Some considerations for ESD testing

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Introduction: Why We Do It

A very good test of the general robustness of a digital product is that of electrostatic discharge immunity (ESD), which is also a common test under the essential requirements of the EMC Directive. The test is specified in IEC 61000-4-2, which includes a standardized pulse generator and a procedure for applying the stress to the equipment under test (EUT). Not only is this method referenced in many commercial product standards, it is now making an appearance in military standards (DEF STAN 59-411) and has been proposed for IC-level testing.

Despite its popularity, it isn't a simple, straightforward test. There are many areas where interpretation and skill are necessary, and a proper and repeatable outcome depends very much on the experience and understanding of the test engineer.

This article will discuss some of the aspects of the test which are open to misunderstanding. It does not consider the vast topic of product design for ESD immunity; rather, it is intended for test engineers who have to apply the test in their everyday work. It is assumed that the reader is already familiar with IEC 61000-4-2, or at least has read it, and has some practice in using the ESD generator.

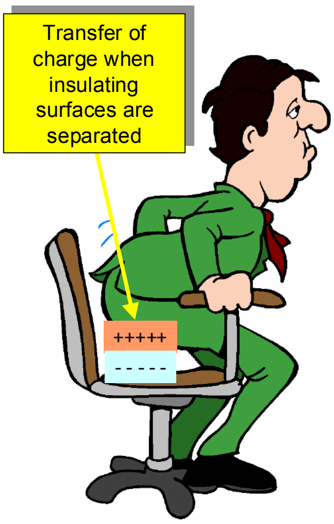

Figure 1 The ESD charging process

The ESD phenomenon begins (Figure 1) when two non-conductive materials are rubbed together or separated, so that electrons from one material are transferred to the other. This results in the accumulation of triboelectric charge on the surface of each material. If the surface covers an object which is conductive in bulk (such as the human body), the charge will distribute itself over the whole object. The electrostatic voltage that is achieved is a balance between the charge transfer Q divided by the total capacitance C of the object (Q = C x V), and the rate at which charge is bled off the surface. Any surface conductivity will accelerate the rate of charge decay and therefore will limit the voltage available for a subsequent ESD event. For this reason, relative humidity (which affects surface conductivity) has a dramatic effect on the build-up of electrostatic voltage: high voltages (10-20kV) are associated with dry atmospheres, and humid conditions keep voltages low.

When two objects with a high electrostatic potential difference approach, the air gap between them breaks down and the charge on each is equalized by the current flow across the resultant ionized path. The current route is completed by stray capacitance between the objects and their surroundings, and the inductance and resistance of the rest of the path (Figure 2). Neither object has to be grounded, although one of them may be.

