Metrology & Methodology of System Level ESD Testing

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Abstract

Parameters which cause the poor reproducibility of system level ESD tests have been identified: simulator calibration methodology and insufficient simulator specifications. Results of round robin tests we performed at three laboratories are reported. A better calibration methodology for ESD current measurement and additional simulator specifications for output current and radiated fields are proposed.

1. Introduction

In spite of quite a bit of work on ESD standards in the past [e.g.1,2 and other references] the reproducibility of system level ESD tests is still poor. The non-expanded uncertainty for ESD test results calculated according to Namas guide NAS 81 has been estimated to be larger than 50 % for certain parts of the test [3]. Tests done with different simulators provide different results [4,5]. Especially the low voltage, fast rise time ESD events [6], which occur quite frequently in the real-world, is not covered by the present 1991 IEC 1000-4-2 ESD standard [7]. This situation is unacceptable to manufacturers and users of ESD simulators.

In this paper, we analyze the reasons for the reproducibility problem and recommend procedures and measurement methodologies to improve over the existing standard document based upon the current understanding of the art. In addition to the effort reported here on Working Group (WG) 14 of the ESD Association [8], there are two other groups working on the same problem: ANSI C63.16 [9] and IEC – TC77b. Working group 14 follows a five step path:

- Analyze the reasons for the reproducibility problem.
- Improve the current measurement methodology.
- Add and/or modify output current specifications.
- Establish a radiated field measurement methodology.
- Add radiated field specifications.

These are discussed in the following sections.

2. Reasons for poor reproducibility in ESD testing

The causes for the above mentioned problem can be separated into problems of the test methodology, the simulator used, and others. Test methodology problems include:

- Test procedures not fully cover statistical and time dependent sensitivity of equipment under test (EUT) [10,11].
- Procedures not restrictive on the test setup (e.g. cabling) for repeated tests.
- Simulator problems include
- Construction specification for the simulator allows much variation
- Measurement system to verify a simulator not calibrated properly

Other problems include

- Statiscal and systematical variations of air breakdown. For nonzero approach speeds, air discharges vary due to the statiscal time lag [12,16,17]. One way to avoid this

1998 EOS/ESD Symposium Proceedings, Paper 1B.3 Pgs. 29 - 39

variation is use contact mode discharge. Some reduction of the statistical time lag variation can be achieved by controlling the humidity, air pressure, and the speed of approach during air discharge testing.

Variation between different brand ESD simulators is a major reason for the lack of reproducibility in ESD tests. Neither ESD standard specifications nor the methodology used to verify the specifications are presently sufficient restrictive to provide acceptable ESD system test repeatability.

IEC 1000-4-2 specifies the discharge current by its rise time and peak values at 30ns and at 60 ns. The specification allows for a wide range of waveforms to be qualified. An example is given in Figure 1 for the early part of the pulses. Both currents shown fulfill the IEC specifications. Their visual difference is obvious, but the link to differences in test results is not as simple.

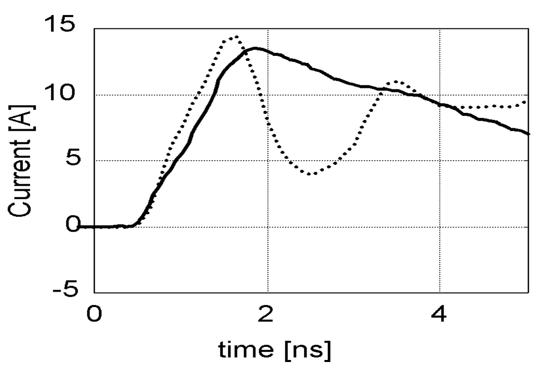


Figure 1: Contact mode discharge current at 4 kV of two simulators which fulfill the IEC 1000-4-2 specification. Measured using a 2 GHz 8Gs/s oscilloscope and a Barth current target.

In fast digital electronics, which are often designed such that a majority of real world discharges directly go to a grounded part of the system, most coupling is caused by induction (near field) or by radiation. For such EUTs, numerous tests suggest that the high frequency components or the current derivatives dominate simulator severity. The EUTs will react differently if tested with simulators of Figure 1 because of different current derivatives.

IEC 1000-4-2 simply states that there should not be unintended radiation (see section 8). It is not possible to define a field just by a current specification at a few points. For that reason, it is to be expected that fields from different simulators vary strongly [13].

