EMC Testing Part 3 – Fast Transient Burst, Surge, Electrostatic Discharge

By Eur Ing Keith Armstrong C.Eng MIEE MIEEE, Partner, Cherry Clough Consultants,
Tim Williams C.Eng MIEE, Director, Elmac Services
Both Associates of EMC-UK

This is the third in a series of seven bi-monthly articles on 'do-it-yourself' electromagnetic compatibility (EMC) testing techniques for apparatus covered by the European EMC directive. This series will cover the whole range of test methods – from simple tests for development and fault-finding purposes, through lowest-cost EMC checks; 'pre-compliance' testing with various degrees of accuracy, on-site testing for large systems and installations; to full-specification compliance testing capable of meeting the requirements of national test accreditation bodies.

Of course, what is low-cost to an organisation of 5000 people could be thought fairly expensive by a company of 50, and might be too expensive for a one-person outfit, but we will cover the complete range of possible costs here so that no-one is left out. Remember though, that the more you want to save money on EMC testing, or reduce the likelihood of being found selling non-compliant products, the cleverer and more skilled you need to be. Low cost, low risk *and* low EMC skills do not go together.

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

The topics which will be covered in these seven articles are:

1) Radiated emissions
2) Conducted emissions
3) Fast transient burst, surge, electrostatic discharge
4) Radiated immunity
5) Conducted immunity
6) Low frequency magnetic fields (emissions and immunity), mains dips and dropouts, etc.
7) Harmonics and flicker emissions

Table of contents for this Part

3 Fast transient burst, surge, electrostatic discharge

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

- Development testing and diagnostics (to save time and money)
- Pre-compliance testing (to save time and money)
- Full compliance testing
- QA testing (to ensure continuing compliance in volume manufacture)
- Testing of changes and variants (to ensure continuing compliance).

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

This part of the series focuses on testing conducted emissions to the EN standards for typical domestic / commercial / industrial environments. Other kinds of immunity tests may be required by the EMC standards for automotive, aerospace, rail, marine and military environments. In particular, the conducted transients and surges in an automotive environment (internal combustion engine with spark ignition, driving an alternator, which charges a battery) can be very different indeed from those typical of a building connected to a 230/415V mains power supply, as shown by ISO 7637 [2], for example. These industries have over the years developed their own test standards based on their own particular kinds of disturbances, for reliability reasons.

IMPORTANT SAFETY NOTE: Some of these tests involve electrically hazardous conductors (e.g. mains), and/or hazardous voltages or energies. These tests can be dangerous, and all appropriate safety precautions must be taken. If you aren't *sure* what safety precautions are needed, ask an expert.

The basic EN test methods described here are identical to the basic IEC test methods (e.g. EN 61000-4-4 is identical to IEC 61000-4-4), so this article may also be of use where non-EU EMC specifications apply.

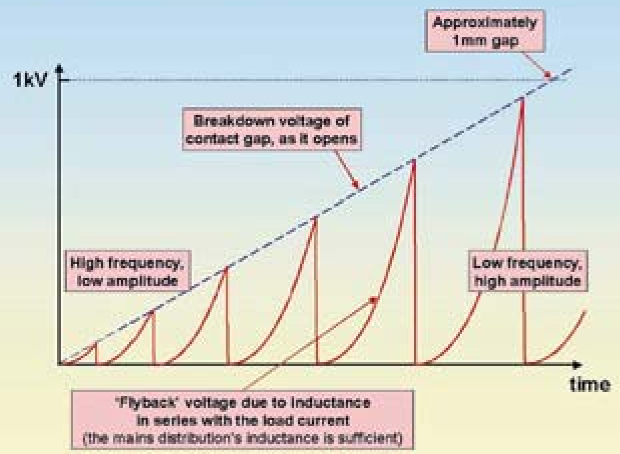
3.1 Standardised immunity testing versus real-life reliability

These three immunity tests use carefully-defined generators with carefully-defined waveforms and test set-ups to try to achieve a repeatable test. There is plenty of experience to show that the tests are not as repeatable as one might wish, and the standards are continually being developed to try to improve this (read [3] for more on this issue).

But it is important to realise that these standards do not necessarily simulate the real-world electromagnetic disturbances very well. The waveforms specified by their tests are more likely to reflect what it is possible to generate cost-effectively and repeatably in a laboratory instrument, than be an accurate simulation of the disturbance waveforms present in real applications.

For example, the fast transient burst test aims to simulate the disturbances created by a 'showering arc' at the contacts of an ordinary AC mains switch or relay contacts as it opens. The inductance of the mains cable (plus any in the load) causes a flyback voltage at the instant the current is interrupted, and the flyback voltage rises until it is sufficient to break down the air gap at the contacts and make an arc. When the arc stops the flyback occurs again, this time with the contacts slightly further apart. So during the opening of a switch or relay contact the transients generated can look something like Figure 3A, starting off with a low amplitude and a high frequency (could be MHz) and with rising amplitude and falling frequency as the contact gap widens. Compare this with the waveform of the standard EN 61000-4-2 test in Figure 3C, which uses a constant amplitude and frequency (5kHz).

Figure 3A Simplified example of a real-life switch transient



It is true to say that a product designed to meet these standards will generally be more reliable (all things being equal) than one which has been designed with little or no thought to surviving these disturbances and no testing. But meeting these standards *does not* guarantee freedom from errors or failure in the field due to the disturbances represented by these three standards.

For example, surge testing according to EN 61000-4-5 is called up by the generic standards and most of the other immunity standards harmonised under the EMC directive, usually at the level of ±1kV for line-to-line surges and ±2kV for line-to-ground. However, it is well known (and recognised by some lightning protection standards) that in Europe and the USA at least the mains power in typical urban buildings will suffer from line-to-ground surges of 6kV at least once per year. This is caused by normal thunderstorm activity in the local area, not direct strikes, and applies to buildings which do not have lightning protection systems designed to protect electronics. Rural buildings whose mains supply is carried by overhead conductors, can reckon on experiencing many tens or hundreds of 6kV surges every year, depending on the length of their overhead line.

The figure of 6kV arises because the typical domestic-style mains sockets flash-over at their rear connections at around this voltage and so act like spark-gap suppressers. In industrial premises mains distribution using three-phase supplies fitted only with the larger three-phase mains sockets might suffer from line-to-ground surges of well over 6kV due to the increased flash-over voltage of these sockets. It is ironic that in buildings whose mains wiring has poor quality insulation, the maximum surge voltages can be much less – due to the accidental spark-gaps (which are also fire hazards) created by the poor quality wiring.

One of the authors has experience of a mains power supply module widely used in Europe that suffered from an excessive failure rate. This turned out to be due to the fact that the creepage and clearance distances between the track to the gate of a switching power FET and the earthed chassis were inadequate at over 5kV (when testing with the EN 61000-4-5 waveshape). These modules would clearly pass all the immunity standards harmonised under the EMC directive, but were almost certain to fail at least once per year in most indoor urban environments in Europe and the USA.

Another example relates to electrostatic discharge (ESD). The test standard called up by EMC directive harmonised immunity standards is EN 61000-4-2, but this only covers personnel discharge (e.g. from people's fingers, keys, etc.). Leaving aside questions about the accuracy of its simulation of actual personnel ESD events into a variety of real-life load impedances, it does not even try to address other types of ESD events which may be very important in real-life applications, such as furniture ESD and machine ESD. Machine ESD can be very severe indeed in some industries, especially where webs of insulating material (paper, plastic film, etc.) or insulating gases, dusts (e.g. flour) or liquids are processed. Even a motor running in plastic bearings can generate severe ESD events between its rotor and its stator.

There are almost as many possible ESD waveshapes as there are applications with machine-ESD problems.

