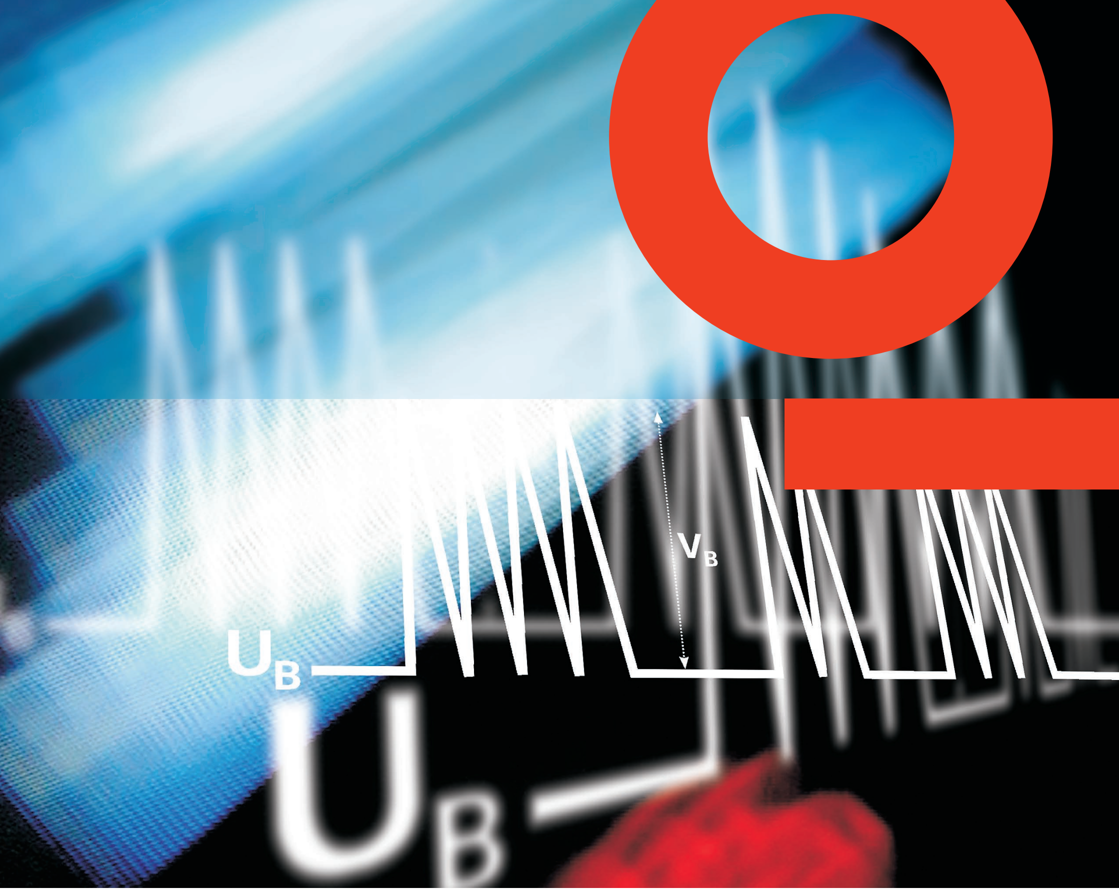

TRANSIENT IMMUNITY TESTING

HANDY GUIDE

TESEQ

Advanced Test Solutions for EMC

691-194A

CONTENTS

1 INTRODUCTION

As well as covering continuous radio frequency phenomena, EMC means ensuring product immunity from several sources of transient phenomena that are present in the electromagnetic environment. These phenomena can be natural, such as electrostatic discharge (ESD) and lightning surge, or man-made such as switching transients and fault surges. These involve short-duration (nanosecond or microsecond) events that have high enough amplitudes to disrupt the operation of electronic circuits, and in some cases have enough energy to destroy or damage components.

Except for ESD, the source of a transient is not normally near to the victim equipment, and its energy is almost entirely coupled into the circuits via cable connections. Therefore immunity testing involves applying a repeatable pulse of a defined waveform and level into each relevant cable port, in a specified and reproducible manner. Apart from the rarely-used pulsed magnetic field and damped oscillatory wave tests of IEC 61000-4-9 and –10, there are no commercial tests which apply radiated transients. ESD is the special case which is the exception to this rule: it is applied from a simulator which attempts to mimic the real-world event, and includes both radiated and conducted components.

Application of a series of transients is accompanied by monitoring the function of the EUT to determine whether it has been disrupted, and if so, whether the disruption is acceptable or not.

This guide discusses the mechanisms involved in generating each type of transient, the IEC standard tests that have been devised to deal with them, and some of the practical issues that arise in performing these tests. Some reference material on the waveforms is given at the end of the guide.

2 ELECTROSTATIC DISCHARGE

2.1 The discharge event

Charging mechanism

All conductive objects have self-capacitance with respect to ground and mutual capacitance with respect to other bodies. This capacitance can maintain a static charge with respect to ground, if the object is insulated from ground. Movement or separation of insulating surfaces causes charge transfer through the triboelectric mechanism, and this leaves a net deficit or surplus of free electrons on the conductive objects that are coupled to these surfaces. Alternatively, proximity to other electrostatically charged objects results in inductive charging.

With perfectly insulating materials, this charge would remain on the object indefinitely, but in reality there is some surface and volume conductivity and the free electrons drift so that the charge differential is gradually neutralised. This occurs more rapidly with greater conductivity. Static dissipative materials, and higher relative humidity, are two ways to increase the conductivity.

The charge Q is related to the voltage differential by the capacitance of the object:

$$Q = C \cdot V$$

For parallel plates, capacitance is determined by surface area A and separation distance d, as well as by the permittivity ε of the dielectric material within the separation gap ($\varepsilon = \varepsilon_0 \cdot \varepsilon_r$, where ε_r is the relative permittivity of the dielectric and ε_0 is the permittivity of free space, $8.85 \cdot 10^{-12}$ Farads per metre):

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot (A/d)$$

For irregular objects, the capacitance can be approximated by applying the above equation to elemental regions of the objects and summing the capacitance due to each element:

$$C = \Sigma_i \{\varepsilon_0 \cdot \varepsilon_r \cdot (A_i/d_i)\}$$

where A_i is the surface area of each element and di is the distance between surfaces for each element.

Human body capacitance depends on the size of the person and on their activity, i.e. whether they are sitting, standing or walking. In a moving person all these factors come together to give a continuously varying voltage on that person. In the worst case – highly insulating materials, low relative humidity and vigorous movement – the voltage may reach up to 25 kV and more. Charge potentials around 30 kV tend to be limited by corona effects. In more typical situations voltages vary between 2–8 kV. Although the human body is the most frequent source of electrostatic charge that is likely to affect electronics, it's by no means the only one – other objects such as furniture and mobile trolleys are also a potential threat.

The effect on electronics

When a charged object contacts another object at a different potential (this second object may be at ground potential but is not necessarily so), the charge is equalised between the two objects, and there is both a voltage v(t) and current i(t) transient as this occurs (Figure 1). The amplitude and waveform of the transient depends on the voltage difference and the total impedance in the equalisation current path. This in turn is determined by the impedance of the source, the victim and of the air gap between the two, which ionises (breaks down) when it cannot support the potential difference gradient.

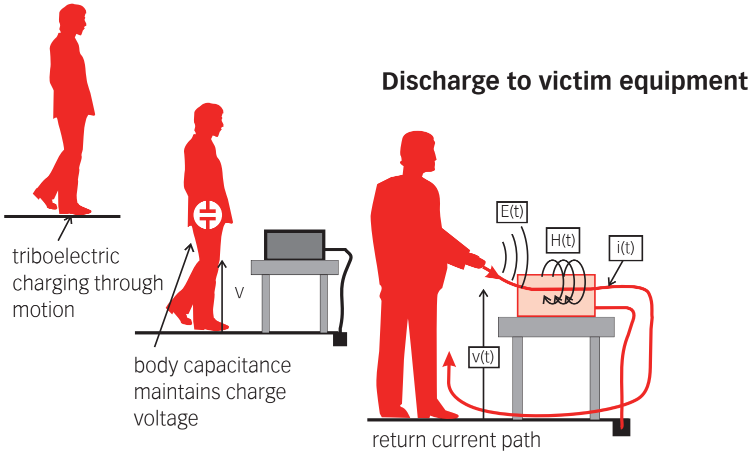

Figure 1: The typical personnel discharge scenario

Associated with the *v(t)* and *i(t)* are electric and magnetic field transients *E(t)* and *H(t)*. All four of these aspects of the event will couple with electronic circuits that happen to be in the path of the current or near to the source of the field. This coupling creates induced transient voltages within the signal circuits themselves. Digital circuits in particular may respond to these induced pulses as if they were intentional signals, and their operation is consequently corrupted.

Application of the stress directly to operating circuits, for instance via connector pins or unexpected flashover, may actually damage sensitive devices. This may be permanent, due to fusing of metallization on-chip, or does result in a weakened but still operational state, due perhaps to degradation of gate oxide. It is also possible for an ESD event to induce latch-up in an operating circuit, where damage is caused not by the ESD energy itself but by subsequent supply currents which pass through the device when it is tripped into a low impedance state.

