EMC Testing

Part 7 – Emissions of mains harmonic currents, voltage fluctuations, flicker and inrush currents; and miscellaneous other tests

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This is the **seventh and final** part in a series of seven bi-monthly articles on 'do-it-yourself' electromagnetic compatibility (EMC) testing techniques for apparatus covered by the EMC Directive (EMCD). This series covers the whole range of test methods – from simple tests for development and fault-finding purposes, through lowest-cost EMC checks; 'pre-compliance' testing with various degrees of accuracy; on-site testing for large systems and installations; to full-specification compliance testing capable of meeting the requirements of national test accreditation bodies. Previous articles are available on-line at www.compliance-club.com, using the site's Archive Search facility.

What is low-cost to an organisation with 5000 employees could be thought fairly expensive by a company with 50, and might be too expensive for a one-person outfit, but we will cover the complete range of possible costs here so that no-one is left out. It is important to understand, however, that the more you want to save money on EMC testing or reduce the risk of selling non-compliant products, the more EMC skills you will need. Low cost, low risk, *and* low EMC skills do *not* go together.

This series does not cover management and legal issues (e.g. how much testing should be done to ensure compliance with the EMCD). Neither does it necessarily describe how to actually perform EMC tests in sufficient detail to do them. Much more information is available from the test standards themselves and from the references provided at the end of these articles.

The topics covered in these seven parts are:

1) Radiated emissions
2) Conducted emissions
3) Fast transient burst, surge, electrostatic discharge
4) Radiated immunity
5) Conducted immunity
6) Low frequency magnetic fields emissions and immunity; plus mains dips, dropouts, interruptions, sags, brownouts and swells
7) Emissions of mains harmonic currents, voltage fluctuations, flicker and inrush currents; and miscellaneous other tests

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7 Emissions of mains harmonic currents, voltage fluctuations, flicker and inrush currents; and miscellaneous other tests

Part 0 of this series [1] described the various types of EMC tests that could be carried out, including:

- Development testing and diagnostics (to save time and money)
- Pre-compliance testing (to save time and money)
- Full compliance testing
- 'Troubleshooting' to quickly identify and fix problems with compliance tests, or with interference in the field
- QA testing (to ensure continuing compliance in volume manufacture)
- Testing of changes and variants (to ensure continuing compliance).

And Part 0 also described how to get the best value when using a third-party test laboratory [1].

This final part of the series focuses on testing for the emissions of harmonic currents, voltage fluctuations, flicker and inrush currents into the mains supply. The standards for these, EN 61000-3-2 [2] and EN 61000-3-3 [3] became mandatory for electrical apparatus within their scopes (briefly: apparatus connected to the public LV supply and consuming up to 16 amps per phase, with a number of exclusions).

These are 'horizontal' EMC standards – which means that they apply regardless of the type of equipment or of any generic or product-family EMC standards – and they have been the subject of a lot of debate during the past couple of years (including an appeal by a large consortium of US manufacturers directly to President Clinton of the USA). This debate resulted in the last-minute publication of Amendment A14:2000 to EN 61000-3-2 [4]. Although most manufacturers will wish to apply A14, it remains optional until the end of 2003. This debate and the scope, applicability and let-outs of these standards are not described in this article.

Other kinds of immunity tests may be required for automotive, aerospace, space, rail, marine and military environments. Over the years these, and other industries, have often developed their own immunity test standards based on their own particular kinds of disturbances, usually for reliability reasons.

IMPORTANT SAFETY NOTE: These tests involve the mains supply and present significant safety hazards. **All appropriate safety precautions must be taken.** If you don't *know* what safety precautions are required to be taken by heath and safety at work legislation, ask a competent person.

The basic EN test methods described here are similar to the basic IEC test methods (e.g. EN

61000-3-3 ≈ IEC 61000-3-3), although there may be some differences between the EN and the IEC (especially between the latest amendments to EN 61000-3-2 and IEC 61000-3-2) so this article may also be of some use where non-EU EMC requirements apply. The differences between the EN and IEC versions are not described here.

7.1 Fully compliant mains harmonic emission testing

This section is based upon Chapter 3 of [5].

Harmonic components of the AC supply input current to an item of equipment arise from non-linearities of the load over a single cycle of the input voltage. The EMC Directive includes requirements for measuring harmonic emissions as embodied in EN 61000-3-2, which covers all electrical and electronic equipment with an input current up to 16A per phase and supersedes the earlier EN 60555-2 (which had a more limited scope).

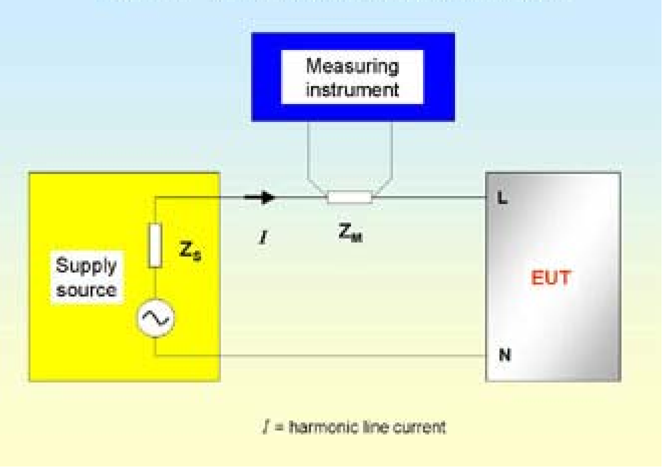
Although the harmonic frequency range extends only up to 2kHz (the 40th harmonic of 50Hz), and therefore the test does not need to use RF measurement techniques, there are some aspects of the measurement which are not entirely obvious. Although you can make a potentially perfectly adequate check with no more than some FFT analysis software, a current transducer and an oscilloscope, compliant measurements are more complicated, particularly if they are close to the limits or where there are fluctuating harmonics.