So, where it is desired to create reliable products, the EMC immunity work done should go beyond the standard EMC directive immunity tests:

- Consider whether the test levels on the standard EMC directive immunity tests should be increased to address the real-life situation for disturbances with a similar waveshape.
- Consider whether the real-life disturbances in the intended environment are sufficiently different from the EMC directive's standard tests to make a different type of test necessary.
- Where a standard test method does not exist to cover your real-life environment, with a little ingenuity it is often possible to design your own fast transient burst, surge, or electrostatic discharge tests that simulate the expected environmental threats. Sometimes this requires little more than replicating whatever it is that is causing the threat (e.g. a 10kVA transformer and its on/off contactor) or – if this would require too much work – taking prototype products to where the threat exists.

The financial rewards of producing reliable products can be very great indeed, as one UK manufacturer discovered when they spent £100,000 on redesigning their products to comply with the latest EMC directive immunity standards, and then discovered that as a direct result their warranty costs fell by £2.7 million per year.

3.2 Hiring test gear may be the best way to Do-It-Yourself

Unlike the emissions tests described in Parts 1 and 2 of this series [1] [4], using alternative test generators for these three tests cannot give any confidence whatsoever that compliance tests to the proper standards would be passed (even though such tests may be valuable for improving the reliability of a product).

Many rental companies have stocks of the calibrated test gear needed to do FTB, Surge, or ESD tests properly, and will rent them out for daily, weekly, or monthly periods. The easiest way to perform these tests with reasonable accuracy and lowest cost is often to hire the equipment and do the tests yourself.

The test set-ups for these tests are not difficult to achieve in a typical manufacturing company, as they don't need special test chambers or open area sites, at the most just an area of ground plane and a wooden table. EMC test laboratories often do these tests inside metal shipping containers or low-cost shielded rooms, but this is to help prevent the tests interfering with other EMC tests that might be going on nearby. Where nothing very sensitive is nearby, such precautions are not needed.

With enough skill and attention to detail, hired test gear can readily be used to do fully compliant testing on these three immunity tests.

3.3 Combination test instruments

A few EMC test equipment manufacturers now supply combination immunity testers. A typical example is the unit shown in Figure3B, which costs in the order of £9,000 when the options and accessories for EN 61000-4-2, -4, and –5 are specified.

Figure 3B Example of a generator with ESD, FTB and surge functions

The "Best plus" from Schaffner EMC Systems Ltd

As a means of saving space, weight, and cost, these combination instruments are an excellent way to achieve compliant testing on your own premises. If you find you are hiring test gear frequently or for long periods, it is a good idea to do a financial analysis based on a two-year break-even to see if it is worth buying the test gear outright.

3.4 Buying second-hand test gear

Some rental companies sell off their rental equipment after a few years, and second-hand test gear is also available from a number of other sources. An un-expired calibration certificate on a second-hand purchase is well worth having, if only because it makes the possibility of expensive repairs to achieve your first calibration less likely.

When buying second-hand immunity test gear it is very important indeed to check that it is capable of testing the versions of the standards that you need to use. Some of the test gear is only available second-hand because it is not capable of performing compliant tests to the latest versions of the relevant immunity standards. Such equipment should cost less than compliant test gear, and may still be useful for preliminary investigations where money is tight.

3.5 Fast Transient Burst (FTB)

3.5.1 Details of the standard test

The FTB test aims to simulate the disturbances created by a 'showering arc' at the contacts of ordinary AC mains switches or relay contacts as they open, due to the flyback voltages caused by inductive energy storage in the current path. Figure 3C shows the standard waveform for the EN 61000-4-4 FTB test. It consists of a single unidirectional impulse repeated at a 5kHz rate in bursts lasting 15 milliseconds each, with three bursts per second. Figure 3D shows the basic scheme of the waveform generator and Figure 3E shows the standard test set-up. These three figures are all developed from the EN 61000-4-4 standard.

Figure 3C The standard EN 61000-4-4 waveshape

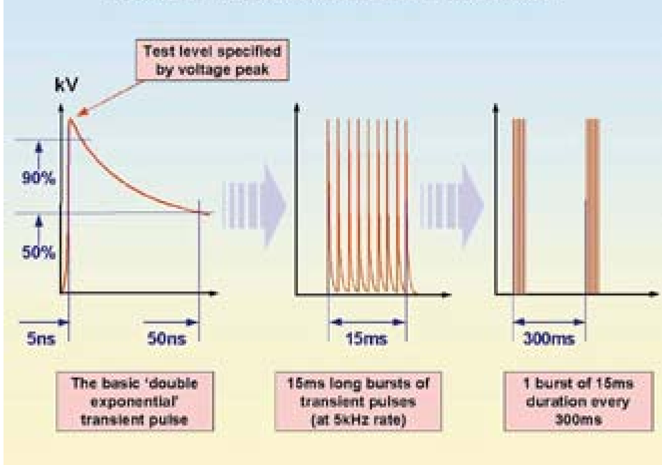


Figure 3D Basic schemes: EN 61000-4-4 generator and coupling network

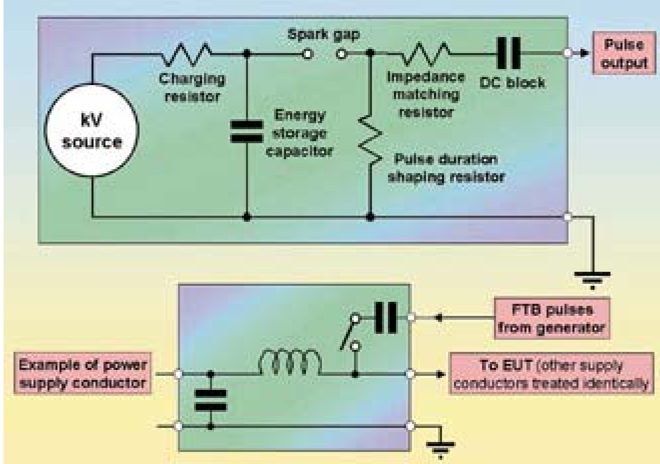
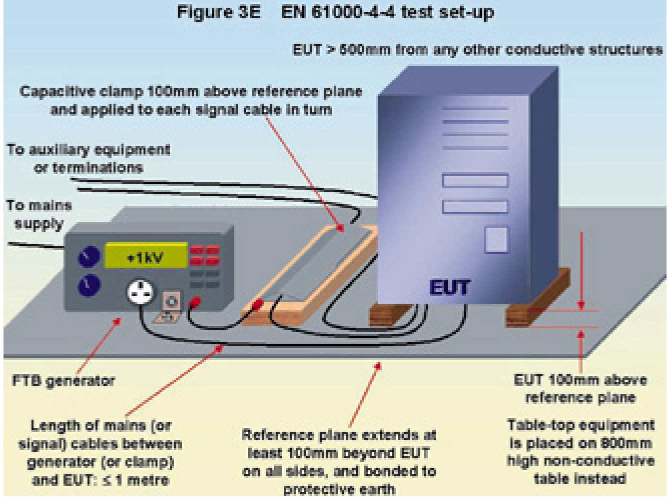


Figure 3E EN 61000-4-4 test set-up



Anyone wishing to perform an FTB test should have a copy of the relevant version of the basic test standard EN 61000-4-4 and follow it as closely as they need to for the test accuracy they require, or can achieve with their test gear.

AC and DC power cables have the transient bursts injected directly into them via specified coupling-decoupling networks (CDNs). These CDNs are contained within proprietary FTB test instruments, but can also be made by following the instructions and schematics in EN 61000-4-4.

Signal and data cables have the transient bursts injected via a specified capacitive clamp. These clamps are easily made using common materials by following the detailed construction drawing in figure 5 of EN 61000-4-4. The clamp can also be replaced with wound tape or conductive foil 1 metre long that creates the equivalent capacitance to the standard clamp (100pF). Shielded 'Zippertubing' 1 metre long on an insulating support can be a simple alternative to a clamp.

