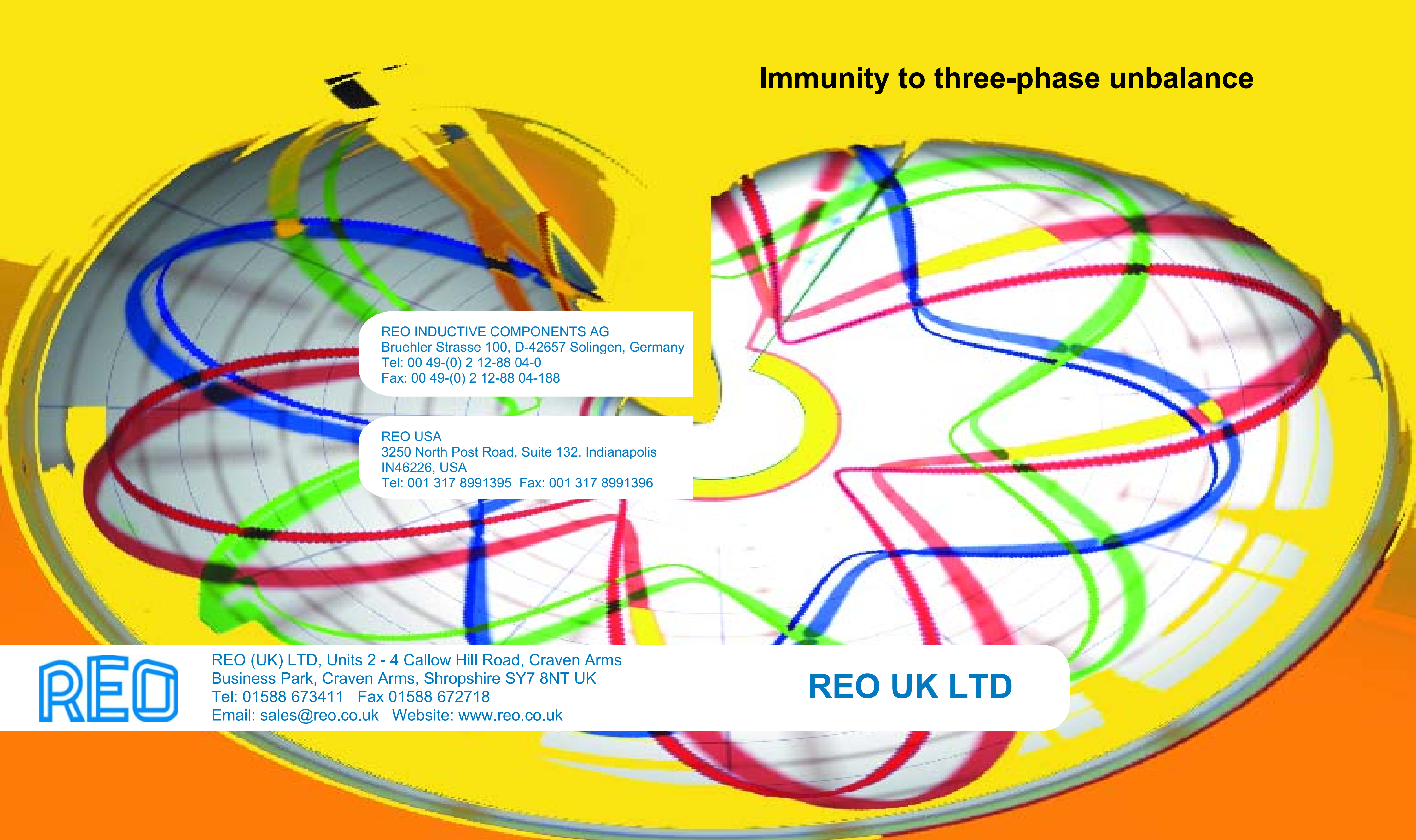
A Practical Guide for EN 61000-4-27

Immunity to three-phase unbalance



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EN 61000-4-27 and compliance with the EMC Directive

EN 61000-4-27 concerns the immunity of electrical or electronic equipment (that is supplied from a three-phase a.c. power supply) to unbalance in its power supply.

IEC 61000-4-27 [1] has been adopted as the harmonised European standard EN 61000-4-27 [2]. These two standards are available to be called up as basic test methods by product and generic standards listed under the Electromagnetic Compatibility (EMC) Directive, 89/336/EEC [3].

The EN version of 61000-4-27 is technically identical to the IEC document, so this booklet is of use where either standard is required. Since many national tests outside the EU, or purchasing contract requirements, are based on IEC standards, this booklet may also be of use in such situations.

EN/IEC 61000-4-27 is what is known as a 'basic test standard', so when following the self-declaration to standards route to conformity (Article 10.1 in [3]) it need not be listed on a equipment's EMC Declaration of Conformity. Only the relevant generic or product harmonised EMC standards are *required* to be listed. Generic or product standards can call-up EN or IEC 61000-4-27 as one of the test *methods* they employ – but it is always the generic or product standard that sets the test *levels*, test *durations* and functional performance criteria that should at least be tested to allow conformity to be claimed.

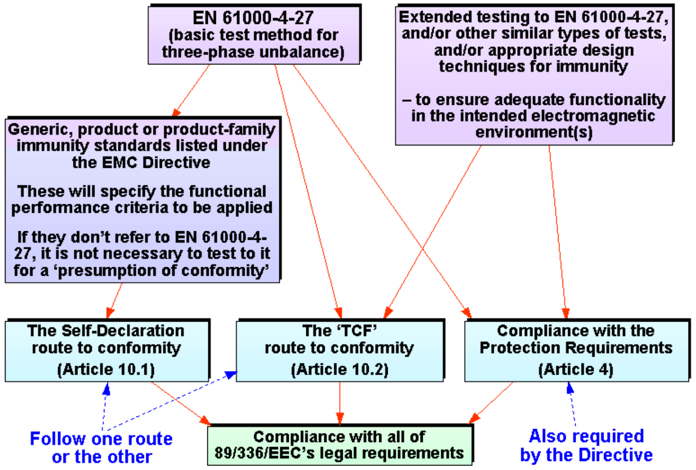
At the time of writing no product or generic EMC standards listed under [3] are known to require testing to EN or IEC 61000-4-27 – but future standards (or versions of existing standards) may well do so. Plus of course this basic standard can be useful when specifying the performance of equipment for suppliers, or for manufacturers who want to improve their equipment's real-life reliability (see later).

When using the Technical Construction File (TCF) route to conformity with the EMC Directive (Article 10.2 in [3]) it is possible to use EN or IEC 61000-4-27 directly, in which case it *should* be listed on the equipment's EMC Declaration of Conformity. In such cases the equipment manufacturer should assess the electromagnetic (EM) environment of the equipment [4] and ensure that it is designed and/or tested accordingly, so as to comply with the EMC Directive's Protection Requirements (Article 4 of [3]).

Compliance with the EMC Directive's essential Protection Requirements applies *in addition* to the requirement to follow one of the conformity assessment routes (Self-Declaration, Article 10.1; TCF, Article 10.2; or Type Approval, Article 10.4 of [3]). Equipment that passes tests to all relevant product or generic standards that are listed under the EMC Directive, but nevertheless is unreliable or fails in normal use because it is not immune enough for the real-life EM environments in the applications it is intended for – does not comply with the EMC Directive's essential Protection Requirements and is therefore illegally CE marked.

So, even when the Self-Declaration Route is being followed, equipment manufacturers are recommended to assess the electromagnetic (EM) environment of the equipment [4] and ensure that it is designed and/or tested to comply with the EMC Directive's Protection Requirements (Article 4 of [3]). Where an item of equipment that is powered from a three-phase a.c. supply could be affected by unbalance in its supply in normal operating environments

The relationship between EN 61000-4-27 and the first edition of the EMC Directive (89/336/EEC)



– as most of them can be – it may prove necessary to test using EN 61000-4-27 (or similar) in order to comply with the Protection Requirements.

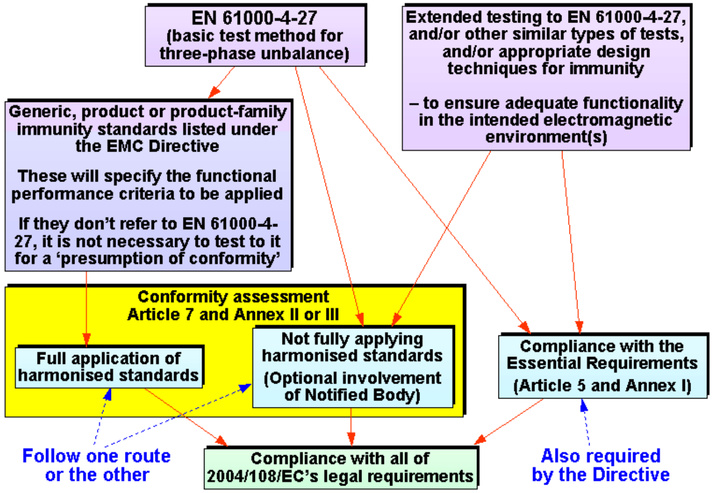
Applying EN 61000-4-27 or similar immunity tests which go beyond the minimum requirements of the EMC Directive's listed product and generic standards can help make equipment more reliable, reduce warranty costs, improve customer satisfaction and reduce exposure to product liability claims. This issue is addressed in the section on 'Test As Real Life', later.

The second edition of the EMC Directive, 2004/108/EC [5], replaces [3] on the 20th July 2007. Equipment already being supplied in conformity with 89/336/EEC will be allowed to be supplied until 20th July 2009, by which date it too must comply with [5] if it is to continue to be supplied in the EU. Whereas [3] requires the involvement of a Competent Body with all TCFs, [5] effectively allows the TCF route to be used with the *optional* involvement of a Notified Body (the new term for Competent Bodies).

Like 89/336/EEC, 2004/108/EC [5] also requires equipment to comply with its Protection Requirements, given in its Article 5 and Annex 1, where it sometimes calls them "Essential Requirements". So it is recommended that all equipment manufacturers assess the electromagnetic (EM) environment of their equipment [4] and ensure that it is designed and/or tested accordingly.