7.1.1 Equipment

EN 61000-3–2 defines the method of measurement and each item of test equipment is specified. Figure 7A shows the basic measurement method, and its basic components are:

- An AC source
- A current transducer
- A wave analyser

Figure 7A Mains harmonic emission measurement



7.1.2 AC supply source

To make a harmonic measurement with the required accuracy you need a source with very low distortion (i.e. a pure 50Hz sine-wave), high voltage stability and settability and low impedance. In general the public mains supply will not be able to meet these requirements, and a special source will be required.

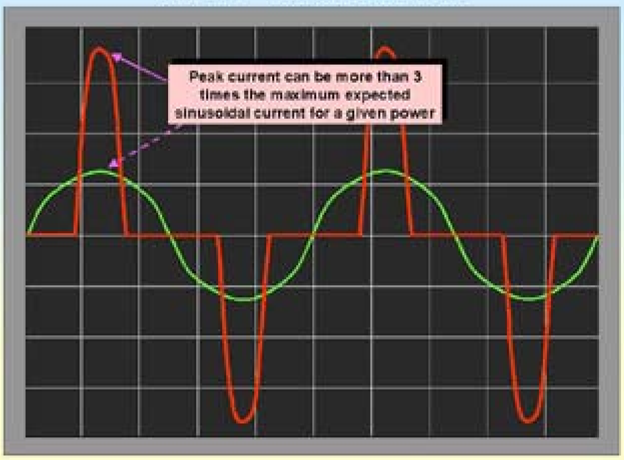
IEC 61000–3–2 requires that the voltage must be stable to within ±2% of the selected level during the measurement, and the frequency within 0.5% of nominal. The harmonic distortion must be less than 0.9% at 3rd harmonic, 0.4% at 5th, 0.3% at 7th, 0.2% at 9th and 0.1% at all the others. Because of the 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.

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. The amplifier will need to be large to cope with the full range of loads – the standard covers equipment rated up to 16A, which is a power level of 3680W at 230V, although for in-house use your product range may not approach this level and a smaller amplifier would be good enough. For high power and highly distorting loads the 'model' AC source becomes quite difficult (large and costly) to realise.

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 distortion (see Figure 7B). 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.

Figure 7B Distorted EUT current



7.1.3 Current transducer

The current transducer couples the harmonic current I_n to the measuring instrument, and it can be either a 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.

7.1.4 Wave analyser

The wave analyser measures the amplitude of each harmonic component I_n for n = 2 to 40. According to the original standard it can be either a frequency domain type, using selective filters or a spectrum analyser, or a time domain type using digital computation to derive the Discrete Fourier Transform (DFT). The original version of EN 61000-3-2 defines the requirements for time domain instrumentation rather differently to those for the frequency domain type. However, its Amendment A14 deletes the requirements in this standard and substitutes those of IEC 61000-4-7, which is a companion standard defining the reference instrument for harmonics measurement. A14 outlaws frequency domain instruments and only allows DFT types (but in practice, all commercial harmonic analysers are of this sort anyway).

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. IEC 61000-4-7 includes more specific details of the smoothing algorithm which performs this function on the discrete data values.

7.1.5 Test conditions

Special test conditions for some types of equipment are given in EN 61000-3-2, including TV receivers, audio amplifiers, VCRs, lighting equipment and various household appliances. Independent lamp dimmers and other phase-control devices should be set for a firing angle of 90^{o}. Information technology equipment is tested with the equipment configured to its rated current.

The original version of EN 61000-3-2 required that other equipment should be operated by setting its user controls or program mode to give the maximum harmonic amplitude for each successive harmonic component in turn. If followed to the letter, this procedure would require an excessive amount of time and effort for a complete test, and is hardly sensible, since finding the maximum level of, say, the 39th harmonic is unlikely to add much to the protection of the electricity supply network. A14 replaces this with the more reasonable requirement to conduct the test in the mode *expected* to produce the maximum total harmonic current under normal operating conditions.