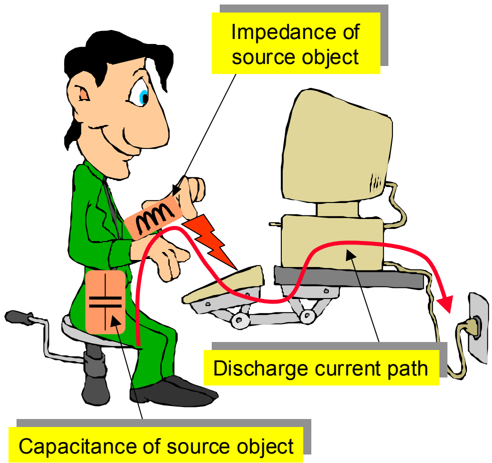

Figure 2 The discharge phenomenon

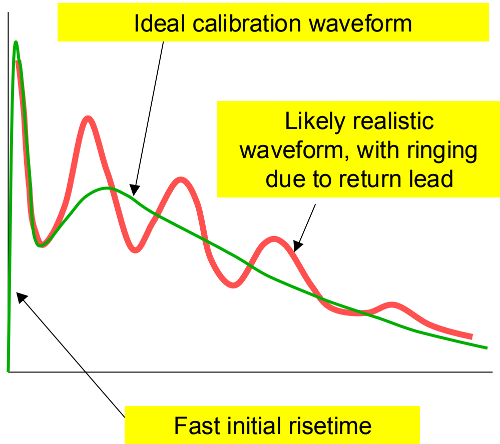

Figure 3 The standardized discharge current waveform

The actual current waveform is complex and depends on many variables. These include speed and angle of approach, and environmental conditions, as well as the effect of the distributed circuit reactances. The discharge mechanism is non-linear; at high voltages (greater than 6–10kV) the increased inductance of the longer discharge path limits the rise time of the waveform. At lower voltages a "precursor" spike due to the local area of the source (a finger or a metal tool) is produced which has a very fast risetime, of the order of a few hundred picoseconds. This spike, although low in energy, can be more damaging to the operation of fast digital equipment than the bulk discharge that follows it, which may have a risetime of 5–15 nanoseconds. IEC 61000-4-2 specifies the waveform that must be created by a calibrated generator (Figure 3), which is intended to represent typical ESD events.

By contrast with the current pulse, the electric field before and during the discharge has a relatively small effect except on some high-impedance circuits. Although the test level is specified in kV, this refers only to the voltage held on the generator's capacitor and is not directly related to the actual stress voltage experienced by the EUT's circuits.

Physical setup

Because of the very fast edges associated with the ESD discharge, high frequency techniques are essential in ESD testing. The use of a **ground reference plane** to regularize the EUT-to-ground capacitance is mandatory. Without it, the discharge current return path would be uncontrolled, the rise time and route of the return current would vary from test to test and there would be no repeatability. The EUT must be spaced a defined distance from the plane but not separately earthed to it, unless this would represent true installation practice. The ground reference plane should project beyond the boundary of the EUT by at least 0.5m, and for safety purposes should be connected to the mains safety earth. The return cable of the discharge generator is always connected to the ground reference plane. During the test it should be kept well away from the EUT, and certainly shouldn't drape over or near it.

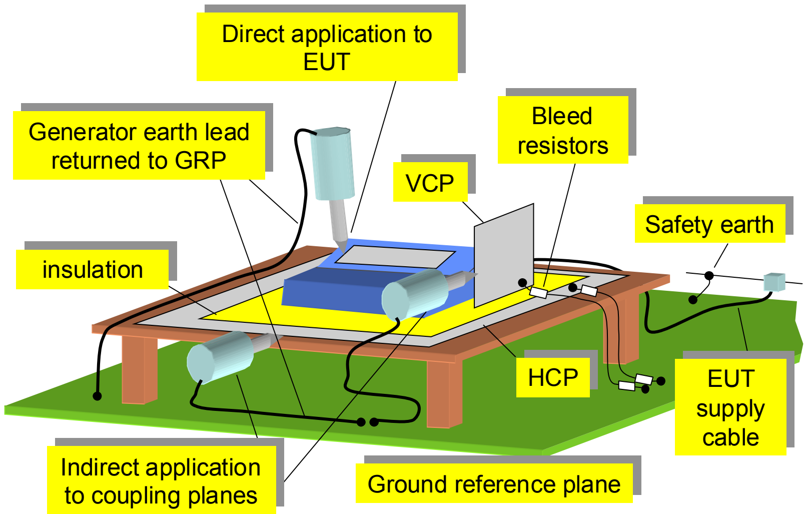

Figure 4 Tabletop general setup

Table-top equipment

Table-top (or wall-mounted, usually treated in the same way) equipment is placed on a wooden or insulating table with a horizontal coupling plane (HCP, typically an aluminium sheet) on its surface (Figure 4). Despite appearances, **this is not a ground plane**: it is connected to the ground reference plane via a cable which includes bleed resistors of 470kΩ at each end. Their purpose is to isolate the HCP from the ground reference plane during the application of the pulse – hence their location at each end of the cable, isolating the wire from the planes – but allow the charge to bleed off (with a time constant in the order of fractions of a millisecond) afterwards. Since these resistors see a high pulse voltage they should be solid carbon composition types rather than the standard carbon or metal film variety.