Under 2004/108/EC, all 'fixed installations' must comply with the EMC Directive's Essential Requirements and have documentation that shows how this has been achieved. Equipment manufactured specifically for use at a named 'fixed installation' may not have to comply with any EMC requirements at all, when it is supplied – but testing to EN 61000-4-27 at specified levels could be one of the EMC specifications imposed on the

The relationship between EN 61000-4-27 and the second edition of the EMC Directive (2004/108/EC)



supplier by the purchaser, to help ensure that a particular 'fixed installation' complies with the Essential Requirements of [5].

This booklet is part of a series that discusses a number of common EM phenomena in domestic (residential, household, etc.), commercial, light industrial and industrial environments and how they are tested according to appropriate EN standards on emissions and immunity. But other kinds of immunity tests may be required for aerospace, automotive, rail, marine, military and other special environments. Some industries may have developed their own immunity test standards based on their own particular kinds of a.c. power supply supplies.

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

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

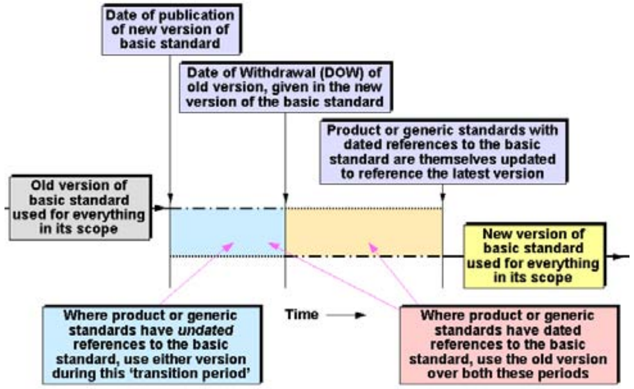
This booklet describes how to apply EN 61000-4-27:2000. Where a generic or product EMC standard requires the use of a basic test method it will specify either a dated reference (e.g. “EN 61000-4-27:2000”), or an undated reference (e.g. “EN 61000-4-27”). If it specifies a dated reference, then this is the version of the basic test method standard that *must* be used. If it specifies an undated reference then the *latest* published version of the standard should be used. (At the time of writing, there are no versions of EN 61000-4-27 other than the 2000 one.)

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

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

A note of caution: the European Commission (EC) has ruled that where Directive compliance is concerned, only dates that are published in the Official Journal of the EU (OJEU) have any relevance, and not any dates put into standards by their committees. This is not a problem in most cases, but basic EMC test standards such as EN 61000-4-27 are never listed in the OJEU. Since DOW dates in the basic standards are not recognised by the EU, there can be no transition period – which is clearly impractical and silly – but this consequence does not seem to have been foreseen by the EC. It is probably less risky to always use the latest version of a basic test standard, except where the regulatory requirements (for the EU or other markets) specify the exact version to be used.

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



What kind of equipment is covered?

Clause 1 of EN 61000-4-27 says that it applies to three-phase powered electrical and/or electronic equipment with a rated current of up to 16A per phase. It applies to 50 and 60Hz powered products, but not to other frequencies such as 400Hz (typical of aircraft a.c. power supplies). Equipment that consists of a group of single-phase loads, each connected between phase and neutral, is not covered.

What is three-phase unbalance, and how does it arise?

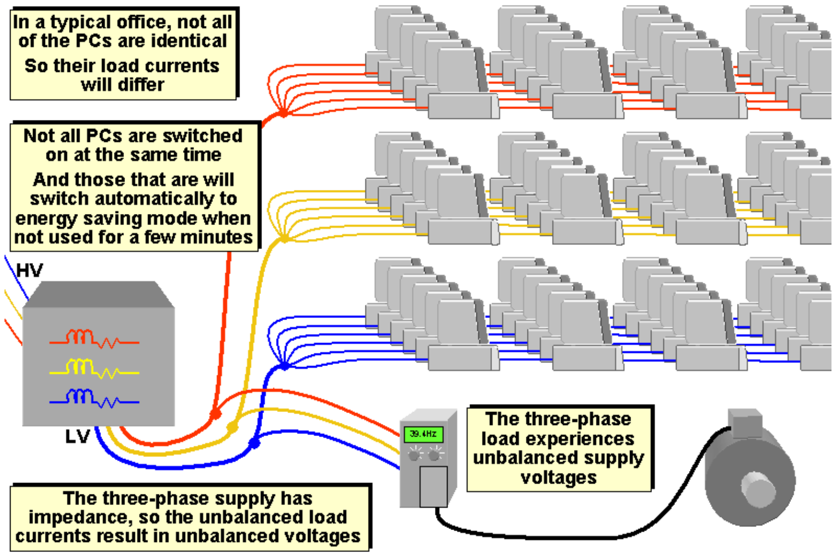
Unbalance can affect the phase-phase and/or phase-neutral voltages of the three-phase mains supply, and/or the phase angles between the three phases.

The main cause of unbalance is the use of single-phase loads. Attempts are usually made to 'balance' the single-phase loads on a three-phase supply, so that each phase is loaded by the same amount, but it is usually impossible to balance them exactly, especially when the current demands of the loads can vary from time to time.

Single-phase loads can be connected phase-phase or phase-neutral, on low-voltage (up 1kV rms), medium voltage (up to 33kV rms) or high-voltage (above 33kV) power supplies. Most of the loads on 230/400V supplies are connected phase-neutral. The most significant loads where unbalance is concerned are traditionally the larger ones, such as single-phase railways and induction furnaces. Even where three railway systems or three induction furnaces are connected to a three-phase supply in an attempt to balance their loads, the current demands of the individual loads will vary without any synchronisation with the others (e.g. as trains accelerate and decelerate), so the load balancing will not be very effective.

Increasingly these days, most of the load in large commercial buildings consists of low-power loads such as computers and luminaires, typically consuming less than 1kW each. Such loads can be balanced very nicely – assuming they are all switched on at the same time – but the trend is to use energy-saving features such as PCs that turn their screens or hard drives off if their keyboard or mouse hasn't been used for some minutes, or luminaires that are controlled by occupancy sensors. So one unexpected result of trying to

An example of three-phase unbalance caused by single-phase loads



reduce energy consumption to save the planet is that unbalances in many three-phase supplies are becoming worse.

Very high levels of unbalance are caused by faults on the network, for example an earth fault in the mains supply circuitry or cabling of an item of single-phase equipment. Faults are a 'natural feature' of all mains supply networks. These unbalances will last for as long as it takes the fuse or other overcurrent protection device to operate and clear the fault – generally less than 1 second for the protection devices associated with an item of low-voltage equipment. But faults in medium or high-voltage installations might take longer to clear.

Some three-phase loads do not consume balanced currents, so can be a cause of unbalance. For example – arc furnaces consume randomly varying currents on each phase, independently of any other phase.

The problems that can be caused by three-phase unbalance

EN 61000-4-27 says that its aim is to investigate the influence of unbalance in a three-phase system on equipment that may be sensitive to this type of disturbance, which could cause…

- Overcurrents in a.c. rotating machines;
- Generation of non-characteristic harmonics in electronic power converters;
- Synchronisation problems or control errors in the control part of electrical equipment.

When induction motors are supplied by unbalanced voltages, their current consumption on one or more phases can rise to levels similar to what they draw at start-up – much higher than their normal operating voltages. But start-up only lasts for a fraction of a second (or for a very large motor, a few seconds) whereas some unbalances can exist for minutes, hours, weeks, even years, so overheating – with consequent damage to the insulation of the windings and implications for future reliability – can be a real problem.

Motors are usually protected by overcurrent devices, but if one phase is opened the motor will soon destroy itself. This is why motor control contactors should always break all of the phases simultaneously, whichever phase(s) are suffering the overcurrent.

Electronic power converters are used to turn mains a.c. power into d.c. power, and some of them then turn it back into a.c. power again at another frequency (typical of variable-speed drives for a.c. motors). Three-phase converters use 6-pulse, 12-pulse and even 24-pulse rectifiers to generate a d.c. voltage that consists of a constant voltage with a small amount of ripple on it – even though they may not be fitted with any storage capacitors. The higher the pulse rating of the rectifier – the smaller the ripple voltage and the higher its frequency.

But the ripple voltage and frequency on the d.c. rails of three-phase rectifiers without storage capacitors is very rapidly affected by any unbalance in their three-phase supply. If the circuits following the rectifier have not been designed to cope with the ripple that can result from likely unbalances – they may be affected by it.

In the case of a.c.-d.c.-a.c. converters (often called 'inverters') the result of an unbalance in their supply is an increased level of interharmonic distortion in their output (waveform distortion that is not harmonically related to the output frequency). This output 'noise' can be harmful to the converter's load.

For reasons of cost, sensors (voltage, current, power, etc.) are usually placed on one phase of a three-phase supply, on the assumption that all of the phases behave in the same way. So when an unbalance occurs the sensors might not measure what is required to control the equipment correctly, and misoperation, overheating and even damage might be the result.

The analysis above overlooks a more general class of effects, due to electrical and electronic circuits being operated on supply voltages that are higher or lower than they have been designed for due to an unbalanced three-phase supply. Most circuits are designed for the range of supply voltages supplied by the electrical utility, but harmonic distortion of the waveform and unbalances can make the range actually experienced by an item of equipment worse than what was expected. This is especially so because many types of equipment derive their unregulated d.c.

rail from the peak of the mains waveform, whereas it is the rms value that is controlled by the Utility (see the REO booklet on harmonics, interharmonics and EN 61000-4-13 [6]).

Supply voltages that are higher than a circuit was designed for can cause misoperation, as well as overheating and even permanent damage. Supply voltages that are lower than a circuit was designed for can cause them to misoperate, but overheating and damage are only a problem for some rare circuits. How a circuit can misoperate depends on the type of circuit and on the details of how it was designed.

Analogue signal processing circuits may simply find that their maximum signal amplitude is reduced, but it is not unusual for bias levels to shift the operating points of semiconductors in such a way that they do not behave as intended – the result can be any amount of error and any type or degree of malfunction. For example, audio power amplifiers might become unstable and 'whistle' at full power at high or ultrasonic frequencies, or they may 'thump' – either of which might destroy the speakers they are connected to.

