A Practical Guide for EN 61000-3-2

Limits for harmonic current emissions (equipment input current up to and including 16 A per phase)

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Mains harmonic emissions testing and compliance with the EMC Directive

The basic test method for emissions of harmonic currents into the mains supply is IEC 61000-3-2 Ed.2:2000 [1]. This has been adopted with some 'common modifications' as the harmonised European standard EN 61000-3-2 Ed 2.2000 [2]. Compliance with EN 61000-3-2 is now a requirement (for all equipment within its scope) for conformity with the Electromagnetic Compatibility (EMC) Directive [3] when using the 'self-declaration to standards' route to conformity.

EN 61000-3-2 is a 'horizontal' EMC standard - which means that it applies regardless of the type of equipment or of any generic or product-family EMC standards which may also apply - and its scope covers all apparatus that is intended to be connected to the public LV supply (i.e. the public 230V ac mains supply) and which consumes up to 16 amps per phase.

But EN 61000-3-2 has a number of exclusions for which either the standard doesn't apply, or where the standard does apply but sets no limits…

- Equipment intended for use on a site which has its own dedicated distribution transformer and so enjoys a 'private LV supply' (a 'public' supply is one that is shared between more than one organisation or household).
- Equipment that consumes more than 16 Amps per phase.
  IEC 61000-3-4 and/or IEC 61000-3-12 are available for optional use, with EN 61000-3-12 probably becoming mandatory for EMC Directive compliance for equipment up to 75A/phase in a few years time.
- Equipment that is powered at supply voltages above 1kV rms.
  EN 61000-3-6 is available for optional use, and will probably be mandatory for equipment powered from an MV or HV supply for compliance with the EMC Directive in a few years time.
- Professional equipment where its instruction manual includes a requirement for its owner/user to ask their supply authority for permission to connect. Recommendations on this are contained in IEC 61000-3-4 and IEC 61000-3-12.
  'Professional' means: used in the course of a trade, profession or industry and not intended for sale to the general public. It is up to the manufacturer to decide whether a product is intended for 'professional use', and to take the necessary steps to prevent it from being sold to the general public.
  Note that the supply authorities could ask for their own tests to be passed, or improvements made to the owner's/user's supply networks, before granting permission.
- Professional equipment which consumes more than 1kW from its mains supply, lighting equipment which consumes under 25W, and all other equipment which consumes less than 75W.
- Symmetrically controlled heating elements with a total rated power less than or equal to 200W
- Independent dimmers for incandescent lamps with a rated power less than or equal to 1kW.
- Incandescent lamps and luminaires which do not incorporate an 'electronic transformer' or dimming device.
- Equipment operating from mains distribution systems which are powered at 220V rms or less.

Where an equipment type falls within the scope of EN 61000-3-2, the standard must still be listed on its EU Declaration of Conformity even if it doesn't comply (e.g. professional equipment where the user asks for permission to connect), or if the standard sets no limits.

Harmonic emissions are an increasing problem for many mains supplies (private and public) so it is recommended that – whether EN 61000-3-2 applies limits or not – the harmonic emissions of your equipment is compared with the levels of harmonics that can be coped with by its intended mains supply without causing problems (taking its existing harmonic loading into account). It could turn out that even though no harmonic emissions limits are *legally* required for EMC compliance, some limitation of your equipment's harmonic emissions might be a good idea for the customer's sake.

It may even turn out that fully complying with the limits of the relevant harmonic emissions standard is not sufficient to prevent problems from arising, or that the user's mains power distribution network needs improvements. For example, the author has seen an example of a road tunnel 'lighting scheme' that had 1MW of total lighting power and a 1MVA distribution transformer to power the lamps. Even though all the lamps met the appropriate limits in EN 61000-3-2, their harmonic currents were still so high that they made it impossible to run the lights at more than 70% of full power without overheating the 1MVA transformer. It was a very embarrassing situation for the designers, and costly and time-consuming to solve.

EN/IEC 61000-3-2 has been the subject of intense debate and lobbying in recent years (including an appeal by a large consortium of US manufacturers directly to the then President Clinton of the USA). All this activity resulted in the last-minute publication of Amendment A14:2000 to EN 61000-3-2:1995, which made some very important changes, especially to the definition of its "Class D".

EN 61000-3-2 Edition 2:2000 now exists and can be used for compliance with the EMC Directive. On 1st January 2004 this 2nd edition will become mandatory for compliance for all equipment (covered by its scope) that is supplied to the EU market, superseding both the 1995 edition and all of its amendments including A14.

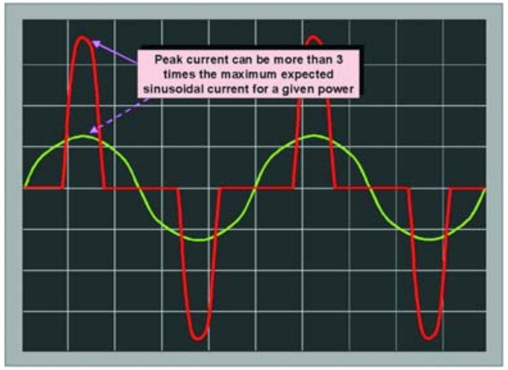
However, the debates and lobbying seem set to continue for the foreseeable future, and could result in significant future changes to either EN or IEC 61000-3-2. This handbook describes how to apply EN 61000-3-2 Ed.2:2000, but you should always ensure that you are using the most appropriate version of EN or IEC 61000-3-2 (plus all of its Amendments and Corrigenda). Although most EN EMC standards don't differ by much from the IEC standards they are based on, this might not be true in this case, so remember that there can be important differences between the IEC and EN versions of 61000-3-2.

Note that where a product has a safety-related function, mere compliance with the EMC Directive is insufficient for ensuring that its 'EMC-related functional safety' is designed correctly – additional and/or tougher emissions and/or immunity requirements may be required. Refer to the IEE's guide [4] and the on-line article

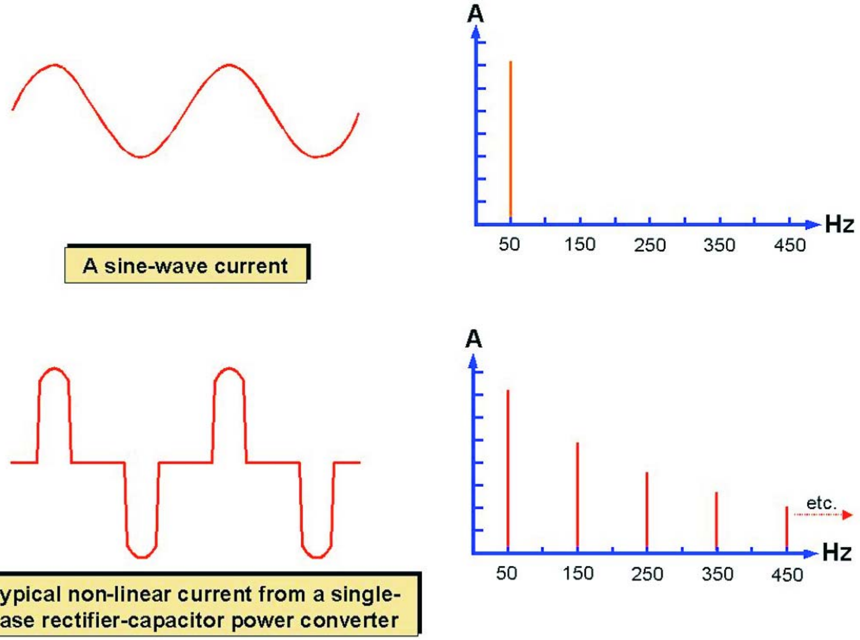
What are mains harmonic emissions ?

The typical rectifier-capacitor ac-dc powe converters used in 'linear' and switch-mode ac-dc power converters to create their unregulated dc voltage rails present a non-linear load to the mains supply. Since they only 'top up' their dc storage capacitors at the peaks of the ac supply waveform, their supply current consumption is discontinuous, non-sine wave, and rich in harmonic currents.