Additional effects are caused by current flowing in the ground strap. Although the ground strap is just intended to carry the slow changing current flowing through the 150 pF capacitor in the simulator, often it conducts parts of the current which forms the fast initial peak. This causes uncontrolled fast changing fields that influence the EUT. See summary of contributors in Table 4 at the end of this page for reproducibility of ESD tests fields that influence the EUT. See summary of contributors in Table 4 at the end of this paper for reproducibility of ESD tests.

3. Error sources in discharge current measurement

The IEC 1000-4-2 document does explain how to construct a current sensor (current target), but it does not state exactly how to make the current measurement. A typical error-prone procedure might proceed as follows: 1) Connect the target to an oscilloscope via an attenuator and a cable, 2) derive the amplitude calibration factor by assuming a 1W transfer impedance and using the nominal attenuation value. Potential errors for this simple procedure are:

- Unknown current target DC resistance -- A 4-wire, 4-contact point resistance measurement is needed to determine the value of the current sensing resistor to ground and the reverse matching resistor. The DC resistance should be small compared to the source resistance to approximate a short circuit measurement. The source impedance of an ESD can be estimated by dividing the pre-discharge voltage by the peak current. With the exception of extreme furniture discharges, ESD source impedance values are usually larger than 100Ω. For a 3.75 A/kV peak value ratio a 2Ω target would cause an error of less than 1%.
- Non-flat frequency response of current target (see section 4.)
- Non linearity of the target and attenuators—The transient power imposed on targets and attenuators by ESD is far beyond their power rating for continuous signals. As the ESD impulse is very short, it does not cause thermal problems but

may cause non-linearity. Our estimate indicated that for the typical ranges of discharge currents (< 100 A) and transfer impedances (< 2Ω) non linearity will not cause significant errors.

- Reflections--The scope, the attenuators, and the target are not perfectly matched to the cable impedance. This will cause reflections, i.e. amplitude errors and echoes in the time domain data. If measurements are carefully analyzed, clear time in time domain measurements usually helps to uncover and eliminate such problems.

- Cable loss – Cable loss of an air insulated cable determined by the skin effect causing an increase of its attenuation according to the square root of the frequency. The high frequency attenuation may seriously reduce the peak amplitude value even with short cables. Most real cables have additional attenuation caused by the dielectric. Some cable constructions also have strong dispersion causing ringing step responses [14]. We suggest using as short a cable as possible (<0.5m). The important selection criterion is not the specified upper cutoff frequency (onset of higher modes), but the skin effect loss of the initial rise and possible dispersion. They can be measured using a fast pulse generator or a network analyzer with artificial time domain.
- Shielding (e.g., a metal cabinet) is usually needed for the oscilloscope equipment.
- Scope amplitude error and rise time limitation can be determined using a known fast rising pulse
- Attenuator value -- The nominal value of an attenuator may be somewhat different from its real value. It may have suffered damage due to previous (ab)use. This may influence the peak value measurement. The significance of the frequency dependence of the attenuators used must be taken into account. A good starting point is to use attenuators rated up to more than 10 GHz.

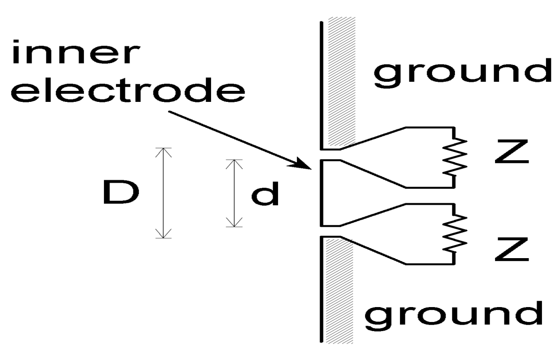
4. Target characterization

It is neither easy to design a resistor that maintains its resistance value up to multiple GHz, nor is it easy to measure the response in the frequency or in the time domain. There are several methods to characterize the target.

If two IEC targets are connected face to face, the source impedance is close to 2Ω for lower frequencies. However, any inductance in the path between both targets will cause a frequency rolloff, as it is in series with the 2Ω source impedance. We do not suggest using this method.