Digital circuits might reset or reboot cleanly. If they don't reset cleanly, or at all, they might experience almost random errors ranging from a change in operational mode (e.g. from crawl speed forward with reduced torque, to full speed reverse with full torque); continuously repeating a section of code; or a 'crash' or 'lock up' where the circuit ceases to operate at all.

In competently designed digital equipment a crash will eventually lead to a reboot, whereupon the equipment might then find itself in an undesirable state, depending on its application. If a reboot leaves the equipment in 'power-up' mode – this could cause problems if what is required is that the function that was being performed before the reboot should be continued. For example, a flashing lamp that indicates a hazard should continue to flash after the disturbance, and not switch off.

But sometimes the time taken by the reboot means that whatever is being controlled should shut down in a controlled manner and then require an automatic or manual restart once the correct starting conditions have been met. For example, where a number of motor drives are controlling the processing of a web of material, their speeds must be synchronised. If any one of them gets 'out of step' it risks breaking the web, which can be very costly. So it may be necessary to bring the web safely to a halt, and restart the process when the disturbance that caused the problem is over.

An often overlooked aspect of a crash or lock-up is that the outputs of the digital circuit can be left in any random combinations of states until the successful reboot. In the case of computerised systems running large operating systems, the reboot time can be measured in minutes. During this time the digital outputs may be sending erroneous control signals to powered actuators that could create undesirable situations. In some applications such random outputs might even cause damage to the equipment being controlled, or safety hazards to its users or third parties.

Some types of high-reliability equipment, such as life-support, cannot be allowed any deviation from full-specification operation. Such equipment is often powered from an uninterruptible power supply (UPS), in which case the UPS must be very reliable and withstand its real-life EM threats, such as three-phase unbalance.

Power control circuits (e.g. inverter drives, switch-mode power converters) might suffer actual damage due to cross-conduction in their power switching devices, when their controlling devices create timing errors due to malfunctions in their circuits. The damage might extend to exploding transistors, which can create safety hazards.

Introduction

This booklet is not a complete recital of everything that is in EN 61000-4-27, only a general guide. Anyone performing tests to this standard should have a copy of the relevant edition, and any relevant amendments, and follow it/them exactly.

Classes of equipment

Annex D of EN 61000-4-27 specifies the three Classes of equipment according to their likely exposure to unbalances in their mains power supplies.

But these classes only apply where products are connected directly to the Point of Common Coupling (PCC), or In-plant Point of Common coupling (IPC), with a reasonable length of mains cable that they don't share with any other products. What to do when this situation does not apply is discussed later.

Class 1

No tests are required for this class. Annex D reveals that Class 1 is for equipment that is so sensitive to mains power quality that it needs to be connected to specially protected mains power supplies, where the levels of unbalance are – *by design* – significantly less than those expected on the normal mains supplies provided to domestic properties. Uninterruptible Power Supplies (UPSs), Constant Voltage Transformers (CVTs) or Motor-Generator Sets (MG sets) are typically used when creating such protected mains supplies.

Class 2

This class is for equipment intended to be connected "…*to points of common coupling (PCCs for consumer systems) and in-plant points of common coupling (IPCs) in the industrial environment in general*".

This generally applies to domestic (residential, household, etc.) and commercial networks, and also to light-industrial and industrial networks where heavy power equipment (e.g. powerful welding equipment) is not used (see Class 3 below).

Class 3

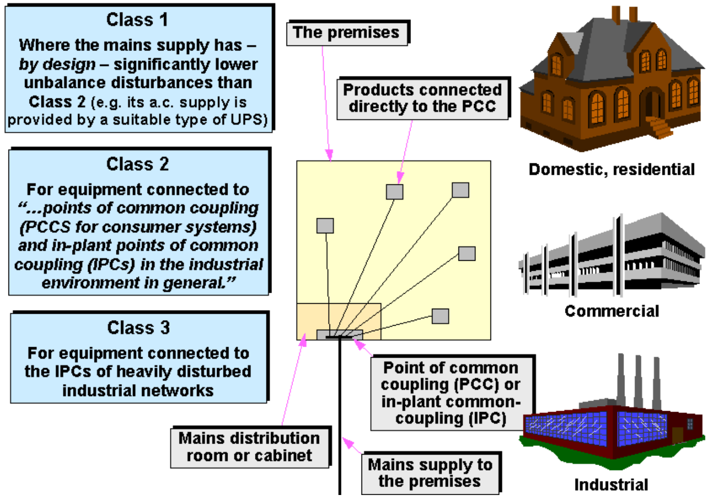
Class 3 is for products connected to industrial mains power networks that are more *heavily disturbed* than Class 2 above. We can distinguish such environments from those covered by Class 2 because they usually have either…

- A major part of their load fed through converters, and/or…
- Welding machines, and/or…
- Large motors or other high-power loads that are frequently started, and/or…
- Loads that vary rapidly.

Note that some *commercial* premises use high-power fluctuating loads, for example the lighting and stage scenery machinery used in some theatres for live stage shows, the audio power amplifiers in discotheques and mobile 'pop concert' installations, etc. In these cases, the test levels appropriate for Class 3 equipment might be appropriate than those for Class 2.

Clause 5 says that even Class 3 might not be tough enough in some industrial situations, for example where a highly disturbing load (e.g. an arc furnace) is powered from a segregated busbar. In such special situations EN 61000-4-27 says the test levels should be agreed upon, presumably between the purchaser and the supplier.

The various Classes of product defined by EN 61000-4-27



The test waveforms and their levels

Clause 5, Figures 1, 2 and Table 1 in EN 61000-4-27 specify the test waveforms, test levels, and test sequences to be applied to an equipment under test (EUT).

There are three 'Classes' of equipment identified (see earlier) and Classes 2 and 3 each have three different 'unbalance test levels' applied. Table 1 specifies the unbalance test levels by the voltage and phase angle of each of the phases, with respect to the test generators reference phase (U_a).

Test number	Test levels for Class 2 equipment			
	Phase	Amplitude (% of nominal)	Phase angle with respect to U_a	Duration of test
1	U_a	100	0°	30s
	U_b	95.2	125°	
	U_c	90	240°	
2	U_a	100	0°	13s
	U_b	90	131°	
	U_c	80	235°	
3	U_a	110	0°	0.1s
	U_b	66	139°	
	U_c	71	235°	
Note: U_b is nominally 120° behind U_a, and U_c is nominally 120° ahead of U_a				

All of the three phases change from the nominal (balanced) mains to the unbalance test level at a point when the reference phase is crossing zero – so only the reference phase's waveform is free from phase angle discontinuities. Each unbalance test is applied for the time specified in Table 1 of the standard.

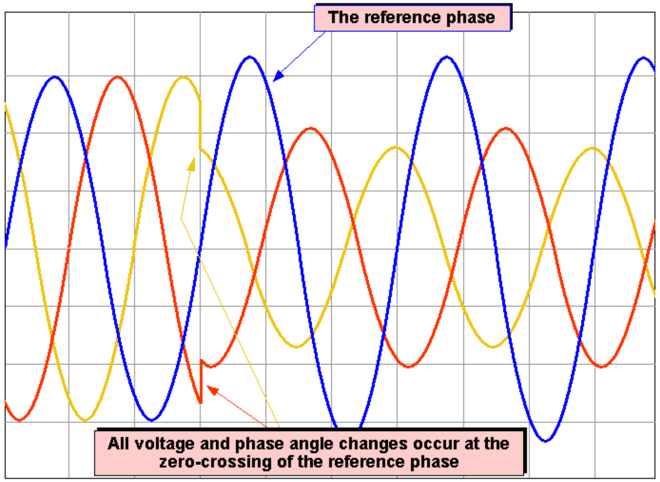
Test number	Test levels for Class 3 equipment			
	Phase	Amplitude (% of nominal)	Phase angle with respect to U_a	Duration of test
1	U_a	100	0°	60s
	U_b	93.5	127°	
	U_c	87	240°	
2	U_a	100	0°	15s
	U_b	87	134°	
	U_c	74	238°	
3	U_a	110	0°	2s
	U_b	66	139°	
	U_c	71	235°	
Note: U_b is nominally 120° behind U_a, and U_c is nominally 120° ahead of U_a				

In addition, each of the unbalance tests is applied with three different connections between the test generator's power outputs (U_a, U_b and U_c) and the EUT's power inputs (L1, L2 and L3) – making nine tests in all for a given EUT.

In-between each of the total of nine unbalance tests there should be a renormalizing period of at least three minutes during which the EUT is supplied with nominal (balanced) mains.

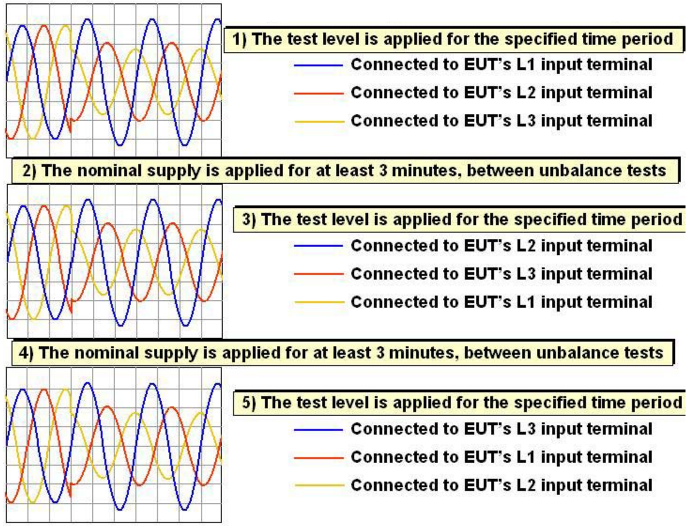
Example of a test waveform

(derived from Figure 1 of EN 61000-4-27:2000)



Example of an unbalance test level sequence

(derived from Figure 2 of EN 61000-4-27:2000)



Unusually, a Level X is not included

All of the standards in the IEC 61000-4 'basic test method' series that the author is aware of have a column for Test Level X, in which the actual parameters of the test are filled in every case with the letter 'X'. This accepts that the tests specified in the basic test method cannot possibly deal with all eventualities, so the 'X' specifications can be chosen by the product or generic standard committee if they feel they are more appropriate for the type of equipment covered by their standard. The 'X' levels can also be specified by a purchaser (usually in the technical specification that forms part of their contract with their supplier), often based on a power quality survey of the particular site in question.