Design to avoid ESD problems includes:

- choose circuit configurations that are unresponsive to short transients
- lay out the PCB to minimise induced voltages at critical nodes
- prevent unavoidable discharge transients from coupling into circuits and cables
- design enclosures as far as possible to prevent discharges from occurring

Reference [1] gives more information on designing for ESD protection.

Secondary discharge

A secondary discharge can occur within equipment if the discharge current through the product attempts to take a path which includes an air gap. The voltage across the gap increases until the gap breaks down, and this secondary breakdown can be more stressful for the circuits than the initial event, because it is closer to them and probably involves a lower path impedance. The breakdown can occur simultaneously with the applied primary discharge, or it can result once several primary discharges have occurred such that an isolated conductive part has built up sufficient voltage to discharge itself. Secondary discharge is best dealt with by ensuring that no sneak air gaps exist, or by making them large enough not to break down, or by bonding across them, and by avoiding sharp edges which encourage high field gradients. Floating (isolated) metalwork or copper areas on PCBs must be avoided.

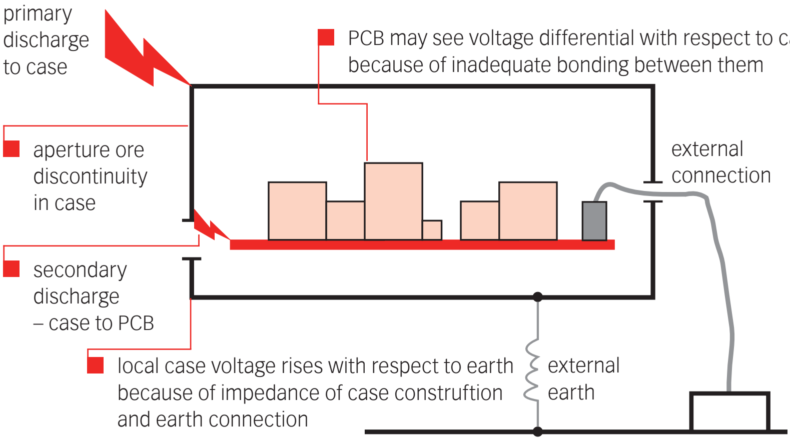

Figure 2: Mechanism of secondary discharge

2.2 The IEC 61000-4-2 standard test method and simulator

IEC 61000-4-2 [2] and its EN equivalent is the principal basic standard for testing electrostatic discharge immunity. It applies a defined current waveform at a specified voltage level from a hand-held simulator (Figure 3), which is essentially a capacitor supplied from a high voltage supply whose charge voltage is discharged via a series resistor through the point of contact to ground. Two methods are given: contact discharge and air discharge.

Figure 3: The Teseq NSG 435 ESD simulator

Contact discharge

In the contact discharge method the stress may be applied directly to the EUT or to a coupling plane adjacent to the EUT. Before each test pulse, the capacitor is charged to the desired level but its voltage is held off the generator's probe by a vacuum relay. The probe is applied to a suitably chosen point on the EUT or the coupling plane. The generator is then triggered, so that the relay contacts close and the capacitor voltage is applied through the probe to the EUT. This creates a pulse of current (with associated field and voltage transients) as the voltage discharges through the combined series impedance of the simulator, the EUT and the ground plane. This action is repeated the desired number of times, at each location, with the appropriate polarities and levels. The locations on the EUT must be conductive so that the probe can make direct contact with them.

Air Discharge

The same simulator is used for the air discharge method, but with a rounded rather than a pointed probe tip. The capacitor is charged to the desired level as before, but the voltage is now continuously applied to the probe, which is held away from the EUT. For each test pulse, the tip is brought up to the chosen point on the EUT, smartly, until it touches. Just before this, the air gap or creepage path will break down and a discharge current will flow, limited as before by the combined series impedance of the generator, the gap, the EUT and the return path. Again, the action is repeated the desired number of times, at each location, with the appropriate polarities and levels. With this method, the EUT location need not be conductive, as the intention is to test the ability of the case insulation to withstand the high voltage without breakdown to internal conductive parts; it is typical to apply this test to seams and apertures in a plastic case.

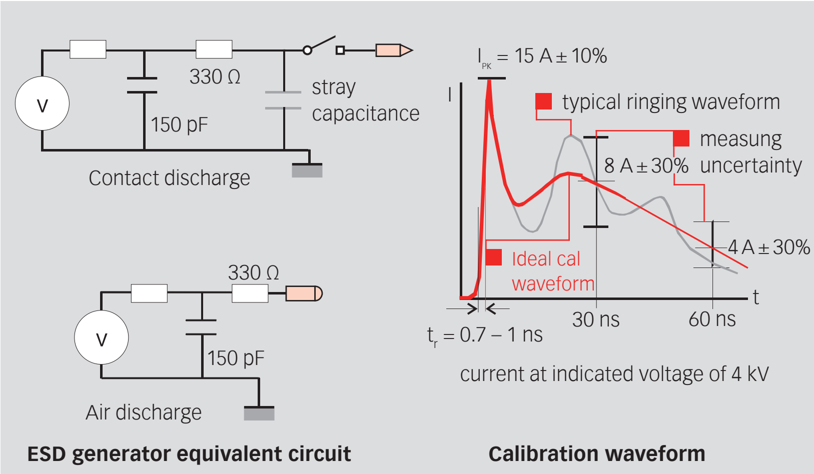

Figure 4: The ESD generator circuit and waveform

2.3 Practical aspects of testing

The test layout

The recommended test layout for table-top apparatus is shown in Figure 5a. The ESD pulse has a sub-nanosecond risetime and so radio frequency layout precautions are vital. The test must re-create the fast risetime found in reality, since this is an important parameter in deciding both the path the discharge takes through the EUT and the response of the EUT itself. The ground reference plane (GRP) is an integral part of the setup and the generator's return lead must be well bonded to it, since this connection forms part of the current return path. It is desirable but not essential to do this test in a screened room; if you don't, then you should be sure that any nearby equipment is not unexpectedly susceptible, since the radiated component of the discharge pulse can be quite aggressive.

The indirect discharge part of the test uses two other planes, different from the GRP, known as the horizontal coupling plane (HCP) and the vertical coupling plane (VCP). The HCP remains in place under the EUT during the direct tests, but the VCP does not. Discharges to these planes simulate the stress caused by the radiated field from real-life discharges to nearby objects. Each coupling plane is connected to the GRP by a resistor lead, to ensure that any charge bleeds off within a few microseconds. The construction of these leads is critical: there should be a resistor close to each end, so that the length of lead between them is isolated from the connections and stray coupling to it is neutralised. Although power rating is unimportant, the resistors themselves should withstand a high pulse dv/dt without breaking down, for which low inductance carbon composition types are best suited.

For the few tens of nanoseconds of the ESD event, the plane carries the full stress voltage, which is capacitively coupled to the EUT. Any stray capacitance from the plane to objects other than the EUT modifies the plane's voltage and current waveforms and hence the applied stress. Therefore it is important to maintain at least 1 m clear space around the EUT, which implies some separation of the table-top setup from walls or other objects. Equally, the separation from the VCP to the EUT is specified as 10 cm; even small variations in this distance can cause large changes in coupling to the EUT, so a convenient means of controlling it, such as plastic 10 cm spacers on the surface of the plane, could be helpful.

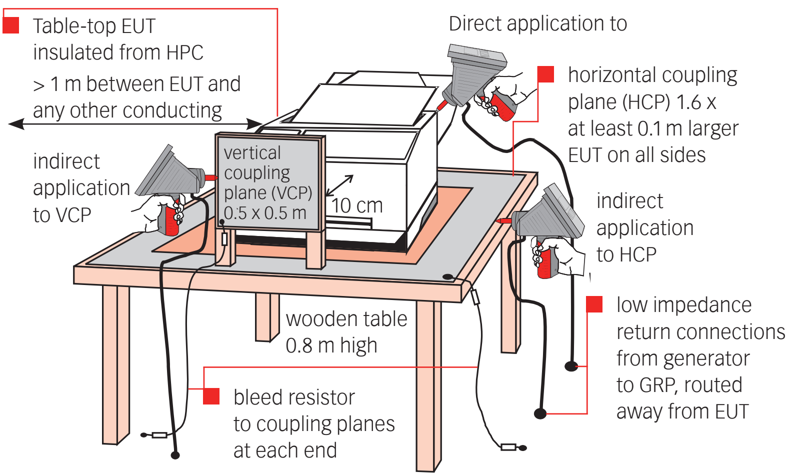

Figure 5a: ESD test layout for bench-top equipment

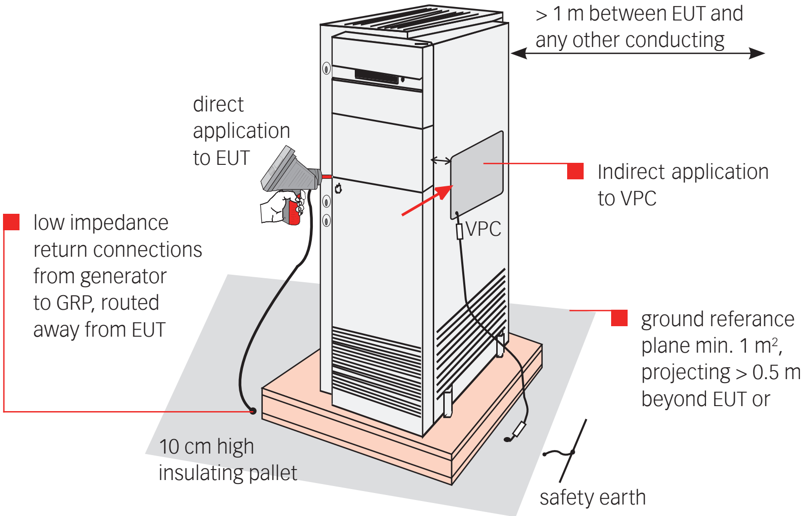

Figure 5b: ESD test layout for floor standing equipment

Floor-standing EUTs

Large EUTs such as cabinets and white goods should be placed on a 10 cm insulating support, such as a fork-lift pallet. The HCP is not used for indirect discharge, but the VCP is. Otherwise the test methods are similar as for table-top apparatus. You may find that the length of the ground return lead limits the height that can be reached at the top of tall EUTs.