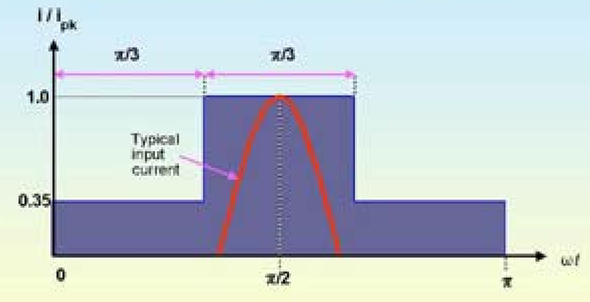
7.1.6 Equipment classification and limits

The original standard established four classes of equipment:

- Class B for portable tools
- Class C for lighting equipment, including dimmers
- Class D for equipment having the “special wave shape” of input current, and an active input power less than or equal to 600W
- Class A for everything else, particularly balanced three-phase equipment

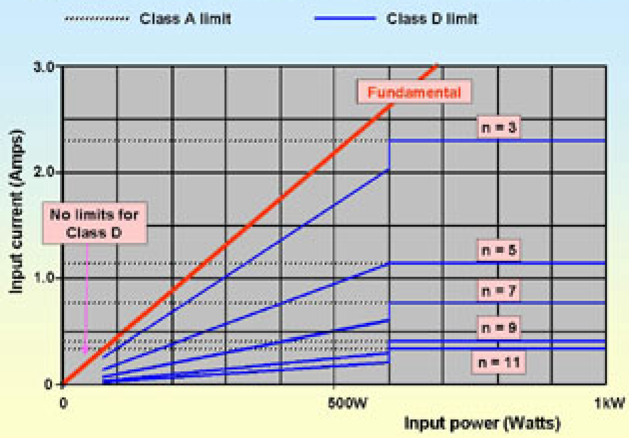
The “special wave shape” is defined by an envelope as shown in Figure 7C and is effectively a means of distinguishing rectifier-capacitor power supply input circuits, which normally draw their current for less than a third of the supply half-cycle. The harmonic limits are quoted as absolute values for Class A, whatever the input power, and as a set of sliding values proportional to input power for Class D. Figure 7D shows these limits graphically. For equipment with an input rating greater than 600W the Class A limits, being fixed, become proportionately more severe as the input power increases.

Figure 7C The "special wave shape" for IEC 61000-3-2 Class D
(Note: if A14:2000 is applied Class D limits are only applied to computers, their monitors, and TVs, and the special waveshape shown below doesn't apply)



Input current falls within shaded area for at least 95% of the half-period.
Centre line at π/2corresponds to peak value of input current.
Note: ωt = 0 is in general not the voltage zero crossing

Figure 7D Class A and Class D harmonic current limits for n ≤ 11



7.1.7 Applicability of the Class D limits

The definition of Class D has caused multiple problems. If the EUT is suspected of being Class D, the test equipment must first check the input waveform to confirm whether or not it falls inside the Class D definition, and then decide on its active input power, before the limits can be applied. The proper input power to use is hard to pin down, especially if the current and/or its harmonic content is fluctuating.

This difficulty is decisively addressed in A14. Since Class D is intended to constrain particular types of equipment which are considered to have the greatest impact on the power network, A14 has turned the definition on its head by specifying particular types of product to which the Class D limits must apply. These are:

- Personal computers and their display monitors
- TV receivers

…with a specified power (see next paragraph) less than or equal to 600W. All other equipment that is not classes B or C is to be regarded as class A. The class D "special waveshape" requirement is effectively removed from the discussion, as is the contentious transition of the lower limit from 75W to 50W, which is now postponed indefinitely.

7.1.8 Power basis for class D limits

The class D limits are given in mA per watt. According to A14, average emissions are to be compared to limits based upon the maximum of the measured values of power 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.

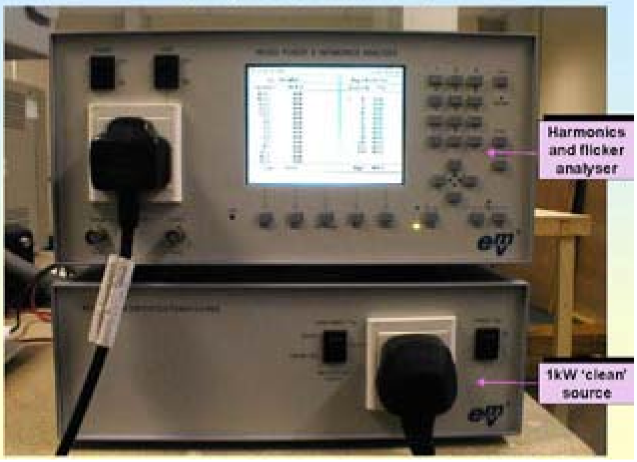
7.1.9 Professional equipment

A significant relaxation, present in the original standard, is that no limits apply (more correctly, limits are "under consideration") for professional equipment with a power of more than 1kW. Professional equipment is defined as "equipment for use in trades, professions or industries and which is not intended for sale to the general public. The designation shall be specified by the manufacturer". A14 relaxes this slightly more, by allowing the connection to "certain types of low voltage supplies" of non-compliant professional equipment, if the instruction manual contains a requirement to ask the supply authority for permission to connect.

7.2 Proprietary test equipment for harmonics and flicker

Figure 7E 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), and Laplace Instruments for a total cost of around £1700. It gives fully compliant measurements (for equipment within the rating of its source) to either EN 61000-3-2:1995 or EN 61000-3-2:1995 + A14:2000, and also to EN 61000-3-3:1995.

Figure 7E Harmonics and flicker analyser, with mains source
(Courtesy of AD Compliance Services Ltd)



When buying EMC test gear for harmonics or flicker measurements, always make a point of asking whether the equipment complies with the relevant test standards, and any amendments (such as A14) that may be relevant to your products, plus the basic harmonics or flickermeter standards (IEC 61000-4-7 and IEC 60868 respectively). Test gear that does not comply with the specifications in the standards might still be acceptable if it is not being used to determine ompliance, or if the golden-product test methods described in section 1.9 of Part 1 of this series [1] are employed.