However, part of the text of Clause 5 *does* permit product standards committees to specify any test level they feel is appropriate – but not lower than the Class 2 test levels for any equipment intended to be connected to public supply networks. It doesn't appear to give the same freedom to generic standards committees, or to purchasers or specifiers, but this booklet assumes that they were intended to be allowed the same freedom of specification.

EN 61000-4-27 seems to be intended to apply to mains power distribution networks, whether public or industrial, in *developed* countries. But, as discussed later, some equipment may be expected to be powered from less-than-ideal mains networks that exist in some countries; from local generation and/or from so-called 'green power' supplies – all of which could suffer unbalances that are not typical of normal mains supplies, and could be as bad as, or even worse than Class 3. When specifying equipment for such applications, a Level X in EN 61000-4-27 would have been very useful.

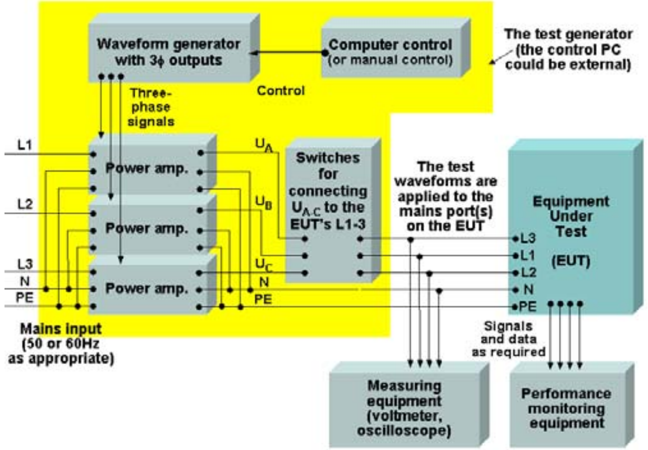
The test generator

Clause 6 of EN 61000-4-27 specifies the characteristics of the test generator, as follows (taken from its Table 2)….

Characteristic	Performance Specification
Output voltage capability	U_N ±50% (U_N is the nominal supply voltage, e.g. 400V phase-phase)
Output voltage accuracy	±2% of U_N
Output current capability:	Sufficient to supply the EUT under all test conditions
Overshoot/undershoot of the actual voltage, generator loaded with 100Ω resistive load	Less than 5% of the change in voltage
Voltage rise (and fall) time during voltage changes, generator loaded with 100Ω resistive load	Between 1 and 5 microseconds
Total harmonic distortion of the output voltage	Less than 3%
Phase shifting	0°, 120°, 240° ±30°
Phase accuracy	1° between any two phases
Frequency accuracy	0.5% of the fundamental frequency (i.e. either 50 or 60Hz)
'Settability' of output voltage	±1% of U_N
'Settability' of output phase	±0.3°

Clause 8 of EN 61000-4-27 adds the requirement for the generator's output impedance to be low during steady-state output and also whilst the output is changing. This can be difficult to implement if using relays or contactors to

An example of a test generator based upon a waveform generator



perform the switching, but easy when each phase is supplied by a power amplifier. But unfortunately it does not say what the generator's output impedances should be, and this could possibly be a problem for test repeatability when different test generators are used.

Since the test levels in EN 61000-4-27 are based upon a mains supply in which each phase conductor has a complex impedance of 0.283Ω (actually 0.24Ω resistive plus 0.15Ω inductive) – according to IEC 60725 [16] – it seems reasonable to assume that the test generator output impedance should be around this value. This booklet recommends that manufacturers design their EN 61000-4-27 test generators accordingly, and that test laboratories choose test generators that have such an output impedance, to try to improve repeatability between tests performed at different laboratories.

If you mean to buy a test generator, check that the supplier guarantees its compliance with EN 61000-4-27 and (ideally) supplies it with a calibration certificate from an independent calibration laboratory. You should then check the calibration data against the specification in Clause 6 of the latest version of EN 61000-4-27 and any amendments. If you want to make your own test generator (which is not a difficult task) you should first purchase the latest version of EN 61000-4-27 and any amendments to make sure you have the correct design data.

EN 61000-4-27 says that the generator should have provisions to prevent the emissions of disturbances that, if injected in the power supply network, might influence the test results. But this ignores the possible effect of emissions from the generator's output terminals on the correct operation of the EUT. So this booklet recommends that in addition to the requirements in EN 61000-4-27 for protecting equipment connected to the same a.c. supply network, the test generator should also have low levels of emissions on its a.c. power output so that it is unlikely to interfere with any type of EUT and confuse the results of the test.

The REO test generator for EN/IEC 61000-4-27 and 61000-4-11

EN 61000-4-27 does not specify the amount of emissions permitted on the test generator's power inputs, and this booklet suggests that the test generator should meet the radiated and conducted emission requirements of the generic emissions standard EN 61326-1, with the conducted emissions being measured on its a.c. output ports as well as on its input ports.

Verifying the test signal generator

Clause 6.2 of EN 61000-4-27 says that the generator's characteristics are to be verified "as required by the particular EUT". In place of the actual EUT, a suitably-rated resistive load that is equal to the resistive component of the load presented by the EUT may be used.

It does not say how the generator's characteristics should be verified, but this booklet believes this can be done using a calibrated 'true-rms' voltmeter and a storage oscilloscope (e.g. a typical 'digital' oscilloscope), always only employing probes, leads and test equipment that are appropriately rated and safety-approved (see the Safety Note below).

EN 61000-4-27 does not specify *when* the test generator's performance should be verified, but appears to imply that it should be done every time a different type of EUT is to be tested. Where an EUT has more than one operational mode, if the modes can have different power consumptions the test generator should probably be verified for each mode. Of course, the use of the word 'verified' means that if a generator does not meet the specification when driving the EUT, it must be repaired or replaced until one is found that does, and then the test can be carried out.

It is good test laboratory practice to verify a test generator several times in-between third-party calibrations, increasing the rate of verifications if the test generator is moved (e.g. for portable use when testing on a customer's site instead of in the laboratory). The best testing practices require the test generator's performance to be verified before each time an EUT is to be tested. It may be reasonable to devise a verification test that is very quick and easy to do, or to only verify a number of its key parameters, as a check that the generator has not been damaged since it was last fully verified or calibrated.

Safety Note: When measuring voltages or currents, only use probes and equipment that have been approved by an independent safety testing body (e.g. BSI, VDE, TUV, UL, CSA, etc.) to all of the appropriate parts of EN 61010 for the appropriate 'Measurement Category' (previously known as 'Overvoltage

Category' or 'Installation Category'). Measurement Category II is the *minimum* requirement, and Category III or even IV may be required for safety.

If you don't understand *exactly* what the previous paragraph means, have someone who is qualified and competent in this area sort it out for you. In some installations, special working procedures may be required. Electrical and electronic engineers are killed every year by accidental electric shocks – don't let it be you or your colleagues!

The test set-up

The test set-up is specified in Clause 7 of EN 61000-4-27, and is very simple. The three-phase a.c. power output from the test generator is connected to the a.c. power input of the EUT using the supply cable that is specified by the EUT's manufacturer. If the EUT's manufacturer does not specify a length for its supply cable, the cable used should be as short as possible. The length of supply cable that is actually used should be recorded in the test report (see later).

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

The EUT should be connected in the normal manner and operated in accordance with the appropriate product or generic standard. Where no product or generic standard applies, the EUT should be tested whilst being operated in each of its modes, connected to all of its loads and auxiliary equipment as appropriate to allow it to operate as intended. The EUT should be loaded to its maximum continuous rating, where appropriate. It is permissible to simulate the auxiliary equipment required to make the EUT work correctly – if the method used will not affect the outcome of the test.

REO can create custom loads to meet any requirements

Monitoring the EUT for performance degradation during the tests

The functional performance degradation allowed during and after the tests may be specified by product or generic standards. Lacking these, the results should be evaluated according to Clause 9 of EN 61000-4-27 (see later).

Well before the tests are begun, the functional specifications for the EUT should be defined, and serious thought should be given to how to monitor its performance both during and after the unbalance tests. The performance monitoring should achieve sufficient levels of accuracy and repeatability to be sure whether the functional specifications are actually being met. This helps determine in advance whether any special testing arrangements need to be organised, equipment hired, special cables and leads made up, etc., etc.

Clause 8 of EN 61000-4-27 requires that monitoring equipment is provided to measure the status of the EUT's operational mode during and after each test, but only to measure the functional performance <u>after</u> each test. But complying strictly with this requirement would not allow the functional performance to be monitored <u>during</u> a test – making it impossible to make a pass/fail judgement for performance classification a) in Clause 9 (see later). It would also make it difficult to comply with the requirements for the test report listed as the eighth bullet point in Clause 10 (see later).

So this booklet recommends instead that where it is a requirement that the functional performance is not degraded by too much <u>during</u> a test – then the EUT's monitoring equipment should measure both the status of its operational mode, *and* its functional performance, with sufficient accuracy both <u>during</u> and <u>after</u> each test.

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

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

Test conditions, test plan and test execution

Clause 8.1.1 of EN 61000-4-27 states that tests can be carried out under any climatic conditions, as long as there is no condensation on the EUT and the conditions are within the manufacturers' specifications for the EUT and the test equipment. Product and generic standards committees can impose climatic conditions when they call up this basic test standard, if they believe that they can affect the test results.

Clause 8.1.2 says that the EM environment in which the test is being conducted should not be so severe as to interfere with the EUT and influence the test results. EMC test laboratories should experience no problems with this requirement, but when performing the test in other locations interference might be a possibility. How to deal with interference at the testing location is discussed in a later section.

Clause 8.2 requires a test plan to be prepared before starting to test an EUT. In some of the other basic test standards in the EN/IEC 61000-4 series a test plan is optional, but in this case it is a requirement. The test plan shall (at least) specify…

- The test number (from its Table 1)
- The test levels and their durations that are to be applied to the EUT
- The EUT ports to which the unbalance tests are to be applied
- The representative operating conditions of the EUT during the above tests (remembering that each of the EUT's operational modes are to be tested)
- The auxiliary equipment required to operate the EUT to simulate normal operation (for each of the EUT's operational modes)

All power supply, signal and other functional electrical quantities should be applied within their rated ranges, and this booklet recommends that how this is to be achieved and verified should also be recorded in the test plan.