Non-linear currents in a rectifier-capacitor type ac-dc converter



Comparison of waveforms and spectra



A sine-wave current

A typical non-linear current from a single-phase rectifier-capacitor power converter

How do mains harmonics cause problems?

A particular problem with single-phase power converters is that they emit significant levels of 'triplen' harmonics (i.e. 3rd, 9th, 15th, etc.), which are a particular nuisance because they add linearly in neutral conductors (no phase cancellation) and in zero-phase transformer flux, and they cause additional (and sometimes unexpected) heating of cables and transformers.

Three-phase ac-dc power converters (sometimes called 6-pulse converters) are also a source of harmonic emissions, but they produce low levels of triplen currents.

There are many other non-linear loads which also cause harmonic currents in the mains supply, such as transformers and motors; arc furnaces and welding equipment. Fluorescent lamps with magnetic ballasts have harmonic emissions too, but they usually don't extend to frequencies as high as those caused by rectifiers.

The ballasts in 'high-frequency' fluorescent lamps (and in many 'energy-saving' lamps) are actually single-phase ac-dc switch-mode power converters, with all of their harmonic emission problems. Low-voltage halogen lighting is increasingly likely to be powered by a so-called 'electronic transformer' – actually a switch-mode ac-dc or ac-ac power converter that also comes with all the harmonic emissions problems that its rectifier-capacitor input circuit causes.

The harmonic currents drawn from an equipment's ac mains supply have a negligible effect on its power consumption, measured in Watts, but increase its consumption when it is measured in VA. The ratio of an equipment's consumption of Watts to its VA is known as its Power Factor (PF), so where an equipment has significant emissions of harmonics it also has a lower power factor.

A PF of 1.0 means that the VA equals the Watts consumed by an equipment, in which case it looks to the supply like a pure resistive load (and therefore cannot possibly emit any harmonic currents). Rectifier input electronic equipment with no harmonic reduction techniques tend to have PFs of around 0.6. Magnetically-ballasted fluorescent lamps (running at 50 or 60Hz) can have a PF as low as 0.3.

Electronic techniques which reduce the emissions of harmonic currents into the mains supply also improve the equipment's PF, so they are usually called Power Factor Correction (PFC) techniques.

Don't confuse real Power Factor (= W / VA) with the 'power factor' traditionally used by electrical generation and distribution engineers, which is the cosine of the angle between the sine-wave supply voltage and the load current, traditionally adjusted by either adding capacitance or inductance to a power line. This 'traditional PF' assumes sine wave voltages and linear loads (resistive, inductive, or capacitive) and is a special case of real PF. The PF of a rectifier-input electronic power converter cannot be corrected using the traditional methods for linear loads. Most mains power distribution networks now drive significant numbers of 'electronic loads' and the Climate Change Levy (in the UK) is increasing the pressure to replace all of the linear loads that can be replaced with electronic loads (because they promise higher efficiency).

IEC 61000-4-7 [6] includes a survey of harmonics in power supply systems. There are four kinds of problems caused by harmonic currents flowing in mains power supply networks…

a. Problems caused by harmonic currents themselves
b. Voltage distortion caused by harmonic currents
c. Problems caused by voltage distortion
d. Telephone interference

Problems caused by the harmonic currents themselves

Due to the 'skin effect' in copper, and the increased eddy current losses in silicon steel used in mains distribution transformers at frequencies above 50/60Hz, the thermal losses in conductors and transformers that carry harmonic currents increase and they run hotter. This causes a number of problems including decreased reliability, damaged insulation (possibility of short-circuits and/or electric shocks), toxic fume and smoke hazards, possibly even fire and explosion in some situations.

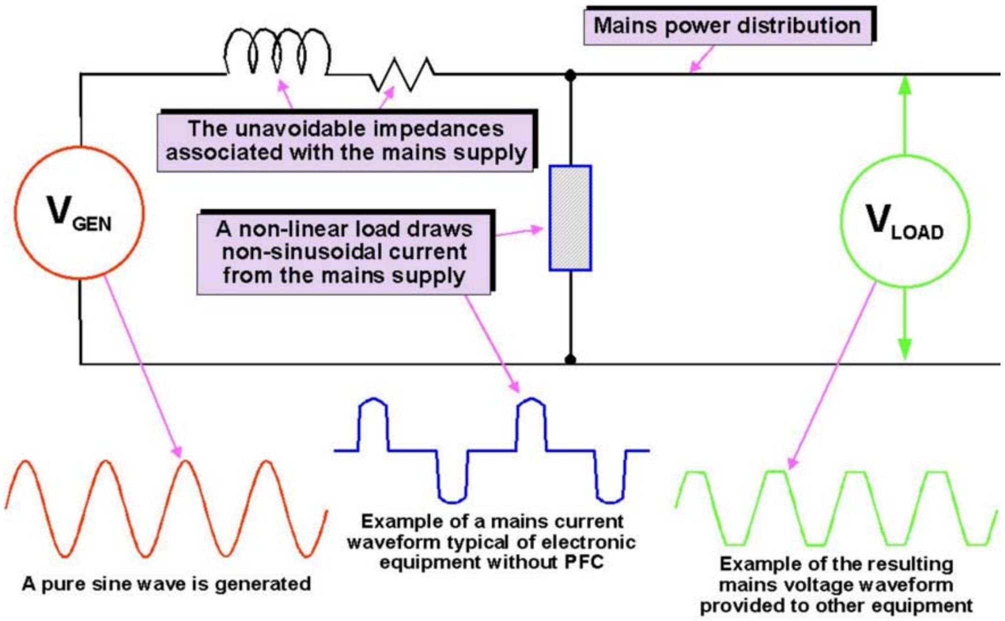
Triplen harmonic currents don't cancel out at all in the zero phase (= neutral) of 3-phase power systems, leading to…

- Excessive harmonic currents (hence overheating) in the neutrals of 3-phase distribution systems;
- The cores of delta-wound mains distribution transformers overheating due to excessive zero-phase flux.

In a larger installation with a lot of single-phase electronic loads (e.g. a modern office) the total neutral currents can be as much as 1.7 times greater than the highest phase current, due to the harmonic currents, especially the triplens, that flow uncancelled in the neutral conductor. Many older buildings are wired with half-size neutrals (quarter-sized or even eighth-sized neutrals are also known), and since building neutrals aren't fused the toxic fume, smoke and fire hazard is clear.

Overcurrent protection devices (e.g. fuses) that detect the actual heating effect of the conductor current will open at lower levels of 50/60Hz current than expected, due to the extra heating effect of the harmonics. The unexpected loss of power when an overcurrent protection device opens can be a big nuisance, but much worse is the habit of some personnel of measuring the current with an average responding ammeter, deciding that the circuit isn't overloaded at all, and fitting a larger rated overcurrent device to stop it from opening 'prematurely'. The result is often overheated cables and a significantly increased risk of shock, toxic fumes, smoke and fire.

The problem with average responding ammeters is that although they are calibrated in rms, their calibration is only accurate for pure sine wave currents and they can read as much as 30% too low with some non-sine-wave currents. All ammeters used on ac power systems should now be true rms types with a bandwidth of at least 2kHz, but since they cost more than average responding meters people will no doubt continue to buy the cheaper ones and make erroneous measurements of mains currents that could possibly lead to dangerous situations.



'Flat-topping' by non-linear currents in electronic power converters

Note: Other load current waveshapes will distort the mains voltage waveform in a different way

As the harmonic currents flow through the impedances of the supply network they give rise to potential differences which distort the waveshape of the supply voltage. The sketch shows how the typical flat-topped mains waveform so familiar these days is caused by the non-linear currents consumed by traditional rectifier-capacitor input mains power converters used by almost all electronic equipment (without PFC in this case).

The distortion of the mains voltage supply gives rise to a number of other problems.

Problems caused by mains voltage distortion

Even nominally linear loads such as transformers, solenoids, capacitor banks, and motors will consume increased levels of harmonic currents, adding to the heating effect in cables and transformers, when they are supplied from a non-sinusoidal voltage waveform. The harmonic currents flowing in the loads also increases their temperatures, due to the skin effect and eddy current losses mentioned earlier and can lead to a shorter operational life. Distortion of the mains voltage also causes torque ripple in electric motors, leading to increased acoustic noise and vibration, and shorter bearing life.