Floating EUTs

If the EUT has a ground connection, the charge that is applied by each test pulse will quickly dissipate, leaving the EUT ready for the next application. But this is not true for those EUTs which are isolated from ground such as hand-held battery-powered devices, or safety Class II mains powered units. When a discharge is applied to these, charge moves from the 150 pF capacitor of the discharge simulator to the self-capacitance of the EUT, leaving it floating at some voltage above ground, the actual value depending on the ratio of capacitances (see Figure 6). This is fine on first application, but it means that the applied stress is progressively reduced on subsequent pulses of the same polarity and level, since the voltage difference between the generator and the EUT is diminishing. Or, if the polarity is reversed, the EUT suffers a much greater applied stress than intended. Small EUTs may have only a few picoFarads self-capacitance, meaning that they instantly reach nearly the full applied voltage, and subsequent pulses are worthless.

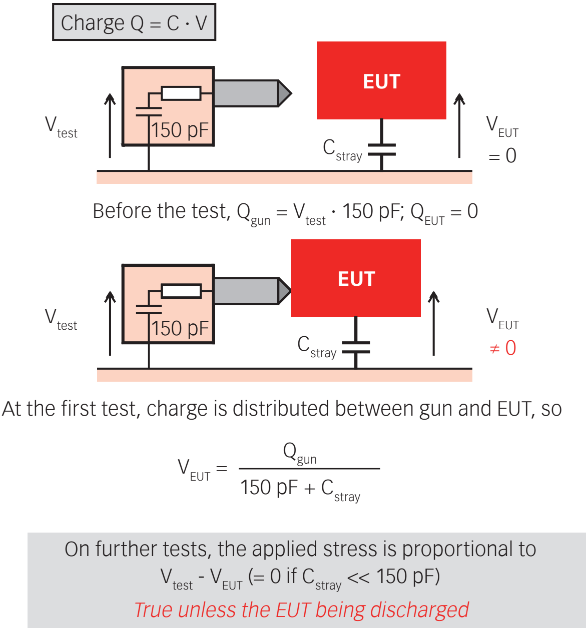

Figure 6: Charging of ungrounded EUTs

You should therefore bleed off the charge between each pulse application. Amendment 2 to the standard achieves this by allowing a bleed resistor cable between the EUT and HCP during the test. As long as the resistors are mounted very near to the ends of the cable (within 2 cm), the cable can remain in place during the test, since its presence probably won't affect the outcome – although in cases of dispute, the cable should not be connected. As with the bleed resistors for the coupling planes, you should take some care to ensure that the resistors are capable of withstanding the full pulse voltage without breakdown.

Alternatives to a permanently connected bleed cable are a bleed resistor brush, applied in between discharges for the same purpose – the resistor must still be at the top end of the cable to ground, otherwise the discharge induced by the bleed could be worse than that applied by the ESD gun, leading to a failure of the wrong test; or the use of an air ioniser, to speed the natural discharge of the EUT. For controlled discharging of floating EUTs Teseq recommends it's specifically designed charge remover device.

Number, location and level of discharges

The standard tells you to do 10 discharges in the most sensitive polarity "at preselected points". Lower levels than the specification must also be satisfied – so if for the typical compliance test you are doing 4 kV contact and 8 kV air, you must also do 2 kV contact and both 2 kV and 4 kV air tests. The test stress is not necessarily linear, so that a product might fail at, say, 4 kV and yet pass at 8 kV, and this would be an overall failure. But the difficult question is, how do you preselect the appropriate points?

Only points which are accessible during normal use are to be tested, but this is often not much of a limitation. Amendment 2 defines what is meant by accessible parts in more detail. Clause A.5 of the standard gives some guidance. Also, product standards such as EN 55024 may be more explicit than the basic standard. But the difficulty usually lies in establishing the most sensitive locations around the EUT. Exploratory testing using a high pulse repetition rate or higher level is sometimes helpful, if the EUT's immunity is only slightly greater than the specification, but this doesn't work if the design gives a good margin of immunity. It also exposes the EUT to greater stress than the compliance test calls for, which may not be acceptable in some cases. On the other hand, eventually worst case testing by means of an extra fast rise time tip could be of interest.

A prototype design may be weaker than the final product, and the weaknesses may be most marked at certain points, which are then prime candidates for the compliance test. But in the end, this question can only be resolved through the skill, experience and perseverance of the test engineer.

Handling the ESD gun

The stress applied to the EUT is not confined just to the voltage and current pulse appearing at the tip. There is a stray field around the front of the gun, and also around the ground return lead as it falls away from the gun. Both of these can couple to the EUT and modify the stress, so it is necessary to control them. You need to ensure that the ground lead does not drape over the EUT but is always held away from it; the standard advises that it is kept at least 20 cm away from the EUT and any conductive parts other than its connection to the GRP. Equally, you should always hold the generator such that its probe is perpendicular to the EUT surface that is being tested, and not handle the simulator near the probe. This will reduce the variability of coupling of the stray field around the front of the simulator.

When the discharge is applied to the coupling planes, the gun should be held edge-on to the plane and opposite the centre of the EUT, for the HCP, or at the centre of one edge of the VCP.

As well as angle of incidence, for the air discharge test the speed of approach is important, since this affects the breakdown of the air gap. The standard says “the discharge tip shall be approached as fast as possible (without causing mechanical damage) to touch the EUT”. In the case of contact discharge, contact pressure is relevant; even a thin film of oxide can cause a high contact resistance, which can give dramatic variations in the applied waveform, so the tip must be pressed as hard as possible against the EUT surface.

Figure 7: NSG 438 30 kV ESD simulator

3 ELECTRICAL FAST TRANSIENT BURSTS

3.1 Source and effect of transients

Fast switching transients are created in the following manner. When a circuit is switched off, the current flowing through the switch is interrupted more or less instantaneously. Put another way, at the moment of switching there is an infinite di/dt. All circuits have some stray inductance associated with the wiring; some types of load, such as motors or solenoids, have considerably more inductance in the load itself. The voltage developed across an inductance L by a changing current i is

$$V = -L \cdot di/dt$$

If di/dt is infinite, then this implies an infinitely high voltage. Of course, this doesn't happen in practice since the rate of rise of voltage is limited by stray or intentional circuit capacitance. Even so, a high instantaneous voltage, added to the circuit operating voltage, does appear across the opening switch contacts.

This causes the increasing air gap across the contacts to break down, and a current flows again, which collapses the voltage spike, so that the briefly-formed arc extinguishes. But this re-interrupts the current, so another voltage spike appears, creating a further arc. This process repeats itself until the air gap is large enough to sustain the applied voltage without breakdown, at which point the circuit can be said to be properly switched off. The visible effect is a brief spark between the contacts, which actually consists of a whole series of micro-sparks, the so-called «showering arc», whose repetition rate and amplitude depend on the circuit and switch parameters.

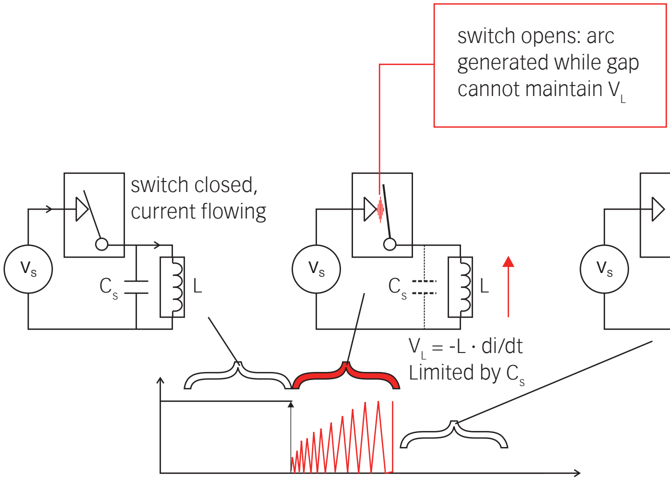

Figure 8: Transient burst generation

The current and voltage waveforms inherent in each spark event propagate along the circuit wiring. In a mains circuit, this burst of noise can appear at other points of connection to the mains distribution ring. Also since the pulses are very fast – of the order of nanoseconds – they couple effectively through mutual capacitance and inductance to other wiring in close proximity to the circuit wiring such as control or sensor lines. Voltage «spikes», typically of hundreds but occasionally thousands of volts, may appear on any such coupled circuits.

