plan contents is recommended in clause 8.1.2, but this list is not mandatory (although some sort of test plan is required for full-compliance testing). This list is not repeated here (refer to [1] or [2]) – but it is a very basic list and it would be hard to argue against omitting any of the listed items.

Clause 8.1.2 also requires that monitoring equipment is provided to measure the functional performance of the EUT during and after the tests. It is very important for a test plan to determine what monitoring equipment is required, and how it needs to be set-up and used, to help avoid wasting testing time during testing.

Monitoring the EUT for performance degradation during the tests

The functional performance degradation allowed during and after the tests may be specified by product-family or generic standards. Lacking these, the results should be evaluated according to clause 9 of EN 61000-4-13 (see later).

Well before the tests are begun, the functional specifications for the product should be defined, and serious thought should be given to how to monitor the product's performance during the tests with the required levels of accuracy and repeatability to be sure whether the functional spec's are actually being met. This helps determine whether any special testing arrangements need to be organised, equipment hired, special cables and leads made up, etc., etc.

An accredited test laboratory should be able to provide basic electrical test gear (check with them first) that is immune enough to the influences of these tests. But where test instruments are provided by the manufacturer (e.g. signal or distortion analysers, display screens, computers, etc.) long periods of time are often spent trying to decide whether it is the EUT or the test equipment that is failing, all the while burning money at premium test laboratory rates.

Also, test laboratories book their time weeks (or even months) in advance, allocating customers testing timeslots that *should* be long enough to perform the required tests. Where customer-supplied functional test equipment is upset by these immunity tests, and no quick fixes seem to work, it is possible to run out of time trying to fix the susceptibility of the test equipment, then having to wait a few weeks (maybe months) until another timeslot can be booked to test the product.

Classes of equipment

Annex C of EN 61000-4-13 specifies three Classes of equipment according to their likely exposure to harmonics and interharmonics in their mains supply.

Class 1

This is for products connected to specially protected mains power supplies, where the levels of harmonic and interharmonic distortion are – *by design* – significantly less than that on the normal mains.

Uninterruptible Power Supplies (UPSs) are often used to create such protected mains supplies, but it is important to realise that not all types of UPS provide low-distortion output waveforms. Some of them create mains power that is more distorted than their original mains supply. Some types even feed distorted mains voltages through to the product for most of the time. So, when purchasing a UPS to create a specially protected mains power supply, always check the output specifications and mode of operation very carefully beforehand.

Class 2

This is for products connected to 'points of common coupling' in consumer systems and industrial plants.

Annex C does not mention commercial premises, despite the fact that some of them (e.g. theatres for live stage shows, mobile concert installations, etc.) can have mains supplies that are much 'noisier' than many industrial plants due to their use of hundreds of kW, even MW, of power converters for stage lighting, moving heavy stage sets around quickly, audio power amplifiers and HVAC. Such installations should be Class 2 unless Class 3 (see below) is more appropriate.

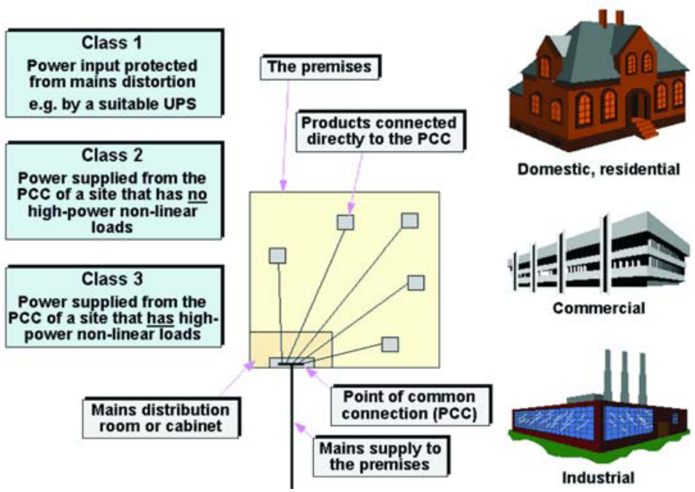
A point of common coupling (PCC) in a domestic house would be the 'consumer unit' (more usually called 'the fusebox' or the 'meter cupboard' by the residents). In a large commercial building or industrial plant the PCC would be in the distribution room.

But not all products are connected in this way – some may share their mains conductors with other equipment, and if this equipment is a significant emitter of harmonic currents the impedance of the conductors back to the point of common coupling can be enough to worsen the voltage distortion seen by the product.

For example, domestic premises in the UK use 'ring main' supplies, in which large numbers of electrical and electronic equipment can be powered from one cable that connects to the PCC at both of its ends. The voltage distortion of a product connected along this ring can be worse than that at the PCC.

EN 61000-4-13 seems to assume that all Class 2 equipment has its own dedicated mains conductors leading to the buildings PCC, and does not address the problem of shared mains conductors. So where Class 2 products might share their mains conductors with non-linear loads that could emit significant levels of harmonics (possibly even including loads that have harmonic emissions complying with EN 61000-3-2), the author recommends testing them with higher levels than are required by Class 2. Even applying Class 3 levels (see below) might be not be inappropriate.

The various classes of product in EN 61000-4-13



Class 3

According to EN 61000-4-13 Annex C, Class 3 is only for products connected to PCCs in certain kinds of industrial environments. These environments differ from those covered by Class 2 in that they have either…

- a major part of the load fed through converters, or…
- welding machines, or…
- large motors that are frequently started, or…
- loads that vary rapidly.

As was mentioned above, some *commercial* premises can have a major part of their load fed through converters too (e.g. theatres for live stage shows, mobile concert installations, etc.), and Class 3 may be appropriate for such installations too.

Note 1 to Class 3 in Annex C says that the supplies to highly disturbing loads, such as arc-furnaces and large converters, that are generally supplied from a segregated bus bar frequently have disturbance levels in excess of Class 3. This seems to acknowledge that some products might be powered from the same cables that feed highly non-linear loads, as was discussed in the section on Class 2 above. The harmonic and interharmonic levels they are exposed to could be higher than those assumed by Class 3.

Note 1 goes on to say that in such special situations, the tests and test levels should be agreed upon, using the Class X facility provided in EN 61000-4-13.

Class X

This level is left unspecified (usually called 'special' in other EN/IEC basic immunity standards) for use by industrial product standard committees, or by customers who wish to specify higher levels of immunity in their contracts.

All of the tables in EN 61000-4-13 that specify the Class 1, 2 and 3 tests have a column for Class X that is filled in every case with the word 'open'. This signifies that each of the Class X specifications can be chosen at will by the product or generic standard committee or by the customer (in the technical specification that forms part of his contract).

Class X might also be useful in situations not covered by the three classes above.

Not all types of low voltage mains supplies are covered by the three classes

The scope of EN 61000-4-13 (clause 1) implies that it covers all types of low voltage mains distribution networks, but the three Classes specified by Annex C only address mains networks that are fed via MV or HV transformers from a 'national grid' structure. The impedance at the PCC for such systems is very low, so the harmonic and interharmonic currents emitted by non-linear loads do not have a *very* great effect on the distortion of the (nominally) sinewave voltage provided.

But, as was discussed earlier, many types of products may be required to operate from local generation from time to time, and some products may have to operate on local generation all of the time. The higher source impedances at the PCC mean that non-linear loads cause increased levels of voltage distortion. Such products are not covered by EN 61000-4-13.

Another situation not covered by the three classes above is when the product is not connected to the site's PCC. This is commonplace in many premises in the UK where 'ring mains' circuits are used to power numerous sockets from one cable connected to the PCC at both of its ends. In industrial sites arises it is commonplace for an electronic product (e.g. a temperature measurement and control unit) to be associated with high-power equipment and supplied by its own mains power. Such units will experience more mains distortion than if they were connected directly to the PCC of their site.