Where the 1 metre length of the clamp or equivalent is too long, alternatives can be used as long as they give the equivalent capacitance, even to the extent of connecting the output of the generator directly to the cable screen or signal terminals via discrete 100pF capacitors (high-voltage ceramic type). Because of the lack of distributed coupling, these alternatives (especially the discrete capacitors) are likely to give different results from the standard clamp method so should be used with caution, and only where the 1 metre clamp can't be used.

When testing signal and data cables be aware that the capacitive clamp has no directionality, so any auxiliary equipment being used in the test set-up is also subject to the FTB on its cables. Suppression techniques may be needed for the auxiliary equipment (such as passing the cables through a bulkhead-mounted filter in a screened-room wall, and/or clip-on ferrite cable suppressers) to allow the EUT's response to be measured correctly. Suppressers based on chokes and ferrites are preferred, as capacitive filters may prevent the signal cable from experiencing the coupled FTB as it will in a real application.

3.5.2 Fully compliant FTB testing

The EN 61000-4-4 standard basically consists of three things: a description of the burst generator, a description of the test layout and instructions for the test procedure. We have seen the specified burst waveform in Figure 3C. This is calibrated into a 50Ω load, but of course the actual test load is anything but 50Ω, since it depends entirely on the EUT. Thus the waveform of the burst applied to the EUT may be different, and particularly, may vary between different models of compliant generator. This is a recognised problem with the standard as it exists at present, and an amendment is shortly to be published which will correct it, by requiring extra calibration steps. Note also that the applied test level is specified as the open-circuit peak voltage, not the calibrated voltage; again, this open circuit level is not the voltage which appears at the EUT, which depends on the ratio of generator source and EUT load impedances.

The FTB is a wideband phenomenon with spectral components up to hundreds of MHz, and therefore as with other RF tests, layout is important for repeatability. The coupling of the burst is strongly dependent on the EUT's stray capacitance to its surroundings. Layout aspects which must be observed are:

- The coupling of the EUT and generator to the ground plane. You cannot perform a compliant FTB test without a ground plane. It must be at least 1m square, and should extend beyond the EUT by at least 10cm all round. The burst generator is bonded to it – by a short strap, not a length of wire, and this means that the generator will normally sit on the floor, not on an adjacent table. (This makes remote software control of the generator more desirable, as a remedy for backache. Alternatively the ground plane could be at table-top height, as long as other distances are maintained.) The EUT is spaced from the ground plane by 10cm or, for table-top equipment, 80cm. The 80cm high wooden table is used here as in many other EMC tests.

- Clear distance around the EUT. The minimum distance from the EUT to all other conducting structures – and this includes the test generator and capacitive coupling clamp, a condition which is sometimes forgotten – must be 0.5m. The coupling clamp itself must also have a clear distance around it of at least 0.5m.

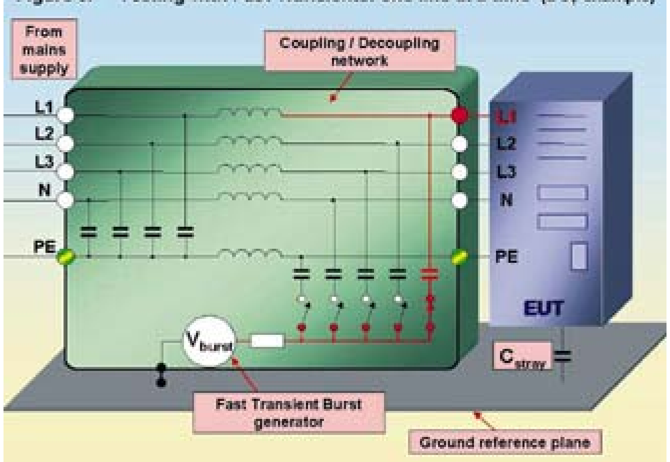
- Earthing of the EUT: if it will be separately earthed in the real installation, then it must be connected to the ground plane in a representative manner, otherwise no connection is made.

- Cable layout: the distance between the EUT and the coupling network or clamp must be 1m or less. Long cables should be coiled with a 40cm diameter, 10cm above the ground plane – note that this differs from the treatment prescribed for emissions tests. It is wise to maintain the cable separation of at least 10cm from the ground plane under all conditions and for all cables, not just the one being tested.

- The capacitive clamp itself must be directly bonded to the ground plane. This introduces a conflict for EUTs which have cable entries greater than 1m above the floor, since either the cable must be further than 1m from the clamp or the clamp has to be raised above the floor. There is no firm guidance on resolving this problem, but we would suggest that it is more important to bond the clamp to the floor so that the induced stress is repeatable at that point, and accept a longer cable, as long as its route is carefully controlled. But there may be arguments for the alternative approach in some circumstances.

The procedures for applying the bursts are generally straightforward – the standard requires at least one minute for each coupling mode, which for a repetition period of 300ms means at least 200 bursts. The product or generic standard being invoked will determine which ports are tested. In contrast to the other tests, only the specified test level need be applied, although you may well want ramp through the levels to check for lower- and higher-level susceptibilities. For the clamp application, this means that only two minutes' testing is needed per port, once in each polarity.

Figure 3F Testing with Fast Transients: one line at a time (a 3ϕ example)



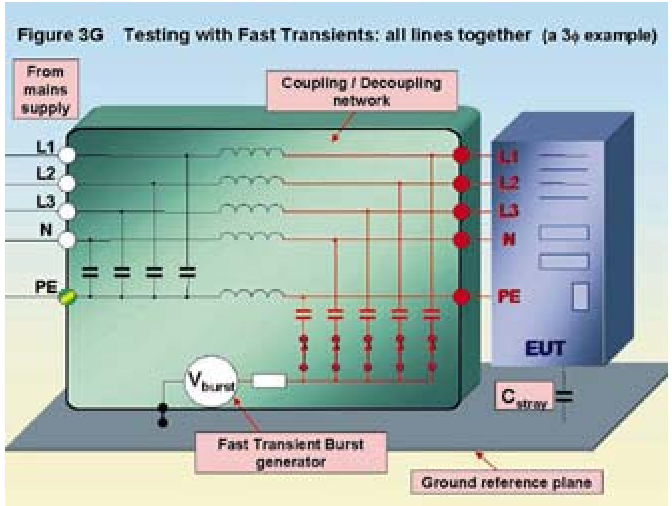


Figure 3G Testing with Fast Transients: all lines together (a 3φ example)

For mains supply tests, you have the possibility of applying the bursts to any combination of the supply wires: L, N, E, L+N, L+E, N+E, and L+N+E (for single-phase earthed supplies), since all of these are tested with a voltage that is referred to the ground plane. The standard merely shows an “example” of coupling via a coupling/decoupling network, and does not mandate any particular combination (see Figures 3F and 3G). A few early product and generic standards refer to testing with EFT bursts in “common mode”, which could be interpreted as requiring application to L+N+E only. The issue from the point of view of compliance could be significant, since immunity often varies markedly between these different modes of application. As a general rule, we would advise you to apply all the separate combinations, since in a real situation the coupling could be dominated by any particular one of them.

3.5.3 On-site testing

On-site FTB testing to EN 61000-4-4 is easy to do, because of the relatively simple test set-ups required, the portability of the test gear, and the fact that suitable methods are described by the standard. Chapter 10 of [5] also describes on-site FTB testing, which requires the use of a 1 metre square reference plane. On-site testing is best restricted to proving that an installation is not susceptible, rather than declaring EMC conformity for a product using the ‘standards’ route. However, an EMC Competent Body could well accept on-site testing when following the Technical Construction File (TCF) route to EMC compliance, especially for custom equipment intended for a specific site.