Burst characteristics

The actual occurrence of these bursts, seen from the point of view of victim equipment which is unrelated to the source, is usually random – although some automatic switching events can occur at regular intervals. Noise from brushed motors and arc welding, two special cases of the above mechanism, usually has a strong periodic content. The amplitude of the bursts decays with distance due to the lossy transmission-line characteristics of the wiring, and so it is usually only sources within a few metres of the victim that are significant.

The burst waveforms are also random, although research has found that the repetition frequency tends to fall within the range 100 kHz to 1 MHz, and the dv/dt of the rising edge is roughly proportional to the square root of the amplitude. The EFT burst is distinguished from the surge (see next section) by being much faster but also in having much less energy, as shown in Figure 20.

Effect on electronics

It is rare though not impossible for the transients to be coupled into a nearby victim by inductive coupling, but generally they enter the product via the cable connections. On signal ports the spikes are almost invariably in common mode, i.e. on all wires (or on the screen) at the same amplitude with respect to external earth. Common mode coupling on mains includes the protective earth wire.

Poor filtering or inadequate screen termination on each interface then lets these transients pass into the electronic circuits where they appear as interfering signals at sensitive nodes. As with other types of transient, digital circuits tend to be more susceptible, since each short pulse can appear as a valid digital signal. Occurring in bursts, there is a high probability that one or more pulses will coincide with a critical timing edge. However, analogue circuits can also be affected, typically by saturation of sensitive amplifiers. Pulse counting circuits are also susceptible if the burst masquerades as a real input.

Good design practice takes two forms [1]:

- the internal circuit design is bandwidth limited wherever possible, and the PCB layout prevents large interference voltages from appearing within the circuit;

- all interfaces must be filtered or screened to a structural low-impedance earth so that common mode pulses are prevented from entering the circuit.

3.2 The IEC 61000-4-4 standard test method and generator

IEC 61000-4-4 [3] and its EN equivalent is the principal basic standard for testing fast transient immunity. It applies a specified burst waveform via a defined coupling network to the mains connection and via a defined clamp device to any signal connection. A second edition of the standard was published in 2004 and this guide refers to that version. Only conducted coupling is used; there is no specification for radiated transient immunity. Choice of ports for the application of the burst depends on the instructions in the product standard being used, but it is generally applied to AC and DC power ports and to signal and control ports that may be connected to cables longer than 3 m.

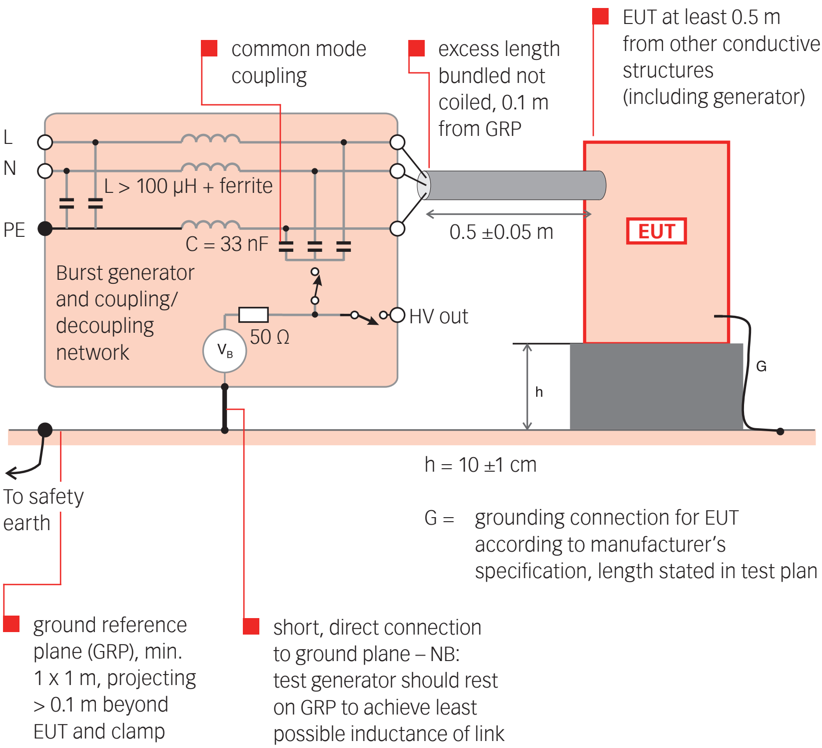

Figure 9: Test setup for mains port

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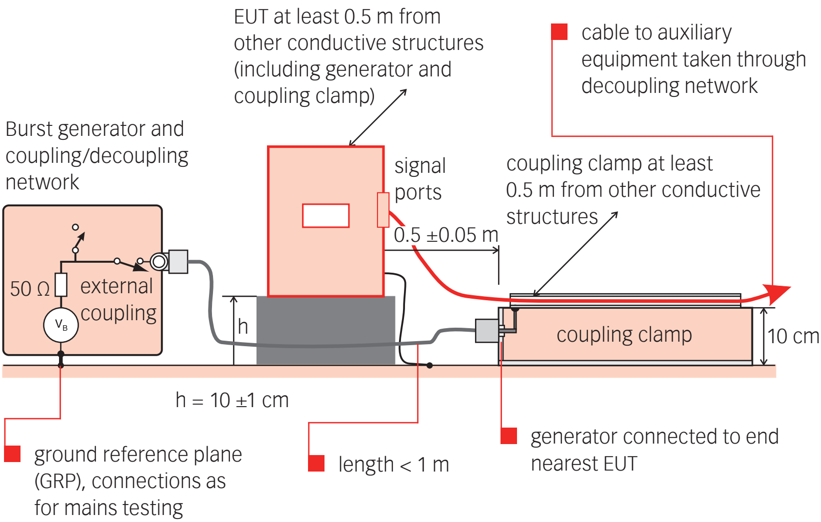

Figure 10: Test setup for signal ports

The power port CDN is essentially a HF filter in series with the lines to isolate the burst application from the supply input, in combination with a capacitor feeding the burst voltage onto the chosen line(s). All lines may have the burst applied, including the protective earth, which must therefore also include a decoupling inductor.

The capacitive clamp is a pair of metal plates, connected together and hinged down one edge so that they can sandwich the cable under test between them. It is expected that the cable under test will be insulated and therefore there is no direct connection, only a capacitive one – if the cable insulation is weak or non-existent this should be anticipated and some extra insulation provided. Because of the length of the clamp the capacitive coupling is distributed, which improves repeatability for the higher frequency components of the transients. The clamp must also be located a defined distance above the ground plane, and the burst voltage is applied with respect to this ground plane.

Waveforms

The burst waveform definitions are shown in Figure 11. To standardise the test, the waveshape, number of pulses, their frequency and the burst length and repetition frequency are all specified. It should be understood that these specifications are explicitly not representative of real life, which as mentioned earlier sees pulse repetition rates in the hundreds of kHz. Instead, they represent the lowest common denominator of what was achievable and repeatable in early test generators. The second edition of IEC 61000-4-4 defines a repetition rate of 5 kHz or 100 kHz, but the latter is not mandatory unless a product standard demands it. It is possible to program most generators for other values and this may be helpful when you are testing your products for their immunity to real (variable) bursts.

The source impedance of the generator is required to be 50 Ω and the waveform is calibrated into both a 50 Ω load, and also into 1000 Ω. This ensures that the waveform of the burst pulse does not change between different generators and different EUTs. The load impedance presented by the EUT is unknown and may be anything from a near short circuit, for a screened cable port on an EUT that is well earthed, to a near open circuit for an unscreened port with a series common-mode choke at the interface. Therefore the actual voltage that appears between the EUT port and the ground plane is similarly unpredictable.