7.3 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 correct the test set-up and interpretation of results should follow the standard. The ‘golden product’ method described in section 1.9 of [1] can also be a great help in improving confidence in the results of low-cost tests.

7.3.1 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. Combined harmonics and flicker testers are not unusual (see Figure 7E).

7.3.2 Mains source alternatives

Figure 7E shows an example 1kW mains source, the AC1000, which the HA1600 is standing on top of. This unit costs around £500 and I understand that it 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 amplifier sources.

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 one (taking all safety precautions, of course).

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 of them have very poor output waveforms indeed, and most of them have a relatively high output impedance which means that their output waveform will be distorted by the non-linear current consumption of the EUT. So you may need to use an M-G set or UPS with a rating up to ten times the EUT’s rated power consumption, maybe more. So make sure to check their output waveforms when they are loaded by the EUT.

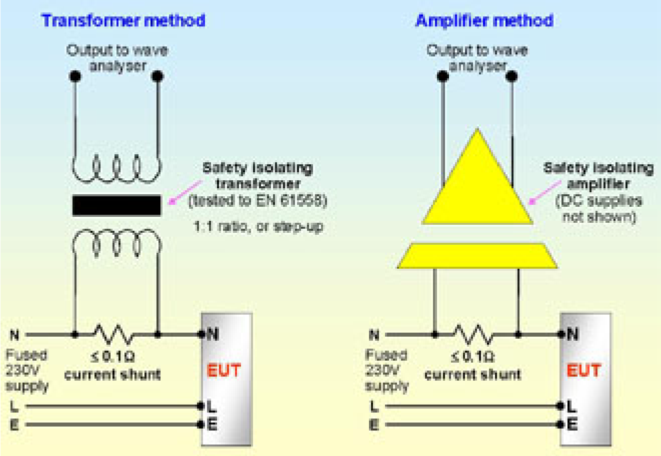
It is a good idea, even with a proprietary ‘clean’ source, to always observe the mains supply waveform with an oscilloscope and/or power quality analyser (see 7.3.4 below) to check that it is a sine wave of adequate quality and that the current demand from the EUT is not causing ‘flat-topping’ or other waveform distortions. Try to ensure that the harmonic distortion of the supply used falls within (or close enough to) the supply specifications in EN 61000-3-2, or else you could find yourself trying to cure harmonic emissions problems which don’t exist.

7.3.3 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.

Figure 7F indicates some techniques which can increase signal amplitudes and provide galvanic isolation when using resistive 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).

Figure 7F Current shunt techniques



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. Alternatively, for single-phase EUTs and where the supply neutral is connected to protective earth at the substation or building's supply inlet, only connect the step-up transformer in the neutral lead, and check that the neutral-to-earth voltage is low, from time-to-time.

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 mains supply. 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.

Figure 7F 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. Safest is to use an amplifier which has isolation complying with EN 61010-1 or EN

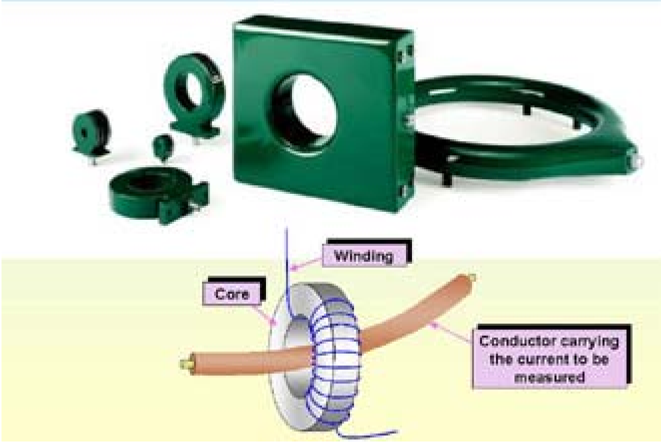
60950, but these may be hard to find and you may have to settle for one which guarantees 3kV or so electric strength and double (or ‘reinforced’) insulation across its isolation barrier. If you can be certain that the current shunt is in the neutral lead and that the neutral has a low voltage to the protective earth, the isolation requirements may be able to be reduced, but I would not recommend this.

Instead of purchasing an IC with built-in 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 supply 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 [7] and [8]. But remember to follow IEC 61010-1 or EN 60950 for all safety issues and don’t assume anything.

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.

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’). Figure 7G shows some example current transformers from Pearson Electronics Inc. while Figure 7H shows clip-on current probes from Fluke and Tektronix.

Figure 7G Examples of current transformers
These are from Pearson Electronics Inc., UK agents: Alrad Instruments, Newbury



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. Versions are available (for instance from LEM-HEME) with solid toroidal cores, or with split cores for clip-on use. The Tektronix A622 probe shown in Figure 7H is a Hall effect type.

Figure 7H Examples of clip-on current transducers

Calibration: purchased current transducers should have a calibration factor, or if they vary with frequency a calibration chart. But if they do not (or if you made them yourself) they can be calibrated by driving a known current through them at a known frequency. This can be easily achieved by amplifying a signal from a sine-wave generator with an audio power amplifier to drive a precision power resistor with the sort of currents to be measured (taking care to avoid overheating the precision resistor). Testing with the signal generator set to various frequencies measures how the calibration varies with frequency (if it does). It is also a good idea to check that the transducer's calibration factor does not vary with the actual current level. The calibration data for a current transducer is its 'transducer factor' and should always be used to correct the raw measurements made with them to get an accurate result.