Figure 3H shows an example of on-site testing of the mains lead of an industrial cabinet. In this case the generator did not use the 1 metre square additional plane specified by the standard so there would be some increased variability expected in the results.

Figure 3H Example of on-site FTB testing of industrial equipment

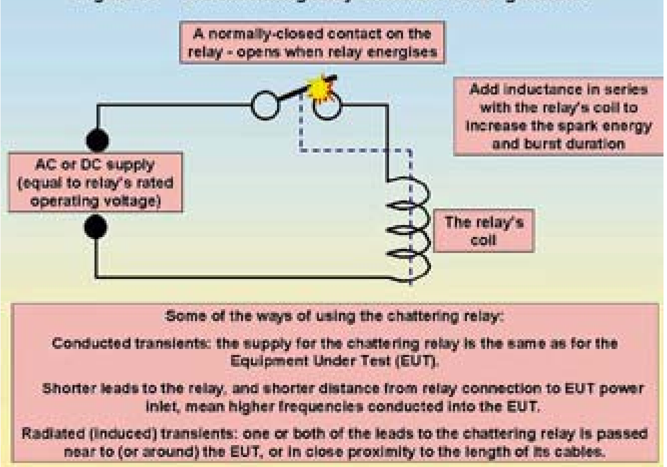
The variability of non-standard test set-ups may be able to be offset to some degree by overtesting, say by testing at up to double the level required by the relevant immunity standard. Of course, the non-standard test method might already be making it a more aggressive test, so increasing the test level might result in a very aggressive test indeed and lead to over-engineering of the product. This is part of the price you pay when you deviate from the standard test method.

3.5.4 Alternative FTB generators

IMPORTANT SAFETY NOTE: *Never* use an unsafe test method or take risks with electricity. If you haven't been fully trained in electrical safety, call in someone who has (and who passed the exams).

A wonderful variety of showering arc simulators exist in companies all over the world, some of them very hazardous to use. An old favourite which is perfectly safe providing the basic electrical safety precautions are taken, is the 'chattering relay' test shown by Figure 3J.

Figure 3J The chattering relay 'transient burst' generator



The chattering relay can be used in a wide variety of ways to generate radiated and/or conducted disturbances. If it is supplied via a safety-isolating transformer (or from a floating DC supply) with sufficient voltage withstand, the bottom side of the coil could be connected to the reference plane (or to any other conductor) and the top of the coil (the node that connects to the relay contact) could be connected via a high-voltage ceramic capacitor to any conductor. This would allow transients to be generated from line-to-line (i.e. differential mode) and each line-to-ground, or all lines-to-ground (common mode).

A popular alternative to the chattering relay is the electric bell. The actual bell dome should always be removed, to avoid the risks of physical injury to the test engineer by nearby colleagues (noise isn't so annoying when it is you that is making it). The electric bell has the advantage that the relay contact gap can usually be adjusted to increase the frequency (at decreased amplitude) or decrease the frequency (at increased amplitude) – a degree of control that is not usually available with relays.

IMPORTANT SAFETY NOTE: Don't forget that the sparks from chattering relays or electric bells can easily ignite flammable materials.

Such simple transient generators can be used as very low-cost alternatives to proper EN 61000-4-4 test instruments. Their usefulness can be increased by golden product testing on a particular product (see section 1.9 of [1] for more on this). They may then be useful for QA testing in production or for testing new variants or new products that use the same circuit techniques and exactly the same ICs. When alternative sources of ICs are used, or significant changes made to any aspect of the design (including software) the correlation with 'proper' FTB testing is lost and would need to be re-established by a new golden product.

However, as mentioned in 3.1 above, it may be that the home-made transient test is *more* representative of the real-life operating environment of the product than is the standard EN 61000-4-4 test. In such cases the test circuit (e.g. a 10kW motor and on/off contactor) should be set-up and related physically to the EUT as close as possible to the real-life situation (proximity, connections to the same supplies, etc.). In the case of a rotating device such as a motor, the energy stored in the rotating parts can significantly affect the transients and surges which are injected into the supply at switch-off, so it is better if the relay or contactor is operated in such a way as to allow the motor sufficient time to speed up and slow down.

When self-declaring compliance to the EMC directive using the 'standards route', even if chattering relay or similar tests have been done to simulate the operating environment and help achieve reliability, it is still best to test to (and pass) EN 61000-4-4 to help avoid the possibility of legal challenges in the future.

But when following the Technical Construction File (TCF) route it may be possible to persuade your Competent Body that the tests you have done represent the environment that the product is going into, and there is no need to apply EN 61000-4-4 as well. This is most likely only possible for custom-designed industrial equipment going into known sites, and not for portable products or equipment which could be used in a range of premises.

3.6 Surge

The surge test aims to simulate the effects of lightning on AC power supplies and any long cables. 'Long cables' is usually taken to mean metallic interconnections longer than 10m between different items of equipment which are themselves some metres apart, or outdoor cables.

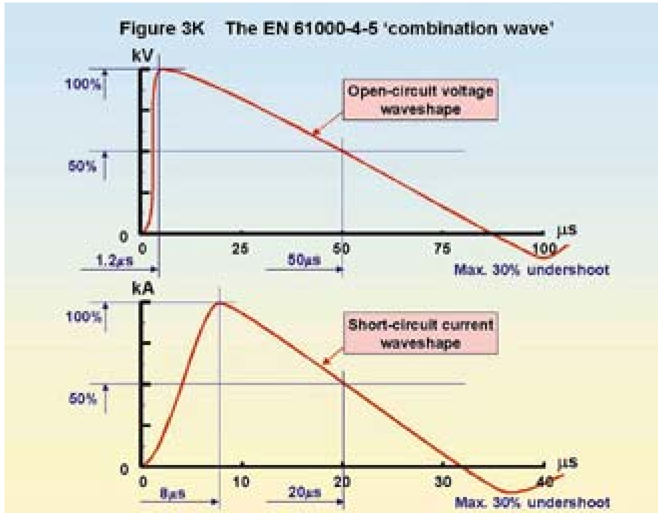
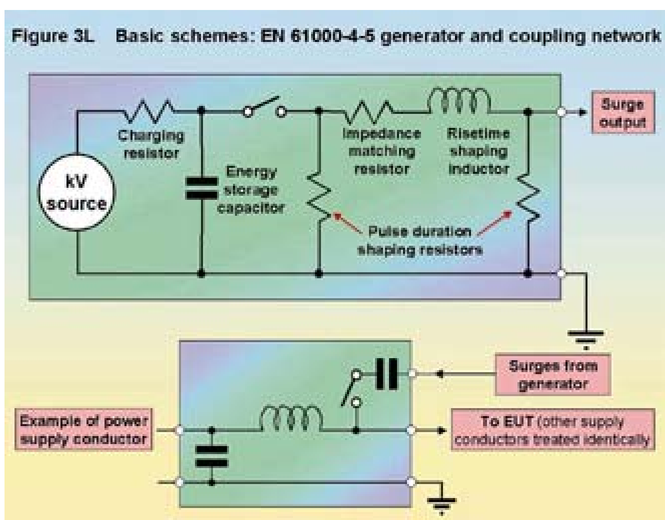


Figure 3K shows the standard waveform for the EN 61000-4-5 surge test, which is a single unidirectional impulse specified by two waveforms at the same time: as a 1.2/50µs voltage impulse into an open-circuit, and as a 8/20µs impulse into a short-circuit – leading to its common name: the 'combination wave'. The standard surge waveform for testing telecommunication cables (that exit a building) has a broadly similar shape, with a 10µs rise time and 700µs fall time. When testing mains inputs the surges are applied (as a positive or negative voltages) at all the zero-crossings and the peaks in a cycle of mains waveform. Time is allowed between each impulse to avoid overheating surge protection devices (SPDs).