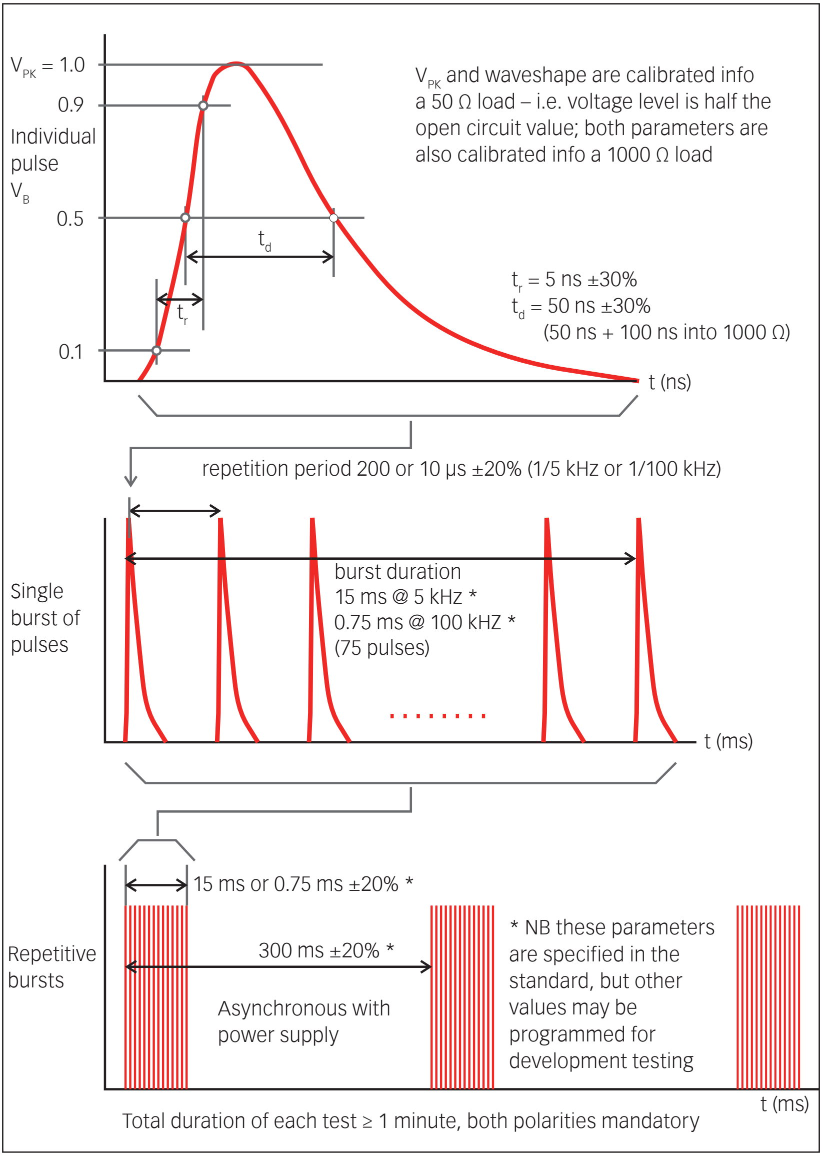

Figure 11: The burst specification

3.3 Practical aspects of testing

The transient burst voltage is always referenced to the ground plane connection point on the test generator, whatever mode of coupling is chosen. The first version of the basic standard was not entirely clear about how the burst should be applied through the CDN (Figure 12). The standard showed it being applied separately to live, neutral and earth lines, but some product standards which call up this test have referred to it as «common mode», that is on all three lines simultaneously. The second edition removes the confusion by showing the burst applied only in common mode (Figure 12(B)).

Teseq generators with built-in single-phase CDN allow you to select any mode of coupling. The result of the test could well be different depending on which type of coupling you choose. However, as compliance testing now only requires common mode coupling, cost effective three phase CDNs designed for quick CM testing may be proposed for the upermost current range.

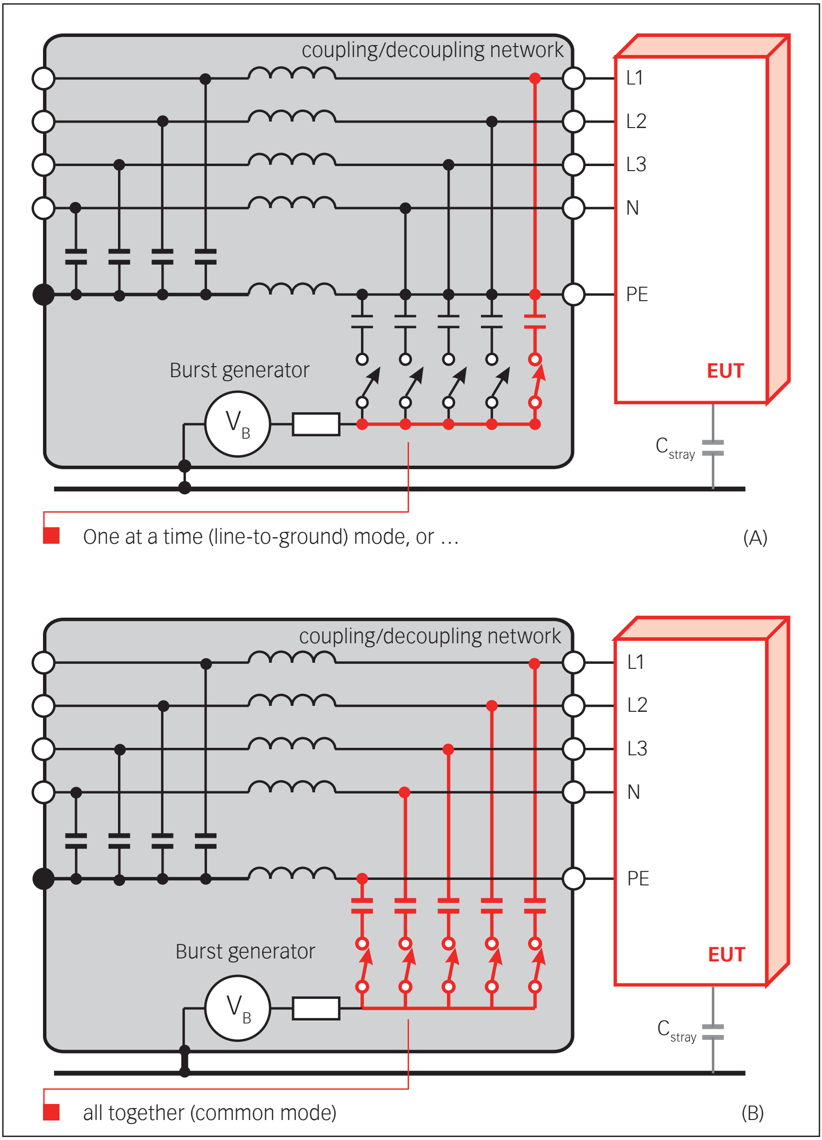

Figure 12: Coupling the burst through the CDN

The question does not arise with the capacitive clamp, which inherently applies the burst in common mode. You are expected to use the capacitive clamp in conjunction with a decoupling network, to prevent the bursts from being applied also to the non-tested auxiliary equipment at the other end of the cable, but the standard gives no suggestions as to what sort of decoupling network to use. In default, the same type of ferrite clamp-on decoupling device (not the EM-clamp) as is used for the conducted RF immunity tests should be suitable for this.

The test layout

This is a high frequency test – the spectrum of the burst extends to hundreds of MHz – and a ground reference plane (GRP) is essential. Trying to do a development test without a ground plane will lead to unrepeatability and lack of correlation to the compliance test. Stray impedances are controlled by the following restrictions (note that some of these are substantially different from the instructions in the first edition of IEC 61000-4-4):

- The EUT should be 10cm ±1cm above the GRP, whether it is table-top, floor- or wall-mounting;
- The GRP should be at least 1m x 1m and further, should extend at least 10 cm beyond the EUT on all sides;
- The EUT and the capacitive coupling clamp should be at least 0.5m from all other conducting structures, including the test generator and the walls of the room;
- The length of the cable between the coupling device (clamp or CDN) and the EUT must be 0.5m ±5cm, with any excess in the mains cable bundled to avoid a loop – it is best to use a standard 0.5m test cable for all EUTs, regardless of what they are supplied with;
- The test generator must be bonded to the GRP with a low-inductance connection, such as a short bracket or braid. Any inductance at this point will “lift” the generator output waveform off the GRP and introduce ringing on the signal that appears at the EUT. This also applies to the earth plate of the capacitive clamp, which terminates the high voltage coax cable

that comes from the generator. This lead must be connected to the end of the clamp nearest the EUT – although clamps generally are provided with connectors at either end, you have no choice as to which to use in the actual setup.

The test layout needs some thought to achieve all these requirements together. Any deviation will affect the stray inductance or capacitance in the coupling path, which in turn will cause variations in the applied stress. But, for instance, it can be difficult to ensure a distance of 0.5m for the signal cable between the coupling clamp which must be mounted on the GRP, and a cable port which is on the top of a tall EUT. Such difficulties require a departure from the letter of the standard which must be carefully assessed and recorded.

Burst application

The basic standard specifies that the bursts should be applied for at least 1 minute in each polarity. Some product standards modify this, for instance to 2 minutes. The main concern is that bursts should be applied for long enough that any coincidence with sensitive states of the EUT has been explored. Unlike the ESD and surge tests, there is no requirement to test lower levels than the specification level, although this may be useful to map the response of the EUT.

The product standards also define to what ports the test must be applied. A common qualification is that ports which are connected to cables that are limited to less than 3 m in length, are excluded from the test. There is nothing magic about the 3 m figure, but the intention is to acknowledge that short cables are unlikely to couple significant amounts of burst interference in real life. Nevertheless, this puts some responsibility on the manufacturer to decide which ports can sensibly be included in this restriction. Annex A of IEC 61000-4-4 gives some information regarding the pulse time and amplitude parameters, and Annex B offers advice on selecting the test levels depending on environment.