The harmonic distortion of the mains waveform can lead to reduced performance or unreliability of electrical and electronic systems because…

- Voltage peaks can be lower than expected, causing unregulated dc power rails to be too low.
- There can be timing errors in the zero crossing points of the mains waveform, causing errors in some types of power control.
- Power consumption metering can be inaccurate.
- Voltage overshoots (peaks) can be higher than expected, causing overvoltage damage (e.g. overstressing the power factor correction capacitors in fluorescent lamps and power distribution centres).

The distortion of the mains voltage waveform from an ideal 50Hz or 60Hz sine-wave is usually measured as total harmonic distortion (THD), although sometimes the distortion for each harmonic is specified instead. It is usually considered that a THD that exceeds 4% is a cause for concern, and one that exceeds 8% is cause for alarm as it is likely to cause significant problems.

Typically, long cable lengths and reactive loads create resonances in mains power distribution networks at much higher frequencies than the fundamental frequency (50 or 60Hz, depending on the country), but they are not higher than all of the possible harmonic currents. Near to a resonant frequency the impedance of the mains distribution system can rise to very high levels, and any harmonic currents flowing in such high impedances can cause some very significant increases in the mains voltage waveform's THD.

Problems of telephone interference

"Hum" on a telephone is bad enough, but "harmonic whine" is much worse because it falls into a part of the audio spectrum where the human ear is much more sensitive.

The most common cause of telephone interference from the harmonic currents in mains supply networks is longitudinal magnetic interference, where fields from the residual currents in power cables couple to telephone lines over long distances.

Other ways harmonics cause audio interference with telephones include loop induction, longitudinal electrostatic coupling, and conduction due to the earth potentials in MEN (multiply-earthed-neutral) mains distribution systems.

Small items of equipment cause most of the problems on public mains supplies

Some high-power items of industrial equipment can emit such high levels of harmonic currents that they cause problems for their 'private' mains supplies. There are no harmonic regulations concerning such installations, although it is clearly in the interests of the owner of such an installation to control the levels of its harmonics to help prevent costly problems.

However, industrial sites are usually faced with harmonic requirements applied by their power supply authorities. Their installations must not emit excessive levels of harmonic currents into their medium-voltage (MV) or high-voltage (HV) electricity supplies, and the relevant specification (for the UK) is called Engineering Recommendation G5/4 [7].

In hospitals, government and commercial buildings (e.g. banks, insurance companies, supermarkets, hotels, call centres, etc.) where there are a lot of personal computers, high-frequency lighting ballasts and/or low-voltage lighting, the harmonic emissions from each computer, high-frequency ballast or 'electronic transformer' are insignificant on their own, but the combined effect of thousands of them can be very significant indeed.

Industrial and commercial users faced with a harmonics problem often deal with it by adding motor-generator sets, star-delta transformers, or 'passive' or 'active' harmonic filters to their installations. (Note that 'active filters' aren't really filters at all but harmonic cancellation devices, although 'active filters' is what they have come to be called). Alternatively, providing they don't exceed the G5/4 limits and don't mind the voltage distortion, an installation can simply uprate its cabling and transformers to cope with the extra heating caused by the harmonic currents.

As far as the public LV mains supply is concerned, harmonic problems are mostly caused by the large numbers of low-power equipment such as televisions, PCs and their monitors, low-energy and low-voltage lamps. The total harmonic currents from thousands of these can be damaging to the network and to other equipment, as described above. It is this situation that EN 61000-3-2 seeks to control, especially through its 'Class D' category (see below) – although of course the standard can be used voluntarily for equipment used on 'private' LV supplies in healthcare, commercial and industrial premises.

Further information about harmonics and their problems

The EMC & Compliance Journals' regular 'Banana Skins' column [8] includes some anecdotes about problems caused by mains harmonics, especially (at the time of writing) numbers: 1, 7, 46, 59, 101, 102, 104 and 200. [9] and [10] may also be useful.

Full compliance testing of mains harmonic emissions

This section is based upon Chapter 3 of [11], updated as required to correspond to EN 61000-3-2 Edition 2:2000.

The range of harmonic frequencies covered by EN 61000-3-2 extends only up to 2kHz (the 40th harmonic of 50Hz), so the test does not need to use RF measurement techniques. Nevertheless there are some aspects of the measurement which are not entirely obvious, making it necessary to carefully follow the standard in every detail.

Although you can make a potentially perfectly adequate check with no more than some FFT analysis software, a current transducer and an oscilloscope (see later), fully compliant measurements are more complicated, particularly if the harmonic emissions from the equipment are close to the limits, or if they fluctuate over time.

The test set-up

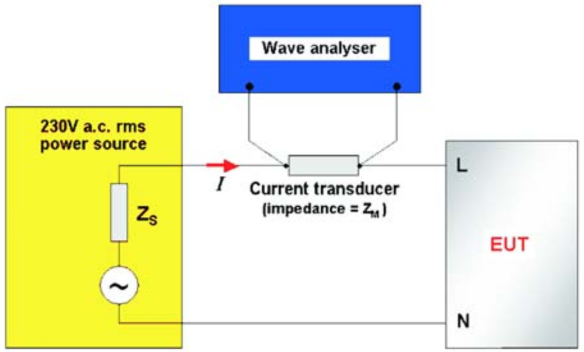
EN 61000-3-2 defines the method of measurement and each item of test equipment is specified. The nearby figure shows the basic measurement method, and its basic components are:

- A 230V ac power source with a low impedance (Z_S)
- A current transducer with a low impedance (Z_M)
- A wave analyser
- The equipment under test (EUT)

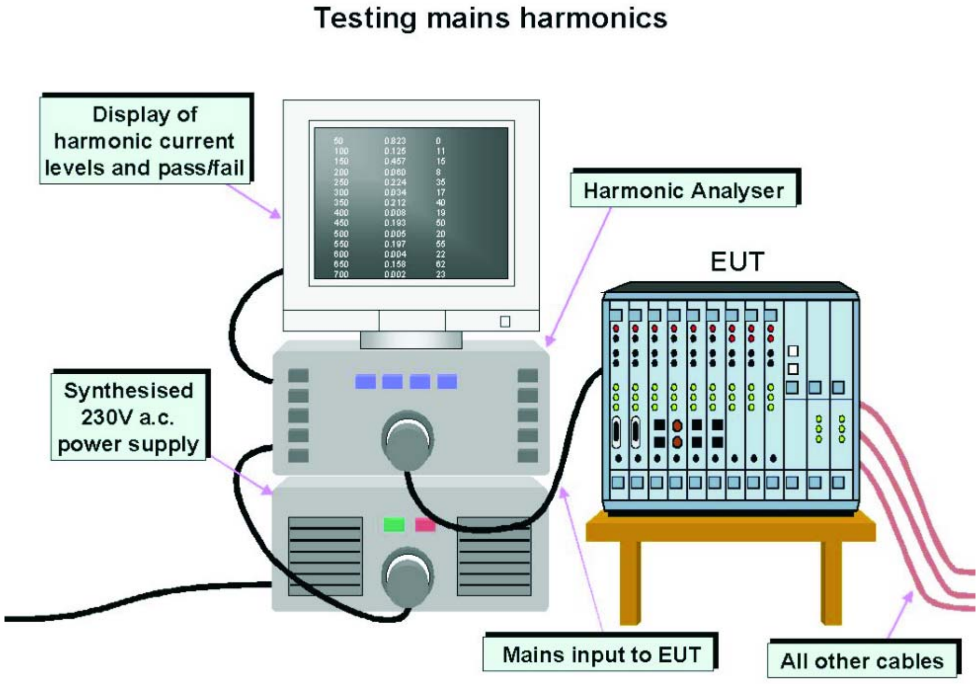
In a practical test, the wave analyser and current transducer are usually combined into one instrument, usually called a harmonic analyser, and the test set-up usually consists of plugging the 230V power source (usually synthesised), the harmonic analyser and the EUT together as shown by the nearby figure.