Figure 3L shows the basic scheme of a surge waveform generator and Figure 3M shows the standard test set-up. These three figures are all taken directly from the EN 61000-4-5 standard.



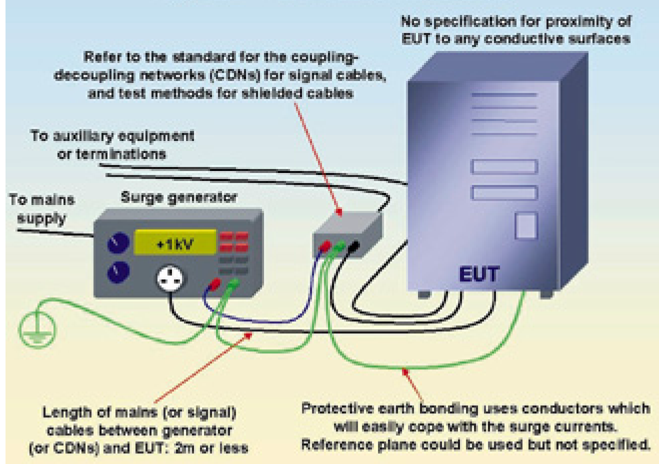


Figure 3M The EN 61000-4-5 test set-up

Anyone wishing to perform a surge test should have a copy of the relevant version of the basic test standard EN 61000-4-5, and follow it as closely as they need to for the test accuracy they require.

The frequency spectrum of the surge test is much lower than that in the FTB or ESD tests, and so the test set-up does not need a reference *plane* (of course it requires an earth, but ordinary wired earth connections will do.) But be aware that the surge current can reach kilo-amps, so the wiring between the generator and the equipment under test must be robust.

IMPORTANT SAFETY NOTE: The instantaneous power and total energy in an EN 61000-4-5 surge test can be quite large – enough to cause electronic devices to explode and eject burning fragments with considerable violence. For this reason surge tests should only be carried out where third parties are positively excluded, and the entire bodies of all operators and others witnessing the tests should be protected at least by a substantial acrylic or other plastic sheet. Fire extinguishers suitable for electrical fires should also be kept charged and handy, and the location of the mains isolator for the whole test area and EUT should be known and it should be readily accessible.

3.6.1 Fully compliant testing

Because of the lower frequency spectrum content of the surge waveform, surge testing is more tolerant of layout variations than the other tests discussed in this article, and the standard is fairly relaxed in this respect. The cable between the EUT and the coupling/decoupling network should be 2m or less in length. Otherwise there are no restrictions on the layout.

The surge waveforms as shown in Fig 3K should appear at the output of a compliant generator when it is calibrated with a short circuit and an open circuit load. The waveform through the mains coupling/decoupling network must also be calibrated and be unaffected by the network, but for coupling devices for signal lines this requirement is waived. The signal line coupling networks include a 40Ω series resistor, which reduces the energy in the applied surge substantially. For mains coupling, the generator is connected directly via a 18μF capacitor across each phase, but through a 10Ω resistor and 9μF capacitor for phase-to-earth application. This means that the highest energy available from the generator's effective source impedance of 2Ω is actually only applied between phases.

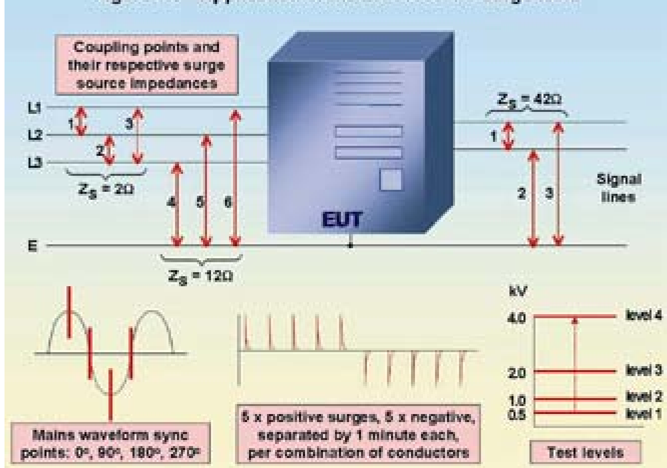
Coupling to signal lines can be problematic since it has to be invasive; no clamp-type devices are available for this test. However for signal lines that would be affected by a 0.5μF capacitor connected to them, it is permissible to use gas discharge tube (surge arrestor) coupling instead. A separate method is shown in the standard for shielded lines, in which the surge is effectively applied longitudinally along the shield, by coupling it directly to the EUT at one end of a non-inductively bundled 20m length of cable, with the further end grounded. This test is carried out with no series resistor, so that the surge current down the cable shield will be several hundred amps.

The test procedure requires you to take the following steps (see Figure 3N), bearing in mind that an agreed test plan may modify them:

- Apply at least five positive and five negative surges at each coupling point
- Wait for at least a minute between applying each surge, to allow time for any protection devices to recover
- Apply the surges line-to-line (three combinations for 3-phase, one for single phase) and line-to-ground (two combinations for single phase, three for 3-phase)
- Synchronise the surges to the zero crossings and the positive and negative peaks of the mains supply (four possibilities)
- Increase the test voltage in steps up to the specified maximum level, so that all lower test levels are satisfied
- Apply a sufficient number of pulses to find all critical points of the duty cycle of the equipment.

Ignoring the last, which doesn't give any specific guidance for how many pulses would be sufficient, a worst case interpretation of the requirements on a 3-phase supply being tested up to level 4 would imply that a single complete test would take 16 hours, not allowing for set-up and test sequencing time. Test labs know that their customers would be uncomfortable with this, and usually some shortcuts are taken so that not all these steps are followed rigorously. This though means that the various interpretations that the standard encourages can lead to different degrees of stringency in testing.

Figure 3N Application of the EN 61000-4-5 surge tests



The rationale for "all lower levels must be satisfied" is that the behaviour of many types of surge suppression is likely to vary between low and high values of surge voltage. A suppresser that would break down and limit the applied voltage when faced with a high level, may not do so at lower voltages, or may at least behave differently. The worst case could well be at just below the breakdown voltage of an installed suppression device. Equally, the EUT response can change either because of circuit operation or because of suppresser behaviour when the surge occurs at varying times during the mains cycle. For example, an unfiltered circuit that looks for zero crossings will have an undesired response when a negative-going surge occurs at the positive peak of the cycle. Unless you are very confident of your EUT's performance in these various conditions, it makes sense to apply testing over as wide a range of variables as possible. This is the merit of pre-compliance testing: to inform the test plan for the full compliance test so that confidence can be had in a restricted set of tests which takes a reasonable length of time.

3.6.2 On-site testing

On-site surge testing to EN 61000-4-5 is very easy to do, because of the relatively simple test set-ups required, the portability of the test gear, and the fact that no reference plane or shielded room is required. Annex B of EN 61000-4-5 describes what it calls 'system level testing', which it recommends to demonstrate reliability in an installation rather than compliance with any regulations. However, it may be possible to get an EMC Competent Body to agree to accept on-site testing when following the Technical Construction File (TCF) route to EMC compliance, especially for custom equipment intended for a specific site.

3.6.3 Alternative surge test generators

Because of the very definitely lethal voltages, stored charge, and energy involved in a surge test generator, we do not encourage anyone to build their own (unless they are very experienced with designing high-voltage equipment for safety and will be applying a safety standard such as EN 61010-1 in full). No example do-it-yourself circuits are therefore given here.