7.3.4 Wave analyser alternatives

As usual, the most expensive part of the measurement set-up is the wave analyser. Alternatives are possible, sometimes using existing laboratory test gear, but of course they will not comply with IEC 61000-4-7 so an understanding of its requirements plus those of EN 61000-3-2 (and A14) would be required to interpret their measurements appropriately. The use of the 'golden product' method described in section 1.9 of Part 1 of this series [1] 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 make a great harmonics 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 using maths functions available in some 'scopes, or if you can download the DFT data to a PC and post-process it there, you could make a reasonable stab at a measuring to EN 61000-3-2 and A14, including its 1.5 second smoothing algorithm for fluctuating harmonics.

Typical outputs from proprietary clamp-on current probe accessories (see Figure 7F above) 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 a 1mV/division sensitivity vertical channel setting available.

The output of a current shunt will not give sufficient S/N to measure to the lower emissions limits at the higher frequencies, unless the 'scope has a special plug-in with 0.1mV/division or a step-up transformer or amplifier is used between the shunt and the 'scope, as described in 7.3.2 above. Several battery-powered galvanically isolated amplifiers are sold for use with oscilloscopes, and using one of these with a shunt should allow reasonable measurements to be made whilst helping to ensure safety.

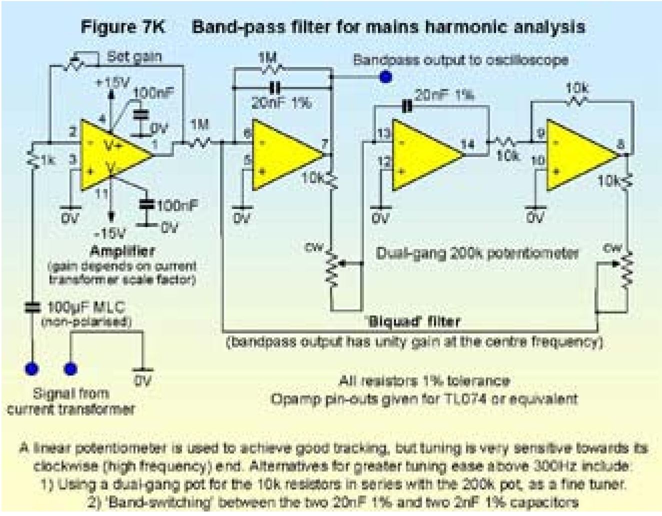
A number of **portable power-quality instruments** are now available. Although intended for testing the power quality and harmonic currents in electrical installations, they can often be used for testing the harmonic current emissions from individual items of equipment. Examples of such instruments include 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. See Figure 7J for examples of some of these products. With the addition of a current probe (see Figure 7H) 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 and its A14.

Figure 7J Examples of hand-held power quality analysers

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 harmonics and flicker analyser shown in Figure 7E. 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 – your company may already own one (ask your site electrician).

Making your own very low-cost wave analyser requires little more than a **biquadratic filter** based on a single quad opamp, and almost any old oscilloscope, as shown by Figure 7K.



Because it is working with such low frequencies (max: 2kHz), this circuit can be made very quickly and cheaply on a piece of prototyping board, and has no layout requirements apart from the siting of 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 can help, too, especially if faster opamps than the TL074 are used). This simple filter requires an oscilloscope to identify the frequency it is tuned to, buy observing its bandpass output. I have not bothered to calculate its filter bandwidth, but I know it is narrow enough to resolve individual mains harmonics clearly.

Operation of the Figure 7K 'bandpass filter' wave analyser (taking all necessary safety precautions at every stage):

a) Attach the current transducer (see 7.3.3 above) to mains lead to be tested.

b) Attach the mains lead to the 'clean' power source (see 7.3.2 above).

c) Switch the EUT on and set it up with the operating mode, power output, etc., as specified in EN 61000-3-2.

d) Connect the bandpass output from the circuit to an oscilloscope vertical channel amplifier with 1MΩ input, AC or DC coupled.

e) Set the 'scope's timebase to whatever best suits the frequency to be measured.

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 good clear waveform.

g) Measure and note the displayed frequency using the oscilloscope, which should be a multiple of the mains frequency.

h) If the waveform isn't a sine wave, or is 'fuzzy, or is not a multiple of the mains frequency – there is a fault, or interference (e.g. a strong magnetic field).

i) Measure the signal's peak-to-peak value and calculate its RMS (you could connect a true-rms voltmeter to the bandpass output and simply use the oscilloscope to indicate correct 'tuning'). If the signal level is varying (not due to variations in the EUT's harmonic current demand), record the maximum value to be on the safe side.

j) 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 (and A14) rules for dealing with fluctuating harmonics.

k) Repeat e) to j) above for the other harmonics until you have the full set from the 50Hz fundamental to as high as you need to measure.
l) Compare the amplitudes of the harmonics with the specifications.