Another method is to attach a cable across the gap between ground and the inner conductor of the target. This method gives a 50Ω excitation, however it does not have a well defined series inductance and no symmetry of revolution. Again, we do not suggest using this method.

We suggest using a conical coax to target adapter (Figure 2). This way a symmetrical 50Ω excitation is achieved. One limit is caused by the fact that the ratio between the inner diameter (d) and the outer diameter (D) of most targets does not result in a 50Ω impedance. One can build a conical target adapter-line such that it matches the inner diameter or the outer diameter. RF-measurements made in this way indicate that different target attenuation values may be measured above a few GHz.



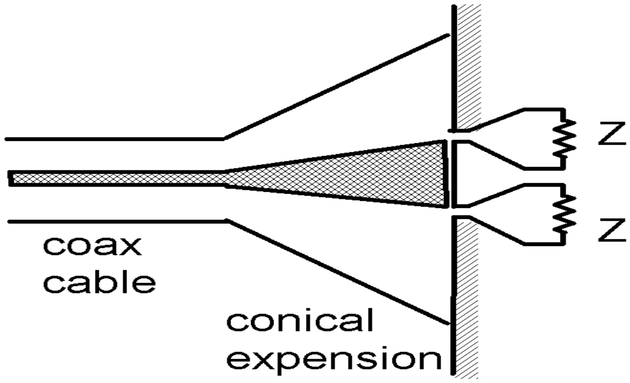


Figure 2: ESD current target with conical adapter line. Inner diameter of this conical line matches d but not D.

Transfer functions are given in Figure 3 for three targets. The transfer impedance of the IEC target shown in Figure 3 increases from its DC-value to

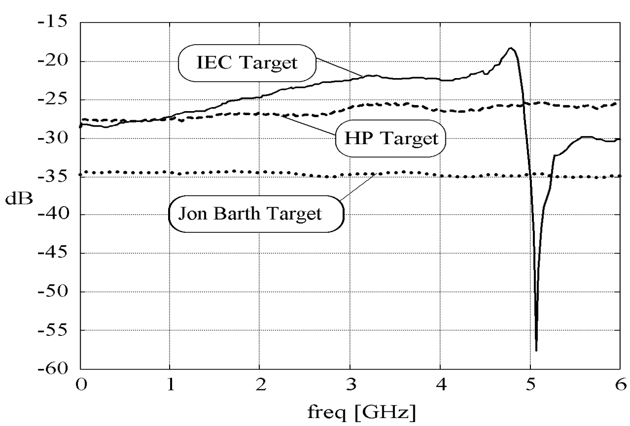


Figure 3: Frequency response of three targets measured with conical adapter lines:
- IEC Target
- HP Target made following instructions in
- Barth Target made b Barth Electronics

1 GHz by approximately 1 dB (+3.5 dB at 2 GHz). It has a resonance at 4.7 GHz. Different IEC targets showed uncontrolled resonances between 2.4 GHz and 5 GHz [15]. The differences of the transfer impedance shown in Figure 3 for different targets will be visible in ESD simulator measurements using these targets, as shown in Figure 4.

Figure 4: (Top) Current measurements using Barth target (dotted) and IEC target (solid) of ESD generated by simulator A. (Bottom) Their current derivatives. Scope is HP54720 with 2 GHz bandwidth at 8Gs/sec.

The IEC target causes a bump in the rise shown in the top panel of Figure 4. This could affect rise time measurements, but the effect is even more drastic in the current derivative shown in the lower panel of Figure 4; current derivative differs by more than 30 % just due to target problems. As WG14 intends to add a current derivative specification for simulators, it is important to use improved targets or to correct target influence by numerical methods. If the measurement is done in the time domain with the largest bandwidth available, we get, in Figure 5, the waveforms of a fast pulse generator with or without the target using the method described in Section 5. Obviously, the IEC target, with non-flat S_{12} shown in Figure 3, gives significant ringing in Figure 5.

Figure 5: Measurements done using the HP54120 sampling scope with 20 ns delay line. Bandwidth approximately 7 GHz, limited by the delayline and other cables. The amplitudes for the target measurements are corrected by the nominal divider ratio of the targets.

Left Panel:

Solid: Picosecond pulse with 15ps rise time into the scope via 50Ω attenuators

Dotted: Picosecond pulse into the IEC target connected to the scope via the delay line.