The test results are displayed on a screen, which might be separate from the harmonic analyser or built in.

The basic measurement technique for mains harmonic emissions



I = the total supply current consumed by the EUT



(Always follow the test standard itself, in full)

The 230v ac power source

Making a harmonic measurement with the required accuracy needs a 230V ac power source with very low distortion (i.e. close to a pure 50Hz sine waveform), good voltage stability and settability, and a low source impedance.

IEC 61000-3-2 requires the voltage to be stable to within ±2% of the selected level during the measurement, and the frequency stable within 0.5% of nominal. The harmonic distortion must be less than 0.9% at the 3rd harmonic, 0.4% at the 5th, 0.3% at the 7th, 0.2% at the at the 9th, 0.2% at all even-order harmonics from the 2nd to the 10th, and 0.1% at all other harmonics up to the 40th. Because of the supply mains' finite source impedance and the non-linearity and variability of other loads on your distribution system, your local mains supply is very unlikely to be capable of complying with these values, and a special mains source will be required.

The measuring impedance Z_M should create a voltage drop of less than 0.15V peak. The source impedance is not specified, but the total set-up is not allowed an error at any harmonic frequency of more than 5% of the permissible limits.

To meet these requirements typical test equipment uses a power amplifier driven by a 50Hz sine-wave oscillator, with negative feedback to maintain the low output impedance. The output may be fed through a power transformer for voltage step-up purposes, but the transformer reactance must not affect the output impedance at the higher harmonic frequencies.

For use in a test laboratory the amplifier will need to be large enough to cope with the full range of possible loads – the standard covers equipment rated up to 16A, which is a power level of 3,680W at 230V, although when testing in-house the product range to be tested might not consume as much power so a smaller amplifier would be adequate (and cost less). Note that even very powerful hi-fi amplifiers are not usually tough enough for this application.

For high power and highly distorting loads the ideal mains source becomes quite difficult to realise (i.e. large and costly). Including the maximum allowable transitory harmonics for class B equipment, legitimate peak currents can be around 40A, although some equipment can substantially exceed this, and the source should be able to deliver this current level without exceeding the waveform distortion limits. If the measured harmonics are well over or under the limit then voltage distortion is a minor consideration, but it becomes important for borderline cases.

The current transducer

The current transducer couples the total EUT mains supply current I to the measuring instrument, and it can be either a resistive current shunt or a current transformer. In both cases, the transducer impedance Z_M is added to the source output impedance and the two together must cause negligible variation in the load current harmonic structure. A resistive current shunt of less than 0.1Ω impedance and a time constant less than 10µs is acceptable, but note that a shunt on its own does not provide galvanic isolation from the measuring circuit – an important safety consideration.

Current transformers do provide galvanic isolation, and should have the necessary electrical strength rating (sometimes called 'voltage withstand', 'hipot', or 'flash test') and insulation type to prevent hazards from arising even during single faults. Unlike resistive current shunts, current transformers need to be calibrated at each harmonic frequency and may suffer erroneous results due to saturation when the measured current includes a dc component (this usually manifests in ac supplies as current consumed by the load at the even-order harmonics: 2nd, 4th, 6th, etc.).

The error in measuring a constant value must be less than 5% of the permissible limit. For compliance purposes, maintaining this accuracy from the lowest to the highest measurement level puts severe demands on the dynamic range of the current transducer and associated input signal processing. Some manufacturers get around this problem by using two transducers, one for high currents and one for low currents.

The wave analyser

The wave analyser measures the amplitude of each harmonic component of I from the 2nd to the 40th. EN 61000-3-2:1995 + Amendment A14, and EN 61000-3-2 Ed.2:2000 only permit the use of discrete Fourier transform (DFT) type wave analysers.

When the harmonic components fluctuate while the measurement is being made, the response at the indicating output should be that of a first order low-pass filter with a time constant of 1.5 seconds. [6] includes more specific details of the smoothing algorithm which performs this function on the discrete data values.

Test conditions

Special test conditions for some types of equipment are given in EN 61000-3-2 Ed 2:2000, including…

Television receivers
Audio amplifiers
Video-cassette recorders (VCRs)
Lighting equipment
Independent or built-in incandescent lamp dimmers
Vacuum cleaners
Washing machines
Microwave ovens
Information technology equipment (ITE)
Induction-type cooker hobs
Air conditioners
Kitchen machines as defined by IEC 60335-2-14
Arc welding equipment which is not for

In general, equipment should be operated in its normal mode(s) of operation connected to its normal loads, and set to operate in such a manner that it creates the maximum total harmonic current emissions it is capable of.

Where a number of individual self-contained items of equipment are installed in a rack or other enclosure, they are regarded as being individually connected to the mains supply. The harmonic emissions from the rack or enclosure as a whole need not be tested.

The 'test observation period' depends upon the way the equipment behaves. EN 61000-3-2 Ed.2:2000 identifies four different types of behaviour and specifies the observation period for each.

Examples of REO Loads - REO can create custom loads to meet any

Equipment classification and limits

The standard establishes four classes of equipment, each with their own harmonic emission limits:

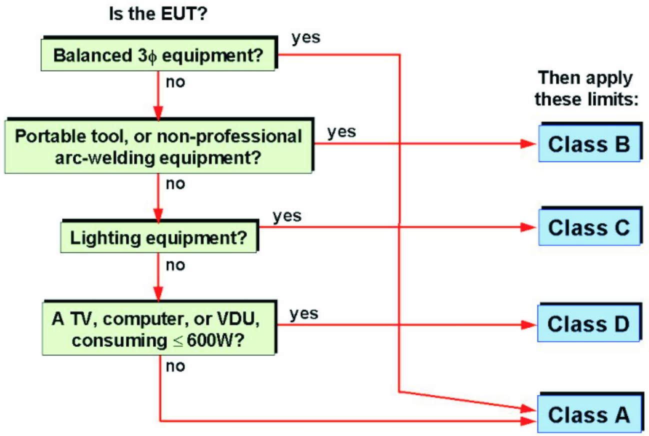
Class B for portable tools

Class C for lighting equipment, including dimmers

Class D for Personal Computers (and their display monitors) and TV receivers, with a 'specified power' (see later) less than or equal to 600W

Class A for everything else, particularly balanced three-phase equipment

Deciding on the limits to apply



The emissions limits in EN 61000-3-2 Ed.2:2000

Relaxations for transitory emissions are specified in the standard

Harmonic order 'n'	Max current Class A	Max current Class B	Max current Class C (% of fundamental current)	Max current Class D (but no more than Class A)
2	1.08 Amps	1.62 A	2%	not specified
3	2.30 A	3.45 A	30λ %	3.4 mA/Watt
4	0.43 A	0.645 A	not specified	not specified
5	1.14 A	1.71 A	10%	1.9 mA/Watt
6	0.30 A	0.45 A	not specified	not specified
7	0.77 A	1.155 A	7%	1.0 mA/Watt
8 ≤ n ≤ 40 (even)	0.23 (8/n) A	0.345 (8/n) A	not specified	not specified
9	0.40 A	0.6 A	5%	0.5 mA/Watt
11	0.33 A	0.495 A	3%	not specified
13	0.21 A	0.315 A	3%	0.35 mA/Watt
15 ≤ n ≤ 39 (odd)	0.15 (15/n) A	0.225 (15/n) A	3%	(3.85/n) mA/Watt

(λ is the circuit power factor)

The harmonic limits are absolute values for Classes A and B, whatever the input power. The Class C limits are expressed as percentages of the 50Hz current consumed, and for Class D they are a set of sliding values proportional to the mains power consumed. For equipment with an input rating greater than 600W the Class A and Class B limits, being fixed, become proportionately more difficult to meet as the mains input power increases.

Even where limits aren't specified, or do not apply, EN 61000-3-2 Ed.2:2000 places limitations on the types of circuits that may be employed. For example, asymmetrical power control (as defined in IEV 161-07-12) and half-wave rectification may only be employed in a few specified situations. Symmetrical power control methods that tend to produce harmonics (e.g. phase-angle controlled triacs) are also subject to limitations. Always read the relevant version of standard very carefully, all through, to discover exactly what limitations are applied to the type of equipment in question.