The EUT is insulated from the HCP by a thin plastic sheet, and placed with its front face 10cm from the edge of this plane. Discharges will be applied to appropriate points on the EUT and also to the HCP. The insulation should be continuous underneath the EUT so that there is no opportunity for a spark-over to occur between the EUT metalwork and the HCP. In addition, contact discharges to a vertical coupling plane (VCP), spaced 10cm from the EUT and of dimensions 0.5 x 0.5m, are required. The VCP is also connected to the ground reference plane, again via a 470kΩ + 470kΩ bleed resistor cable. There needs to be a clear area all around the table to maintain separation between the edge of the HCP and any metallic walls or other structures.

Floor standing equipment

Floor standing EUTs should stand on an insulating pallet 10cm high over a ground plane as above. This allows for easy movement of large systems into and out of the test facility, and also simulates typical distances between equipment and concrete reinforcing bars in a real installation. Positioning of power, signal and earthing leads should be representative of installation practice. To avoid variations, they should be laid at a constant height above the ground plane; a default of 10cm using dielectric spacers is suggested.

As with table top equipment, the simulator ground return lead is bonded to the ground reference plane via a low-inductance clamping arrangement. It should not be grounded to the EUT cabinet for any purposes except diagnostic checking; this would have the effect of reducing the electric field transient between the lower part of the cabinet and the ground plane, which may be an important coupling factor especially when cables penetrate the cabinet near to the ground.

Indirect contact discharges to a vertical coupling plane spaced 10cm from the cabinet are required, as well as direct discharges to the EUT. Indirect discharges to the ground plane itself are not appropriate.

Choice of test points

The test procedure encompasses direct discharges to the EUT using either or both air or contact application, and indirect discharges, applying the contact probe to the horizontal and vertical coupling planes. The latter is intended to represent a near-field radiated stress from a discharge to a nearby conductive object; there are many types of product for which this part of the test is trivial, but some products have been known to fail it without failing direct application.

Direct discharges should be applied to points accessible to the operator or user during normal use. Amendment 2: 2001 gave a definition of accessible parts. In brief, excluded from testing are:

- points that are only accessible under maintenance, including servicing carried out by the end user
- points and surfaces that are no longer accessible after installation
- contact pins of connectors that have a metallic connector shell – contacts within a plastic connector should be tested by air discharge only
- contact pins which are ESD sensitive because of functional reasons and that have an ESD warning label

The ITE immunity standard (CISPR 24) does specifically exclude discharges to contacts of open connectors. The issue of direct discharges to connector pins (Figure 5) is often contentious, since if they are to be applied there must be a significant investment in protection circuitry behind each pin. But leaving aside the question of compliance with standards, protecting potentially exposed pins will generally make for a more robust product. It's good practice to test such pins unless there is a strong rationale for deciding that they will not be exposed in their working environment.

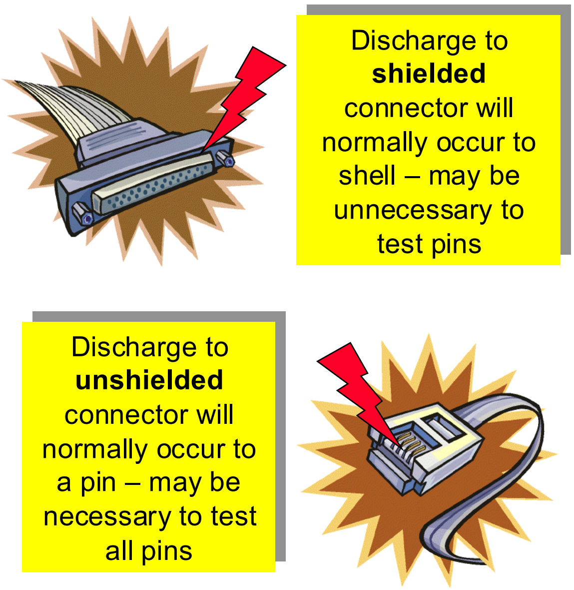

Figure 5 Testing connector pins

The actual points of application must be chosen experimentally by investigating all around the surface of the EUT with both contact and air discharges (Figure 6). If the EUT is apparently immune at the scheduled test levels, it may be feasible to increase the level to attempt to find the worst case application points. The standard warns against over-testing: "The final test level should not exceed the product specification value in order to avoid damage to the equipment." But since manufacturers don't of themselves specify a particular value of test level for their products, the best course is to decide in advance with the product designer what maximum level would be acceptable for investigatory purposes.