Right panel:

Solid: Picosecond pulse with 45 ps rise time into the scope via 50Ω attenuators.

Dotted: Picosecond pulse into Barth target connected to the scope via the delayline

5. Verification of current measurement system

The method to measure the discharge current of ESD simulators proposed here does not differ

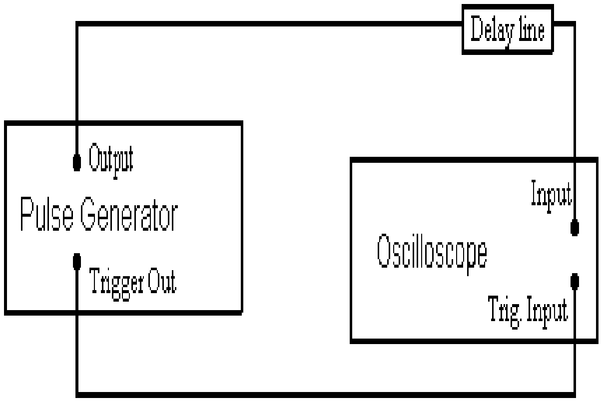


Figure 6. Measurement of pulser reference waveform with the pulse directly measured by the oscilloscope. This set up is for a low voltage pulse generator. For a high voltage pulser, proper attenuators are needed...

much from the method described in IEC 1000-4-2. But before verifying an ESD simulator, one needs to verify the measurement setup. This should be done in the time domain by the methods shown in Figure 6 for the reference waveform (without a target) and in Figure 7 for the waveform which passes through the target.

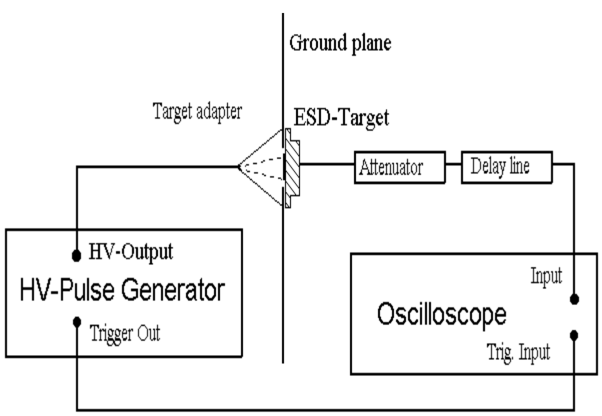


Figure 7 Measurement of pulser waveform through a target for target characterization. This is a typical test set up for verification of an "ESD current measurement system" using a high voltage pulse generator. The attenuator may not be needed for a low voltage pulser. This method is the preferable method as the target - oscilloscope chain does not need to be changed between calibration and measurement. The high voltage (HV) generator must be able to provide at least 10 A in the target. If external trigger is needed it is suggested to trigger the scope by the transient fields to avoid a power splitter. The pulse generator can be referenced to a sampling scope.

In the frequency domain, the following steps are recommended:

1. Measuring the frequency response of the target – attenuator – cable chain.
2. Measuring the frequency response of the oscilloscope by applying a signal generator to its input.
3. Adding both frequency responses to obtain an estimate for the system frequency response.

Note that the frequency domain method outlined above is not exact as it only uses magnitude data and neglects reflections at the input of the oscilloscope. This is allowable because the errors are usually small.

The system error must be in the bounds shown in Figure 8 in the time domain or in Figure 9 for the frequency domain.

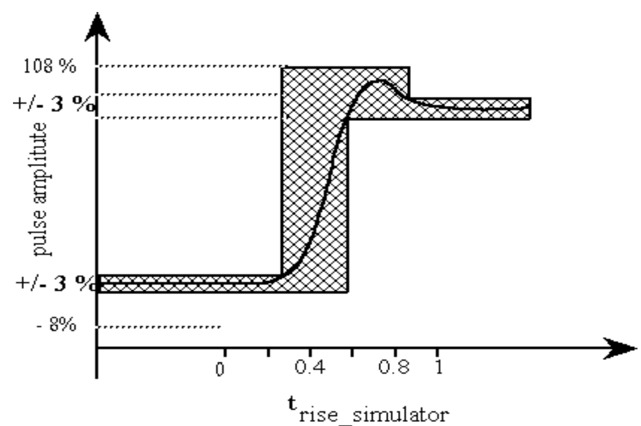


Figure 8. Acceptable system step function range of the target - oscilloscope chain in the time domain. The rise shown will allow a rise time measurement with an accuracy of 5% for signal with a rise time of $t_{rise\_simulat}$