To calibrate the Figure 7K bandpass-filter 'wave analyser', connect a known linear load (e.g. a precision high-power resistor) in series with an accurate ammeter (true RMS or calibrated RMS) in place of the EUT. Compare the ammeter reading with bandpass filter reading on the 'scope when the filter is tuned to the fundamental of the mains frequency (any harmonic signals should be very small, if the source is clean enough). Comparing the ammeter reading with the 'scope signal gives the calibration factor at 50Hz, and the gain of the amplifier stage can be adjusted so that it is a handy number, such as 100mV/A or 1V/A. Remember, that as described in 7.3.2 above, some current transducers may require calibrating at other frequencies too.

If you have plenty of spare time, you might like to automate the filter tuning and lock it to the sweep of the oscilloscope to create a rudimentary low-frequency spectrum analyser (more precisely: a sweep-tuned receiver). The sweep rate should not be so fast that the amplitudes of the harmonics is affected. The narrower the filter bandwidth, the slower the maximum sweep rate for an accurate measurement.

7.4 Fully compliant voltage fluctuation and flicker testing

This section is based upon Chapter 3 of [5].

EN 61000-3-3 [3] places limits on another type of low frequency 'emission' into the mains supply. Flicker is defined as the "impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time". Varying current loads on a power supply network can result in voltage fluctuations at common points of connection, due to the series impedance of the network. These voltage fluctuations, if of sufficient amplitude, can cause flicker in luminaires connected to the same supply. This is a very old interference problem that dates from the very first public electricity supplies, and was responsible for the very first item of EMC legislation ever – the UK's 'Lighting Clauses Act' of 1899 [6].

Therefore, EN 61000-3-3 – which applies to much the same wide range of apparatus as does EN 61000-3-2 – regulates the degree to which a given item of equipment can cause voltage fluctuations capable of causing perceptible flicker. It does so by limiting the voltage variations that are generated across a reference load, and it places limits on three factors:

- The relative voltage change (maximum, d_{max}, and steady-state, d_c)
- The short-term flicker value P_{st}
- The long-term flicker value P_{lt}

These limits do not apply to emergency switching or interruptions, and the P_{st} and P_{lt} limits do not apply to manual switching or voltage changes occurring less frequently than once per hour. But the voltage change limits d_{max} and d_c do apply to such occasional events, and this effectively places a limit on allowable switch-on inrush current for any apparatus, even where the switch-on is done manually. A recent amendment to the standard proposes d_{max} of 6% for manual switching (7% for attended equipment or equipment which will be switched on no more than twice a day) and states that for manual switching, equipment is deemed to comply without testing if the maximum rms input current including inrush over each half period does not exceed 20A. If inrush current measurements have to be made, then 24 inrush events are recorded, the highest and lowest are discarded and the average is taken of the remaining 22 to calculate the final result.

Equipment that typically produces flicker in normal operation includes any device which switches varying loads during its operating cycle. Many household appliances fall into this category, and particular offenders are products which have heaters whose temperatures are controlled by burst firing, i.e. power is provided to the heater for a few cycles of the mains supply at a time, and the on/off ratio of the bursts controls the temperature. If the heating load is at all substantial this kind of equipment easily falls foul of the flicker limits. It is a pity that simply replacing burst firing with its common alternative AC power control method – phase angle control – makes it likely to fail to meet EN 61000-3-2 without suitable filtering.

7.4.1 Measuring instrumentation

The basic instrumentation used to measure flicker has essentially the same block diagram and characteristics as the harmonics analyser shown in Figure 7A, and for this reason harmonics and flicker analysers are often packaged together. The difference can be seen in Figure 7L, which gives the circuit for a three-phase supply. The measured variable is now the voltage across the point of supply rather than the current drawn from it. The source impedance of the supply generator is carefully defined so that load current changes in the EUT produce a defined voltage change which is then analysed to compare it with the various limits.

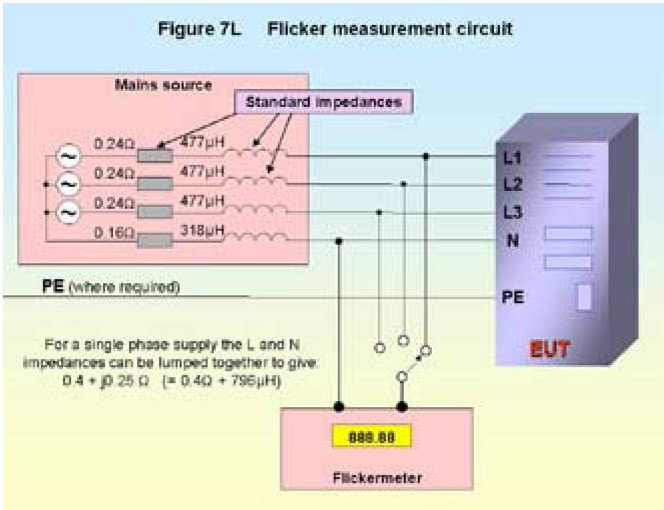


Figure 7L Flicker measurement circuit

The accuracy of this set-up is required to be such that the relative voltage change can be measured with a total accuracy of better than ±8% of the maximum allowed value. The measurement errors can be distributed between the reference impedance and the analyser as long as the total remains within this limit.