The electronic products in 'control cabinets' used in a wide variety of commercial and industrial power-control applications only connect to the PCC by a long cable that is also carrying the currents of the load that is being controlled. Luminaires are typically connected in series along a long length of mains cable, rather than each being connected to the PCC by its own cable. Such products will suffer more mains distortion than if they were individually connected directly to a PCC.

Where local generation or non-PCC connection obtains, it is always best to perform a detailed analysis and/or measurement of the mains distortion and specify appropriate test levels using Class X. Computer analysis is not very difficult (although it may be tedious), using SPICE or similar circuit simulators, if sufficiently accurate data exists on a network and the loads connected to it. If all the resistances, inductances and capacitances are included, for the loads too, it should be possible to determine network resonant frequencies too.

Where detailed knowledge or measurement is lacking, but competent analysis indicates that the additional distortion should not be severe – where Class 2 would apply to PCC connected products it may be better to use Class 3 instead. And where Class 3 would apply to PCC connected products it may be better to use Class X with test levels at least 50% more than Class 3.

But where the additional distortion of the mains supply waveform is thought likely to be harsh – in the absence of any more detailed knowledge the Class X test levels should probably be at least double the Class 3 levels.

The six basic tests

There are six basic tests that can be applied by EN 61000-4-13, and they are labelled A1, A2, B, C1, C2 and D in this booklet for convenience. Which tests are applied depends up on the Class of the product, and also depends upon the test results achieved whilst going through the test sequence (see later).

As clause 8.1.2 says: “For each test, any degradation of performance must be recorded”.

The Harmonic combination test Tests A1 and A2

Clause 8.2.1 of EN 61000-4-13 describes what it calls the “harmonic combination” tests. There are two of these – the “Flat Curve” test (called Test A1 in this booklet), and the “Over Swing” test (called Test A2 in this booklet. Each test is applied for 2 minutes.

“Flat curve” Test A1

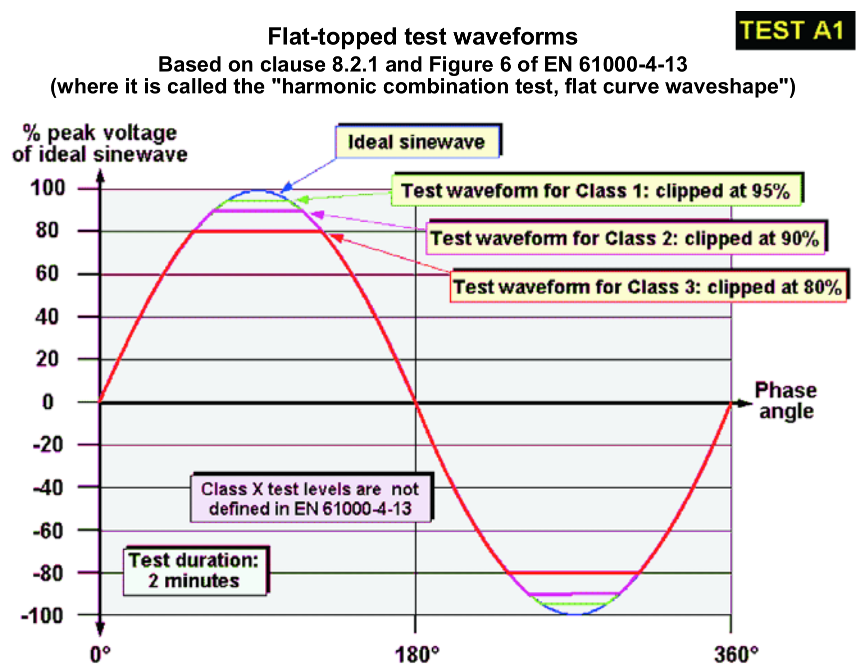
This is simply a 'flat-topped' or 'clipped' sinewave. It is typical of mains supplies that feed a lot of electronic equipment with rectifier-capacitor mains circuits. Class 1 products are tested with sinewaves that are hardly clipped at all (95% of their peak voltage); Class 2 are tested with sinewaves clipped at 90%; Class 3 are tested with a clipping level of 80%.

It is possible to specify (and create) a clipped sinewave as a combination of odd-numbered harmonics, all in-phase with the fundamental, but in these days of computerised arbitrary waveform generators it is more usual to specify it as 4 segments with different governing equations, as is done in Table 7 in EN 61000-4-13 (not repeated here).

“Over swing” Test A2

This is a waveform that combines the fundamental sinewave with various proportions of 3rd and 5th harmonics, the 3rd harmonic being 180° out of phase with the fundamental. Instead of the flat-topped waveform of Test A1 above, this waveform has a peak voltage higher than the peak of the fundamental sinewave (hence the term “over swing”).

Table 8 of EN 61000-4-13 specifies the various proportions of 3rd and 5th harmonics to be applied depending on the Class of the product.

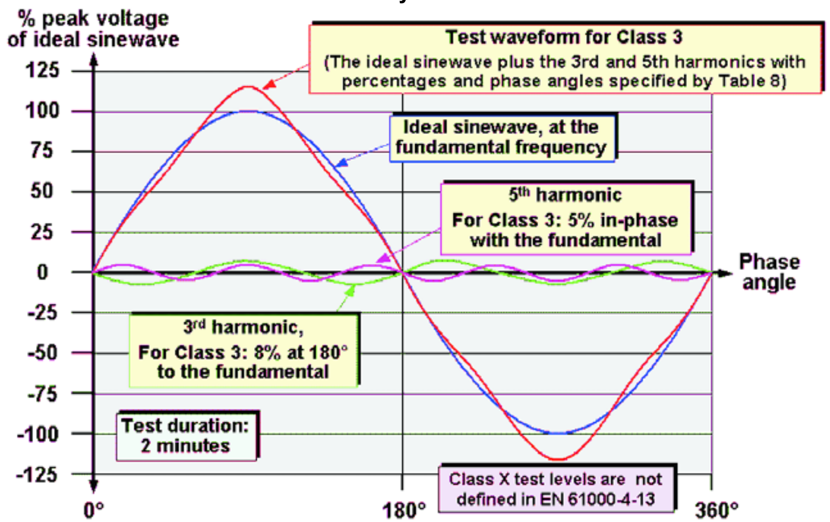


Harmonically distorted test waveforms

TEST A2

From clause 8.2.1 and Figure 7 of EN 61000-4-13
(where it is called the "harmonic combination test, over swing waveshape")

Class 3 only shown here



The "Sweep in Frequencies" test
Test B

This simply tests by adding a single frequency to the nominal value of the fundamental sinewave, in a proportion that depends upon the Class of the product. The added frequency is swept (if using an analogue signal generator) or stepped (if using a digital or digitally-controlled signal generator) over the range from 0.33 to 40 times the fundamental frequency.

Clause 8.2.2 of EN 61000-4-13 specifies the details of this test, including the fastest rate at which the test is to be performed – 5 minutes per decade of frequency, making the shortest test last a little over ten minutes. Table 9 divides the test into five 'sub-ranges' of frequency and for each sub-range specifies the step size and the test levels for each Class.