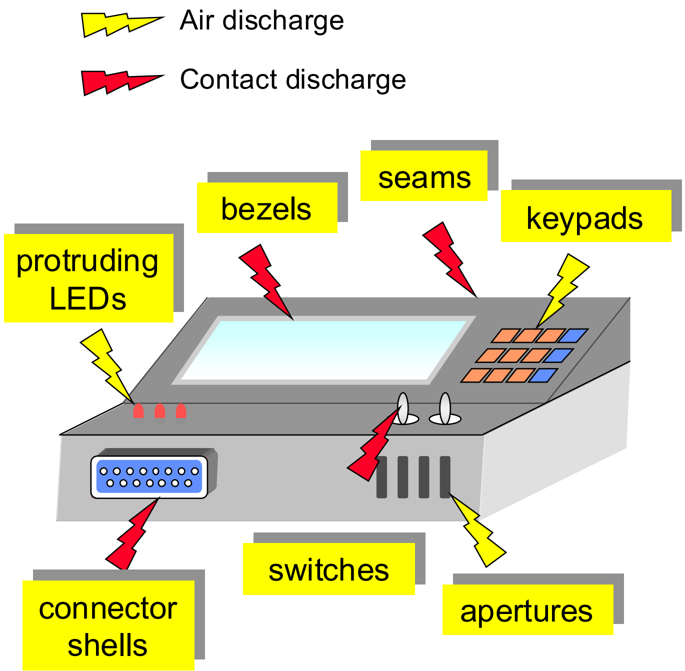

Figure 6   Choice of discharge points

Contact versus air discharge: when to use each

The contact discharge mode is preferred, because the resulting stress doesn't depend on the vagaries of a hard-to-control air gap; but it has to be applied to a conducting surface, and cannot be used on plastic or other insulating parts. In the contact discharge mode, the pointed tip makes contact perpendicular to the conducting surface before the discharge is initiated. Favourite points of attack are around the edges of panels, along joints between parts, on protruding metalwork such as switches, on screw heads and connector shells, and along the edges of plug-in cards. The tip is used to penetrate any insulating finishes (such as paint) unless the manufacturer declares that these will withstand the required level of air discharge voltage – in which case this is proven using the air discharge tip, which is not pointed. (It's rare to find a painted metal finish which can withstand the usual level of 8kV without allowing a discharge.) All indirect discharges to horizontal or vertical coupling planes are carried out using the contact method.

Air discharges are attempted at slots, seams, insulated switch and keypad apertures and other areas where a discharge might occur but which cannot be adequately tested by the contact method. The air discharge test generally uses a higher voltage, which will more easily seek out creepage paths along insulating surfaces to conductive areas which are behind the insulation. Such creepage path breakdown distances are often dramatically increased by contamination, dust and moisture; to have the highest chance of avoiding a discharge in this part of the test, the EUT should be as clean, dry, shiny and new as possible.

Test levels

IEC 61000–4–2 offers a range of test levels (Table 1) from which the manufacturer may select the level most appropriate to the environment in which the equipment is expected to operate. The environmental conditions are related to the lowest expected relative humidity, and the presence or absence of static-inducing materials in the neighbourhood. Because of the element of choice available in selecting these levels, IEC 61000–4–2 or its EN equivalent is not suitable for use directly as a mandatory standard for the purposes of the EMC Directive.

Many product specific and generic immunity standards which reference the ESD test have been published. The ESD requirements are generally well harmonized across the product sectors, requiring usually 4kV contact and 8kV air discharge levels. Note the comment in IEC 61000-4-2:

The voltages shown are different for each method due to the differing methods of test. This does not imply that the test severity is equivalent between test methods.

Because the most critical parameter of an ESD event is the rate of rise of discharge current, the actual ESD stress is not a linear function of the discharge voltage but depends also on the method of application (air or contact). It has been found that with a moving spark gap the resulting rise time of the discharge current can vary between 1 ns and more than 20 ns, as the approach speed is varied. But keeping the approach speed constant does not result in constant rise time. For some voltage/speed combinations, the rise time still fluctuates by a factor of up to 30. Not only that, but there are sometimes surprising inconsistencies, especially with the air discharge; it is quite feasible for a lower stress level, say 4kV, to cause a failure, while a higher level (8 or 15kV) does not. It is for this reason that the first edition of the standard requires all lower levels to be tested (see later regarding the second edition), which requirement is sometimes overlooked by test engineers – it appears right at the beginning of Clause 5. It is also why the contact method, which doesn't suffer from these problems, is preferred.