7.4.2 Relative voltage change

The RMS voltage is evaluated over successive half-periods (each 10ms) to build up a time-dependent view of the voltage changes. The voltages are normalised to the nominal value to give d(t) and two characteristics are derived:

- The relative steady-state voltage change d_c, which is the difference between two adjacent steady-state voltages separated by at least one change (steady-state is defined as persisting for at least 1 second);
- The maximum relative voltage change d_{max}, which is the difference between maximum and minimum values of the voltage change characteristics.

The original (un-amended) standard requires that d_c does not exceed 3% and d_{max} does not exceed 4%, and that the value of d(t) during a voltage change does not exceed 3% for more than 200ms. These values are multiplied by 1.33 for manual switching or events occurring less often than once an hour. The amendment which relaxes this (see above) has – at the time of writing – yet to be harmonised in the Official Journal of the EC, so could only be used for compliance to the EMC Directive if it was part of Technical Construction File (TCF).

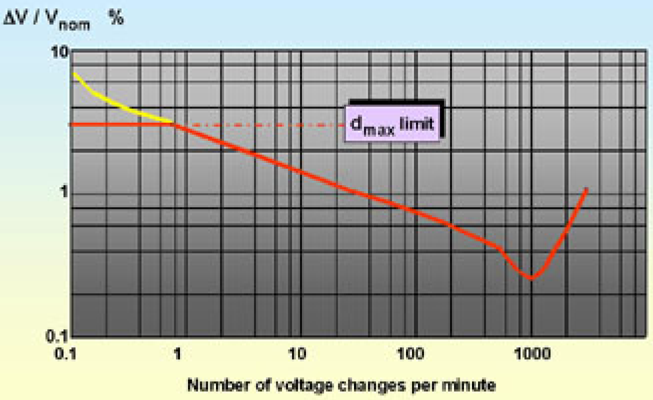
7.4.3 Short-term flicker

Voltage changes by themselves do not adequately characterise the flicker perceptibility. The human eye-brain combination varies in sensitivity to flicker as the flicker frequency changes. To account for this, the voltage changes must themselves be processed over a period of a few minutes to take account of the frequency of changes, the shape of the voltage change characteristic, and the cumulative irritating effect of repeated changes. Whilst in some special cases this can be done analytically, and in one case by direct comparison to a graph (see below), in general the voltage changes are passed to a "flickermeter", whose specifications are given in a separate standard, IEC 60868. The flickermeter applies a weighting to the voltage change characteristic depending on its waveform, and is the reference method.

The output of the flickermeter gives the short-term flicker indicator P_{st}. P_{st} is observed over a period of 10 minutes, to include that part of the operating cycle in which the EUT produces the least favourable sequence of voltage changes. P_{st} is not allowed to exceed a value of 1.

For the special case of rectangular voltage changes of the same amplitude separated by equal time intervals, the P_{st} value can be derived from a graph published in the standard and reproduced in Figure 7M. This shows the value of d(t) versus frequency which gives a P_{st} of 1, and illustrates the maximum physiological sensitivity at around 8Hz or 1000 voltage fluctuations per minute.

Figure 7M Curve for P_{st} = 1 for rectangular equidistant voltage changes



7.5 Low-cost non-compliant testing for flicker

It can be difficult to assess flicker without a flickermeter (such as Figure 7E) because of the complex requirements in the flickermeter specification, which are in turn due to the fact that flicker is a complex human physiological phenomenon.

But for the very many types of products that consume relatively steady power from the mains supply, a few quick measurements of current and a few 'back-of-an-envelope' calculations will show that they are certain to pass a flicker test to EN 61000-3-3.

Many manufacturers have not bothered with testing their products to EN 61000-3-3 because they did this calculation (or their test laboratory did) and the result was negligible flicker. Unfortunately, this does not necessarily mean that they will pass the inrush current specification in EN 61000-3-3 (see 7.4 below).

Before you decide to design your own flickermeter, consider that the combined harmonics and flicker instrument shown in Figure 7E costs around £1700 and gives compliant results (for equipment within the power rating of its source). It may be a more effective use of time and money simply to buy such an instrument.

Section 4.2.3 of EN 61000-3-3 gives some guidelines to designers for estimating the effects of waveshape on peak voltage fluctuation for a few commonly-encountered shapes – but only for fluctuations that occur less than once per second. This makes it easier to estimate the likely voltage fluctuation emissions from an equipment calculation, simulation, or by simple measurements using standard laboratory equipment (oscilloscopes, for example). The accuracy of these estimates is claimed to be no better than ±10%, so results which are within 20% of a limit should be checked with a flickermeter on the actual equipment to ensure it complies.

If you are using a test supply with a total harmonic distortion of under 10% and a supply impedance as specified by EN 61000-3-3 you can measure the voltage fluctuation directly with an oscilloscope (using 'scope probes which comply with EN 61010-1 for mains use).

If instead you measure the load current fluctuation with another supply impedance you would need to transform it mathematically into the voltage fluctuation that could be expected using the standard impedance. But beware – the load current fluctuations will themselves depend upon the supply impedance, so if measuring the load current it is best to make sure your supply impedance is equal (both in resistance and inductance) to the standard supply impedance, or less.

Synthesised sources of mains voltage are now available, either with programmed impedances (or zero) achieved by feedback techniques or with the standard impedance. As time goes on more manufacturers are entering this market and the cost of these sources is falling. Figure 7E shows an example of a 1kW mains source with an impedance which is understood to be close to zero.