Phase relationships

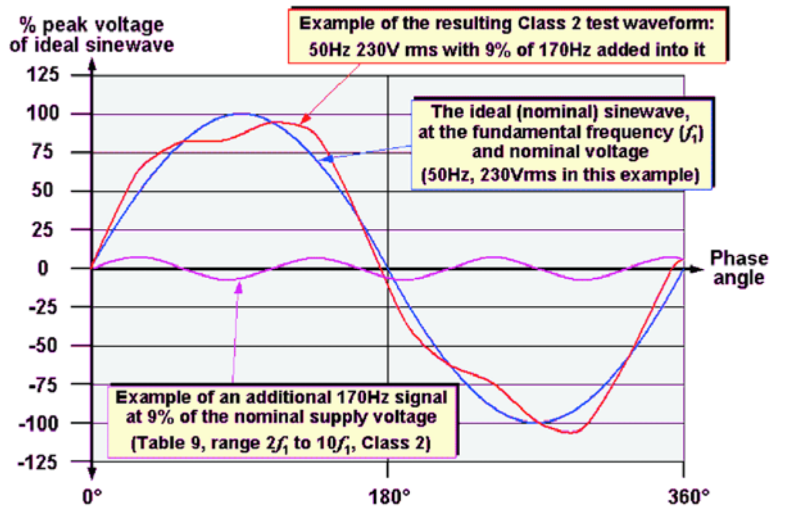
The phase relationship between the added frequencies and the fundamental is not specified in the standard, and indeed the concept makes no sense at all for interharmonics. For interharmonics the peaks of the resulting mains waveform will 'ripple' at the beat frequency between the fundamental and the added frequency.

But at harmonic frequencies the harmonic waveform is static with regard to the fundamental, so – if they are in-phase – odd harmonics will cause the peaks of the resulting waveform to be lower than nominal. But in-phase even harmonics will cause them to be higher. When the harmonics are in anti-phase, the effect will be reversed (odd harmonics causing higher peaks and even harmonics, lower).

Swept frequency test – an example wave form

TEST B

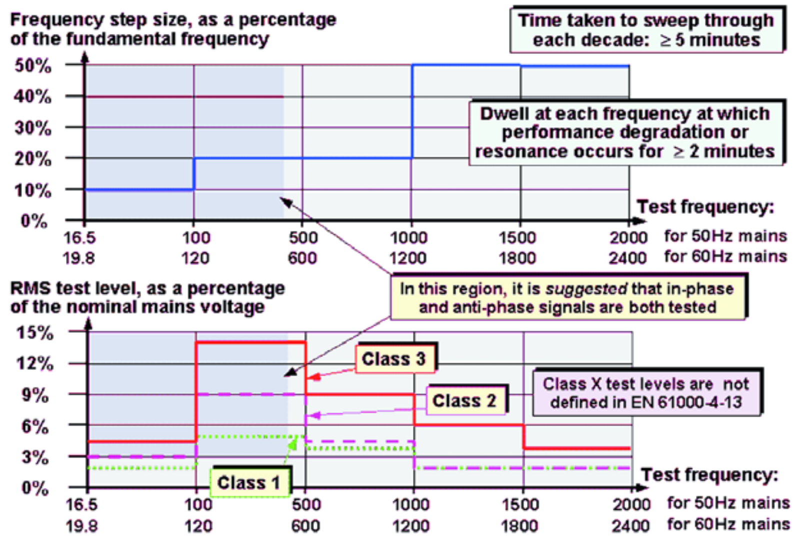
From clause 8.2.2 and Table 9 of EN 61000-4-13
(where it is called the "sweep in frequencies" test)



Swept frequency test – frequencies and levels

TEST B

From clause 8.2.2 and Figure 5 of EN 61000-4-13
(where it is called the "sweep in frequencies" test)



So, what phase relationship should be employed when adding the two harmonics used in Test B? It is suggested that the instructions for Test C1 (see below) are followed. These require all harmonics up to the 9th to be tested twice, once when they are in-phase and then again in anti-phase. Doing this covers the arguably worst-case combinations that can occur in real life, at the expense of extra test time.

Checking suspect frequencies

During this test, whenever a 'performance anomaly' is detected in the functioning of the product, the added frequency at that time is noted in a 'suspects' list.

During or after the main test (the programmed sequence of tests described above) any resonances are detected in the mains power supply to the EUT. Some commercial test equipment will automatically detect resonances during testing [27]. A resonance is detected by monitoring the current and voltage consumed by the EUT at the added frequency, using an oscilloscope (or other method) to view their magnitudes. If resonance is tested after the main test, it need not stick to the step sizes, sweep rates or test levels of the main test – they can be configured to best suit the test engineer and resonance monitoring method. Clause 8.2.2. gives the rules for deciding if a resonance has occurred, and they will not be repeated here. Any resonant frequency detected is also noted in the suspects list.

After the completion of the main and resonance tests, each of the frequencies on the 'suspect' list are applied for at least 2 minutes each, and the performance of the EUT monitored as usual.

The "Individual harmonics and interharmonics test" Tests C1 and C2

Clause 8.2.3 describes two tests – the individual harmonics test (called C1 here for convenience) and the interharmonics test (called C2 here).

Throughout both of these tests, the rms value of the resulting waveform is kept constant at the nominal mains voltage level chosen for the test. This is not like all the other tests in EN 61000-4-13 (called Tests A1, A2, B and D in this booklet), which require the fundamental to be set to the required rms voltage and then the harmonic or interharmonic superimposed upon it.

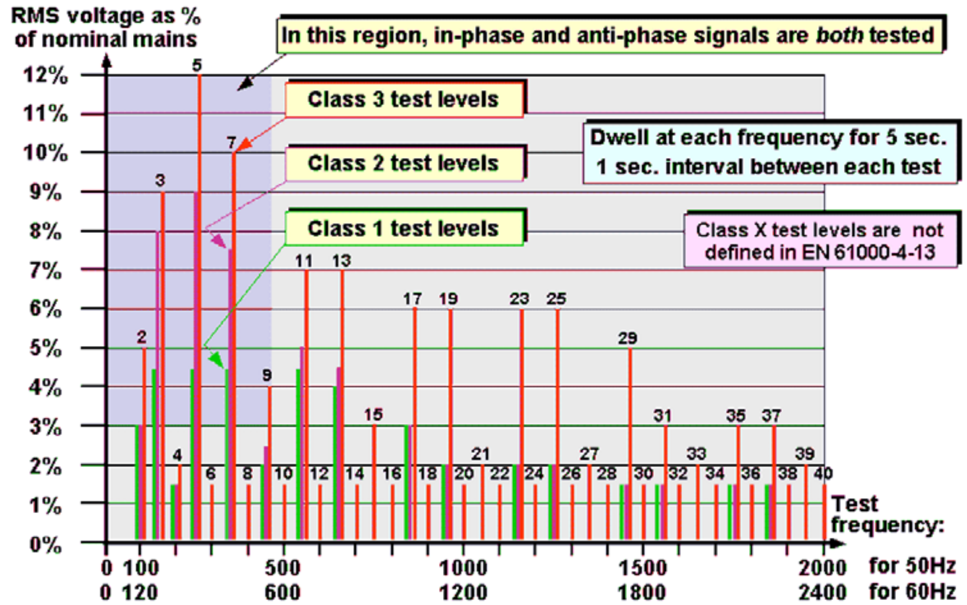
Individual harmonics Test C1

In this test, individual harmonics are added to the fundamental waveform, with their frequencies and levels set by Table 1 (odd-order harmonics), Table 2 (odd-order harmonics that are triplens) and Table 3 (even-order harmonics). Each distorted waveform is applied for five seconds, with a one second period of pure sinewave fundamental separating them.

According to clause 5 of EN 61000-4-13, the individual harmonics up to and including the 9th in Tables 1, 2 and 3 are tested twice – if they have a test level of 3% of more – one test when they are added in-phase with the fundamental, and the other when they are added in anti-phase. The phase of these low-order harmonics has a big effect on the resulting waveshape, either flattening or increasing the peak value.