This booklet also recommends that the equipment used for monitoring the EUT's performance during and after the tests is also listed in the test plan, along with a description of how it is to be set-up and used – and an explanation of how the measurement uncertainties have been dealt with to be able to determine whether the functional performance specification (see later) has been achieved or not.

It is always a good idea to create a test plan well beforehand, to help identify testing and monitoring requirements ahead of time. This helps to avoid wasting time sorting out unforeseen problems whilst paying premium test laboratory rates.

The test procedure

The test procedure is very simple: once the EUT and the (verified) test generator are set up as described above, and the equipment required to monitor the operation of the EUT is in place, the EUT is operated in each of its normal modes of operation, fully loaded and connected to auxiliary equipment that simulates its real-life applications. A complete sequence of tests is then applied to each a.c. power input port on the EUT, as described earlier (three types of unbalance, with three types of connection to the EUT, making nine tests in all, each test separated by a period of at least three minutes of operation at nominal mains voltage).

Where there are several modes of operation, the tests are repeated for each mode, unless there is a good technical reason why this is not necessary. For example, a variable speed motor drive may need to be retested if it can be used in different speed control modes (e.g. open-loop, tacho feedback or 'vector'). If any tests are not carried out for good technical reasons, the reasons should be recorded in the test report.

Evaluation of the test results

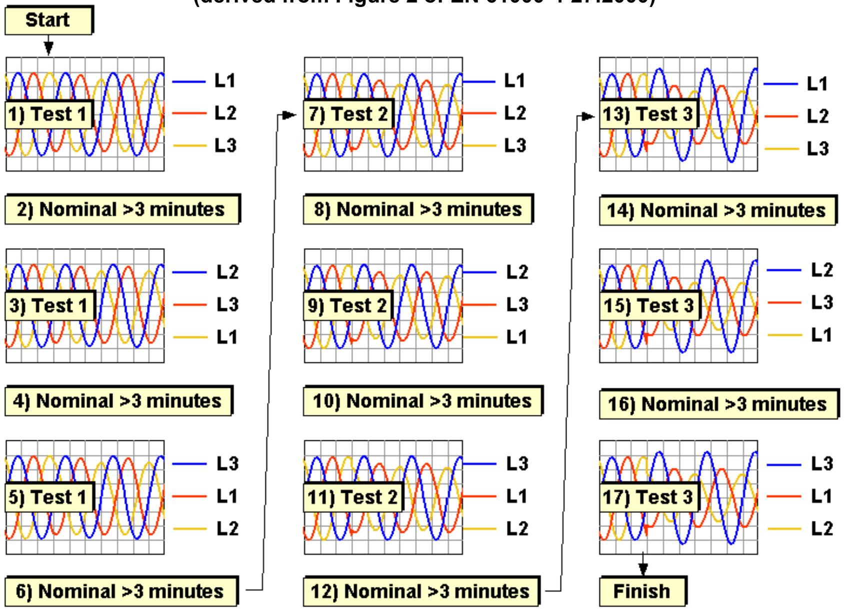
Clause 9 of EN 61000-4-27 requires the EUT's functional performance during and after each test to be assessed against performance specifications defined by its manufacturer (or the person who requested the test). It recommends that the results be classified according to the following scheme…

a) Normal performance within the limits specified by the manufacturer, requestor or purchaser;

b) Temporary loss of function or degradation of performance which ceases after the disturbance ceases, and from which the EUT recovers its normal performance, without operator intervention;

c) Temporary loss of function or degradation of performance, the correction of which requires operator intervention;

Example of a full sequence of unbalance tests on an EUT
(derived from Figure 2 of EN 61000-4-27:2000)



d) Loss of function or degradation of performance that is not recoverable, owing to damage to hardware or software, or loss of data.

This classification is offered by EN 61000-4-27 as a guide to immunity standards committees if they call up this basic test method in their product or generic standards. It is very similar to the 'Performance Criteria' A, B, C (and sometimes D) already commonly used in product immunity standards, which first appeared in the generic immunity standards.

Determining a PASS or a FAIL

Being a basic test method standard, EN 61000-4-27 cannot specify how to determine whether an EUT has passed or failed its tests – but selling a equipment with a data sheet that says it achieves classification d) (see above) is potentially misleading to an uninformed purchaser, and a joke to any purchaser who is familiar with the standard. In any case, classification d) could never be associated with a PASS result.

Where some of the unbalance tests applied by EN 61000-4-27 might be expected to occur fairly frequently, depending on the application, performance classifications a), b) or c) might be acceptable for a PASS result in the test report (see below).

Equipment expected to operate automatically and unattended for several hours or longer would probably have to achieve a) or b) for a PASS. But if the equipment was always used by an operator, it might be possible to claim a PASS result when its performance on the immunity tests was c) – unless they could be so very unskilled that they could not be expected to know how to restore normal operation – in which case a) or b) would be required.

If the consequences of momentary errors or non-functionality were considered to be very undesirable, a) might be the only option. But if the consequences were acceptable, then b) or c) might be considered a PASS.

Although it is not mentioned in EN 61000-4-27, it is also suggested in this booklet that a FAIL result is recorded if the EUT becomes unsafe during any of these tests, emits any smoke or vapour, or otherwise displays anything that is clearly unacceptable – even if the issue concerned is not covered in the agreed performance specification.

Test report

Clause 10 of EN 61000-4-27 describes what is required to be included in the test report, as follows:

- The items specified in the test plan (see above)
- Identification of the EUT and any associated equipment, e.g. brand name, product type, serial number
- Identification of the test equipment, e.g. brand name, product type, serial number
- Any special environmental conditions in which the test was performed, e.g. inside a shielded enclosure
- Any specific conditions necessary to enable the test to be performed
- The performance level(s) defined by the manufacturer, the requestor of the test, or the purchaser
- The performance criterion specified in the generic, product or product-family standard. (However, where this test was performed despite not being called-up by a generic, product or product-family standard – this booklet recommends that the performance criteria defined by the manufacturer, purchaser, or any other person who requested the test be detailed instead.)
- Any effects on the EUT observed during or after the application of the test disturbances, and the duration for which these effects persisted
- The rationale for the pass/fail decision (based on the performance criterion specified in the generic, product or product-family standard, or agreed between the manufacturer and the purchaser)
- Any specific condition of use, for example cable length or type, shielding or grounding, or EUT operating conditions, which are required to achieve compliance

Don't forget that Clause 7 also requires the length of supply cable used in the test to be reported in the test report.

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

Repeatability concerns

EN 61000-4-27 does not say what the generator's output impedances should be, only that they should be 'low' at all times (even during switching). As mentioned earlier, this is a possible cause of variability between the test results obtained for the same EUT if tested by different generators, even though they are all fully compliant with the test generator specification in EN 61000-4-27.

On-site testing

On-site testing to EN 61000-4-27 is as easy to do as testing in an EMC test laboratory. The only requirements are that the climatic conditions are suitable for the EUT, auxiliary equipment and test equipment; and that the EM environment is not so severe that it interferes with the EUT (making it difficult to tell whether it is the environment or the test that is causing the functional performance to go out of specification).

It is also very important to ensure that on-site tests do not cause interference, and this is the subject of the next section.

Important Safety Note: Don't forget that interference, especially with aircraft or other vehicular systems; emergency services; some machinery or process control systems; life-support equipment and implanted electronic devices such as pacemakers; can have lethal consequences and appropriate precautions **must** be taken to make sure that nobody's safety is compromised by EN 61000-4-28 testing. It is also a good idea to take precautions where there is a possibility of significant financial loss being caused by interference during testing.

The programmable a.c. power supplies or power amplifiers normally used for unbalance testing use switch-mode power conversion techniques have the potential to emit significant amounts of RF noise from their a.c. mains inputs and/or a.c. output connections, that might interfere with the EUT, its ancillary equipment or the functional test equipment. Test generators commercially available from well-known EMC test equipment manufacturers would not normally be expected to cause such problems, but it is best to check they comply with EN 61326-1 or similar in any case.

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

If either of the above situations arises, there are a number of issues that will need to be taken into account to suppress the interfering frequencies effectively. Suitable filtering and shielding techniques are described in [7].

A selection of typical REO Filters for AC supplies

An example of a low-cost shielded tent
(courtesy of Hitek Electronic Materials Ltd)

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

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

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

Examples of REO isolating transformers

REO isolating transformer with low primary to secondary capacitances

Important Safety Note: Always take all safety precautions when working with hazardous voltages, such as voltages above 25V RMS a.c. or 35V peak or d.c., or with hazardous currents, energies or stored charges. If you are not sure about all of these precautions – obtain and follow the guidance of a qualified and competent electrical health and safety at work person. When constructing equipment that employs hazardous voltages, always fully apply the latest versions of all relevant parts of the EN/IEC 61010 series, at least.

'Test As Real Life' (TARL) for low warranty costs, other financial benefits and safety

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

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

But fully complying with any or all of the immunity test standards listed under the EMC Directive, or in the IEC standards catalogue, does not necessarily ensure good enough performance in real life to achieve compliance with the EMC Directives essential Protection Requirements (see earlier) – or to achieve sufficient confidence in financial risks or safety.

So additional and/or tougher EM immunity tests may need to be applied to an equipment, based upon the real-life EM environment(s) it could be exposed to. This concept is sometimes called 'Test As Real Life' (TARL), and it is vital where high reliability is required for whatever reason. In some applications it will be necessary to base the test programme on the equipments foreseeable EM environment(s) over its whole lifetime [4]. This is too large a subject to discuss here – refer to [8] [9] [10] [11] and [12].

If the modified or additional tests can be based on calculations based on known characteristics of the intended mains power supply network, or on measurements of the intended operational sites over a long enough period to capture the range of unbalance that can occur, this will help avoid both under-engineering and over-engineering.