Severity level (environment)	Test voltage (contact)	Test voltage (air)
1 (35% RH, antistatic)	2kV	2kV
2 (10% RH, antistatic)	4kV	4kV
3 (50% RH, synthetic)	6kV	8kV
4 (10% RH, synthetic)	8kV	15kV

Levels in yellow are harmonized across most product and generic standards

Table 1 Test levels

Method of application

IEC 61000–4–2 recommends at least ten single discharges on preselected points, together with ten single discharges to each of the vertical and horizontal coupling planes. It recommends an interval of 1 second between each discharge, but accepts that a longer interval might be needed in order to be able to tell if a failure has occurred. Unless the sensitivity of the EUT is known in advance, preliminary testing will always be necessary to ascertain the most sensitive points; this can be carried out with exploratory discharges at a rate of 20 per second or whatever the generator is capable of. The discharges should be applied "in the most sensitive polarity", but it is not always possible to discover reliably which polarity is the most sensitive for any particular point, and so standard practice is to apply both polarities at each point. The ITE immunity standard (CISPR 24) calls for 200 contact discharges each of positive and negative polarity at a minimum of four test points. It is usual to apply a complete set of discharges in one polarity and one level before switching to the other polarity or the next level, rather than alternating polarities or levels.

As outlined above, for the air discharge method, the approach speed can make a considerable difference to the resulting stress, particularly the pulse rise time. To minimise variations, it's best to move the generator as positively as you can. On this subject, the standard says "the round discharge tip shall be approached as fast as possible (without causing mechanical damage) to touch the EUT", and it means it: this is not a procedure for nervous operators. The greatest difficulty is usually experienced when testing keypads, when it is impossible to follow this advice without actuating a key, and thereby invalidating the test.[†]

† Purists would design and use a mechanical contrivance for this purpose.

Another factor which makes a difference to the outcome is the angle at which you hold the generator. The capacitance between the front of the generator and its tip, and the EUT surface being tested, is a parameter in the equivalent test circuit which determines the detail of the pulse waveshape. To keep this capacitance repeatable, it is necessary to hold the generator perpendicular to the EUT surface. On the other hand, when you are applying discharges to the planes, the gun should be held on the centre of the edge of the plane and with the tip aligned with the plane, not perpendicular to it – see Figure 7.

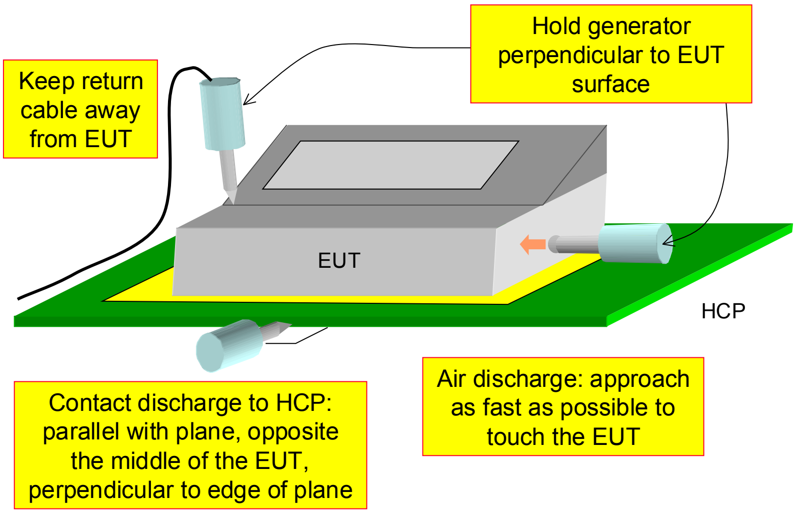

Figure 7 Factors in applying the generator to the EUT

Environmental conditions

The ESD test is the only one in the whole range of EMC tests in which the environmental conditions might affect the stress that is applied. (Environmental conditions may have a direct effect on some types of EUT, of course.) The air discharge is controlled by the breakdown properties of the air gap between the tip of the generator and the EUT, and these can be affected by humidity, temperature and pressure. The standard gives allowable ranges for these properties in the test environment as shown in Table 2; normally, the only one which may cause difficulty is relative humidity, but this is important, and it will typically mandate air conditioning and/or humidification in the test laboratory. The atmospheric pressure requirement would prohibit testing at altitudes of more than a few thousand feet above sea level.