Load currents can be measured using exactly the same sources and current transducers as were discussed in 7.3.2 and 7.3.3. above, and simply viewed on an oscilloscope.

If you know your equipment's load current waveshape – whether calculated, simulated, or measured with the standard source impedance or zero ohms – you can calculate or simulate the resulting mains voltage fluctuation waveshape. By referring to 4.2.3 and figures 5, 6 and 7 in EN 61000-3-3 you may find that you can predict the flicker emissions from your equipment.

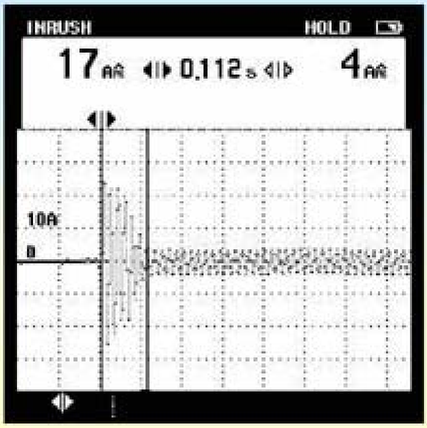
If you have a circuit simulator running on your PC or workstation, you may be able to input the measured current into a circuit which is identical to the supply impedance specified by EN 61000-3-3, and discover the output voltage variations which result. Voltage fluctuations lasting less than 10 milliseconds are 'smoothed out' by the 10ms integration process required by EN 61000-3-3 and the flickermeter specification, and it may be possible to add a functional block to your simulator to give the corresponding output.

7.6 Low-cost non-compliant testing for inrush current

The switch-on inrush current limits in EN 61000-3-3 are relatively easy to understand (compared with flicker limits for repetitive voltage fluctuations with various waveshapes). It is also easy to use the current transducers as described in 7.3.2 and 7.3.3. above with an oscilloscope to measure the switch-on inrush.

A digitising (or analogue storage oscilloscope) is the best for this purpose. Some of the power quality instruments mentioned in 7.3.4 above will operate as storage 'scopes to capture and display switch-on inrush current. Figure 7N shows an example of a large inrush current captured by a Fluke 43B. When not using a flickermeter, don't forget that EN 61000-3-3 uses a 10ms integration time for each measured sample. Many rectifier-capacitor circuits draw very high currents at switch on to charge their capacitors, but the current 'spike' is very narrow and when integrated over 10ms measures a great deal less than its peak value. Figure 7N shows an inrush event lasting over 100ms (could be something like the starting up of a large induction motor), and this would not be reduced by 10ms integration.

Figure 7N Example of switch-on inrush current
(captured with a Fluke 43B and current probe)



The mains source used may be a problem for inrush current tests. Current capability is very important when measuring inrush currents, and many types of 'clean' source might be current limited and unable to supply the current that the EUT would take from a real mains supply with the standard impedance. So when purchasing or designing a mains source it is best to ensure that it will source a short-term current which is very much larger than the EN 61000-3-3 limit for inrush current.

7.7 On-site testing of harmonics and flicker

There are no requirements in EN 61000-3-2 or 61000-3-3 to perform their tests on an EMC test site. So tests can be carried out on-site as well as in a laboratory – as long as the above sections are taken into account.

7.8 Miscellaneous other EMC tests

There are a great many other EMC tests we could have written about, including many in the IEC 61000-4-x series, but we didn't because they are not required by the majority of the standards harmonised under the EMC Directive.

Standards such as EN 55013 (TVs and radio receivers) or EN 500083-2 (cable distribution for sound and TV) can sometimes include special tests that only appear in those standards, and in general these have not been described in this series.

There are also special EMC standards developed for military, automotive, civil aerospace, tele- and radio-communications and other specialised industries, or for immunity of civilian equipment to nuclear electromagnetic pulse, which have not been covered here.

EMC standards developed by other countries have not been addressed (e.g. FCC, GOST), but this is gradually getting to be less of an issue as most countries are changing over to EMC standards based on IEC and CISPR.

All these other standards could be used in an EMC Technical Construction File, with the agreement of your Competent Body. You may also find some of these other test standards useful in helping to make your equipment reliable in some more specialised real-life situations, for example MIL-STD-462 and DEF STAN 59-41 describes test methods for electric field emissions and immunity from 10kHz to 18GHz; conducted emissions and immunity down to 20Hz; immunity to 'structure currents' from 60Hz to 100kHz; and also immunity to a wonderful variety of transients and surges found in various kinds of land/sea/air vehicles.

7.9 References

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[2] EN 61000-3-2:1995 "*Electromagnetic compatibility (EMC) Part 3-2: Limits – Limits for harmonic current emissions (equipment input current up to and including 16 A per phase)*"
[3] EN 61000-3-3:1995 "*Electromagnetic compatibility (EMC) Part 3-3: Limits – Limitation of voltage fluctuations and flicker in low-voltage supply systems for equipment with rated current up to 16 A*"
[4] Amendment A14:2000 to EN 61000-3-2:1995
[5] "*EMC for Product Designers, 3rd Edition*" Tim Williams, Newnes 2001, ISBN 0-7506-4930-5
[6] "*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
[7] "*Low cost isolation amplifier suits industrial applications*" Andrew Russel, EDN Europe magazine, Feb 2000, pp 59-60, www.ednmag.com
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