TEST C1

Testing with individual harmonic frequencies
From clause 8.2.3 and Tables 1-3 of EN 61000-4-13
The RMS value of the resulting voltage (fundamental plus harmonic, or just the fundamental) must remain constant during the test



Interharmonics Test C2

This test adds interharmonics to the fundamental waveform, with their frequency ranges and levels set by Tables 4a and 4b. Table 10 sets the frequency step size for each frequency range, and each distorted resultant waveform is applied to the EUT for five seconds, with a one second period of pure sinewave fundamental separating them.

No guidance is given for the rate of change of frequency where analogue swept frequency measurements are used probably means that only stepped frequencies (with one-second periods of pure fundamental between each) should be used for full compliance tests.

But if analogue swept frequencies *are* used (for example, during 'pre-compliance' or QA testing) – the following sweep rates are comparable with the testing times resulting from Table 10…

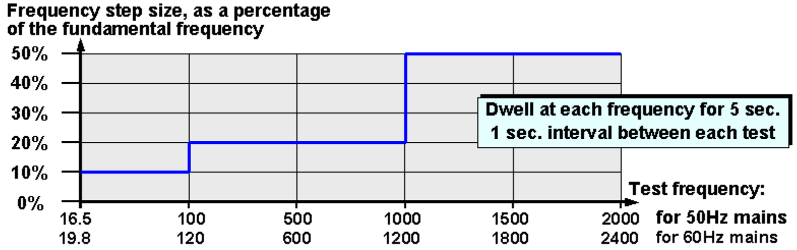
- 0.33 to $2f_1$ 3 minutes /decade
- 2 to $10f_1$ 8 minutes /decade
- 10 to $20f_1$ 25 minutes /decade
- 20 to $40f_1$ 10 minutes /decade

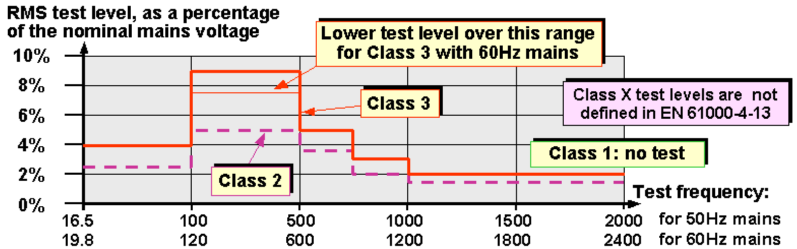
Testing with Interharmonic frequencies

TEST C2

From clause 8.2.3 and Tables 4a, 4b and 10 of EN 61000-4-13

The RMS value of the *resulting* voltage (fundamental plus harmonic, or just the fundamental) must remain constant during the test





The "Meister Curve" test Test D

This test is described in clause 8.2.4 of EN 61000-4-13, which says it is only applied to Class 2, 3 or X products that are to be used in countries where mains signalling and/or ripple control is employed on their mains networks.

This test is very similar to test C2 described above, but with generally higher test levels, and analogue sweep is permitted. Table 11 specifies the frequency ranges, frequency step sizes and test levels for this test. As for test B (see above) the frequency may be stepped or swept with a rate of no less than 5 minutes per decade.

The test sequence

Tests A1, A2, and B are quick tests that have a higher test level than tests C1, C2 and D.

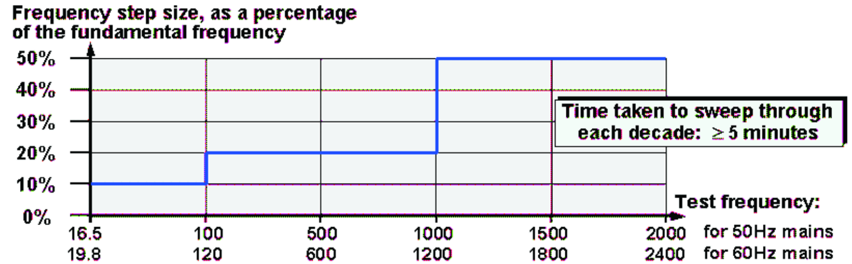
Figures 1a and 1b of EN 61000-4-13 show the logic behind the test sequences – Figure 1a for Classes 1 and 2, and 1b for Class 3. It is not stated which test sequence applies to Class X, but presumably it is Figure 1b. For *all* products, tests A1 and A2 are done first, and if an EUT fails them it has failed EN 61000-4-13. If the EUT passes A1 and A2, what tests are then done depends on its Class.

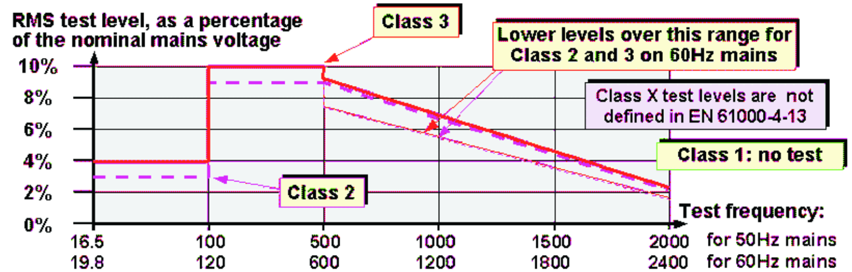
Testing mains signalling and ripple control

TEST D

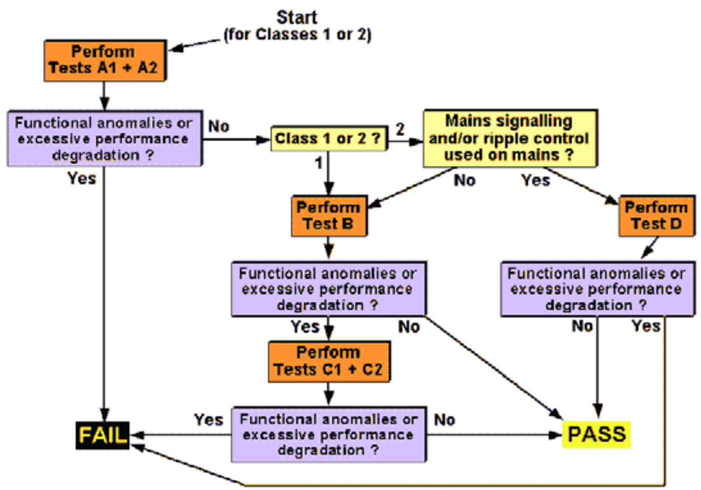
From clause 8.2.4 and Table 11 of EN 61000-4-13 (where it is called the "Meister Curve" test)

The RMS value of the *fundamental* voltage remains constant during this test

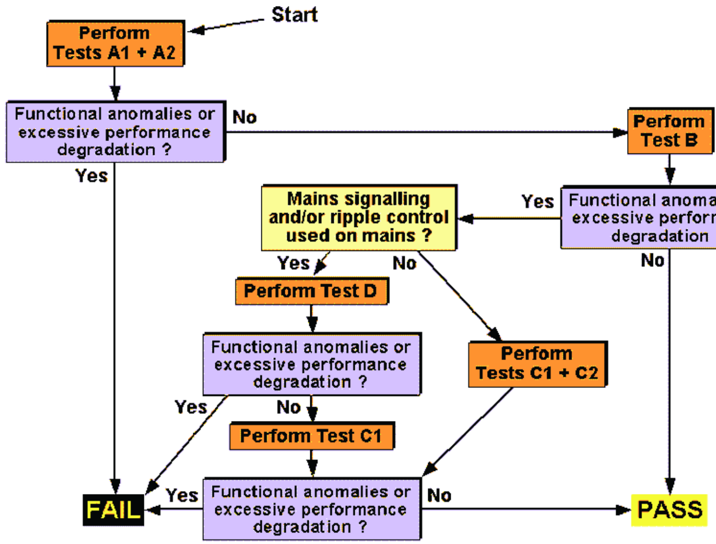




The test sequence for class 1 and 2 products



The test sequence for Class 3 products



Testing three-phase equipment

Clause 8.2.5 in EN 6100-4-13 covers the testing of multi-phase EUTs. It requires harmonic and interharmonic distortion to be added simultaneously to all line-neutral phases. The harmonic frequencies added to each phase must have the same phase relationship with the fundamental waveform of their phase. So the three distorted waveforms will be identical, just shifted by 120° of the fundamental mains frequency.

