A New Proposal for the Uncertainty Evaluation and Reduction in Air Electrostatic Discharge Tests

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Abstract— **The technique used in air electrostatic discharge (ESD) immunity tests to approach the generator tip to the equipment under test is here dealt with. Specifically, the uncertainty contribution associated to the measurement technique is analyzed in depth. To this aim, a number of simulations and experiments are carried out by means of a proper test bed, which includes a purposely-developed slide system. Through this system, the effects of different type A uncertainty contributions are compared and the ESD repeatability is assessed. Taking into account the type B uncertainty contribution too, the purpose of the work is to provide an original and efficient proposal for improving the uncertainty evaluation in air ESD tests.**

Keywords: ESD, electrostatic discharge, air discharge, uncertainty, approach speed, measure variability.

I. INTRODUCTION

Electrostatic discharges (ESDs) represent a well-known phenomenon in electronics, occurring when the electrostatic charge in a body (human body, pieces of furniture) abruptly flows to a near located electronic circuit or system. The effects of such phenomena can be rather critical for electronic devices, and may provoke system failures or even permanent damages. In order to assess the immunity level of an equipment under test (EUT) to ESD, specific standards can be followed [1], [2]. In these standards, the immunity requirements and the test methods are defined for both contact and air discharge. The characteristics of the ESD discharges are also provided. They are used in the setup stage of the ESD generator (also known as "gun") in order to provide discharges similar to those generated by the human body.

One important issue of ESD tests is the evaluation of the test uncertainty, and in particular the uncertainty contribution associated to the repeatability. In these tests, in fact, repeatability is usually very low and the corresponding uncertainty contribution is typically rather high. In the literature, the repeatability of ESD tests is in-depth investigated in a number of specific contributions. For instance, [3] provides interesting results from an international comparison among ESD-generator calibration tasks. The results reported in this paper confirm the high variability of ESD test outputs and underline the importance of the measurement setup, which, in the comparison, was different from one laboratory to another. In [4], the uncertainty budget of an ESD test is discussed, with special regard to some specific uncertainty factors like the measurement repeatability, cable and adaptor loss and time resolution. The uncertainty contributions in an ESD test are also dealt with in [1]. Specifically, the influence on the test of parameters like the position and orientation of the ESD gun is studied. Unfortunately, in most of such contributions attention is paid to the only case of contact discharges. Air discharge tests are instead seldom taken into account and a little information is provided in terms of uncertainty evaluation. Interesting results are however provided in [5], in the case of air discharge tests and in terms of current waveform versus some physical parameters.

The contact discharge method represents the approach most considered in the standards. It also represents the simplest case to be analyzed in an uncertainty evaluation budget. In fact, being based on fixed positions of the gun, it requires a smaller number of terms to be accounted for. However, air discharge tests become needed any time contact discharge tests cannot be performed. In this case, the IEC standard [1] recommends to approach the gun tip as fast as possible to touch the EUT. Conversely, the ISO standard [2] recommends to move the tip very slowly in order to minimize the multiple discharges and ringing in the measurement equipment.

In this paper, the uncertainty of air discharge tests is analyzed with special regard to the contributions associated to the different parameters like speed and movement of the gun tip during the approach phase, gun inclination and relative humidity. To this aim, selected results from proper simulations and experiments are presented to confer reliability and generality to the research activity. The purpose of the work is to provide an original and efficient proposal for improving the uncertainty evaluation in air discharge tests. Details

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concerning the test bed, which includes a purposely-developed slide system, measurement procedure and experiment are also provided.

II. Measurement Setup

A. Test Repeatibility

The starting point is, as already mentioned, to acknowledge that the ESD phenomenon is scarcely repeatable by nature. Indeed, this fact affects remarkably the calibration task of an ESD generator too. The calibration of the generator, performed as recommended in [1] or [2], gives the first important contribution when evaluating the uncertainty budget of an ESD test. From the examination of many ESD calibration reports produced by accredited laboratories, it is evident that:

- the uncertainty values associated to the measurement of the contact discharge parameters are lower than those associated to the air discharge parameters (typically, 8 % for the peak of the current waveform and for current values at fixed discharge times, 5 to 7 % for the rise time, in a contact mode calibration; in the order of 25 % for rise time and 10 to 15 % for discharge time constant, in an air mode calibration);
- the type A contribution (σ) to the uncertainty value [6] (mainly due to the measurement repeatability) cannot be better than 20 % (for instance, in the case of INRIM calibration reports) for ten to twenty repeated air discharges, while it is usually in the order of 3 to 5 % for ten repeated contact discharges.

To investigate this matter a measurement system will be proposed and described in the following section.