Ambient temperature	Relative humidity	Atmospheric pressure
15 °C to 35 °C	30 % to 60 %	86 kPa (860 mbar) to 106 kPa (1060 mbar)

Table 2 Environmental range

The contact discharge method is unaffected by these parameters, although any secondary discharge that may occur within the EUT could be affected by them.

Ungrounded EUTs

Amendment 2: 2001, and the subsequent second edition, provides for a method of discharging the EUT in between applications of the ESD pulse, in situations where the equipment cannot discharge itself because of lack of an earth connection. The problem is that, unlike earthed products, battery-powered or Safety Class II products have no way for the charge to bleed off after a pulse. Without a bleed mechanism, the entire EUT will hold onto the charge that has been delivered to it by the first pulse. The capacitance between the whole EUT and the ground reference plane will determine the voltage that the EUT reaches: during the discharge pulse, the charge (Q = C x V) that was carried by the generator is shared between the generator's capacitance and the EUT's capacitance (Figure 8). So for instance, with a generator capacitance of 150pF, a test voltage of 6kV will create a charge of 900µC; if say the EUT capacitance is 50pF, then during the discharge, the 900µC is shared across 150 + 50pF, leaving a voltage of (900/200) = 4.5kV on each capacitor afterwards.

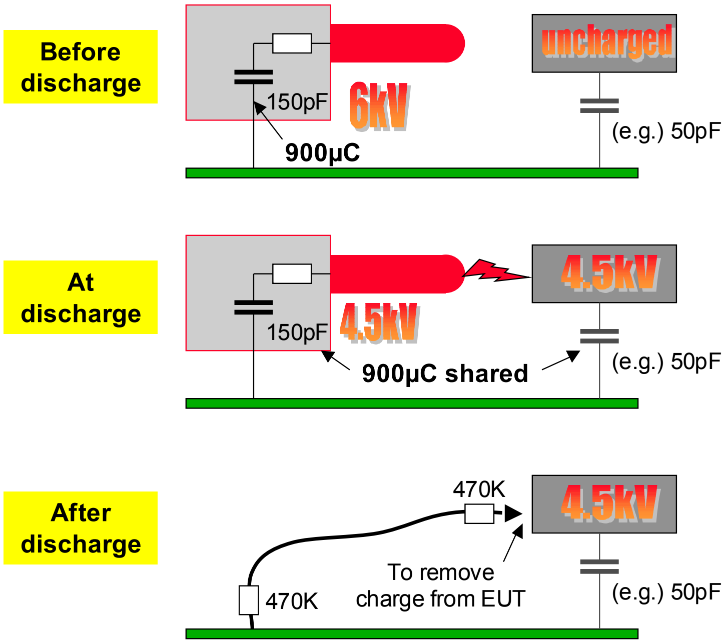

Figure 8 Testing an ungrounded EUT

If nothing were done, this clearly would create a problem when the next pulse is applied. If, as is usual, it is the same polarity, then the voltage difference between the generator and the EUT is now only 1.5kV, and therefore the stress is considerably less. Also, the EUT voltage will ratchet up a further amount, and the third and subsequent pulses will see an even smaller voltage difference. On the other hand, if the next pulse has the opposite polarity then the voltage difference is 10.5kV and the stress is considerably more. So to keep the stress the same, it is vital that the charge is removed from the whole EUT between pulses, as will occur naturally if the EUT has a direct earth connection.