For three-phase EUTs without a neutral connection, EN 61000-4-13 does not require the triplen harmonics (3, 9, 15, 21, 27, 33) to be tested at all. This assumes that the source of the triplen harmonics on the mains supply is perfectly balanced, so that their triplen emissions cancel out in the three-phase supply, but this is often not the case in real life (see later).

EN 61000-4-13 does not say how to apply interharmonics to the three phases. Interharmonics do not have any phase relationship with the fundamental, as harmonics do. There appears to be a choice between applying a single interharmonic signal identically to all three waveforms at the same time – or else creating three interharmonic signals at the same frequency but each phase-shifted by 120° of the fundamental and added to the appropriate phase (as is done for harmonics).

Interharmonics created by fluctuations in the voltages on the d.c. links of AC-AC converters (e.g. inverter motor drives, frequency changers), and AC-DC or DC-AC converters, will tend to be simultaneously applied to all three phases with respect to the neutral. But other sources of interharmonics, such as mains signalling, might be different.

Some proprietary test generators apply the interharmonics to each phase with a time delay between each phase that is the same as 120° of the fundamental. This makes it easy to use a single arbitrary waveform generator to generate the three-phase test signals, but it may not be relevant to real life.

The method chosen should be relevant to the interharmonics present in the operational environment, or else relevant to the method that causes the greatest problems for the design of the EUT. The method that is used should be noted in the test report.

The external impedance network

Note 5 of Table 5 (Characteristics of the Test Generator), and Annex A of EN 61000-4-13 discuss the use of an external impedance network between the output terminals of the test generator and the input terminals of the EUT. The purpose of this is to make the test more comparable with real life by making resonances between the EUT and the mains network more likely.

Unfortunately, as was mentioned earlier, the recommended 'standard impedance' merely simulate the wiring and transformers in a network – they don't simulate the capacitances and inductances that will exist in real mains networks when all of their equipment is connected. Tests with such over-simplified networks would not have prevented the 'lifting crane' incident mentioned earlier [11].

But even if a product or generic standard committee did come up with an example network that simulated a real-life installation complete with all of its other loads, it will resonate at different frequencies than real-life installations, simply because every mains network with its loads is different in practice, and possibly different from time-to-time as well. So the resonances that are excited using a standard committee's external network will be different from the resonances excited in real life, and this will create very different waveshapes which might have different effects on EUTs.

Evaluation of test results

Clause 9 of EN 61000-4-13 requires the monitoring of the EUT's functions during each test to be assessed against performance specifications defined by its manufacturer (or the person who requested the test). It also requires the results to be classified according to the following scheme…

a) Normal performance within the specified limits.
b) Temporary loss of function or degradation of performance which ceases after the disturbance ceases, and from which the EUT recovers its normal performance without operator intervention.
c) Temporary loss of function or degradation of performance, requiring operator intervention to correct.
d) Loss of function or degradation of performance which is not recoverable, owing to damage to hardware, or software, or loss of data.

This classification is offered by EN 61000-4-13 as a guide to immunity standards committees if they call up this basic test method in their product or generic standards. It is very similar to the 'Performance Criteria' A, B, C (and sometimes D) already commonly used, which first appeared in the generic immunity standards.

Determining a PASS or a FAIL

Unfortunately, EN 61000-4-13 does not specify how to determine whether an EUT has passed or failed its tests. This is normal for the basic test standards in the EN/IEC 61000-4 series – but selling a product with a data sheet that says it achieves classification d) to EN 61000-4-13 is potentially misleading to an uninformed purchaser (and a joke to a purchaser familiar with the standard). Classification d) can never be associated with a PASS decision, in any case.

Most of the harmonics and interharmonics tested by EN 61000-4-13 can be expected to be continually present, or at least frequent in real life, so only classification a) will do for a PASS result in the test report (see below). There is no way that classifications b) or c) would be acceptable in such situations, because they would mean that the product would not function correctly, all or most of the time.

But some harmonics and interharmonics may only be present occasionally – for example mains signalling. For some types of product, in some applications, some functions may be allowed to degrade to classifications b) or even c) for harmonics or interharmonics that only occur intermittently.

Unfortunately, EN 61000-4-13 gives no information on which of its tests relate to infrequent distortions – and which do not. Also, its test sequences in Figures 1a and 1b (clause 8) do not permit the separation of test D, (which might be considered an intermittent disturbance) from tests B, C1 and C2, which are more likely to be considered continuous or frequent disturbances.

So, in the absence of any more specific information on the type of product and its application, it is suggested here that if the results of test D are to be judged PASSED or FAILED according to classifications b) or c) in clause 9 then tests B, C1 and C2 should all be applied (despite Figures 1a and 1b) and their results judged PASSED or FAILED according to classification a).

It is also suggested that a FAIL is recorded if the EUT becomes unsafe during any of these tests, emits any smoke, or otherwise displays unacceptable behaviour, even if the issue concerned is not covered in the agreed performance specification.

Test report

Clause 10 of EN 61000-4-13 describes what is to be included in the test report, for full compliance testing. This list is not repeated here.

It is a good idea to include details of the test generator verification (see above) and a judgement on whether the test generator is functioning correctly, either in the EMC Test Report or in some other QA controlled document. This is so that years later, when all the personnel have changed, it can still be discovered whether a particular test had been done with a fully working generator.

On-site testing to EN 61000-4-13 is as easy to do as laboratory testing. The only requirements are that the climatic conditions are suitable for the EUT, auxiliary equipment and test equipment; and that the EM environment is not so severe that it interferes with the EUT (making it difficult to tell whether it is the environment or the test that is causing the functional performance to go out of specification).

It is also very important to ensure that on-site tests do not cause interference. When not using test generators commercially available from well-known EMC test gear manufacturers, generators that use PWM techniques have the potential to emit enormous amounts of interference and very serious attention to filtering (and maybe shielding) may be required (see later).

All types of products

Real-life waveshape issues

The discussion of the EN 61000-4-13 tests above shows that it does not test for all the possible effects of distorted mains waveforms. Extending the frequency range of the EN 61000-4-13 tests, and/or increasing the test levels, and/or using test waveforms that better simulate the anticipated real-life harmonic and interharmonic distortions and effects of system resonances (see above), can help produce more reliable and/or safer products.

Since most commercially available EN 61000-4-13 test generators employ arbitrary waveform generators, there is no restriction on the waveform that can be created. So it is possible for them to sum numerous harmonics and interharmonics together to recreate real-life waveforms. (Some commercial generators may have user-interface software that limits the waveforms that can be created. Some may also have problems driving real distorted waveforms into real loads. So always check with the manufacturer first.)

In industrial engineering it is often the case that the operational site of a particular product (often a custom-engineered equipment) is known, so its mains waveform can be captured by an oscilloscope or harmonic analyser and recreated by an EN 61000-4-13 tester to test whether the product will operate as desired in its real-life environment.

For products made in larger volumes and which may be used in a variety of environments, it should be possible to take the information from [29], or make a number of measurements of mains waveforms, and test the product to ensure it will work correctly in any of its likely operational sites.