4 SURGE

4.1 The causes and effects of surges

High energy transients (by contrast with low energy but fast transients, see previous section) appearing at the ports of electronic equipment are generally a result either of nearby lightning strikes, or are due to major power system disturbances such as fault clearance or capacitor bank switching. Lightning can produce surges with energies hundreds of joules by the following mechanisms (Figure 13):

- direct strike to primary or secondary circuits: the latter can be expected to destroy protective devices and connected equipment; the former will pass through the service transformers either by capacitive or transformer coupling
- indirect cloud-to-ground or cloud-to-cloud strikes create fields which induce voltages in all conductors
- ground current flow IG from nearby cloud-to-ground discharges couples into the grounding network via common impedance paths, and causes substantial potential differences between different ground points
- primary surge arrestor operation or flashover in the internal building wiring causes voltage transients

Lightning protection of buildings and their installations is covered by various standards, including IEC 62305-4:2006 and BS 6651:1999. These standards define hierarchical protection zones within installations, but they admit some level of surges even in the deepest zone, so there is still a need to ensure that individual products can show a degree of immunity from lightning-induced surges.

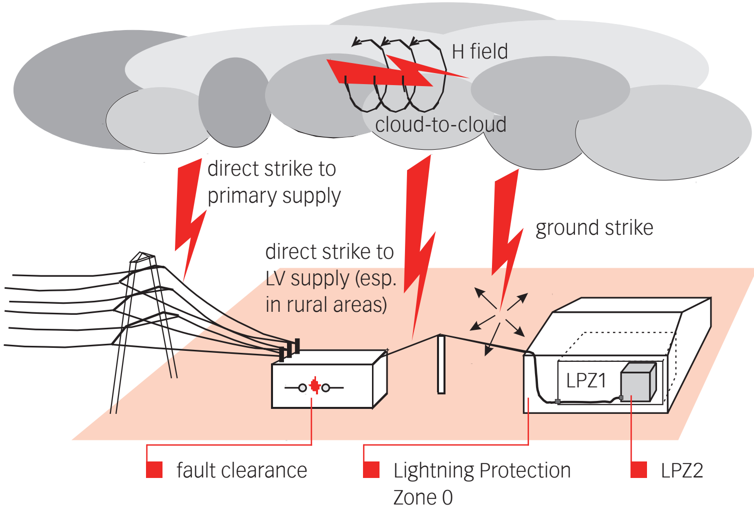

Figure 13: Surge generation

Fault clearance upstream in the mains supply distribution network produces transients with energy proportional to 0.5 · L · I2 trapped in the power system inductance. The energy will depend on the let-through current of the clearance device (fuse or circuit breaker) which can be hundreds of amps in residential or commercial circuits, and higher for some industrial supplies. Power factor correction capacitor switching operations generate damped oscillations at very low frequency (typically kHz) lasting for several hundred microseconds.

Effect on equipment

Surges impinging on electronic equipment may cause hardware damage and complete failure, or in lesser cases, operational upset. Figure 14 gives an indication of the relationship between surge parameters and these effects.

Below some level dependent on equipment design, no effect is observed. Above this level, a surge may cause the operation of the equipment to change state, without any long-term effect on the circuit components. But at a higher level still, there may be enough energy to cause breakdown in critical components. The maximum voltage that is likely to occur is limited by flashover considerations, for instance in a typical domestic mains supply no more than about 6 kV can be withstood by the wiring components. The designer has to know what surge voltage can be sustained by the product's interfaces without protection, and what voltage is expected in the protection zone in which the product will be used, in order to decide whether any of these interfaces need additional protection.

Typically, protection involves adding parallel surge suppression devices such as clamping diodes, varistors or spark gaps. The purpose of these devices is to break down in a controlled manner at a voltage lower than can be sustained by the circuit, and dissipate the surge energy within themselves. They must therefore be sized to withstand the maximum surge energy to be expected in a particular application, and/or the interface should include some series impedance to limit the applied energy.

The rate-of-change of applied voltage and current also has a bearing on both the susceptibility of a particular interface to upset and on the ability of protection devices to cope with the surge.

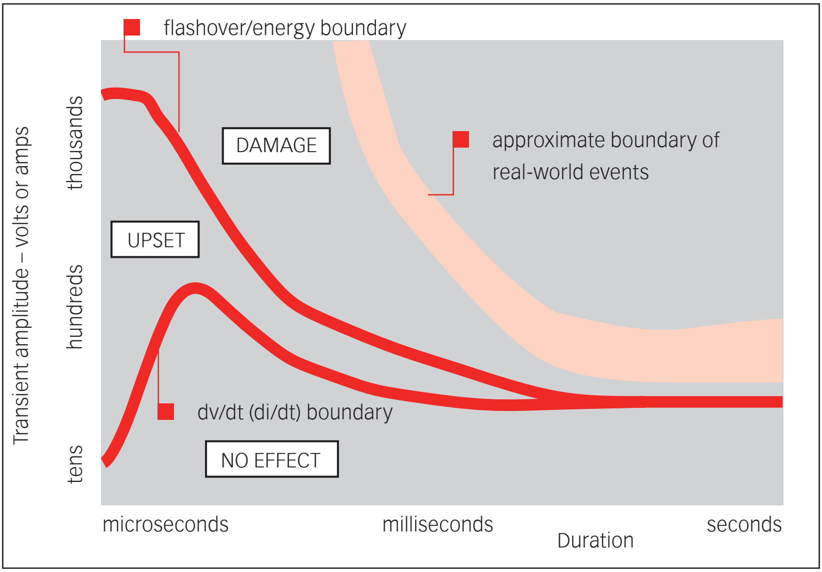

Figure 14: Relationships between surge parameters and equipment effects

4.2 Standard test waveforms

IEC 61000-4-5 defines the 1.2/50 µs (V) – 8/20 µs (I) combination wave. It also refers to the CCITT (ITU K.17) 10/700µs wave to be applied to telecom ports. IEC 61000-4-12 defines the waveform for the ring wave which maybe found also in ANSI (IEEE) C.62.41:2006 [6].

Combination wave

The surge generator called up in the test to IEC 61000-4-5 has a combination of current and voltage waveforms specified, since protective devices in the EUT (or if they are absent, flashover or component breakdown) will inherently switch from high to low impedance as they operate. Thus part of the surge will be delivered into a high impedance and part into a low impedance. The values of the generator's circuit elements are defined so that the generator delivers a 1.2/50µs voltage surge across a high-resistance load (more than 100 Ω) and an 8/20µs current surge into a short circuit (Figure 14).

These waveforms must be maintained with a relaxed decay time with a coupling/decoupling network in place, but are not specified with the EUT itself connected, and for coupling devices for signal lines this requirement is waived. Since the surge waveform is specified as both a voltage and current, it has to be calibrated into both an open circuit and a short circuit.

Figure 15: The combination surge waveform

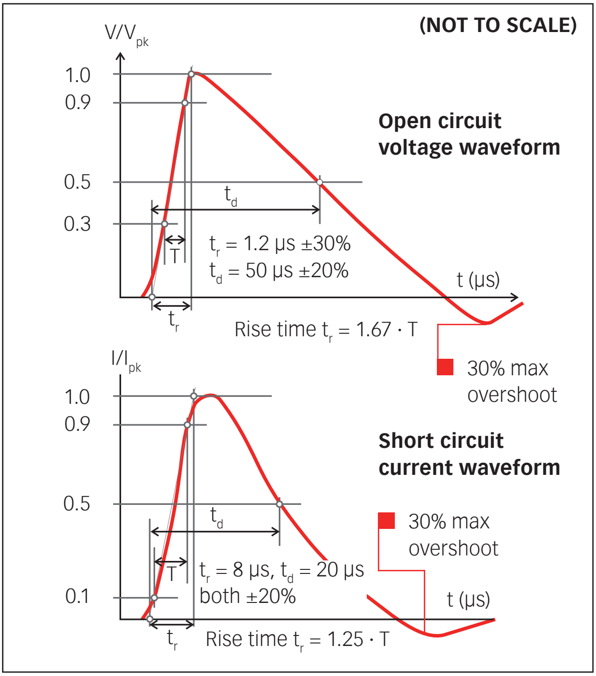

Figure 16: The combination surge waveform

Ring wave

Measurements have shown that most surge voltages in indoor supply systems have oscillatory waveforms. Even if it is unidirectional to start with, an incoming surge excites the natural resonances of the system. The frequency of oscillation can vary between 1–500kHz and can have different amplitudes and waveforms at various places in the system.

IEC 61000-4-12 [5] defines a "ring wave" with the characteristics shown in Figure 16, and with the choice of source impedances and repetition rates as given in the table below. It is said to be representative of a wide range of electromagnetic environments of residential and industrial installations. Despite this, it has not found favour with product committees who are responsible for choosing basic standard tests and as a result it is not widely applied in product testing.