Harmonic emissions are not measured until 10 seconds after the EUT is switched on, and the EUT must not be in standby mode for more than 10% of any observation period.

For each harmonic, its short-term fluctuations (after smoothing by the 1.5 second time-constant in the harmonic measuring circuit) are allowed to exceed the specified limits by 50% – as long as its average value falls below its limit.

'Specified power' and the Class D limits

The Class D emission limits are given in mA per Watt, and average emissions are compared with the limits based upon the maximum mains power consumed in each observation time window over the entire duration of the test. The harmonic currents and active input power are measured under the same test conditions but need not be measured simultaneously.

In order not to arrive at a power at which limits change abruptly (for example, 600W or 75W), the manufacturer is allowed to specify a power level for establishing the limits, but this specified value must be within ±10% of the actual measured value. The purpose of this approach is to prevent the situation in which equipment operating near the boundary and tested under slightly different conditions might be subject to widely differing limits. The specified power for this purpose is not necessarily the same as the manufacturer's rated power for safety or functional purposes.

Commercial test equipment

The nearby photograph shows a combined harmonics and flicker emissions measuring equipment, complete with 1kW mains source, in use at AD Compliance Services Ltd. This equipment is available from Thurlby-Thandar, EMV (pictured) or Laplace Instruments, for a total cost of about £2,000. It gives fully compliant measurements (for equipment within the 1kW rating of its source) to EN 61000-3-2.

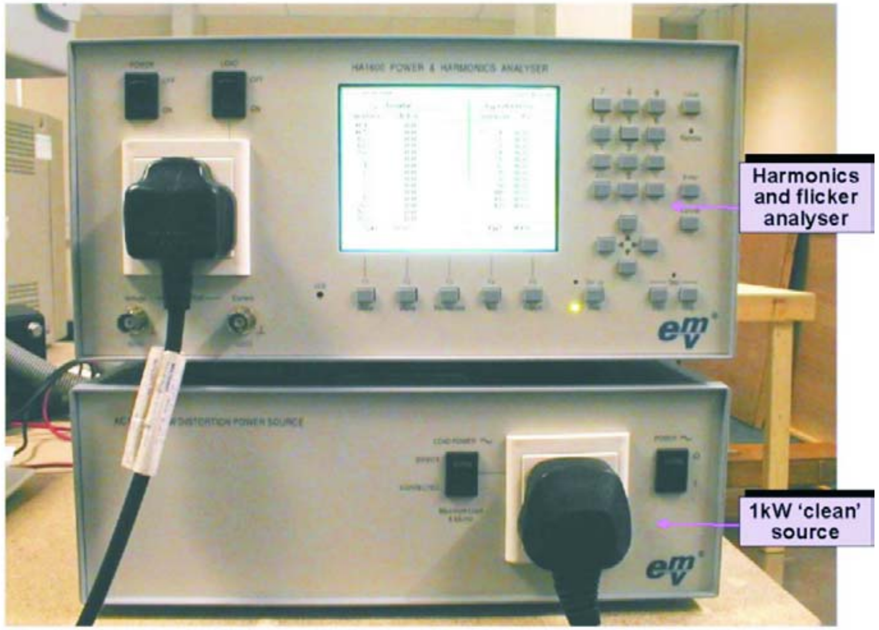
This harmonics and flicker tester is also capable of measuring emissions of voltage fluctuations and flicker to EN 61000-3-3 (the subject of another REO booklet).

Before purchasing EMC test gear for harmonics or flicker measurements, always discover which version of the standard (and its amendments) you need to apply, plus the version of the basic harmonics analyser standard [6], and ensure that the test gear meets their requirements. However, test gear that does not comply with the specifications in the latest versions of the standards might be able to be made compliant with software upgrades from their manufacturers.

Even if the test equipment is not fully compliant it may still be acceptable if it is being used for development, 'pre-compliance' or QA purposes.

A commercially-available harmonics analyser, with mains source

(Courtesy of AD Compliance Services Ltd)



Low-cost non-compliant testing for mains harmonic emissions

As always, using alternative testing methods or test gear could give terribly inaccurate and misleading results unless a number of precautions are taken. It is essential to understand the relevant standards and their associated test gear very well, and to understand how your methodology and test gear might influence the result.

It is almost always very important to follow the relevant standards as far as is possible. Even if the test gear is not the best, the test set-up and interpretation of results should follow the standard. The 'golden product' method described in section 1.9 of [12] can also be a great help in improving confidence in the results of low-cost tests.

The make / buy decision

As was mentioned above, testing for mains harmonics does not involve any RF issues, making it easier to design and construct your own test gear. However, a number of test gear manufacturers have entered the market for this type of equipment with various levels of price and performance, so it may be more cost-effective (and probably safer!) simply to purchase the appropriate equipment.

Mains source alternatives

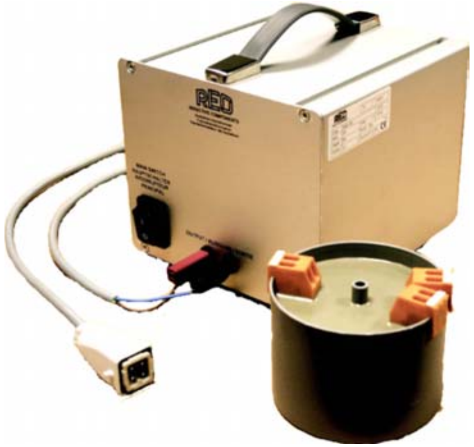
The combined harmonics and flicker tester pictured earlier uses a 1kW mains source, the 'AC1000', which costs around £500 and can be used on its own if you wish to use an alternative wave analyser (see below). Recent developments in switch-mode power conversion (digital power amplifiers) and 'anti-harmonic injection waveform correction' techniques (such as the 'active harmonic filters' used for mains waveform correction in installations) may lead to lower cost 50Hz sources than the traditional linear power amplifiers.

An example of a REO synthesised mains source for testing to EN/IEC 61000-3-2

Of course, it is possible that your regular mains supply is clean enough to use as a source for your harmonic current emissions tests. You will probably find that the mains is 'cleanest' in an industrial building which has its own distribution transformer, when no machinery or HVAC is running. Turning off the fluorescent lighting may also help clean up the waveform. If you are testing single-phase equipment, you may find that one of the phases in the building is 'cleaner' than the others – so use that.

Some people like to power their EMC tests via an isolating power transformer, to help reduce the low-frequency interference from the rest of their site (filters are required to suppress radio frequencies). If working on exposed live equipment, an isolating transformer can be used to help reduce electric shock hazards – in this case, it is best to choose special 'high isolation' types with a very low value of primary-to-secondary capacitance.

Examples of REO isolating transformers



Example of REO isolating transformers with built in filter to provide attenuation up to 90dB

Motor-generator sets with electric motors can produce a 'clean' sine wave from a building's supply, or if the motor is a petrol or diesel engine it can of course generate a totally independent supply. Uninterruptible Power Supplies (UPSs) with reasonable power ratings are almost commonplace but the only suitable ones for this purpose are 'continuous double-conversion' types, or other types run solely from batteries without a mains input. Second hand M-G sets or UPSs may be available at very reasonable prices.

Two potentially serious problems with M-G sets or UPSs are the quality of their output waveform, and their output impedance. Some M-G sets use crude electronic voltage regulators which result in poor quality output waveforms, and most M-G sets and UPSs have a relatively high output impedance (compared with the mains supply) which means that their output waveform can be more easily distorted by the non-linear current consumption of some EUTs. So you may need to use an M-G set or UPS with a rating that is much more than the EUT's rated power consumption.

Even when using a proprietary 'clean' mains synthesiser it is a good idea to always observe the mains voltage waveform with an oscilloscope and/or power quality analyser to check that it is a sine wave of adequate quality and that the current demand from the EUT is not causing 'flat-topping' or other waveform distortions. Any current transducer and wave analyser that can be used for EN 61000-3-2 testing can also be used with a resistive load in place of an EUT to check the distortion of the mains voltage waveform.