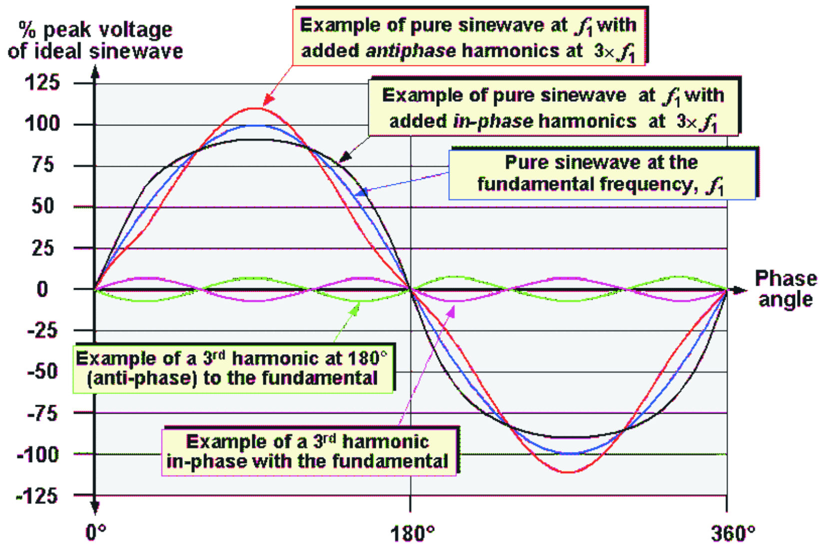
It is usual to only consider harmonics and interharmonics up to 40 times the fundamental (2kHz for 50Hz mains, 2.4kHz for 60Hz) – as is done in EN 61000-4-13 – but modern semiconductors can switch so rapidly that it may be necessary in practice to consider higher frequencies.

Whilst it is true that real waveforms can be 'degenerated' into lists of harmonics and interharmonics, each with its amplitude (and phase, in the case of the harmonics) – it requires the summation of *all* of those frequency components to recreate the waveform.

The levels of the harmonics and interharmonic frequency components used by EN 61000-4-13 are understood to be based upon the years of analyses of real mains waveforms reported upon in EN 61000-2-2 [29]. But, apart from its first two tests (A1 and A2, see earlier) EN 61000-4-13 applies individual harmonic and interharmonic components *one at a time*, so the mains waveforms it applies to the Equipment Under Test (EUT) are much simpler than those it will experience in real life.

In particular, spurious zero-crossings that can occur in real life, and which can cause problems for many types of equipment (see earlier) may not be accurately recreated by any of the tests in EN 61000-4-13.

An example of the effect of the phase of a harmonic on a mains waveform



Real-life resonance issues

System resonances are a common cause of many real-life interference problems due to harmonics and interharmonics, and they will generally coincide with only one frequency at a time. This implies that the single-frequency tests in EN 61000-4-13 (tests B, C1, C2 and D) might help 'test-as-in-real-life' (abbreviated to TARL by the Ford Motor Company) after all – if their test levels were increased to correspond to the levels that can occur at resonance.

But EN 61000-4-13 uses a test generator with a very low-impedance output, which is not representative of any real mains network or local generation. Resonances can occur due to the mains input stage of the product, and test B (see earlier) searches for these and dwells at them for a longer period. But system resonances are not simulated except when EN 61000-4-13 has been called up by a product or generic standard whose committees decided to include an “external impedance network” (see earlier).

Even so, the usual impedance networks just simulate the wiring and transformers, and don't simulate the capacitance that will exist in real mains networks when other equipment is connected to them, so such tests would not discover the 'lifting crane' problem mentioned earlier [11].

If it is desired to test for the possibility of system resonances but the mains network impedance is not known, or is subject to variations as equipment is added or removed over time, it may be a good idea to test using EN 61000-4-13 as described below but to at least double the levels of the harmonics on tests A2, B, C1, C2 and D. Testing with three or four times the listed test levels (or more) would give even more confidence of reliable operation in real life.

Better still – devise a manually-tuned external impedance based on the standard mains impedances given in Annex A of EN 61000-4-13 but with added inductance and capacitance, and track the distortion frequency applied during tests B, C1 and C2, and/or D. The extra dwell time required by test B at resonant frequencies would apply to *all* of the tested frequencies, making it quite a long test. Two kinds of resonant network would be required – one that was series-resonant and one that was parallel-resonant – doubling the test time.

Testing in this way would help ensure that real-life mains networks were unlikely to cause unreliable operation. Test time will be reduced if an 'actively controlled' external impedance is devised, that has a resonance (series and then parallel) that automatically tracks the added harmonic or interharmonic frequency.

Real-life magnetic field issues

As mentioned earlier, EN 61000-4-13 does not test for magnetic field coupling of mains harmonic and interharmonic noise. The best way to test for these is to use the EN 61000-4-8 test but feed distorted mains current waveforms (instead of pure sinewaves) into the coil that generates the magnetic field. The distorted waveforms can be those that are used by tests A1, A2, B, C1, C2 and D, but of course they will be current waveforms instead of voltage waveforms. The voltage will be whatever is required to drive the coil (see the Safety Note below). The REO Handbook on testing to EN 61000-4-8 [30] will be helpful.

System resonances of the series type can amplify the harmonic and interharmonic *currents,* leading to more powerful magnetic fields at their resonant frequencies, so to be sure of covering this problem test with at least twice the test levels given in EN 61000-4-13. (Three or more times would give even greater confidence of real-life robustness.)

Real-life electric field issues

As was mentioned earlier, EN 61000-4-13 does not test for electric field coupled mains harmonics and interharmonics. There is no basic IEC test standard for immunity to low-frequency electric fields, but they are easy to test for using a parallel plate stripline, TEM cell, or the triplate beloved by Ford Motor Company EMC department. Most EMC test labs have one or more such devices, especially those who do military or automotive product testing, although the size of EUT they can test may be limited.

However, at these low frequencies it is very easy to make your own parallel plate stripline out of sheets of metal and plastic spacers, or even long wires, and they can be made large enough to fit the very largest products. (Constructional details are not given in this booklet.) The distorted mains waveforms should be applied between the top and bottom plates (or wires) of these electric-field generating devices, the distorted waveforms used can be taken from tests A1, A2, B, C1, C2 and D (see earlier).

System resonances of the parallel kind can amplify the harmonic and interharmonic *voltages,* leading to more powerful electric fields at their resonant frequencies. To be sure of covering this problem, test with at least twice the test levels given in EN 61000-4-13. Testing with levels that are three or more times higher would give even greater confidence that the design would be robust enough in real life.

Alternatively, a slowly-swept or stepped frequency can be applied to the plates, with sufficient voltage to generate the required fields, varying the test level accordingly (it will need to be highest at the fundamental).

Safety Note: When working with voltages above 30Va.c. (rms) or 42Vd.c. or earth leakage currents above 0.7mA, use all relevant electrical safety precautions. If you don't understand *exactly* what this means, and if you aren't very familiar with the relevant safety standards – have someone who is qualified and competent in this area sort it out for you. Electrical and electronic engineers are killed every year by electricity – don't let it be you!

Real-life common-mode voltage issues

As mentioned earlier: EN 61000-4-13 does not test for common-mode harmonic and interharmonic conducted voltages in signal and data cable inputs or outputs (caused by earth/ground voltage differences between the products connected by cables).

EN 61000-4-16 [31] is the basic test method to use for this type of interference. It includes test levels up to 3V rms, from d.c. to 150kHz, noise voltages that are clearly capable of causing significant levels of interference in inadequately-designed electronic products interconnected by cables.

Three-phase products

EN 61000-4-13 assumes (clause 8.2.5) that harmonics in three-phase systems are perfectly balanced, in magnitude and in phase – but this is often not the case in practice for reasons. In some installations the harmonics can be very significantly unbalanced, especially the triplen harmonics – and this might create problems for some products that passed tests with balanced harmonics and no triplens (as specified by EN 61000-4-13).