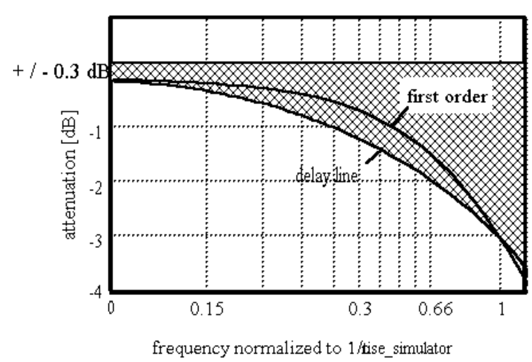


Figure 9 Acceptable system characteristic range for the target - oscilloscope chain in the frequency domain. The roll-off shown will allow a rise time measurement with an accuracy of 5% for a signal with a rise time of $t_{rise\_simulato}$. Note that $t_{rise\_simulator}$ signifies the expected rise time for the simulator (e.g. 0.7 ns for present IEC 1000-4-2 simulators.)

6. Round robin testing on ESD simulator calibration

To test the calibration methodology, we shipped two ESD simulators and three targets to three locations, checked the measurement system, and measured the performance of ESD simulators. Table 1 summarizes the equipment used. At each location the following measurements were performed:

1. DC-resistance of the targets.
2. Frequency response of the targets with cables and adapters.
3. Time domain response of the target-attenuator-scope chain.
4. System bandwidth/response
5. Simulator characteristics

Table 1 Equipment for round robin tests.

Location	Tar-gets	Pulse generator	Network Analyzer	Oscilloscope
Roseville	IEC,HP Barth	Barth 723 PSP*	HP 8553D	HP54720D/54722A
Boulder City	IEC,HP Barth	Barth 723 PSP*	HP 8553D	HP54720A /54120
Princeton	IEC,HP Barth	PSP* Barth 632	HP 8753B	HP 54720D

*PSP=Pulser of PicoSecond Pulse Laboratory.

It was assumed that the simulators provide a stable source at each location. Results using the Barth target and the HP54720 scope for simulators A and B are shown in Tables 2 and Table 3 respectively. Data taken using the HP target were quite similar. The system did not pass the frequency response requirement at either location using the IEC target.

Table 2: *Round robin results for simulator A, contact mode 4 KV*

Location	Peak value [A]	Pos derivative [A/kv/ns]	Neg derivative [A/kv/ns]	Rise time [ns]
Roseville	13.71 13.11 12.78 13.34	3.63 3.5 3.3 3.3	-0.98 -0.90 -0.74 -0.82	0.946 0.965 0.96 0.935
Boulder City	13.89 13.34 13.57	3.79 3.34 3.23	-0.91 -0.99 -0.90	0.97 0.965 0.946
Princeton	12.33	3.41	-1.33	0.952

Table 3: *Round robin results for simulator B, contact mode 4 KV.*

Location	Peak value [A]	Positive derivative [A/kv/ns]	Negative derivative [A/kv/ns]	Rise time [ns]
Roseville	13.67 13.79 13.86	4.95 4.9 4.7	-6.1 -5.7 -5.6	0.734 0.762 0.762
Boulder City	13.99 14.23	5.27 4.9	-6.02 -5.97	0.751 0.77
Princeton	14.26	5.33	-5.5	0.77

From Tables 2 and 3 it can be seen:

1. Simulator A shows an average peak current value below the IEC specification of between 13.5A to 16.5A at 4KV.

2. There are shot-to-shot variations of about 11% in the peak value. Many discharges are needed to allow a good statistical analysis.
3. The rise time and the derivative values are quite similar from location to location
4. Simulator B provides a larger negative derivative than its positive derivative. It would fail the proposed positive and negative current derivative limit in Table 4.

The round robin has shown that a reliable rise time, current derivative and peak value measurement can be done if the system parameters are correctly determined and taken into account. The discharge-to- discharge variability of the simulators was larger than the differences from measurement site to measurement site.