Safety Note: Always take all safety precautions when working with hazardous voltages, such as mains electricity.

Current transducer alternatives

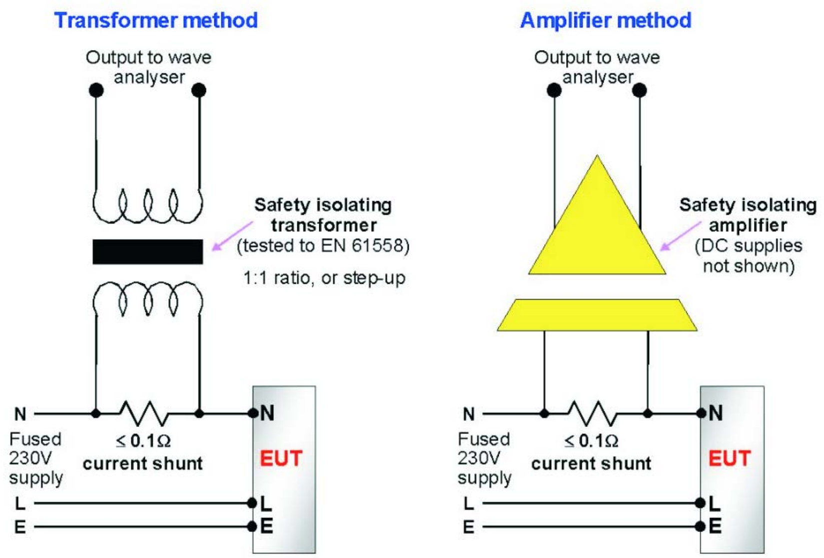
The **resistive current shunt** is attractive because it has a naturally flat frequency response in the range of interest. But it does not provide galvanic isolation and is limited to a maximum resistance of 0.1Ω so as not to affect the circuitry of the EUT so much that its harmonic emissions alter significantly. This low resistance means low output voltages with consequent difficulty in achieving a decent signal-to-noise ratio (S/N) for the higher frequency harmonics where the EN 61000-3-2 limits are lowest.

The nearby figure indicates some circuit techniques which can provide galvanic isolation and/or increase signal amplitudes when using resistive current shunts. A 1:1 isolating transformer (compliant with the relevant parts of EN 61558 or EN 60950) can provide galvanic isolation, and a step-up isolating transformer can provide signal gain too. Step-up transformers can be made using an ordinary step-down transformer 'backwards', with its low voltage secondary connected across the shunt and its 110 or 230V primary connected to the wave analyser. A 1:10 or 1:20 ratio is probably as much as is needed to get a good S/N with most analysers – but take care not to step-up the voltage so much that the primary current component or the initial switch-on current surge of the EUT causes overvoltage damage to the wave analyser inputs (or safety hazards to personnel).

Step-up transformers must be used with fairly high-impedance loads so that they don't affect the accuracy of the 0.1Ω current shunt resistance. For example, with a 1:10 step-up and a 1% tolerance shunt the load on the analyser side should be 10kΩ or more.

A safety issue with using mains transformers 'backwards' to boost the output of a current shunt is that the secondaries of typical mains transformers may not have mains-rated insulation (double or 'reinforced' insulation tested at around 3kV electric strength). In such cases, or if you are not sure, you could instead use two transformers in series: a 230:230V safety isolating transformer (with mains-rated insulation for both windings) connected to the shunt, followed by the step-up transformer.

Current shunt techniques



Always install the current shunt and any transformers or isolating amplifiers (and their power supplies) in an enclosed protectively-earthed metal box with suitable warning signs (“isolate before removing cover”, etc.) – and don't forget to fit suitably-rated fuses or overcurrent circuit breakers in the incoming mains supply.

Safety Note: The safety precautions to take when building such test gear are described in detail in EN 61010-1, and should always be followed in full and appropriate tests carried out to check that the design is safe.

The nearby figure also shows an isolation amplifier method. A number of analogue IC manufacturers (Linear Technology Corporation, Analog Devices, Burr-Brown, etc.) produce amplifiers specifically for galvanically isolated measurements.

These use a variety of techniques (e.g. optical, capacitive, magnetic) to get dc power and signal across the isolation barrier. Because the current shunt is connected to the mains, a suitably rated isolation is required. It is safest to use an amplifier which has a Safety-Agency Approved 250V isolation according to EN 61010-1 or EN 60950. But these may be hard to find and you may have to settle for one which guarantees 3kV or so electric strength and double (or reinforced) insulation across its isolation barrier.

When measuring single-phase equipment, putting the resistive current shunt in the neutral lead instead of the phase lead – and checking that the neutral lead really does have a low voltage with respect to the protective earth – can help reduce safety risks, but even so I would not recommend reducing the galvanic isolation requirements.

Instead of purchasing an IC or module with built-in galvanic isolation, you could design your own. For example you could use a voltage to frequency converter to drive an LED into a short length of fibre-optic (or a 3kV rated opto-isolator with double insulation) then convert back from F to V for the wave analyser. The dc power for the mains voltage side could be from a battery, or a 3kV isolation (double insulated) dc-dc converter, or from a separate mains power converter which is rated and safety certified for use with its dc output referenced to the mains supply. For more ideas on building your own isolation amplifier, see [13] and [14].

Safety Note: But remember to always follow IEC 61010-1 or EN 60950 in full, or else use equivalent levels of safety expertise for all safety issues. And never *assume* anything where safety is concerned.

Although the resistive current shunt has a flat frequency response, the overall response when transformers or amplifiers have been included may not be as good and should be checked to see if calibration at more than one frequency is required (see later).

Current transformer techniques use a toroidal core with a winding for the output. The conductor carrying the current to be measured is simply passed through the middle of the toroid. Split toroid cores can be used to create clip-on current transformers (often called 'current clamps' or 'current probes'). The nearby figures show some example current transformers from Pearson Electronics Inc., plus clip-on current probes from Fluke and Tektronix.

Examples of REO Current Transformers

Examples of clip-on current transducers

Fluke i200s Current Clamp
0.1 to 24 A @ 100mV and 0/5 to 240 A@ 10mV/A
40Hz - 10Hz BNC or twin banana plug output
Max test conductor 20mm

Tektronix A622 Current Probe
0.05 to 100A @ 10 or 100mV/A DC - 100kHz
BNC or twin banana plug output

Example of a REO current transformer suitable for testing to EN/IEC 61000-3-2

Safety isolation is a key benefit of using current transformers, automatically achieved because the insulation of the mains conductor being measured is not compromised (as it is when using resistive current shunts).

Hall effect technology can be used to make current sensors with a response from dc to 2kHz or more. The actual Hall effect devices are placed in a gap in a toroidal core through which the current-carrying conductor is passed, just as for a current transformer. The core may have a winding on it too, and a small electronic circuit produces a current or voltage output which is proportional to the tested current. The Tektronix A622 probe is a Hall effect type.

Calibrating current shunts and current transformers. Purchased current transducers should be provided with a calibration factor, or a calibration chart that shows how the calibration factor changes with the frequency of the measured current. But if they do not have either - or if you made the transducer yourself they can be calibrated by driving a known current through them at a known frequency and measuring their output voltage. The driving voltage can be easily achieved by amplifying a signal from a sine-wave generator with an audio power amplifier, driving a precision power resistor with the sort of currents to be measured (taking care to avoid overheating the precision resistor) and measuring this current with the current transducer.

Testing with the signal generator set to various frequencies and a standard test current (say 0.1A, controlled by measuring the voltage across the precision resistor), and measuring the output voltage from the current transducer (into its intended load resistor) will result in a graph of frequency versus transducer output which is the calibration factor for the transducer. It is also a good idea to check that the transducer's calibration factor does not vary with the actual current level, by testing at, say, 0.01A, 1A and 10A, all at 50Hz (saturation effects in transformers and current transformers are more likely to appear at low frequencies).