The harmonic emissions from most three-phase equipment are usually naturally balanced, and if they have neutrals (i.e. are 'star' or 'wye' connected) their triplen harmonics (3, 9, 15, 21, 27, 33) will cancel out inside themselves. If they do not have neutrals (i.e. they are 'delta' connected) their triplens are emitted into the supply in balance on all three conductors, and cancel themselves out at the first star-connected transformer they come to, so they do not propagate very far within the mains distribution system.

If a product is connected to the same branch of mains distribution that supply well-balanced star connected non-linear loads, the levels of triplen harmonics it experiences will be very small, usually negligible. But if is to be connected to the same branch as a delta connected three-phase non-linear load, the EUT will be exposed to balanced levels of voltage distortion on its supply at the triplen frequencies.

But in many installations single-phase equipment is the major cause of triplens. If it is unlikely that the VA loads of the single-phase equipment will be well-balanced across all three phases, it is even more unlikely that their harmonic contributions will be well-balanced.

For example, if in an office building there are 3000 PCs and visual display monitors, 1000 of them connected to each phase, there is very little chance that the loading on each phase will match to within ±30%. This is especially true because modern PCs and PC monitors are fitted with energy-saving measures that dramatically reduce their power consumption if either the keyboard or the mouse has not been used for a while.

A similar problem with load balancing arises with a building fitted with energy-saving lights, that switch on and off according to occupancy detectors, or according to the level of natural light in each area. These two examples of balancing single-phase loads assumed a large number of identical items of equipment (PCs, monitors, lights) and showed that achieving a good load balance in practice is unlikely in real life.

But in many real situations different kinds of single-phase equipment may be allocated to different phases to try to balance their total VA loadings, but the different kinds of equipment will emit different levels of harmonic currents in proportion to their VA rating, so it will be almost impossible to balance both their VA loads *and* their harmonic emissions. It will be truly impossible to balance their VA and their loading *at each individual harmonic frequency*.

The result of unequal VA balancing of single-phase loads is unequal loading per phase and unequal phase voltages (usually called phase imbalance). The result of unequal harmonic loading is unequal levels of harmonics on the three phases, including the triplens. The unbalanced proportion of a triplen will pass through star-connected transformers, so will not be contained to one branch but spread widely throughout a mains distribution network, even via MV (and possibly HV) interconnections.

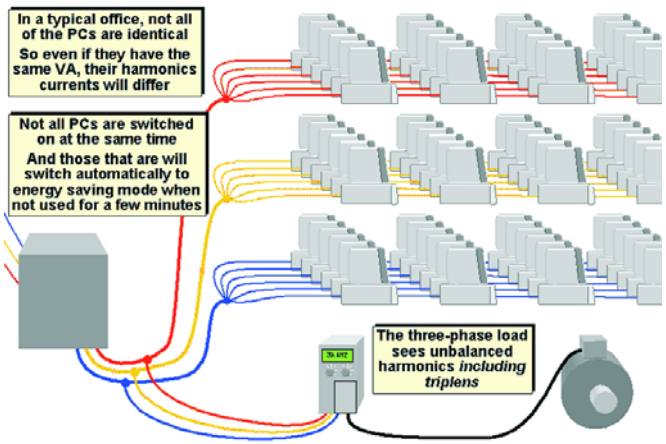
EN 61000-4-13 does not require delta connected three-phase equipment to be tested with triplen harmonics, since this would be a waste of testing time when testing with perfectly balanced triplens. But as the above discussion has shown, in many real-life three-phase systems it is more likely that none of the harmonics, including the triplens, will be balanced.

To prove that star and delta connected equipment will function reliably in three-phase systems with unbalanced harmonics it will be necessary to do additional testing to that described by EN 61000-4-13. Obviously, very many unbalanced harmonic voltage ratios could occur in real life, and we don't want to have to test them all.

In the absence of any specific knowledge of the characteristics of the mains supply the product will be used on, it is suggested that most three-phase equipment is tested fully to EN 61000-4-13, but including the triplen frequencies. In addition, it is suggested that the tests are repeated with all of the harmonics and interharmonics applied to at least one of the phases (with respect to the neutral). The schematic should be studied to identify the phase that will be the most susceptible, and that is the one that should be tested. For example, this should be any phase that is used for measuring the mains frequency or detecting zero-crossings or other characteristics of the mains waveform. If more than one phase could be susceptible for different reasons, test each one.

If the product presents a symmetrical load, and no reason can be found for any phase to be any more susceptible than any other, choose one at random and record it in the test report. Where there is insufficient knowledge of the design of the product, for greatest confidence, reliability and functional safety (where appropriate) it is suggested that each of the three phases be tested in turn, to be sure of testing the more susceptible one(s).

Most three-phase systems have unbalanced harmonics when the majority of the load is single-phase



Important Safety Note: Don't forget that interference, especially with aircraft or other vehicular systems, some machinery or process control systems, and implanted electronic devices such as pacemakers, can have lethal consequences and appropriate precautions **must** be taken to make sure that nobodys safety is compromised by EN 61000-4-13 testing. It is also a good idea to take precautions where there is a possibility of significant financial loss being caused by the interference from on-site testing.

If the test generator has been designed well it should not emit high levels of harmonics, interharmonics or RF interference into the mains supply that feeds it, and its output waveforms (distorted mains voltages) will also be free of RF noise. RF suppression at the inputs and outputs of the test generator is not a small concern. Modern test generators almost always use pulse-width-modulated switch-mode techniques in their power amplifiers to generate their output signals, and these are very rich indeed in RF energy.

Of course, the EUT must operate properly in the first place, and if testing on a site that suffers from high levels of EM disturbances it may be necessary to use filtering and shielding techniques to be able to distinguish the effects of the ambient noise from the effects of the test. Similarly, where the RF emissions (conducted or radiated) from the test generator itself might interfere with the EUT, auxiliary equipment, other test gear or any other equipment, it may be necessary to use filtering and shielding techniques to prevent this from happening.

If either of the above situations arises, there are a number of issues that will need to be taken into account to suppress the interfering frequencies effectively. Suitable filtering and shielding techniques are described in [32].

A selection of typical REO Filters for AC supplies

An example of a low-cost shielded tent

It may be possible to shield the system being tested from incoming or outgoing RF with a shielded tent, and filter each of the cables entering or leaving the tent at least with a large ferrite clamp or number of small clip-on ferrite clamps, placed at the point where the cable penetrates the tent. Ferrishield, Inc. make some very large ferrites for this purpose: their CS28B2000 has its peak impedance at 300MHz, CS25B2000 at 700MHz, and CS20B2000 at 2.45GHz. Don't forget that for a shielded tent (or other enclosure, such as mesh over a wooden framework) to be effective usually requires a shielded base that is joined to the walls all around its edges. It might not be enough to simply drape a five-sided shielding tent (or mesh structure) over the equipment being tested.

If working on exposed live equipment, an isolating transformer may be able to be used to help reduce electric shock hazards. It is best to choose special 'high isolation' types of transformers, which have a very low value of primary-to-secondary capacitance, plus choose transformers that are rated for the likely surge levels (at least 6kV, using the IEC 61000-4-5 test method) to help ensure safety.

High-isolation transformers may also be used to help prevent harmonics and interharmonics tests from injecting RF noise into the mains distribution network of the rest of a site.

Important Safety Note: Always take all safety precautions when working with hazardous voltages, such as 230V or 400V (3-phase) electricity. If you are not sure about all of these precautions – obtain and follow the guidance of a qualified and competent electrical health and safety at work person. When constructing equipment that employs hazardous voltages, always fully apply the latest versions of all relevant parts of the EN/IEC 61010 series, at least.