Where large inductive loads are switched, the stored energy they contain can do a lot more than merely create some showering arcs in their switch contacts. Joules of energy in the collapsing magnetic fields of motors, transformers, and other power inductive devices can transfer large surges to their power supplies in the arcing of their switches, relays, or contactors, as they open. Here is another example where the standard EN 61000-4-5 test may not represent the surges that a product is exposed to in its intended applications. Surges due to inductive load collapse may be a lot faster than lightning induced surges, and may also have more energy in them. An example of a 10kW motor and on/off contactor was used earlier. Where such large inductive loads may be connected to the same branch of the mains distribution and no special surge protection is applied by the installation, testing with a representative surge generator may help improve reliability in the field and reduce warranty claims. (In the case of a motor, the rotational inertia of its load is not important unless the motor is capable of significant generation efficiency when not energised remotely.)

An extreme example of a problem load is the superconducting magnets used in MRI scanners. These can take several weeks to charge up from kA rated power supplies, and when their field collapses they can put surges of around 1MJ back into their supplies, and any other conductors they can arc across to, in just a few microseconds. This is approximately 10,000 times larger than the energy in an EN 61000-4-5 mains surge test at 1kV, and capable of destroying structural metalwork rather like a direct lightning strike. MRI scanner manufacturers almost certainly take whatever steps are necessary to absorb these surges, if only to protect the electronics in their own product.

At a more mundane level, designing to pass a suitable surge test can be very helpful in reducing field returns due to thunderstorm activity – rarely a serious problem in the UK, but much more so in some other parts of the world, where the infrastructure to deal with such returns is harder to set up.

3.7 Electrostatic discharge (ESD)

The ESD test aims to simulate the effects of discharges from the fingers of personnel, either directly or via keys or other metal objects held in the hand, the personnel having been charged to a high voltage by tribo-electric charging, usually due to rubbing contacts between their shoes or clothing and dissimilar materials used for flooring, storage, etc.

Figure 3P The standard EN 61000-4-2 current waveshape

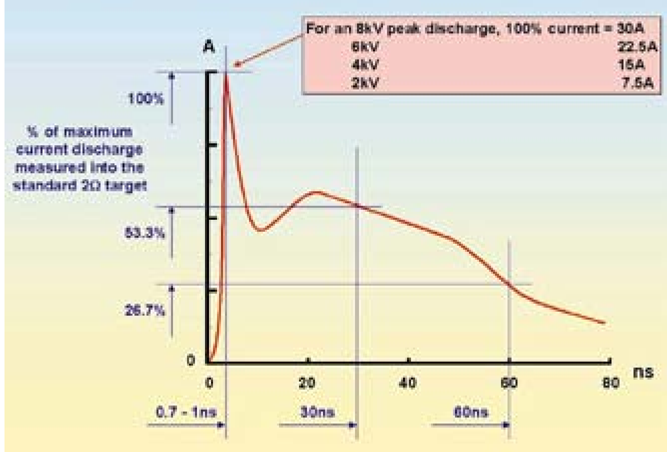
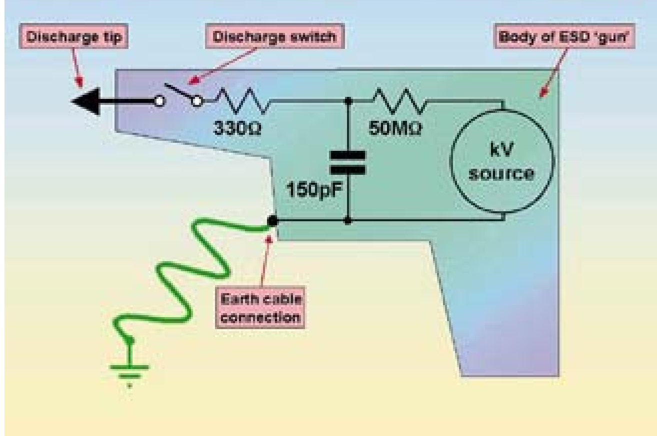


Figure 3P shows the standard waveform for the EN 61000-4-2 ESD test, which is a single unidirectional impulse. Figure 3R shows the basic scheme of an ESD generator or ‘gun’ and Figure 3S shows the standard bench test set-up. These three figures have all been developed from the EN 61000-4-2 standard.

Figure 3R The basic human body circuit model used by EN 61000-4-2



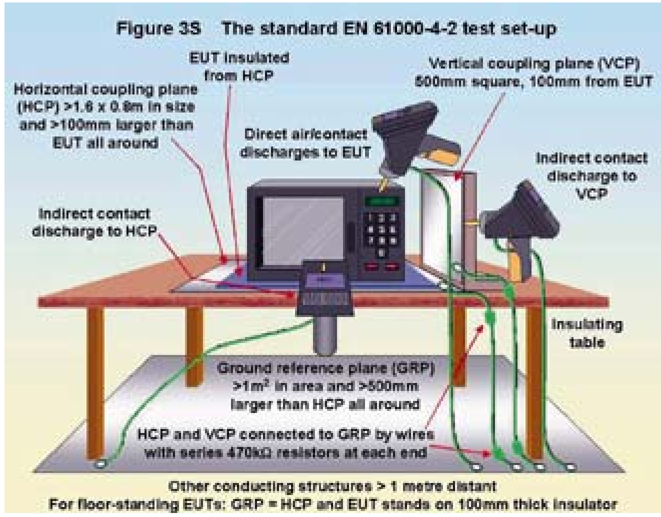


Figure 3S The standard EN 61000-4-2 test set-up

Anyone wishing to perform this type of personnel ESD test should have a copy of the relevant version of the basic test standard EN 61000-4-2, and follow it as closely as they need to for the test accuracy they require. Compliant ESD guns are easy to hire and relatively straightforward to use, and an example of one is shown in Figure 3T.

Figure 3T Example of an EN 61000-4-2 compliant ESD 'gun'

3.7.1 Fully compliant testing

In contrast to the two previous test types, where the mode of coupling of the transient is reasonably well defined, the ESD test – even done fully according to the standard – is not well controlled. Much depends on the skill and experience of the test engineer, particularly in selecting the test points and in actually applying the stress.

The basic layout is straightforward. The EUT is placed over a ground plane to which the ESD generator is returned. This must project at least 0.5m beyond the EUT or coupling plane, i.e. further than is required for the EFT test. The ground return lead is calibrated with the generator and this should be exactly the same lead as is used for the testing. Different leads will have different inductances, and this could modify the discharge waveform, particularly its trailing edge. The lead should always be kept away from the EUT and other structures (by 0.2m minimum, according to the standard), and the test engineer's body. The separation distance for the EUT above the ground plane, as with the EFT burst test, is 10cm for floor standing and 80cm for table-top apparatus. (The distance of 10cm here is helpfully the same as the thickness of a fork lift truck pallet.) There should also be at least 1m clear area around the EUT.

For table-top testing, directly underneath the EUT but insulated from it there is a secondary plane, known as the horizontal coupling plane (HCP). This is connected to the ground plane by a bleed resistor lead. The construction of this lead is important: its purpose is to isolate the HCP during the actual discharge but allow charge to bleed off afterwards. The resistors are located at each end of the lead so that the lead's stray inductance and capacitance are isolated from both the HCP and the ground plane. Since the resistors must withstand nearly the full applied ESD voltage, they should be large enough to prevent tracking across their surface. Carbon composition (not carbon or metal film) are good for these components.

The (table-top) EUT is placed on the HCP with its front face 10cm from the edge of the plane. Cables are draped off the HCP and taken away from the test area as necessary. In fact the standard is weak in this respect: although as with other RF tests cable layout and termination can make a large difference to the test outcome, EN 61000-4-2 says virtually nothing about how they should be treated, except that they should be "representative of installation practice".