B. Measurement System and Setup

A schematic representation of the measurement system used in the experiments is sketched in Fig. 1. The system is compliant with the standard [1] and is suitable for the assessment and verification of ESD generator characteristics.

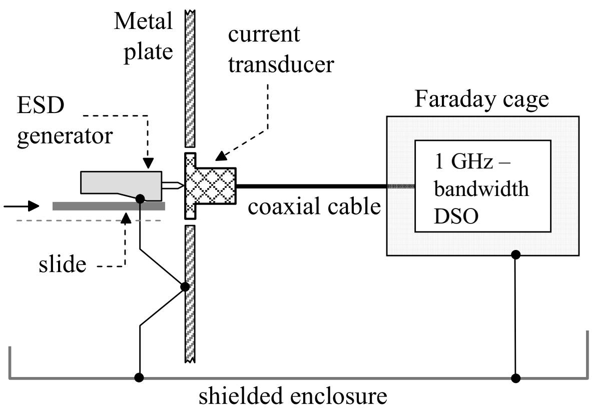

Figure 1. Description of the used measurement system

The measurement system includes the following items:

1) a slide allowing horizontal movement, with speed control;
2) an ESD generator KeyTek MZ-15/EC MiniZap, placed over the slide;
3) a 1.0 m × 1.0 m vertical metal plane;
4) a coaxial current transducer mounted in the centre of the vertical metal plate;
5) a radiofrequency (RF) interconnection coaxial cable;
6) a digital storage oscilloscope (DSO) Tektronix DPO 7054 (1 GHz frequency band), placed inside a Faraday cage to prevent it from the electromagnetic field radiated by the ESD generator discharge.

Indeed, the latest draft revision of the IEC ESD standard requires a larger dimension of the metal plate and a wider bandwidth of the DSO (2 GHz), but for the relative comparisons proposed in this paper, the employed plate dimensions and DSO bandwidth can be considered adequate.

As shown in the figure, the metal plate and Faraday cage are both grounded to the surrounding shielded enclosure. The ESD generator is instead connected to the metal plate. A picture of the test system, with a detail view of the ESD generator and the sliding mechanism is given in Fig. 2. The two micro-switches are used to monitor the length of the time interval in which the gun is moved.

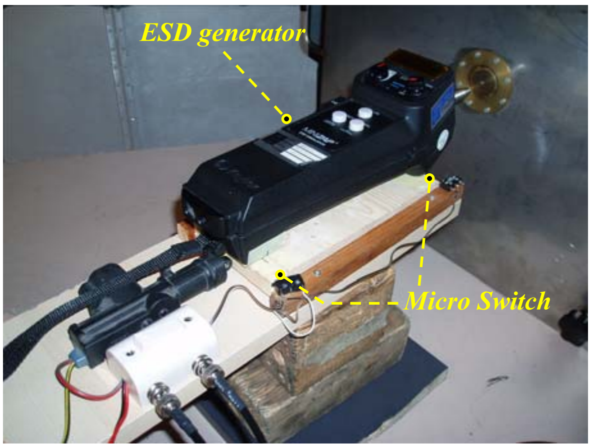

Figure 2. Detail of the used test system

A typical waveform of the output current from the ESD generator is shown in Fig. 3 [1]. The figure highlights the main parameters to be considered for the characterization of an ESD generator: the peak value of current, I_P, the current values at 30 ns and 60 ns from the peak instant, I_{30ns} and I_{60ns}, respectively, and the rise time t_r.

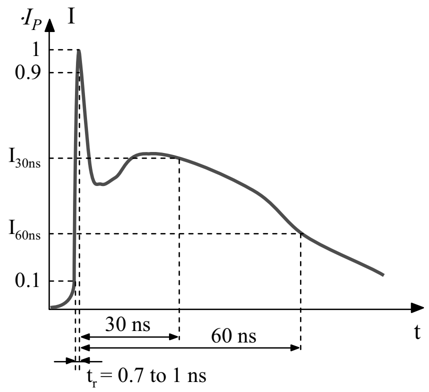

Figure 3. Typical waveform from an ESD generator output

During the experiments, special attention has been paid in order to reduce the influence of humidity variations on test repeatability and accuracy. To this aim, both the humidity and temperature have been properly monitored and controlled in all the performed tests [4]. An effort has been also made to reduce the influence on test accuracy of the variations of the angle between the ESD gun tip and the target plane (current transducer) [7]. To this aim, the angle has been maintained as orthogonal as possible with respect to the target plane, during all the performed experiments.