But if the knowledge required for reasonably accurate TARL cannot be obtained, the manufacturer should decide how far to go with modified or additional unbalance testing, based upon their sensitivity to warranty costs and customer perceptions of their product. The author knows a large and very successful manufacturer of domestic appliances whose EMC testing goes well beyond what is required for compliance with the immunity standards listed under the EMC Directive. The reason they give for this is that their industry is highly competitive so their profit margins are very small, so they can hardly afford to have any warranty claims at all. So it is much more cost-effective for them to improve the EM design of their appliances, even though this adds to their manufacturing costs, to reduce warranty costs.

When performing unbalance measurements on a site, it is important to measure any unbalances at the fundamental frequency of the supply (50 or 60Hz), because harmonic distortion of the supply waveform can cause errors in the result (if the measuring device has a bandwidth wide enough to include them).

A problem with any automatic power quality monitoring equipment is that if it is not set up correctly, it will soon fill its memory (or use up all of its paper) recording too-detailed data. If you are not skilled in these matters, and if you don't want to spend time and money going through a learning curve – instead of hiring power quality monitoring equipment from one of the many companies that provide it – hire a power quality consultant instead and have him/her do the work using their own equipment, analyse the results and produce a report.

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

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

TARL and real-life unbalance possibilities

EN 61000-4-27 is one example of a test that probably should be done, where an equipment is powered from a three-phase a.c. power supply network, if real-life reliability or compliance with the EMC Directive's essential Protection Requirements is a concern. This is despite the fact that it is not (yet) called up by any product or generic standards under the EMC Directive.

This section now discusses a number of situations that show why – to have sufficient confidence in reliable, accurate or safe operation in real life – it may be necessary to modify or add to the EN 61000-4-27 tests to achieve TARL (Test As Real Life, see earlier).

Zero-sequence voltages

Three-phase power engineers analyse the unbalance of their supplies by reducing them to positive-sequence, negative-sequence, and zero-sequence voltage components as described in Annex A of EN 61000-4-27.

But the tests applied by EN 61000-4-27 assume that there is no zero-sequence unbalance component. Zero-sequence voltage components mainly are the result of zero-sequence currents of unbalanced loads flowing in the power supply network – essentially the unbalance due to the net current in the neutral conductor. Zero-sequence unbalance only affects the phase-neutral voltages, not the phase-phase voltages.

Zero-sequence currents can affect three-phase equipment that is connected phase-neutral (known as star or four-wire connection). But the majority of three-phase equipment is connected phase-phase (known as delta or three-wire connection) so is unaffected by zero-sequence unbalance.

So EN 61000-4-27 ignores zero-sequence unbalances even though they are common occurrences and can interfere with star-connected equipment. The author has seen zero-sequence unbalances in industrial plant of more than 60V. So this handbook recommends that star-connected three-phase equipment should be tested for zero-sequence voltage unbalances up to at least 100V, unless knowledge of the EM environment of the application permits a more precisely targeted test level. Refer to Annex A of EN 61000-4-27 to learn more about zero-sequence unbalance.

Long-term effects

One of the consequences of unbalanced mains voltages is that induction motors can draw excessive currents and overheat. At some sites, significant levels of unbalance can be present for very long periods of time, even for years. But EN 61000-4-27 only applies its chosen tests for 30, 15 or 0.1 seconds – which may not be long enough to discover any reliability or overheating effects.

So, where unbalances can exist for longer than the tests in EN 61000-4-27, and where the EUT contains anything that could be affected by such longer periods of unbalance, this booklet recommends testing the EUT with the anticipated long-term unbalances. The tests should last for as long as the unbalance could exist, or else for as long as it takes the EUT to reach thermal equilibrium (in the case of a 100kW motor, this could be some hours).

One of the major causes of unreliability is the degradation of insulation caused by operation at prolonged high temperatures. So when conducting these unbalance tests, temperature sensors should be applied to the areas of interest to find out whether insulation is likely to be degraded in real-life unbalance situations.

IEC/TS 60034-26 covers the effect of unbalance on the performance of three-phase induction motors, but the author does not know if this document (a TS is not – yet – a full IEC standard) covers testing for reliability and overheating effects.

Extreme unbalance

In the case of a phase-neutral or phase-earth short-circuit fault on a supply network or in a load, it is possible for one of the phases to collapse to as low as zero, causing an extreme unbalance. Another type of extreme unbalance will occur in the case of a phase-phase short-circuit fault (this is mentioned in Annex C to EN 61000-4-27). In either case, the unbalance will persist until the overcurrent protection devices in the supply network isolate the fault (usually within one second).

An extreme unbalance will also occur if one or more phase conductors are interrupted by an open-circuit, such as might happen if a mechanical digger or drill accidentally breaks through a supply cable, or when connections in a supply network go high-impedance for a variety of reasons. Open-circuit faults can persist, causing extreme unbalance in the supply, for almost any length of time.

The tests applied by EN 61000-4-27 use unbalance errors that are no higher than 25% (with phase errors no higher than 20°) and so do not simulate any of the above extreme unbalance situations.

In most installations, phase-earth faults are the most likely to occur. These are simulated by the dips, dropouts and interruptions tests of EN 61000-4-11, which includes test methods for three-phase powered EUTs. EN 61000-4-14 extends the testing of phase-earth faults to include rapid voltage fluctuations. So this booklet recommends applying the relevant tests from EN 61000-4-11 and EN 61000-4-14 to all three-phase EUTs to cover the effects of these types of extreme unbalance faults (there are REO booklets on both of these test standards [6]).

But neither EN 61000-4-27, -4-11 or -4-14 address phase-phase shorts, so this booklet suggests that additional tests are added to the repertoire of unbalance tests in EN 61000-4-27 to simulate such faults. It is easy to use vector addition methods to calculate the voltages and phase angles that should be applied, when simulating a phase-phase fault. These tests should be applied for one second, for each pair of (simulated) shorted phases, unless there is a better specification based on knowledge of the characteristics of the overcurrent protection devices in the intended operational location. As for the other tests in EN 61000-4-27, a period of three minutes of operation on nominal mains should be allowed between each test, to allow any thermal effects of the test on the EUT to subside.

Equipment that is not powered from a PCC or IPC

The tests levels set by Clause 5 of EN 61000-4-27 assume equipment is connected to a PCC or IPC. The PCC in a domestic house would be the 'consumer unit' (more usually called 'the fusebox' or 'the meter cupboard' by the residents). In a large commercial building or industrial plant the PCC or IPC would usually be in a dedicated room, often called the switchgear or distribution room.

The reason that the standard assumes products are connected to a PCC or IPC is that the standards committees only have figures for the unbalance that occur in the mains distribution networks themselves. The figures on which EN 61000-4-27 are based are said to be related to those reported in EN 61000-2-4 [13].

Beyond the PCC or IPC, the standards committee cannot predict what unbalances might occur, because they do not know what cable impedances are being used to power the loads, and they don't know if different products are sharing the mains supply at the ends of a long cable, far away from a PCC or IPC.

For example, domestic premises in the UK use 'ring main' supplies, in which large numbers of electrical and electronic equipment can be powered from a single cable that loops around the building and connects to the PCC at both of its ends. The aim of this is to reduce the cost of the copper used in a building, but a product connected along such a ring main can suffer from worse power quality than if it had its own direct feed from the PCC.

Clearly, where a product is powered from a mains cable that also supplies an unbalanced three-phase load, the levels of unbalance it might experience could be worse than those that occur at its PCC or IPC. It is even possible for a single product that is connected to the PCC or IPC by a long mains cable, to give rise to unbalance that causes it to interfere with itself!

So where products are powered from a PCC or IPC by cables long enough to add significantly to the impedance of their mains supply, and/or when products share such long mains cables with other products, it is possible for the levels of unbalance to be higher than those specified in EN 61000-4-27 for the appropriate class.

Products in what would normally be considered a Class 2 environment might need to be tested to Class 3 or higher. Likewise, products in what would normally be considered to be a Class 3 environment might need to be tested to using test levels that are higher than Class 3. It is up to the manufacturer to recognise where such situations can occur and test their products accordingly to be sure they comply with the EMC Directive's essential Protection Requirements, and also to supply products that will be reliable enough not cause unacceptably high warranty costs. Where a purchasing contract is being placed, the unbalance test levels to be applied should ideally be agreed between the purchaser (or specifier) and the supplier.

Simultaneous EM disturbances

All of the EN/IEC basic EMC test methods only test with one type of disturbance at a time, but in real-life an item of equipment can be exposed to two or more EM disturbances at the same time. Very little work has been done into the effects of simultaneous EM disturbances, but [14] shows that when an EUT is exposed to its full test level of one type of phenomenon (e.g. a radiated RF field of 100MHz at 3V/m) its immunity to a test that it passes perfectly well when applied on its own (e.g. fast transient bursts at 2kV) can be very severely compromised. Another transient event that might happen when an RF field (for example) is simultaneously present is an electrostatic discharge from someone's fingers.

So where a type of equipment is to be installed in areas where there is a continuous exposure to a reasonably high level of an EM phenomenon (e.g. an RF field, RF noise on the supply, mains waveform distortion, magnetic fields, etc.) its immunity to transient disturbances – such as unbalance in its three-phase a.c. supply – might be compromised. TARL techniques would require testing with the transient disturbances in the presence of the continuous EM phenomenon, and some analysis might help avoid a lengthy (and expensive) test programme.