REO isolating transformer with low primary to secondary capacitances

REO isolating transformers

'Pre-compliance testing' is an undefined term, but usually means testing with less accurate test equipment, or testing in a much shorter time than the standard allows, or both. Testing using alternative methods from those in EN 61000-4-13 cannot give any real confidence that 'full-compliance' tests for immunity to harmonics and interharmonics would be passed.

But such non-compliant tests may be valuable for improving the reliability or quality of a product, and they may even be better at doing this than full testing to EN 61000-4-13 – if they are better at simulating the actual mains waveforms, voltages and currents that the product could be exposed to in real-life (see earlier).

The test set-ups are easy to achieve in a typical manufacturing company, as they don't require special test chambers – but see the earlier section preventing these tests from causing interference.

A number of alternative test generators and test methods can be used where EN 61000-4-13 compliance is not required. In particular, generators that create distorted waveforms directly, instead of synthesising them from sinewaves in some Fourier series could be used. Tests with such waveforms could take a lot less time than running though the whole series of 'single-distorting-frequency' tests in EN 61000-4-13.

One technique would be to make standard audio frequency recordings of the typical (or worst-case) distorted waveforms that products may be exposed to, even using an audio compact cassette recorder if necessary. The audio signal must be taken from the mains via a safety-isolating step-down transformer that complies fully with the relevant part of EN 61558 for the mains voltage concerned (see the **Important Safety Note** above). Care should be taken to ensure that the audio recording level is high enough that the added noise is insignificant, but not so high that it overdrives the recorders input and adds to the distortion of the waveform.

These signals can then be played back through a suitably rated power amplifier (hired if necessary, *not* a hi-fi amplifier even if its ratings seem adequate) to provide the mains power to the EUT.

Types of EUT that do not measure the mains frequency, or detect its zero-crossings or other characteristics – and which use rectifier-capacitor mains inputs – may simply need to be tested with…

i) the worst-case clipped (flat-topped) sinewaves at the lowest RMS voltage specified on their rating plate, and…

ii) the highest peak voltages ever likely to be experienced.

If the highest peak voltages caused by voltage tolerances and waveform distortion are known or can be estimated, they can easily be applied to the EUT by passing whatever mains supply is available at the time through a step-up transformer and a variable transformer. It is suggested testing with this level of overvoltage for at least a week (after all, products may have to survive it for their entire life). An EUT that is not damaged by such a test is much less likely to be damaged by real-life overvoltages caused by harmonics or interharmonics.

There are many other possibilities for alternative test generators and alternative test methods, and this booklet does not seek to limit the ingenuity of electrical and electronic engineers, always assuming that health and safety is the prime concern and ensured by suitably qualified and competent people (see the **Important Safety Note** above).

For all but compliance and 'pre-compliance' tests, using an uncalibrated test (for which the quantitative measurement is not traceable to the national physical standards) is not very important. But it *is* very important for *any* tests to be *repeatable* – so consistency is always required in the test equipment and test methodology.

During design, development or QA testing, always try to reproduce the final assembly of the circuit being tested (shielding, earth bonding, proximity to metal objects or structures, etc.), as the stray inductances and capacitances in the final build state can have an important effect on the behaviour of the product, especially 'noise' pickup from magnetic and electric fields coupling from the mains circuits. And always carefully record all the details of the test set- ups and build states in the test documentation. Digital photographs can be very useful, especially if annotated at the time.

When self-declaring compliance to the EMC directive using the 'Standards Route' to conformity (Article 10.1 of [3]) – even if alternative test generators have been used to simulate the operating environment and help achieve reliability – passing full compliance tests to EN 61000-4-13 can help avoid the possibility of legal challenges in the future.

But when following the Technical Construction File (TCF) route under 89/336/EEC (or when not fully applying harmonised standards under 2004/108/EC) it may be possible to persuade the mandatory Competent Body (or optional Notified Body) that the alternative tests and test methods represent the environment that the product is going into and there is no need to apply EN 61000-4-13 as well. This argument would probably be easier to win for a custom-designed (bespoke) industrial product intended for use at a specified site, than it would be for portable products or equipment that could be used in a number of locations or sites.

Correlating alternative test methods with EN 61000-4-13

When an alternative test generator or method is used for design, development, or troubleshooting after a test failure, repeatability of the test is very important (even though the correlation with EN 61000-4-13 may not be). All such tests will need to follow a procedure that has been carefully worked out to help ensure that adequate repeatability is achieved.

When alternative methods are used as part of a QA programme, or to check variants, upgrades, or small modifications, a 'golden product' is recommended to act as a sort of 'calibration' for the test equipment and test method. Golden product techniques allow low-cost EMC test gear and faster test methods to be used with much more confidence. Refer to section 1.9 of [33] for a detailed description of how to use the golden product correlation method.

If alternative methods are used to gain sufficient confidence for declaring compliance to the EMCD, the golden product method is very strongly recommended. Without a golden product or some similar basis for correlating a proper compliance test (using EN 61000-4-13) with the alternative method actually used, the alternative method might only provide any confidence at all if gross levels of overtesting are applied, and this can result in very expensive products.

The closer a test method is to using the proper test transducers and methodology in EN 61000-4-13, the more likely it is that a good correlation will be achieved. So testing with a mains waveform that has been amplified from output of a cassette tape recorder (for example) might only be able to correlated with EN 61000-4-13 for a particular build state of a specific product.

Determining an 'engineering margin'

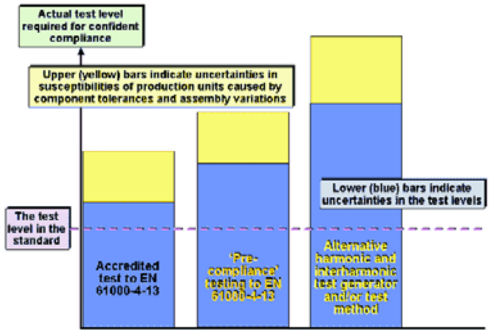
Even having EN 61000-4-13 fully applied by the same accredited EMC test laboratory cannot guarantee that a given EUT will be exposed to *exactly* the same stimuli each time it is tested. But if EMC enforcement agents test a product, they are unlikely to use the same test laboratory or model of test generator as the manufacturer. So, an 'engineering margin' is recommended, because…

- There might be variations in the actual waveforms produced by different models of generators when testing the same product;
- There can be variations in the test methods, even when applied by the same staff at the same test laboratory, leading to different results;
- Serially-manufactured products have variable immunity performance due to component and assembly tolerances (e.g. variations in the routes taken by cables or cable bundles, in some types of products, might make them more likely to pick up magnetically-coupled noise);

So, when testing an example product to EN 61000-4-13 in a fully compliant manner, performing an additional test with at least 20% higher levels of harmonics and interharmonics is suggested, with the product still meeting its required functional specifications.

Where a manufacturer is using an alternative test generator or test method to that described by EN 61000-4-13, a larger engineering margin is recommended (but how much larger is very hard to determine other than by direct comparison of the effects of the different test methods on the same EUT).

The need for engineering margins



EN 61000-4-13 requires testing to not exceed the specified maximum test level, to avoid damage to the product – but if the customer requests testing to higher levels the test laboratory should be happy to oblige.

As far as doing the minimum required to achieve a presumption of conformity to the EMC Directive is concerned – saving costs and/or time by using alternative test generators or test methods can lead either to over-engineering or to non-compliance. The additional cost to make the product pass the alternative test method with the necessary engineering margins should be weighed against the cost of doing the testing properly.

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Keith Armstrong graduated in electrical engineering with a B.Sc (Hons.) from Imperial College London in 1972, majoring in analogue circuit design and electromagnetic field theory, with a Upper Second Class Honours (Cum Laude). Much of his life since then has involved controlling real-life interference problems in high-technology products, systems, and installations, for a variety of companies and organisations in a range of industries.

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