The procedure followed in the test is divided into direct application of contact and/or air discharges, and indirect contact application to the coupling plane(s). The discharge gun itself is capable of both contact and air discharges. For the contact discharge, the pointed tip makes contact with the test point, and to create a pulse a relay within the unit is closed, which applies the test voltage to the tip. This removes the variability associated with the breakdown of the air gap in the air discharge method, and it is the preferred method wherever a conducting surface is accessible. But if your EUT has insulating surfaces where a discharge might still be possible, the air discharge method using a rounded tip is still necessary. Favourite spots are apertures or seams in a plastic enclosure, behind which there may be metallisation or metal parts, and the gaps between key caps or around windows.

The ESD gun must be held perpendicular to the surface being tested, since any departure from this affects the stray capacitance between the front of the gun and the EUT, and is a source of variability. In addition when doing the air discharge, you should be positive in your handling of the gun. The standard says "the tip shall be approached as fast as possible (without causing mechanical damage) to touch the EUT". This is important, because the stress applied is greatly affected by the approach speed. A wavering, cautious approach will result in large variations of stress between discharges.

The indirect discharge to a vertical coupling plane, and to the HCP for table-top equipment, has also to be performed for all types of product. This is a contact test only, i.e. the air discharge tip is not used. It simulates the effect of a discharge to a nearby conductive object. In the case of a well-insulated product, it is in fact the only test in which a discharge actually occurs. In many cases this is less stressful than a direct discharge and a good product will be unaffected by it, but you cannot assume this until the test has been done. Amendment 1 to the standard modifies the method to make clear that the gun should be held edge-on to the plane, at the centre of the face of the EUT, which is different from the original standard's wording. You will usually have to rotate the EUT to test all four sides; this is likely to be easier than making sure that each appropriate face of the EUT is 10cm from the edge of the HCP.

The actual application of a compliance test should proceed as follows:

- Select a suitable set of points for the test application, and make sure that you document these with reference to a drawing of the product. You may have a good empirical idea of the likely weak points – for instance the edges of aperture, seams or joints, or control or ventilation openings – or you have already done some exploratory testing at a fast pulse rate to actively identify such points.

- At each point and for each test voltage you will apply at least ten pulse discharges, allowing at least a second in between, checking for the EUT's response. Unless you know the most sensitive polarity, apply ten discharges in each polarity. This could be ten positive followed by ten negative, or alternate positive and negative, or any combination in between. Provided that the EUT discharges after each pulse it shouldn't matter how you do it, although this may depend on the design of the EUT.

- For each point and each of these sets of discharges, start off at the lowest test level (2kV) and ramp up through the levels to the specification value, typically 4kV for contact and 4kV + 8kV for air. This is to check for non-linearities in the stress response and is a requirement of the standard.

The test is only required at such points and surfaces which are accessible to personnel during normal use of the equipment. This may mean that some potentially susceptible points need not be tested directly. A second amendment to the standard, published in November 2000, gives clearer guidance on what is meant by accessible points. It also clarifies the procedure for ungrounded EUTs. If the applied charge cannot bleed off the EUT between pulses – because, for example, it has no external connections – then the stress voltage will change after each pulse application. This will either reduce the applied stress, if the voltage on the EUT rises towards the applied value on consecutive applications of the same polarity, or it will increase it, if the polarity is changed between applications. To deal with this you need to ensure that the EUT is properly discharged each time. The amendment recommends that a bleed resistor cable is attached to the EUT during the test, as long as this will not affect the test outcome. Otherwise, a bleed brush can be applied after each pulse, or an air ioniser can be used.

The root ESD test standard IEC 61000-4-2 has been around since 1995 and it was virtually unchanged from the original IEC 801-2: 1991 document. It has stood the test of time reasonably well, but enough experience has been gained to lead to the desire for a complete revision. A first draft of this revision (IEC 61000-4-2 second edition) was circulated on 5th January 2001. This is a complete re-write of the existing standard: anybody concerned with ESD testing or test equipment should read it. The major novelties are described below.

- The number of tests has been increased to 50 on each test point
- A clear area around the test site is defined
- The generator specification is substantially more detailed
- There are new requirements for calibration
- There are extra requirements on the GRP, HCP, VCP and bleed wires
- In the setup: the EUT cables are to be terminated with CDNs or EM Clamps; there is a new setup for “small” table-top EUTs; the method for ungrounded equipment is included as per A2 to the first edition
- There is more detailed guidance on test methods; for contact discharge, it is no longer necessary to satisfy all lower levels, though it still is for air discharge
- An “escalation strategy” is presented for difficult-to-reproduce failures
- There are several new guidance annexes.

3.7.2 On-site ESD testing

On-site ESD testing to EN 61000-4-2 is very easy to do, because of the relatively simple test set-up required and the easy portability of the test gear (e.g. the ESD ‘gun’ shown by Figure 3T is battery powered and comes with a spare battery pack so one can be charging while the other is in use). In addition, section 7.2 and Figure 7 of EN 61000-4-2 describe what it calls ‘post installation tests’ which merely require the addition of a 0.3 x 2 metre reference plane, also quite a portable item. On-site ESD tests are also described in considerable detail in chapter 10 of [5].

3.7.3 Alternative ESD test generators

Figure 3U shows the old favourite, the modified piezoelectric gas lighter. These can be purchased for a very low cost (a few £) and easily modified to make a crude ESD gun. Their output waveforms are unknown (although they could perhaps be calibrated by using an EN 61000-4-2 style calibration fixture) and they work on the principle that some sort of ESD testing is a lot better than nothing.

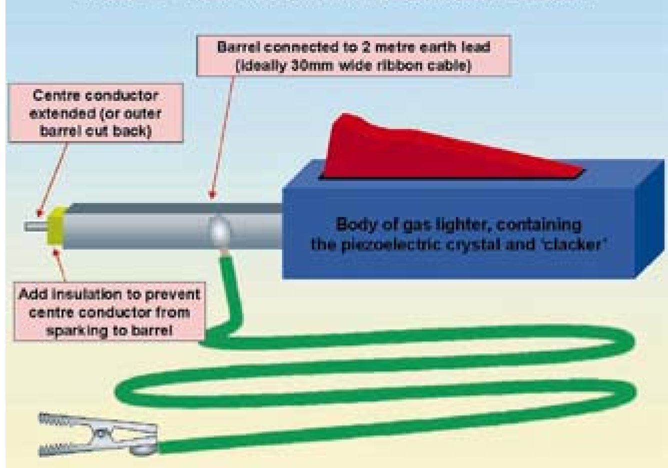


Figure 3U A modified piezoelectric gas lighter 'ESD gun'

Alternative ESD generators can easily be made using the spark ignition circuits used in gas or oil-fired boilers. Another alternative is to use an automotive ignition coil and circuit, with the coil energised by a simple monostable driving a power FET or relay. It is also possible to make high-voltage generators from TV set circuits, or from ladder networks, or neon lamp power supplies. In all cases a carefully insulated hand-held probe is required, with a hemispherical tip of 8mm diameter to match the air-discharge tip in EN 61000-4-2. Of course, all these different generators will have quite different characteristics, and those that use inductive or piezo-electric components to directly produce the high voltage spark will most probably not achieve the very fast rising edge of the proper ESD test which causes much of the disruption experienced by typical digital circuits.

Home-made ESD guns can have their output voltage controlled in the same way that a 'proper' air-discharge ESD gun can – by setting the instrument to continuous discharge when it produces one spark every second, or fraction of a second depending on the internal HT generator's capability (an automotive spark generator should be capable of 100Hz spark rate) – and then varying the distance of the discharge tip from the target. Since the breakdown of air is approximately 1kV/mm, a gap of 4mm gives sparks at approximately 4kV, and a gap of 15mm gives a spark of 15kV.

With a little practice you will be able to explore the ESD weaknesses of your product very quickly, whether using a compliant ESD gun or a home-made one, by setting the gun to continuous operation and moving the probe tip over the product's surfaces while varying the tip distance from 2 to 10mm so as to expose each tested point to a wide variety of test voltages.