The 'calibration factor' for a particular transducer, at a particular frequency, should always be used to correct their raw measurements to obtain an accurate result.

Wave analyser alternatives

Alternatives to the standard wave analyser are possible, sometimes using existing laboratory test gear, but of course they will not comply with [6] so an understanding of its requirements plus those of EN 61000-3-2 would be required to interpret their measurements appropriately. It is always the same – if you want to save money on EMC test gear you have to be even cleverer and apply more skill than you would have to if you had the expensive full-specification test equipment. The use of the 'golden product' method described in section 1.9 of [12] is a good way of getting useful 'pre-compliance' type test results from alternative test gear - for a specific type of EUT technology and design.

An **audio frequency spectrum analyser** would of course be a great wave analyser, and should be sensitive enough to work with current shunts as well as with other types of current transducers. Maybe a second-hand one could be found for a reasonable price.

Many **digitising oscilloscopes** now have DFT (or similar kinds of Fourier transform) facilities built-in or available as a retrofitted options, and these can be very effective at obtaining a spectrum analysis of the harmonic content of the mains current. If you have some ability with mathematics using paper and pencil, or the maths functions available in some 'scopes – or if you can download the DFT data to a PC and post-process it there using a spreadsheet or maths application package – you could probably make a reasonable stab at a making measurements in accordance with EN 61000-3-2 Ed.2:2000, including its 1.5 second smoothing algorithm for fluctuating harmonics.

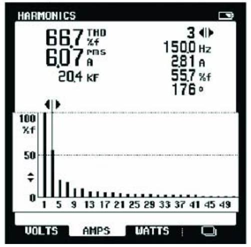
Typical outputs from proprietary clamp-on current probe accessories for currents up to 20A are 100mV/Amp, which means that when measuring to the lowest current limits in EN 61000-3-2 (at the highest frequencies) the typical voltage is of the order of 5mV. This is enough to get a reasonable S/N on most oscilloscopes. Most current transformers will also give reasonable output voltages, especially as the output from them naturally rises with frequency, assisting the S/N when making the measurement of the lower harmonic current limits at the higher frequencies. However, the oscilloscopes used will need to have at least a 2mV/division sensitivity vertical channel setting.

The output of a resistive current shunt will not give sufficient S/N to measure to the lower emissions limits at the higher frequencies, unless the 'scope offers a 0.1mV/division range, or unless a step-up transformer or isolation amplifier is used between the shunt and the 'scope, as described earlier. Several battery-powered galvanically-isolated amplifiers are sold for use with oscilloscopes, and using one of these with a resistive current shunt should allow reasonable measurements to be made whilst also helping to ensure safety.

A number of **portable power-quality instruments** are now available. Although intended for testing the power quality and harmonic currents in electrical installations, they can often be used for testing the harmonic current emissions from individual items of equipment. Examples of such instruments include the Fluke 39, 41B, and 43B (www.fluke.com) which seem to have started life as hand-held multimeters to which have been added oscilloscope-type features; and the Tektronix THS700 series – hand-portable oscilloscopes to which have been added multimeter features. The Fluke 39, 41B and 43B and the Tektronix THS720P include DFT software and display features which makes them into wave analysers. The nearby figure shows examples of some of these products. With the addition of a current probe accessory (see earlier) they can analyse harmonic currents. Once again, post processing maths could be used to get closer to the way the measurement is done by EN 61000-3-2.

Examples of hand-held power quality analysers

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



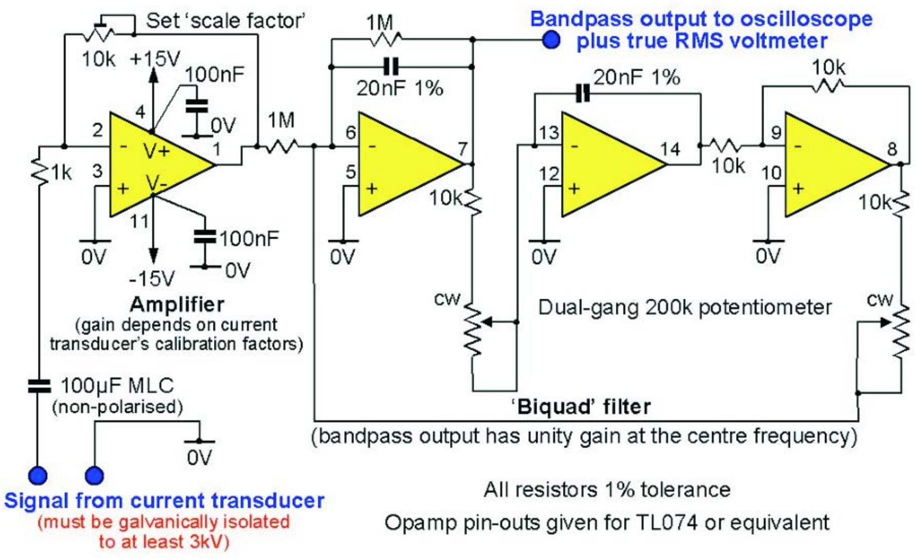
A TekScope® THS720P

Unfortunately, the accuracy or display resolution or S/N available in some of these hand-held products might not be enough to check the compliance of a product's higher-order harmonics. Although these instruments say they will measure to the 31st or 50th or whatever, the EN 61000-3-2 limits for the high order harmonics just might not be discernible on their screens.

Some of these portable power quality instruments could be comparable in cost with the combined harmonics and flicker analyser pictured earlier. But although they don't make compliant measurements and might not be sensitive enough for the high order harmonics, they can be used for a multiplicity of other purposes so this might help justify their expense. In fact, your company may already own one – ask your site's chief electrical engineer.

But it is easy to make your own very low-cost wave analyser, with a simple tuneable bandpass filter based on a single quad opamp, almost any old oscilloscope and a true rms voltmeter, as shown by the nearby circuit. As shown, the circuit does not provide the 1.5 second smoothing filter or any of the other complex measurement features required by EN 61000-3-2 and described in [6], but at least it will allow you to actually see harmonic currents easily and at low cost, and get some idea of whether a product would pass or fail a proper test to EN 61000-3-2 Ed.2:2000. (And any decent analogue designer should be able to add a 1.5 second smoothing filter with a reasonable match to [6]'s specifications.)

‘Bandpass filter wave analyser’ for harmonic emissions testing



All resistors 1% tolerance

Opamp pin-outs given for TL074 or equivalent

A linear dual-gang potentiometer achieves good tracking, but tuning is very sensitive towards its clockwise (high frequency) end. Alternatives for greater tuning ease above 300Hz include...
1) Replacing the 10k resistors in series with the 200k pots with a dual-gang 10k pot and use as a ‘fine tuner’.
2) ‘Band-switching’ between two 20nF 1% and two 2nF 1% capacitors

Because it is working with such low frequencies (max: 2kHz), this biquadratic filter wave analyser can be constructed very quickly on a piece of prototyping board. It has no layout or wiring requirements apart from the need to site the two 100nF decoupling capacitors very close to the power pins of the opamp to help it stay stable and reduce power supply noise (a ground plane under the opamp is also a good idea, especially if faster opamps than the TL074 are used). This simple filter requires an oscilloscope to permit the 'tuning in' of each harmonic and also to identify the frequency of the harmonic that has been tuned to, plus a true rms voltmeter to actually measure the harmonic's level. I have not bothered to calculate the bandpass filter's bandwidth, but it is narrow enough to resolve individual mains harmonics clearly, which is all that matters.

The current transducer to be used with this 'bandpass filter wave analyser' can either be a resistive-current-shunt-plus-isolating-transformer type, or a current transformer, both described earlier.

Safety Note: This circuit is not galvanically isolated from its input signal source, so the current transducer that is used must be galvanically isolated and insulated sufficiently to protect the circuit from at least 3kV ac rms on the mains circuit being tested.