7. Status on simulator specifications

7.1 Current derivative of human ESD

The arm position, the size of the metal piece, the relative arc length (relative to the Paschen value at the pre-discharge voltage), and the voltage will influence the current derivative. To obtain values for a reasonable simulator specification, simulations [17] and some additional measurements were done using a Barth target, an HP54720D scope with 2 GHz bandwidth and 8GS/s single shot sampling rate.

Let's look at the influence of the metal piece size. This is done at first for very short arc lengths. Measurement under such conditions will allow analyzing the waveform with minimal influence from the arc, as its arc resistance drop approaches an ideal switch.

Shown in Figure 10 are 2KV discharges through tweezers and through a quarter (approx. 2 cm diameter) coin. The tweezers are 7 inches long and closed. The index finger was stretched to 1 inch from the tip of the tweezers. This is a rather thin structure. If the transmission line impedance is estimated by the impedance of the smallest diameter cone which can enclose the tweezers-hand structure, an impedance of approx. 180Ω is calculated.

In contrast, the coin is a rather short and thick structure. The quarter was held between the index finger and the thumb. The hand was held quite close to the body. As we compare a very thin to a rather thick structure we make sure that the range of most practical hand-held metal structures is included. The following summarizes the characteristics observed:

- We do not see a second hump,
- Peak current values reaches more than 10A/KV for the coin and 5 A/KV for the tweezers.
- Peak positive current derivatives reach 10 A/KV/ ns for the tweezers and 40 A/KV/ns for the coin.
- Peak negative current derivatives reach hardly anything for the tweezers and approx. one third of the positive value for the coin.

This indicates that a negative current derivative of approx. 1/3 of the positive current derivative value would cover even the extreme case of the hand-coin ESD.

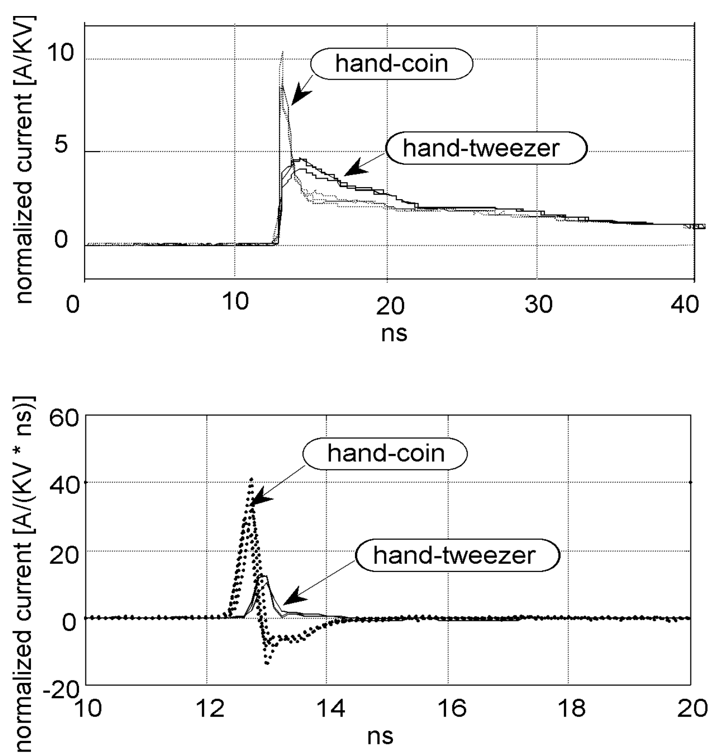
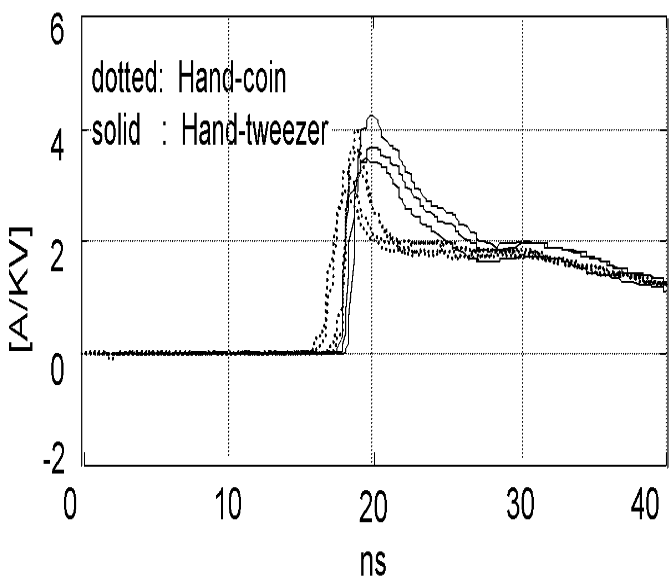


Figure 10. Current (upper) and current derivative (lower) for the discharge of a hand held tweezers (solid) and a

hand held coin (dotted) measured at 2 KV at rise times of less than 200 ps. Note the different time scales.