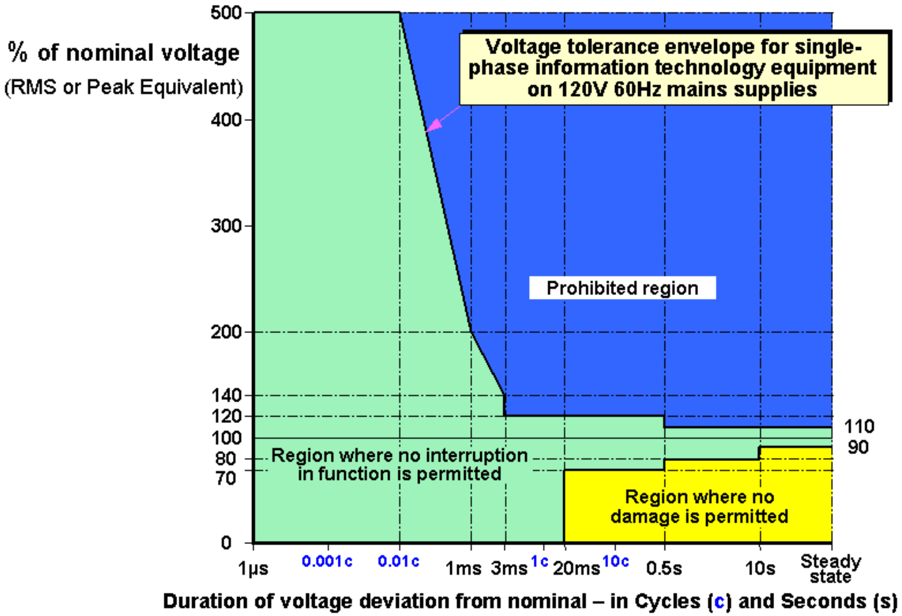
The likelihood of two *transient* events happening at the same time is usually very small, and often not worth worrying about except where high levels of safety integrity are required [11].

Mains voltages that vary from their nominal values

The unbalance tests in EN 61000-4-27 are all based around U_N, the nominal supply voltage – but in real life an unbalance can occur at a time when the mains voltage is lower or higher than nominal, due to normal variations in the supply and/or maybe due to harmonic distortion of the supply waveform by non-linear loads (see the REO booklet on EN 61000-4-13 [6]).

So this booklet suggests testing with the EN 61000-4-27 unbalance test levels with U_N reduced below the actual nominal supply voltage by 10%, and then again U_N increased above the actual nominal supply voltage by 10%. If the EUT passes both of these tests, there is probably no point in testing with U_N set to the actual nominal supply voltage, as it is for the normal EN 61000-4-27 tests.

The ITI (CBEMA) Curve (2000 revision)



It is important to realise that real-life mains voltages can sometimes have minimum and/or maximum values that go well beyond ±10% of nominal. One of the author's customers had a problem with a number of products they had supplied to a part of Spain, which turned out to be due to the (supposedly 230V nominal) mains voltage 'browning out' to under 180Vrms during the daytime, every Monday through Friday. They had to modify the d.c. power supplies in the products accordingly, and probably made a loss on those sales as a result. The author has also experienced a brown-out from the normal 240V to 140Vrms for eight hours, in the UK in 1998.

The ITI (CBEMA) curve [15] indicates that typical computer equipment in the USA can expect to suffer mains voltages that can fall by up to 30% for up to 0.5 seconds, and increase by up to 20% for up to 10 seconds. So it may well be that the unbalance tests suggested above with U_N decreased/increased by 10% from the actual nominal values may not represent the real-life mains voltages that the EUT will be expected to operate from. Where TARL is important, it is important to know the full range of the supply voltage and to test with the levels of unbalances that might also occur at the same time.

Temporarily high levels of unbalance

During maintenance or building work (for example) – welding or other high-power electrical equipment might be connected to a site's mains network at various points, causing higher levels of unbalance than would normally be expected to occur, and/or longer durations of unbalance than would normally be expected. Or it might be that temporary power connections are made between the site and the public network, so that the mains supply has higher impedance than usual, amplifying the unbalance caused by the existing unequal loading of the phases. Of course, both of these situations might occur at the same time.

Because such situations are not 'normal operation' the EMC Directive does not care whether the equipment suffers interference or not. But testing to cope with such situations might be an important consideration, especially for equipment that must operate with high-reliability, is mission-critical, or has financial or functional safety implications.

Possibilities for higher phase impedances, hence higher levels of unbalance

The unbalance test levels specified by EN 61000-4-27 are based upon a mains supply in which each phase conductor has a complex impedance of 0.283Ω (actually 0.24Ω resistive plus 0.15Ω inductive) – according to IEC 60725 [16]. But the actual impedance of the mains supply in a large industrial plant can be much lower than the impedance in a domestic house (this is recognised in EN 61000-3-11, see the REO booklet on this standard [6]). A lower phase impedance would have the effect of reducing unbalance disturbances caused by unequal loading of the phases.

But on the other hand, higher phase impedances than those assumed by EN 61000-4-27 can be a cause of higher levels of unbalances than are tested by that standard. For example, some large old buildings such as theatres or industrial sites can have phase impedances approaching 1Ω over some of their area, due to the long lengths of 'legacy' mains cables installed in days when there was less use of electricity than today.

Even in developed countries, like those in Europe, North America and Australia, parts of the mains supply network can be found that have much higher impedance than is normal for those countries. Usually, these areas are very remote, and have a single MV or HV cable feeding them over a long distance. In some remote parts of Australia the mains power is still supplied via a single conductor, using the earth (i.e. the soil) as the neutral for the return current, creating a very high source impedance indeed.

These days, many types of electrical or electronic equipment are sold to many different countries around the world. But when developing equipment in a developed country it is easy to take the high-quality mains power supply network for granted, and assume that the mains power around the world will be just as good. This assumption can be very wrong, and could lead to great expense.

For example, [17] describes the very poor quality of the mains waveform in a residential area of Israel in 2000. Although the problems described in this example were caused by waveform distortion and RF noise, they arose because equipment with high levels of emissions were connected to a mains network that had a high impedance. High levels of unbalance and other power quality issues should be expected in such an environment.

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

Where phase impedances (as defined by [16]) are more than 10% higher than 0.283Ω (0.24Ω resistive plus 0.15Ω inductive) higher levels of unbalance tests might need to be applied to be sure of TARL.

The effects of local generation and green power on unbalance

EN 61000-4-27 does not cover locally generated mains supplies independent of the mains network, which can have power quality that varies from very good to appalling. Locally generated 110/230/400V power usually has a higher phase impedance than is provided by a connection to the public mains supply network.

As discussed earlier, a consequence of higher phase impedance is that the supply could suffer from higher levels of voltage unbalance, for given amounts of load unbalance. Locally generated power may also permit voltage variations of greater than the ±10% assumed for the normal mains supply, and they may not be as stable as a national power supply network, and these power quality issues might make it more difficult for an equipment to withstand EN 61000-4-27 unbalance test levels applied at the same time.

Many types of products may be required to operate from locally generated power from time to time, such as…

- All hospital equipment, telephone exchanges and 'internet hotels' when the emergency generators are tested (typically once per week) or when running on emergency power due to loss of the normal mains supply.
- All domestic and commercial equipment when run on emergency power due to a loss of the normal mains supply (for example, all the equipment in the author's office building usually has to run from a small standby generator for several hours, several times each year).
- Mains-powered products used in vehicles (marine, inland waterways, road vehicles including caravans, aircraft, diesel trains, etc.) and offshore oil and gas platforms which, of necessity, have to generate their own 110/230/400V mains power locally. As more and more high-power electronic power converters are used in such vehicles (e.g. marine thrusters, and even main propeller drives at several MW) the unbalances in their mains networks may be expected to increase.
- Equipment used in open-air concerts, travelling fairgrounds, etc., supplied by portable generators.

In-service failures and mains unbalance disturbances

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The number of sites powered by green energy is set to rise, as products for domestic, commercial and industrial sites become more affordable, and also due to numerous initiatives intended to help reduce global warming.

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

These electronic converters could provide higher phase impedances than 'normal' mains connections; so could suffer from higher levels of voltage unbalance for given amounts of load unbalance.

Where phase impedances (as defined by [16]) are more than 10% higher than 0.283Ω (0.24Ω resistive plus 0.15Ω inductive) higher levels of unbalance tests might need to be applied to be sure of TARL.

If it is suspected that an unbalanced supply could be a cause of malfunctions or failures in the field, a survey with appropriate power quality measuring instruments can discover what power disturbances are occurring and whether they correlate with the failures. The instruments used are generally data-logging instruments that can be left for days (maybe weeks) unattended and automatically record details of the unbalances that have occurred over that period. It is rare to know in advance exactly what the cause of a problem is, so it is normal to survey a number of other power quality parameters, as well as unbalance, to try to correlate the likely EM disturbances with the failures that are occurring.

It helps to correlate disturbances with failures if one channel of the survey instrument can monitor something about the equipment that is suffering the problem, that indicates whether the fault has occurred or not. Then when the survey instrument's record is analysed later on, the time stamp on the event that marks the failure of the equipment can be compared with the time stamps on the disturbances that were detected, to see what EM disturbance is most likely to have caused the fault.

Where the failing equipment cannot be monitored automatically, it may be possible to have its operator, or someone else, note the date and time when it fails, for eventual correlation with the power quality survey results. If the equipment is normally unattended, it should at least be checked on a regular basis to see if it has failed or not, and the date and time noted once again. The period between checks should be no more than half of the normal time between failures, and even more frequent checking helps achieve better correlation with the measured disturbances.

When performing unbalance measurements on a site, it is important to measure any unbalances at the fundamental frequency of the supply (50 or 60Hz), because harmonic distortion of the supply waveform can cause errors in the result (if the measuring device has a bandwidth wide enough to include them).

A problem with any automatic power quality monitoring equipment is that if it is not set up correctly, it will soon fill its memory (or use up all of its paper) recording too-detailed data. If you are not skilled in these matters, and if you don't want to spend time and money going through a learning curve – instead of hiring power quality monitoring equipment from one of the many companies that provide it – hire a power quality consultant instead and have him/her do the work using their own equipment, analyse the results and produce a report.

Where the failure rate is low (e.g. once per month) a site survey to try to locate the cause of a problem could take a very long time. But an experienced EM engineer might already have an idea of what type of EM disturbance is the most likely cause of the failures, and after learning about the site and the other equipment installed on it might already have a good idea of what is the most likely source of that disturbance. The engineer might then be able to suggest ways of creating the EM disturbance in question (rather than wait for it to occur naturally) to see if it does indeed cause the failure. This can save a great deal of time.

Low-cost non-compliant test generators and test methods

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Testing using alternative test generators and/or different types of test waveforms from those specified by EN 61000-4-27 may not be able to give 100% confidence that full-compliance tests to EN 61000-4-27 would be passed. But such 'non-compliant' tests may actually be better than full testing to EN 61000-4-27 for improving the reliability or safety of a equipment – as discussed in the previous section – if they TARL (test as real-life).