Before using the 'bandpass filter wave analyser' to measure an EUT its scale factor should first be measured and adjusted if necessary. To do this, follow the normal measuring procedure (see below) but with a precision high-power resistor in series with a precision ac ammeter (either true rms or calibrated rms) in place of an actual EUT. For example a 2,300Ω load resistor will result in a current of 0.100A rms when powered from 230.0V rms, and will dissipate 23 watts. Tune the filter to the fundamental mains frequency (any harmonic signals should be very small, if the source is clean enough) and then compare the precision ac ammeter reading with the output from the 'bandpass filter wave analyser', to find the scale factor at the fundamental mains frequency. It usually helps to adjust the gain of the amplifier stage in the 'bandpass filter wave analyser' so that the scale factor is a handy ratio, such as 100mV per Amp of EUT mains current, or 1V per Amp.

The normal measuring procedure for the 'bandpass filter wave analyser' is as follows…

a) Attach the current transducer to the mains lead to be tested.

b) Attach the mains lead to the 'clean' 230V power source (see earlier).

c) Set-up, switch-on and operate the EUT exactly as specified in EN 61000-3-2.

d) Connect the bandpass output from the filter circuit to an oscilloscope vertical channel amplifier with 1MΩ input, ac or dc coupled. Also connect it to a true rms voltmeter (if the 'scope doesn't provide that function).

e) Set the 'scope's timebase to best suit the first harmonic to be measured (100Hz).

f) Adjust the dual-gang potentiometer to 'peak-up' (= tune in) the desired frequency on the oscilloscope. This should look like a fairly pure sine wave. Adjust the 'scope's input sensitivity and trigger levels as appropriate to get a good clear waveform display.

g) Measure and record the displayed frequency, which should be a multiple of the mains frequency, using the oscilloscope.
If the waveform is not a good sine wave, or is 'fuzzy, or is not a multiple of the mains frequency – there is a fault, or interference.

h) Measure the signals rms level using the voltmeter.
If the signal level of the harmonic is varying (not due to variations in the EUT's harmonic current demand), record the maximum value to be on the safe side.
Where the signal measured is varying as a result of the EUT's current demand (e.g. an EUT that goes through a repetitive cycle of operations with different current demands in each) then make a number of measurements as necessary to apply the EN 61000-3-2 Ed.2:2000 rules for dealing with fluctuating harmonics.

i) Repeat e) to h) above for 150Hz, 200Hz, 250Hz, and so on for all of the harmonics until you have all that you need to measure.

j) Apply the current transducer's calibration factors, for each of the measured frequencies, to the measured results to calculate the actual amplitudes at each of the harmonic frequencies.

k) For Classes A and B simply compare the calculated amplitudes for each of the harmonics with its limits as specified in EN 61000-3-2 Ed.2:2000 and decide whether each is a pass or a fail.
For Class C the mains current consumption at the fundamental frequency, and its phase angle with the

supply voltage, are also required to calculate pass/fail, and these can be had by tuning the bandpass filter to measure at 50Hz.
Class D really requires a true rms wattmeter to be used to measure the input power to the EUT during the test. But if such an item of equipment isn't available the 50Hz mains current can be measured along with its phase angle relative to the 230V sinewave voltage supply by tuning the bandpass filter to 50Hz, and the power calculated from that data.

Note that even if great care has been taken in measuring, calculating and interpreting the above in accordance with [2] and [6], the results will still not be very accurate. However, if you do take such care and the harmonics you measure are less than 50% of their limits, the chances are that the equipment would pass a 'proper' harmonics test.
And if the harmonics you measure are more than 50% higher than their limits, the chances are that the equipment would fail a proper test.

A lot of future time could be saved by automating the filter's tuning and locking it to the sweep signal from the oscilloscope to create a rudimentary low-frequency sweep-tuned receiver. The sweep rate should not be so fast that the amplitudes of the harmonics are affected (the narrower the filter bandwidth, the slower the maximum sweep rate for an accurate measurement). So try a few sweep rates and only use those that give the same peak amplitudes.

Safety Note: All the safety issues associated with mains power must be dealt with correctly! Always apply all the relevant parts of the latest issues of the relevant safety standards, such as IEC (or EN) 61010-1, *in full*.

On-site testing of mains harmonic emissions

There are no requirements in EN/IEC 61000-3-2 to perform the tests on an EMC test site, so tests can be carried out on-site as well as in a laboratory. But note that some of the test methods (e.g. for lighting equipment) specify some environmental conditions that should be met.

Testing three-phase equipment

EN/IEC 61000-3-2 Ed.2:2000 requires three-phase equipment to be tested for mains harmonic emissions one phase at a time.

References

[1] IEC 61000-3-2 Edition 2, 2000, *“Electromagnetic compatibility (EMC) – Part 3-2: Limits - Limits for harmonic current emissions (equipment input current up to and including 16 A per phase).”*

[2] EN 61000-3-2 Edition 2, 2000, *“Electromagnetic compatibility (EMC) – Part 3-2: Limits - Limits for harmonic current emissions (equipment input current up to and including 16 A per phase).”*

[3] European Union Directive 89/336/EEC (as amended) on Electromagnetic Compatibility. The Directive's official EU homepage includes a downloadable version of the EMC Directive; a table of all the EN standards listed under the Directive; a guidance document on how to apply the Directive; lists of appointed EMC Competent Bodies; and progress on the 2nd Edition EMC Directive; all at: http://europa.eu.int/comm/enterprise/electr_equipment/emc/index.htm.

[4] The IEE's 2000 guide: *“EMC & Functional Safety”,* can be downloaded as a '*Core'* document plus nine '*Industry Annexes'* from http://www.iee.org/Policy/Areas/Emc/index.cfm. It is recommended that everyone downloads the Core document and at least reads its first few pages. Complying with this IEE guide could reduce exposure to liability claims.

[5] “EMC-related Functional Safety – An Update”, Keith Armstrong, EMC & Compliance Journal, Iss. No. 44, January 2003, pp 24-30, on-line at: http://www.compliance-club.com/KeithArmstrongPortfolio

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

[7] Engineering Recommendation ER G5/4: *"Planning levels for harmonic voltage distortion & the connection of non-linear equipment to transmission systems & distribution networks in the United Kingdom"*, The Electricity Association, 2001, http://www.electricity.org.uk.

[8] *"The Banana Skins Compendium"*, EMC & Compliance Journal, www.compliance-club.com. Scroll down the home page to find 'Banana Skins' and click where shown to download the compendium.

[9] *"Why the electricity industry needs to control the harmonic emissions and voltage changes associated with equipment rated less than 16A"* G.S.Finlay, EMCTLA Seminar concerning EN 61000-3-2 and EN 61000-3-3, 19th May 2000. www.emctla.org.

[10] "*Power System Harmonics*", Arrilaga, Bradley and Bodger, John Wiley 1985, ISBN 0 471 90640 9. This is a key work on power harmonics: what causes them; how to measure them; and what effects they can have.

[11] *"EMC for Product Designers, 3rd Edition"* Tim Williams, Newnes 2001, ISBN 0-7506-4930-5.

[12] *"EMC Testing - Part 1: Radiated emissions"*, Keith Armstrong and Tim Williams, EMC & Compliance Journal February 2001, pages 27-39, www.compliance-club.com/Keith ArmstrongPortfolio.

[13] *"Low cost isolation amplifier suits industrial applications"* Andrew Russel, EDN Europe magazine, Feb 2000, pp 59-60, www.ednmag.com.

[14] *"Simple current sensor features galvanic isolation*", Jose A. Carrasco, Electronic Design magazine, July 20 1998, page 110, www.elecdesign.com.

EN and IEC standards may be purchased from British Standards Institution (BSI) at: orders@bsi-global.com. To enquire about a product or service call BSI Customer Services on +44 (0)20 8996 9001 or e-mail them at cservices@bsi-global.com.

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This guide is one of a series. Email us at main@reo.co.uk if you would like to receive all of our mini guides and to be entered onto our mailing list

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Keith has been a Chartered Electrical Engineer (UK) since 1978, a Group 1 European Engineer since 1988, and has written and presented a great many papers on EMC. He is a past chairman of the IEE's Professional Group (E2) on Electromagnetic Compatibility, is a member of the IEEE's EMC Society, and chairs the IEE's Working Group on 'EMC and Functional Safety'.

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