Now let's see what happens if discharges are analyzed for those events having a rise time close to the IEC specifications. The measurement was done at 6 KV (The data are normalized to the pre-discharge voltage. This is meaningful even for air discharge: Air discharges for different voltages but with the same rise time scale linearly with pre-discharge voltage). Many waveforms were captured but only those waveforms with a rise time between 0.7ns and 1ns were analyzed for the current derivative.



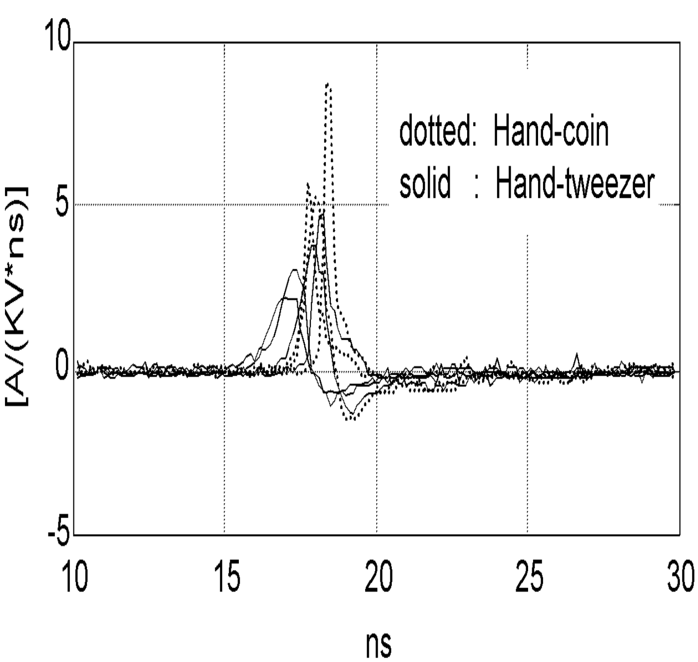


Figure 11. Current (upper) and current derivative (lower) for the discharge of a hand held tweezers (solid) and a hand held coin (dotted) at 6 KV for rise time between 0.7ns and 1ns.

Again, the negative current derivative for the tweezers is very small, less than 1/6 of the positive value. For the short and thick structure it is approx. 1/4 of its positive counterpart. The interesting result obtained in Figures 10 and 11 is that for every rise time up to at least 1ns, the peak value ratio between the positive and the negative peak derivative value is independent of the rise time. The positive peak value will certainly increase for very short arc lengths using a faster oscilloscope.

We have not come to a final conclusion on a negative current derivative value yet. One possibility would be to limit the negative derivative to not more than 1/5 of its positive counterpart or to allow it to be 1/3 of its positive counterpart but with an additional specification to reduce ringing. In both cases we try to specify discharges close to those of thin structures. This will narrow the brand-to-brand simulator variations and eliminate most of the ringing seen in some present day simulators.

7.2 Which are the correct current values?

The previous paragraph showed the parameter variation range of human-metal ESD. It is large. If we take additionally into account the fact that in the real world there are other types of ESD, like furniture ESD or human-skin ESD, the problem of finding a representative waveform becomes much more difficult. Any waveform is a compromise. Presently there is a 0.7ns to 1ns rise time requirement in IEC. ANSI proposes a faster value.

A faster rise time, like 200 ps, will cover more of 1) low voltage ESD events which occur quite often in the real world and 2) fast rising high voltage ESD events (usually in very dry air). However, it may be too fast compared to many ESD events above 4 kV in moderately humid air. If such a value were part of a standard, it is likely that it would force overdesign of equipment.