The preferred method is through use of a cable with 470kΩ bleeder resistors at each end, attached at one end to the horizontal coupling plane or ground reference plane (for floor-standing equipment) and at the other end to the point where the ESD pulse is applied. The bleed cable can be in place during the application of the pulse, although this may affect the EUT's response. Alternatively, you can sweep the area of application of the discharge with a 470kΩ earthed carbon fibre brush after each pulse; or if you have plenty of time, just wait for the EUT to gradually discharge itself. Simply applying a grounding wire, without resistors, to the EUT between pulses is not advisable as this will create a reverse stress that is greater than the test pulse, with the potential to disrupt or even damage the EUT.

Performance criteria

Some means of determining malfunction must be provided without any extraneous connection to the EUT, such as monitors or oscilloscopes, which would affect coupling paths and hence the overall susceptibility. The typical performance criterion, applied in virtually all product and generic standards which call up this test, is criterion B:

> *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...*

Of course, this generic wording has to be interpreted for each product. For a typical digital product with perhaps a display, data communications and a well-defined quiescent operating state, you might expect to observe the display and run a communications utility during the test, and run an internal diagnostic checking program before and after the test. Flicker of the display or loss of data packets when a discharge pulse is applied would be acceptable ("during the test, degradation of performance is allowed”). Latch up of the display or communications link, or loss of internal memory data or a change in operating state, which are not recovered transparently by the end of the test applications, would not be acceptable.

Most often, until the test is done the designer has no real idea of what might happen as a result of an ESD test. Discussion between the designer and the test engineer is usually necessary to arrive at a practical monitoring regime and acceptable performance criteria.

The implications of the second edition

The second edition of IEC 61000-4-2 was published in December 2008. It has been a long time in gestation; since there are many thousands of ESD generators in use worldwide, there was considerable resistance to any change that might have meant a wholesale redesign of the generator construction. In the event, very few changes have been made to the test method itself. With regard to the generator, the second edition adds a new specification for the calibration target and procedure, which has certainly had an impact on calibration laboratories. But at the same time, it slightly relaxes the waveform rise time spec (from 0.7–1ns to 0.8ns ±25%) and peak current spec (from ±10% to ±15%). Annex A has added a "rationale related to the generator specification" which explains why a more severe change to the generator was not deemed necessary; a round robin had been performed with generators modified to give a more tightly controlled waveform, but “the new waveform did not lead to any significant improvement in the reproducibility of the test results on actual EUTs.” It also points out that the E-field radiated by the generator could be a cause of reproducibility concerns, but

> *… the resources required to undertake a further round robin series of tests would be significant with no guarantee that this parameter was the cause of reproducibility issues. Substantial technical study is needed to quantify the impacts from radiated fields on actual EUTs and to understand how to control the associated parameters that impact reproducibility of test results.*

There is a new informative annex for measurement uncertainty (MU), but this relates to calibration of the generator parameters only. However, it does throw a spanner in the works when compared with the present approach taken by accredited test labs and formalised in LAB 34, which describes the UKAS default method of applying uncertainty to the ESD test. Its final paragraph states

> *Generally, in order to be sure the generator is within its specifications, the calibration results should be within the specified limits of this standard (tolerances are not reduced by MU).*

In LAB 34, the tolerances allowed for the generator’s parameters **are** reduced by the calibration MU, which is necessary to give a 95% confidence that the required stress levels are met. The consequence of the statement in IEC 61000-4-2 Edition 2 is that this level of confidence is not achieved.

There are two other notable changes in Edition 2. The first is an explicit recommendation for pre-test verification, in clause 6.3. Accredited labs tend to do this as a matter of course, but it is always good practice, since there are a number of ways in which the generator setup could be damaged without it becoming apparent that the correct stress is not being applied. A simple pre-test check is to apply the generator to a fixed air gap against the ground plane, and check that a spark appears when a pulse is triggered above the correct threshold voltage, set immediately after calibration.

The second change is that the requirement to test "all test levels up to and including the specified test level " now applies (in Clause 5) only to air discharge. This is reasonable, since although the air discharge method is known to be flaky, the contact method is far more predictable and does apply a stress which is proportional to the test level.

Conclusion

The ESD immunity test is widely used, but its superficial simplicity belies a wide variety of factors which can create varying outcomes if they are not understood and controlled. The experience and skill of the test engineer are paramount in gaining reliable and repeatable results.

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