EMC Directive enforcement agencies generally assume that equipment in serial manufacture are tested for continuing EMC compliance on a sampled basis, to show that no accidental changes have occurred in components, design or assembly. The costs of such a QA programme can often be considerably reduced by the use of quick, low-cost, non-compliant tests.

Because unbalance tests do not involve RF, it is easy to develop low-cost alternative test generators that give results useful for development and QA even though they might not fully comply with EN 61000-4-27.

Important Safety Note: Always take all safety precautions when working with hazardous voltages, such as voltages above 25V RMS a.c. or 35V peak or d.c., or with hazardous currents, energies or stored charges. If you are not sure about all of these precautions – obtain and follow the guidance of a qualified and competent electrical health and safety at work person. When constructing equipment that employs hazardous voltages, always fully apply the latest versions of all relevant parts of the EN/IEC 61010 series, at least.

There are many possibilities for constructing test generators and creating alternative test methods, and this booklet does not seek to limit the ingenuity of electrical and electronic engineers, always assuming that health and safety is the prime concern and that it is ensured by suitably qualified and competent people.

For all but full compliance and 'pre-compliance' tests, using an uncalibrated test (for which the quantitative measurement is not traceable to the national physical standards) is not very important. But it *is* very important for *all* tests to be *repeatable* – so consistency is always required in the test generator, test methodology and test waveforms and levels. And all of the details of the test set-ups and build states should be carefully recorded in the test documentation. Photographs can be very useful, especially if annotated at the time, and digital cameras make this much easier and less costly than it used to be.

When self-declaring compliance to the EMC Directive using the 'Standards Route' to conformity (Article 10.1 of [3]) – even if alternative test generators have been used to simulate the operating environment and help achieve reliability – passing full compliance tests to EN 61000-4-27 can help avoid the possibility of legal challenges in the future.

But when following the Technical Construction File (TCF) route under 89/336/EEC (or when not fully applying harmonised standards under 2004/108/EC) it may be possible to persuade the mandatory Competent Body (or optional Notified Body) that the alternative tests and test methods represent the environment that the equipment is going into and there is no need to apply EN 61000-4-27 as well. This argument would probably be easier to win for a custom-designed (bespoke) industrial equipment intended for use at a specified site, than it would be for portable equipment or equipment that could be used in a number of locations or sites.

Example of a REO single phase variable transformer

Example of a REO automatically regulated and/or remotely controllable variriable transformer

Correlating alternative test methods with EN 61000-4-27

When an alternative test generator or method is used for design, development, or troubleshooting after a test failure, repeatability of the test is very important (even though the correlation with EN 61000-4-27 may not be). All such tests will need to follow a procedure that has been carefully worked out to help ensure that adequate repeatability is achieved.

When alternative methods are used as part of a QA programme, or to check variants, upgrades, or small modifications, a 'golden product' is recommended to act as a sort of 'calibration' for the test equipment and test method. Golden product techniques allow low-cost EMC test gear and faster test methods to be used with much more confidence. Refer to section 1.9 of [18] for a detailed description of how to use the golden product correlation method.

If alternative methods are used to gain sufficient confidence for declaring compliance to the EMCD, the golden product method is very strongly recommended. Without a golden product or some similar basis for correlating proper EN 61000-4-27 testing with the alternative method actually used, the alternative method might only provide any confidence at all if gross levels of overtesting are applied, and this can result in very expensive equipment.

The closer a test method is to using the same tests and methodology as EN 61000-4-27, the more likely it is that a good correlation will be achieved. Testing with a non-compliant test generator might only be able to correlated with the results from a 'proper' EN 61000-4-27 test generator for a particular build state of a specific equipment. Note that the software version is an important part of the build state – even a simple 'bug-fix' could have a significant effect on EM immunity.

Determining an 'engineering margin'

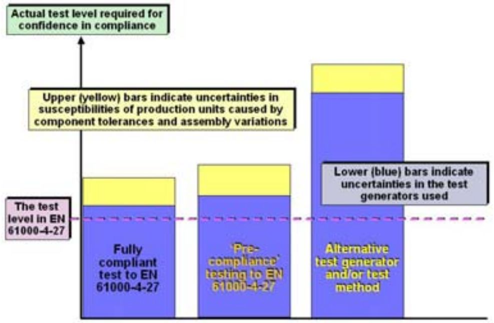
Even having EN 61000-4-27 fully applied by the same accredited EMC test laboratory cannot guarantee that a given EUT will be exposed to *exactly* the same stimuli each time it is tested. But if EMC enforcement agents test an item of equipment, they are unlikely to use the same test laboratory or model of test generator that was used by its manufacturer. So, an 'engineering margin' is recommended, because…

- There might be differences in the actual test stimuli produced by different models of generators when testing the same EUT, for example due to the lack of a specification for the generator's output impedance (see earlier);
- There can be differences in the test methods, or in the assessment of the functional test during and after the EMC test, even when applied by the same staff at the same test laboratory – possibly leading to different results;
- Serially-manufactured equipment have variable immunity performance due to component and assembly tolerances (e.g. variations in the routes taken by cables or cable bundles, in some types of equipment, might make them more likely to pick up magnetically-coupled noise from currents in the a.c. supply).

So, when testing an item of equipment to EN 61000-4-27 in a fully compliant manner, it is recommended that additional tests with higher test levels are also performed, with the equipment still meeting its required functional performance specifications. This will not cover the repeatability problems associated with generator impedance described earlier, but it will help take care of the second and third bullet points above.

At the time of writing it is understood that no product or generic standards listed under the EMC Directive call-up EN 61000-4-27 tests, so how (or if) a manufacturer tests for three-phase unbalance is entirely optional. But if EN 61000-4-27 is referenced in a product or generic standard, or if it is called up in a purchase specification, complex questions arise if alternative test methods are used instead of EN 61000-4-27 for demonstrating compliance. A larger engineering margin is recommended, at least, but how much larger can be hard to determine other than by direct comparison of the effects of both test methods on the identical equipment.

The need for engineering margins
(not to scale)



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

References

[1] IEC 61000-4-27:2000, "*Electromagnetic Compatibility (EMC) – Part 4-27: Testing and measurement techniques – Unbalance immunity test*".

[2] EN 61000-4-27:2000, "*Electromagnetic Compatibility (EMC) – Part 4-27: Testing and measurement techniques – Unbalance immunity test*". (Note: the BS version of the same EN is dated 2001).

[3] European Union Directive 89/336/EEC (as amended) on Electromagnetic Compatibility. The Directive's official EU homepage includes a downloadable version of the current EMC Directive and its successor; 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; etc., all at: http://europa.eu.int/comm/enterprise/electr_equipment/emc/index.htm.

[4] "*Assessing an Electromagnetic Environment*", Keith Armstrong, downloadable from the '*Publications and Downloads*' page at http://www.cherryclough.com.

[5] European Union Directive 2004/108/EC on Electromagnetic Compatibility (2^{nd} Edition), from:http://europa.eu.int/eur-lex/lex/LexUriServ/site/en/oj/2004/l_390/l_39020041231en00240037.pdf

[6] A number of REO booklets on other types of EM disturbances and their corresponding EN test standards can be downloaded from http://www.reo.co.uk.

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[8] 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.

[9] "*EMC-Related Functional Safety – An Update*", Keith Armstrong, EMC & Compliance Journal, Issue No. 44, January 2003, pp 24-30, on-line at: http://www.compliance-club.com/keith_armstrong.asp.

[10] "*Why EMC testing is Inadequate for Functional Safety*", Keith Armstrong, IEEE 2004 International EMC Symposium, Santa Clara, August 9-13 2004, ISBN 0-7803-8443-1, pp 145-149. Also: Conformity magazine, March 2005 pp 15-23, downloadable via http://www.conformity.com.

[11] "*The IEE's Training Course on EMC for Functional Safety (also for high-reliability and legal metrology)*", visit http://www.iee.org for their event calendar to check the date of the next course. If no courses are listed contact the IEE's Functional Safety Professional Network (via the same IEE homepage) and ask.

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[14] *"Combined Effects of Several, Simultaneous, EMI Couplings"*, Michel Mardiguian, 2000 IEEE International Symposium on EMC, Washington DC, August 21-25 2000, ISBN 0-7803-5680-2, pp. 181-184.

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[16] IEC 60725 "*Consideration of reference impedances and public supply network impedances for use in determining disturbance characteristics of electrical equipment having a rated current ≤ 75 A per phase*".

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[18] "*EMC Testing Part 1 – Radiated Emissions*", Tim Williams and Keith Armstrong, EMC & Compliance Journal February 2001, pp 27-39. On-line at http://www.compliance-club.com/keith_armstrong.asp.

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

IEC standards may be purchased with a credit card from the on-line bookstore at http://www.iec.ch, and many of them can be deiivered by email within the hour.

The Author

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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

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

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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3 phase column transformer ideal for voltage fluctuation testing.

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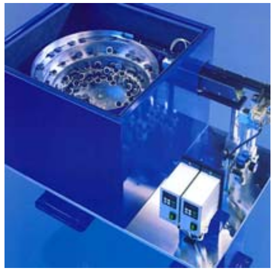
REO - Market Sectors

Train Systems

Chokes and high frequency transformers

Inductive Components

Chokes, resistors and transformers

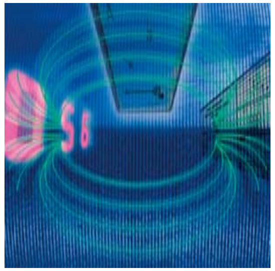


Automation Systems

Controllers for vibratory feeders

Communication Systems

Field bus and gsm

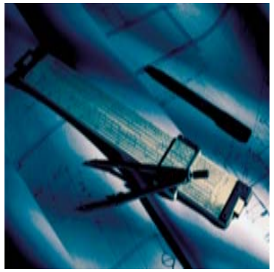


Test Systems

Power supplies and load banks

Power Electronics

Phase-angle and frequency controllers



Classics

Rheostats and variacs

Renewable Systems

Solar transformers

Drive Systems

Filters and braking resistors

Medical Systems

Medical Transformers

Motor Control Systems

Soft-starts