Another argument to consider is the following. An aim of WG 14 is to specify a smooth waveform as we see it in reality. Some of the present simulators show quite a bit of ringing. If one would keep the present rise time value but enforce a smooth waveform, the severity of the test impulse would be reduced compared to ringing simulators. To keep the severity at a constant level, the rise time would need to be reduced.

An alternative is to use a voltage dependent rise time. This could be done with or without steps. Looking at the present technology, we are not aware of any ESD simulator which allows a continuous variation of the rise time.

The arguments regarding the rise time are also true for the peak value.

7.3 Additional Specification

If we keep the present IEC specifications but adds additional specification, the values would be:

Peak value:	3.75 A/kV
Rise time:	0.7 ns - 1 ns
Max. positive current derivative: at 1.5 GHz bandwidth	5 A/ns/kV
Max. negative current derivative at 1.5 GHz bandwidth. (A tighter specification of 5/6 A/ns/kv is also under discussion.)	1.75A/ns/kV

This would eliminate most ringing waveforms and allow simulators which do not show a local minimum at approx. 20 ns. The discharge current would need to rise quite smoothly to fulfill the positive current derivative limit, which is set close to a linear rise. It is under discussion to reduce the rise time to a more realistic value at 4 KV.

8. field measurement methodology

Often the use of the term ‘unintended radiation’ implies that there should be no radiation from simulators. This is misleading. Every ESD causes strong radiated fields. Radiated fields of simulators should match the radiated fields of real ESD but they should not cause radiated fields stronger than that nor produce other fields (e.g. low frequency magnetic fields from the simulator DC-DC converter). Some data on calibrated field measurements can be found in [5,13,16,17,18,19,20] but the data base is still incomplete and widely available technology for our needs is still insufficient or very costly. Even if all simulators could have identical currents, the radiated fields may be significantly different. Differences in fields have been shown [5,16,17]. There is a need for a field specification. Two problems that need to be overcome are:

1. A methodology is needed which is repeatable, traceable, easy enough to apply and not too expensive.
2. Field specification values and allowed variation ranges need to be set and justified.

Fields can be measured in the near or the far field, in the time or frequency domain, as electric and/or magnetic field, ground based or in free space. As ESD events can occur very close to the EUT, maybe a near and a far field measurement are needed. In the near field, the electric and the magnetic fields need to be measured. Due to the nature of the ESD pulses and the availability of oscilloscopes (a fast scope is already needed for the current calibration), a time domain measurement is preferred. Free space sensors require a fiber optic link to avoid the problems usually caused by cables. This will increase the price significantly. If possible, ground plane based sensors should be used. To reference or even analyze field sensor concepts or their commercial availability is beyond the scope of this paper [21,22,23].

The consequences of the yearly simulator re-calibration need to be considered, if a field specification is added. It seems justified to limit the re-calibration of the simulator to its current provided that the field specification was originally met for the new simulator. The rationale is that if a simulator was designed and tested to specification that it is very unlikely to experience a change which effects the fields but not the current or voltage.

9. simulator field specifications

Radiated fields of simulators need to be specified in light of the following problems:

- Fields of simulators may not show symmetry of revolution.
- The ground strap influences the fields.
- Fields vary with distance. The variation does not follow a simple function. Very close to the discharge tip the magnetic field decays according to 1/r. The field in the far field region also follows a 1/r law. But intermediate region is more complex.
- Transient fields of humans vary in spite of the same charging voltage for the same reasons which cause the current variations. Our measurements show that the peak far field values increase with decreasing arc length approximately by $E_{peak} = A\ (1/d)^k$ where *A*=a constant; *d*=arc length,and *k* between 1.5 and 2.
- Fields vary with elevation angle.
- Distinguishing between the near and the far field is needed.

Presently the database for fields of humans is not sufficient to specify values. But the value should be chosen such that the fields match the fields of a human-metal ESD for the same rise time as specified in the simulator current specification. If a value of 0.7 ns rise time in contact mode is taken, the values specified in Table 4 are presently the best estimate for fields [17].

10. Conclusions

The most widely used system level ESD test standard, IEC 1000-4-2, causes irreproducible results. Poor calibration methods and uncontrolled simulator parameters are potential causes. Procedures for calibration of individual measurement equipment and the entire measurement system are offered. An expanded list of critical parameters, including maximum current derivatives and field values, is recommended and is summarized in Table 4.

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