Generator output impedance Z	Minimum repetition period	Application
12 Ω	10 s	EUT supply ports connected to major feeders; application between communication ports on cabinets interconnected with 10m long screened data comms cables
30 Ω	6 s	EUT supply ports connected to outlets
200 Ω	1 s	I/O ports, unless the test involves protection devices or filters, in which case 12 Ω or 30 Ω is applicable

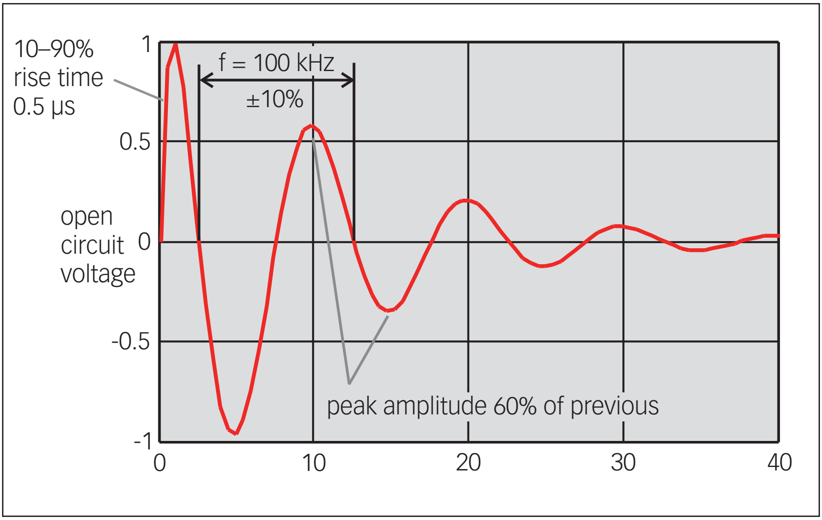

Figure 17: The ring wave

Telecom waveforms

For ports connected to telecommunications lines, a further 10/700 µs surge is required. The voltage waveform is specified in the same way as for the combination wave above, with a front time of 10 µs ±30% and a time to half value of 700 µs ±20%. The second edition of IEC 61000-4-5 also gives current waveform parameters of 5µs front time, 320µs half value time, both ±20%. The generator has an effective output impedance of 40 Ω which may be provided either internally (15 and 25 Ω resistors) or by external coupling resistors (see top diagram of Figure 18).

4.3 Practical aspects of surge application

Because of the lower frequency spectrum content of the surge waveforms, surge testing is more tolerant of layout variations, and the standards are fairly relaxed in this respect. The cable between the EUT and the coupling/decoupling network should be 2 m or less in length (1 m for the ring wave). For the combination wave and telecom wave there are no other explicit restrictions on the layout. The ring wave test is best carried out over a ground plane, but even this can be waived for table-top equipment if the earthing connections are well controlled.

Safety

However, you should remember that the surge has a high energy content. The peak voltage that can be applied is 4 kV, and the peak current is 2 kA. In specific cases it coult even go as high as 3 kA and over. This means that some protective safety measures are strongly recommended while in some cases essential. If there is any likelihood that the surge voltage could appear on external conductive parts, for instance because the integrity of the earth connection is not assured – or because, as in the test on screened line interfaces, you are applying the surge directly to the enclosure – then personnel must be kept away from the EUT during the test. In any case, the EUT should be disconnected from other equipment where possible and the whole setup should be well insulated to prevent flashover.

Also, high resistances in the path of the surge current will be subject to high dissipation and could overheat with a consequent fire risk. The same applies to surge suppressors within the EUT, which despite the one-minute cooling-off period may fail catastrophically. Make sure all appropriate connections are tight and capable of taking the expected current, and keep a fire extinguisher handy.

Coupling

For coupling to the mains supply of the combination wave, the generator is connected directly via a 18µF capacitor across each phase, but through a 10 ohm resistor and 9 µF capacitor for phase-to-earth application (Figure 17). This means that the highest energy available from the generator's effective source impedance of 2 ohms is actually only applied between phases. The signal line coupling networks include a 40 ohm series resistor, which reduces the energy in the applied surge substantially.

Coupling to signal lines (Figure 18) has to be invasive; no clamp-type devices are available for this test. It is permissible to use gas discharge tube coupling for signal lines to maintain bandwidth. A separate method is used 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.

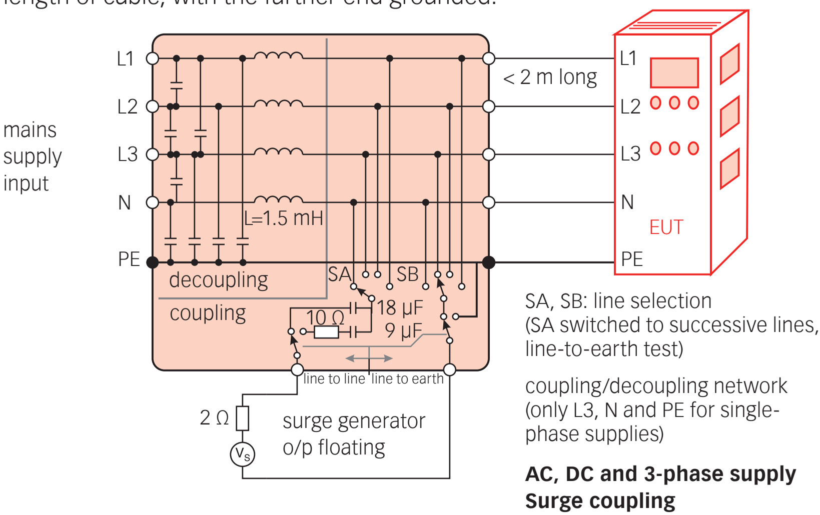

Figure 18: Surge coupling to supply lines

An alternative is offered for data communications lines that can't stand any invasive connection. The interface is functionally checked, and then data lines are removed and the surge is applied directly to the terminals with no coupling/decoupling network. After the surge, the interface must be re-tested to confirm that it has not been damaged. The EUT should be operational during the surge test even with the port disconnected.

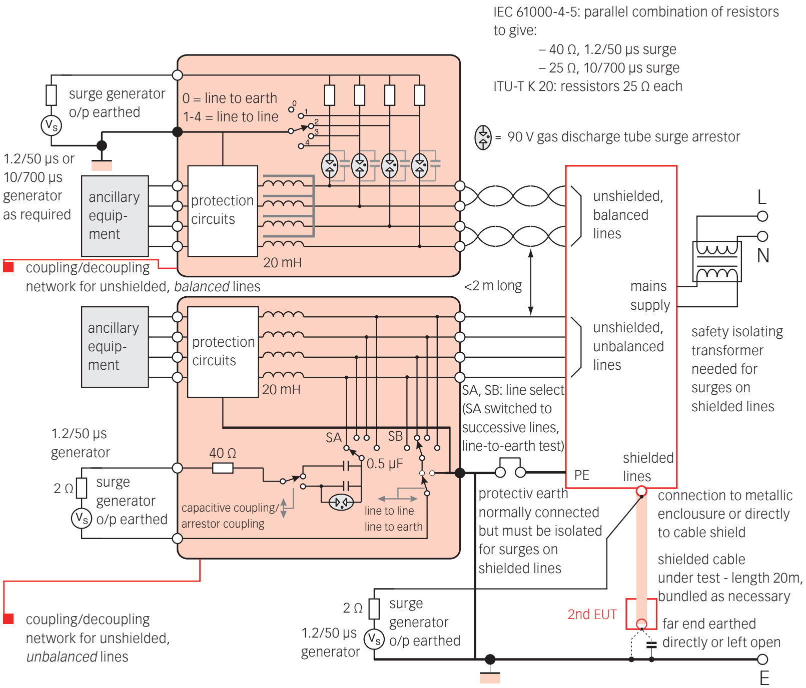

Figure 19: Surge coupling to signal lines

Procedure

The test procedure requires the following steps, bearing in mind that an agreed test plan or a particular product standard 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 (but see below)
- For ac mains,
  - Apply the surges line to line (three combinations for 3-phase delta, six for 3-phase star, one for single phase) and line to earth (two combinations for single phase, three for 3-phase delta, four for 3-phase star)
  - Synchronise the surges to the zero crossings and the positive and negative peaks of the mains supply (four phase values), and apply five pulses in each polarity at each phase
- Increase the test voltage in steps up to the specified maximum level, so that all lower test levels are satisfied – the step size being generally interpreted as a level at a time, rather than a fixed voltage step such as 500V

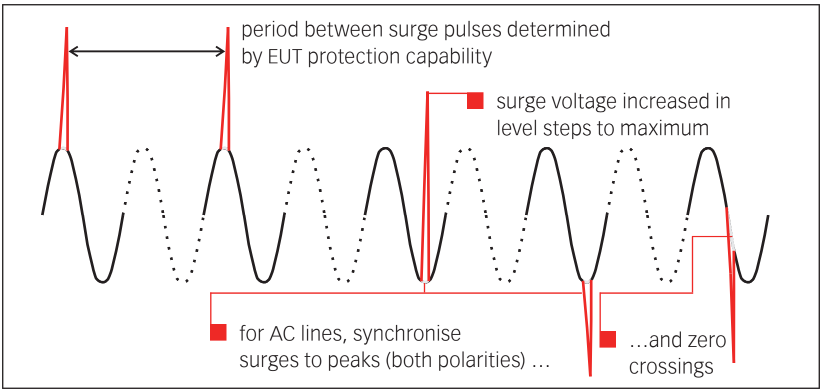

Figure 20: Surge application

A worst case interpretation of the requirements on a three-phase star supply being tested up to level 4 would imply that a single complete test would take nearly 27 hours, not allowing for setup and test sequencing time. The test time can be reduced by waiting for less than 1 minute between consecutive applications; 20 or 30 seconds is quite common. But this may overstress any protection devices in the EUT. If tests fail at rates faster than 1/minute but tests done at 1/minute do not, the test done at 1/minute prevails.