Given the low cost of hiring a compliant ESD gun and the very low cost of the test set-up there seems little point for most companies to make their own ESD gun and then having to worry about whether they are over-testing or under-testing, or just testing their product differently.

But it may be that a home-made ESD simulator is needed to simulate an actual environmental threat, such as the discharges from a particular industrial process, as an aid to reliability in the field rather than any concerns about regulatory compliance. When constructing such simulators, it is important to get the charging capacitance and the impedance of the discharge path reasonably accurate (within 50% is probably the ESD equivalent of perfection), and this may involve some measurements of the construction of whatever it is that is causing the discharge (almost always a metal object) and a reasonable amount of empirical calculations. Note that the polarity of the discharge is often important, as many electronic circuits can behave differently with the same voltage levels but different polarities.

IMPORTANT SAFETY NOTE: EN 61000-4-2 ESD discharges are not dangerous (although they are not recommended for anyone fitted with a pacemaker or other implanted or body-worn electronics) but custom-made ESD generators could well be lethal. EN 61010-1 says that voltages up to 15kV peak or DC are considered unsafe if they can discharge > 45μC (micro-coulombs), and voltages above 15kV are unsafe if the energy associated with them exceeds 350mJ (milli-Joules), and it is probably wise to follow the guidance of this safety standard and take all necessary personnel high-voltage protection measures if these limits are exceeded. 45μC implies a maximum value of capacitance of 3nF at a voltage of 15kV (or 5.6nF at 8kV). For inductively-generated ESD at under 15kV it is probably safest to apply the 350mJ limit.

3.8 Locating faults during immunity testing

3.8.1 Test instruments

As anyone who has tried has discovered, regular test instruments (digital multimeters, oscilloscopes, logic analysers, etc.) are usually quite useless during immunity testing. Either they are so perturbed by the test itself that it is hard to tell what, if anything, is being measured; or the impedance of their probes so affects the circuits being probed that they respond differently. Another possibility is that the probes themselves act as injection points for the tested disturbance, making the circuit's response much worse.

A few manufacturers have developed tiny probes that are connected to external measuring gear (well away from the effects of the tests being applied) by fibre-optics. Two of these are described in [6] and [7]. Tiny probes used by these types of systems have been developed for measuring voltage, current, and local field strengths, sometimes with bandwidths exceeding 1GHz.

3.8.2 Localised immunity testing

The close-field magnetic and electric field probes as described in [1] can be used as localised sources of disturbances in immunity tests. While the home-made probes in [1] should be robust enough to survive such abuse, if you are using purchased probes check that they are capable of handling the proposed use *before* using them.

Localised immunity testing can be used in a number of ways:

- during design – to test proposed circuits or devices
- during development – to test prototypes
- during certification – to help fix compliance problems
- during production – to help check the quality of devices at goods-in, and/or products in serial manufacture.

The close-field and current probes shown in figures 1, 2 and 4 of [1] can be connected directly to the output of an FTB generator, generating localised magnetic or electric fields (or in the case of those shown in figure 4 of [1]: magnetic and electric fields simultaneously) corresponding to the FTB waveform. The procedure for using the probes is similar to that used for detecting localised sources of emissions – the probe is scanned carefully over the suspect areas of the product, very close to any devices or conductors, until the most sensitive areas are located. The home-made current probe shown in figure 5 of [1] and proprietary transducers such as those shown in figures 1 and 3 of [4] can also be used to inject FTB disturbances into specific cables (but always check that proprietary transducers are rated for such use).

A 'pin probe' similar to the one shown in figure 2 of [1] could be used to inject FTB signals directly into conductors and component leads, but would need to use a high-voltage capacitor (say, 100pF). It may need to be fitted with a wide-band power attenuator for injecting into some internal signals and PCB components without damaging them.

It is usual to start off with the lowest test level set on the generator, increasing the level until significant responses are discovered, fixing those, and then increasing the test level until the next batch of sensitive areas are discovered. As for close-field emissions testing, not all the areas which cause significant responses may be relevant for the 'proper' whole-product test.

Localised ESD testing can also be done with the home-made magnetic probes (shielded or unshielded) and the current probe. However the electric or pin probes would just charge up to the ESD voltage and then be useless until they discharged, unless they were modified to incorporate a high-voltage bleed resistor of about 1kW. A problem with using ordinary BNC (or N-type) connectors is that they won't interconnect with ESD generators and will anyway probably arc-over internally at above 4kV. It would be better to make new probes which had connectors that would plug directly into the ESD gun's output (maybe by modifying a spare discharge tip).

If using the converted gas-lighter or automotive spark-plug ESD generators it would be fairly straightforward to construct a magnetic loop or electric-field probe that fitted directly to them to make a hand-held probe system.

Both FTB and ESD problems can occur because of conducted voltages and currents or by radiated and induced fields. Different types of localised probes and test methods will simulate different aspects, and unless the cause of the problems is known (or at least suspected), all relevant probe types may need to be used.

It is not recommended to do localised surge testing. In any case, it is not usually necessary as the test failure points are often found by scorch marks or visibly damaged components, or by seeing the location where a spark occurs within a product (remember to *always* use blast shields – never expose your body and especially not your eyes, to any part of a product during a surge test). Most surge test failures are caused by conducted low-frequency over-voltages, and not by the high-frequency induced or radiated couplings which are common for FTB and ESD, so the vulnerable areas are usually easily spotted from a schematic diagram and the internal construction of the product and layout of its printed-circuit boards. The creepage and clearance distances required to prevent a 6kV surge from arcing-over, on a clean PCB surface, can exceed 10mm.

References

[1] "*EMC Testing Part 1 – Radiated Emissions*" Keith Armstrong and Tim Williams, EMC + Compliance Journal February 2001, pages 27-39. (Also includes Part 0.) Available on-line at www.emc-journal.co.uk.
[2] ISO 7637-0:1990 "*Road Vehicles – Electrical Disturbance by Conduction and Coupling*" parts 0 to 3. Published by British Standards as BS AU 243:1991.
[3] "*Subjecting Failure Modes in Immunity Tests to Uncertainty Analysis*", Brian Jones, IEE Colloquium on "*The Implication of Measurement Uncertainties for EMC testing*", 11th June 1997. Reproduced in the EMC Journal, June 1997, pages 7-10 and available on-line from www.emc-journal.co.uk.
[4] "*EMC Testing Part 2 – Conducted Emissions*" Keith Armstrong and Tim Williams, EMC + Compliance Journal April 2001, pages 22-32. Available on-line at www.emc-journal.co.uk.
[5] "*EMC for Systems and Installations*" Tim Williams and Keith Armstrong, Newnes, January 2000, ISBN 0-7506-4167-3 (available from RS and Farnell).
[6] "*Advancements in Locating Susceptible DUT Wires*" W A Rogers and J J Laggan, ITEM 1993, pages 198-206.
[7] "*Daily Verification and Failure Analysis System for ESD and Burst Testing*", R Heinrich, D Pommerenke, K Hall, Compliance Engineering May/June 1997, pages 64 –66.

Corrections to Part 2

Figure 5 showed five LISNs. The Thurlby-Thandar LISN shown is supplied by Laplace Instruments Ltd.

Eur Ing Keith Armstrong C.Eng MIEE MIEEE
Partner, Cherry Clough Consultants, www.cherryclough.com, Associate of EMC-UK
Phone: 01457 871 605, Fax: 01457 820 145,
Email: keith.armstrong@cherryclough.com

Tim Williams C.Eng MIEE
Director, Elmac Services, www.elmac.co.uk, Associate of EMC-UK
Phone: 01243 533 361, Fax: 01243 790 535,
Email: elmactimw@cix.compulink.co.uk