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 suppressor 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 suppressor 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, pre-compliance testing over as wide a range of variables as possible is advisable.

5 PERFORMANCE CRITERIA

All of the transient immunity tests require that the performance of the EUT is monitored against a defined criterion, in order to determine whether it has passed or failed the test. The basic standards give a generalised set of criteria but it is up to the product or generic standards which reference the tests to be explicit about what is an acceptable performance for a particular product. While some product standards do this in depth, the generic standards can only put forward a universal criterion which has to be interpreted for each product. It is the manufacturer's job to do this, not that of the test house, although test houses are often called upon to help with interpretation. The wording for the generic standards' criterion B, which applies to all transient testing, is as follows:

> The apparatus shall continue to operate as intended after the test. No degradation of performance or loss of function is allowed below a performance level specified by the manufacturer, when the apparatus is used as intended. The performance level may be replaced by a permissible loss of performance. During the test, degradation of performance is however allowed. No change of actual operating state or stored data is allowed. If the minimum performance level or the permissible performance loss is not specified by the manufacturer, either of these may be derived from the product description and documentation and what the user may reasonably expect from the apparatus if used as intended.

From this, it should be clear that the manufacturer is able largely to set the terms of the performance criteria, provided that he "specifies" any performance degradation effects, and provided that the EUT continues to work correctly after the transients have been applied with no change of state or stored data. Some product standards, though, are considerably more rigorous than this.

6 REFERENCE MATERIAL

6.1 Equations

Except for ESD, these equations for the waveshape of the quoted transient waveforms are derived from IEEE C62.41:1991 [6].

ESD current waveform (4 kV indicated voltage, t in ns)

$$I(t) = 25.5 \cdot \left[\left(\exp\left(\frac{-t}{3.5}\right) - \exp\left(\frac{-t}{0.7}\right)\right) + 1.56 \cdot \left(\exp\left(\frac{-t}{28}\right) - \exp\left(\frac{-t}{15.5}\right)\right)\right]$$

Surge voltage 1.2/50 µs waveform (t in µs)

$$V(t) = 1.037 \cdot V_P \cdot \left(1 - \exp\left(\frac{-t}{0.407}\right)\right) \cdot \exp\left(\frac{-t}{68.22}\right)$$

EFT 5/50 ns waveform (t in ns)

$$V(t) = 1.27 \cdot V_P \cdot \left(1 - \exp\left(\frac{-t}{3.5}\right)\right) \cdot \exp\left(\frac{-t}{55.6}\right)$$

0.5 µs/100 kHz ring waveform (t in µs, $w = 2\,\pi \cdot 10^5$ rad/s

$$V(t) = 1.59 \cdot V_P \cdot \left(1 - \exp\left(\frac{-t}{0.533}\right)\right) \cdot \exp\left(\frac{-t}{9.788}\right) \cdot \cos(wt)$$

6.2 Surge and transient energy

The energy content of transients and surges is not simple to define. Not all the actual energy stored in the test generator is dissipated in the load. That proportion which is, depends on the ratio of the load and generator impedances. In general, a load such as a surge suppressor will be non-linear and will also have a time or frequency dependence.

The "energy measure" of a given waveform can be described by

$$S = \int_0^T V^2(t)dt$$

The previous equation gives the energy that would be delivered by that voltage waveform into a 1 Ω resistor, whether or not the generator is capable of this (i.e., assuming zero output impedance). These figures are shown in the lower graph of Figure 20.

Alternatively, the actual energy delivered by the generator into a defined resistive load can be calculated. For the ESD and EFT waveforms, these can be the calibration loads of 2 Ω and 50 Ω respectively. For the surge and ring waves, a load which matches the output impedance can be chosen, and the voltage or current waveform is delivered into this resistance with half the open circuit (or short circuit, for current) amplitude – although this simplifying assumption does not occur in practice as the current and voltage waveforms vary depending on the load impedance.

In these cases the energy in Joules (watt seconds) is shown in the upper graph of Figure 20 and is given by

$$W = \frac{1}{R} \cdot \int_0^T \left(\frac{V(t)}{2}\right)^2 dt \qquad W = R \cdot \int_0^T \left(\frac{I(t)}{2}\right)^2 dt$$

where V(t) and I(t) are the open circuit voltage and short circuit current waveforms, respectively.

These graphs are for comparative purposes only – the real energy delivered to a particular EUT can only be calculated if the load impedance and characteristics, and the actual waveshape applied to this load, are known accurately.

The symbols on the graphs represent test levels 1 to 4 as defined in each standard.

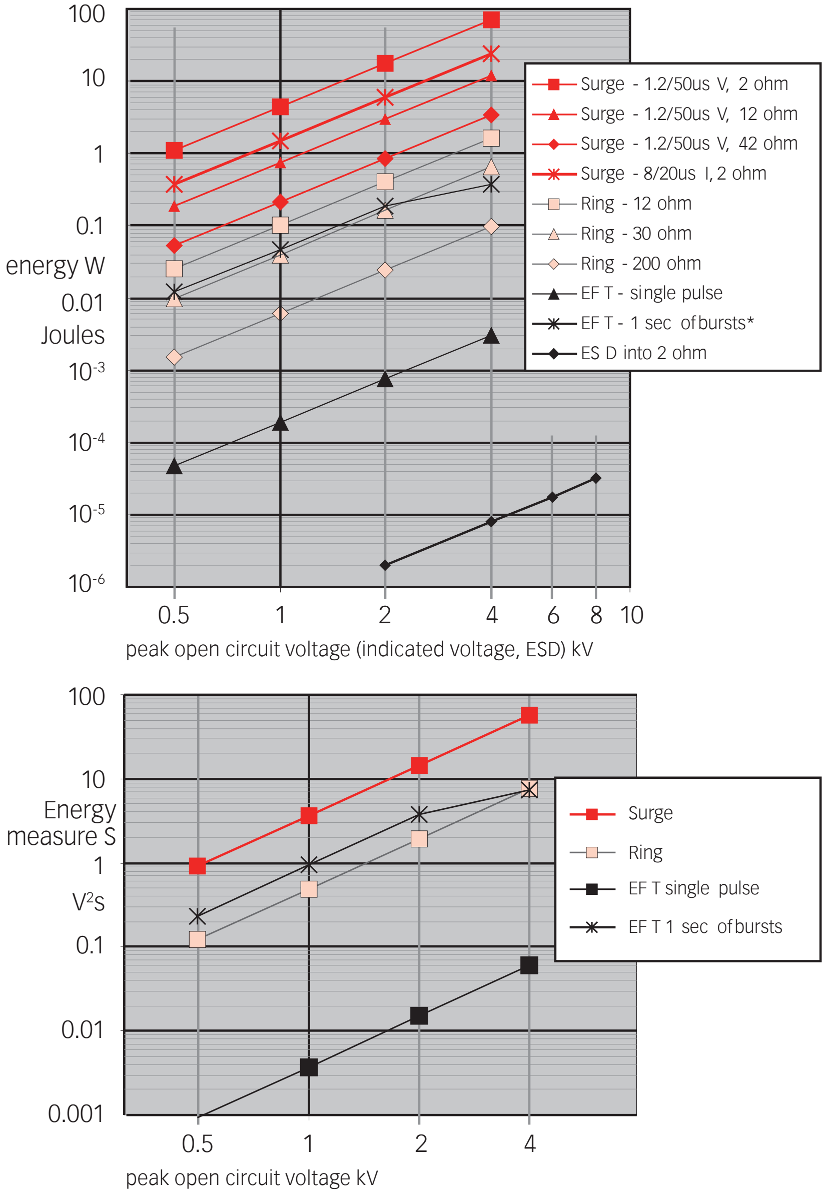

Figure 21: Transient energy content

6.3 References

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[2] IEC 61000-4-2 Ed. 1 + A1 + A2: Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 2: Electrostatic discharge immunity test. Basic EMC Publication

[3] IEC 61000-4-4 Ed. 2.0: Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 4: Electrical fast transient/burst immunity test. Basic EMC Publication

[4] IEC 61000-4-5 Ed. 2.0: Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 5: Surge immunity test

[5] IEC 61000-4-12 Ed. 2.0: Electromagnetic compatibility (EMC) - Part 4: Testing and measurement techniques - Section 12: Ring wave immunity test. Basic EMC Publication

[6] IEEE C62.41-2002: IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits

[7] ITU-T Recommendation K.17 (1993): Tests on Power-Fed Repeaters using Solid-State Devices in order to check the Arrangements for Protection from External Interference

Figures

NOTES

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