In order to investigate the effects of the gun speed on the measurement, five different values have been considered: (i) very slow (~1 cm/s), (ii) slow (~2 cm/s), (iii) normal (~4 cm/s), (iv) fast (~7 cm/s), (v) very fast (~12 cm/s). Such values have been chosen considering the experience of some in-the-field operators, interviewed on purpose about their perceived meaning of the speed concept introduced in [1] and [2].

The voltage at the tip side has finally been set at the following peak values: 4, 6, and 8 kV, while the current, *I*, has been measured through the DSO, by means of ten repeated observations.

III. Experimental Results

A number of experiments have been performed with the measurement setup described in Section II. Tests have been repeated in different setup configurations, upon the varying of the gun speed, humidity and tip angle.

A. Gun speed effects

In Figs. 4, 5, and 6, the results obtained from ten acquired waveforms of *I* and for the voltage levels 4, 6, and 8 kV are shown. The standard deviation (σ) for each time sample is shown to better highlight the variability of the current estimates around the mean value, and, ultimately, to check the repeatability of the test. In the diagrams, only the two boundary speed configurations ("very fast" and "very slow") are shown.

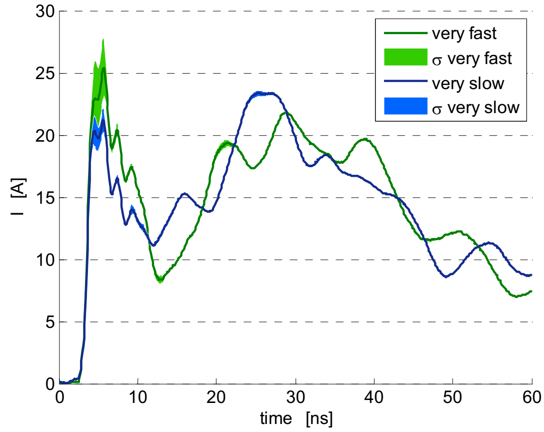

Figure 4. Acquired current waveforms with a 4 kV voltage

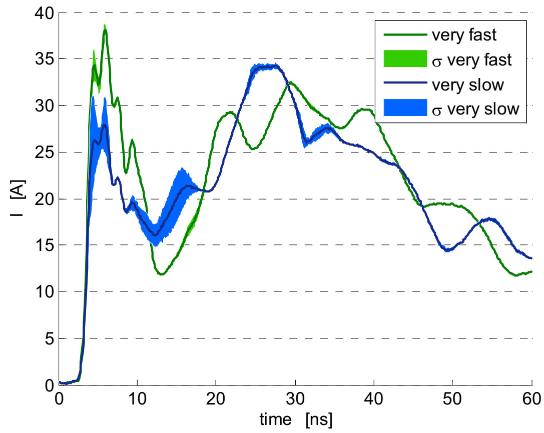

Figure 5. Acquired current waveforms with a 6 kV voltage

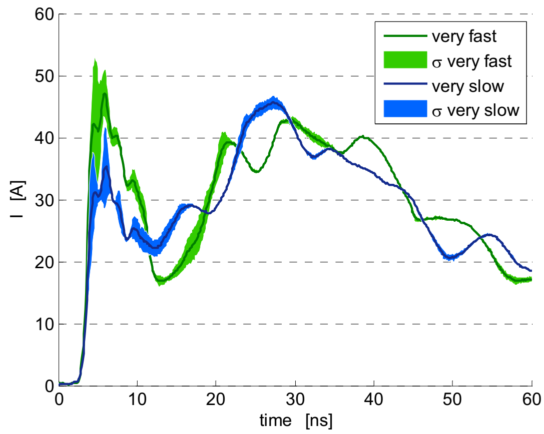

Figure 6. Acquired current waveforms with a 8 kV voltage

The diagrams clearly show a remarkable difference between the curves obtained with a very slow speed compared to those obtained with a very fast speed. In particular, the major differences can be noted at the peak time instant. This confirms the strong influence that the chosen ESD gun speed may have on the current waveform and on parameters like the peak value. They also highlight non-negligible values of the standard deviation around the mean value, especially at the peak time instant (in Figs. 4 and 6). Clearly this fact has severe consequences in terms of measurement repeatability.

From the curves of Figs. 4, 5 and 6, the above recalled parameters I_P, I_{30ns}, I_{60ns}, and t_r can be estimated. Such results (mean values) are summarized in Tables I, II, and III.

TABLE I. RESULTS WITH A 4 KV VOLTAGE

4 kV	t_r [ns]	I_P [A]	I_{30ns} [A]	I_{60ns}[A]
Very Fast	1.4	25.41	18.87	8.01
Fast	1.5	24.40	18.00	7.85
Normal	1.1	20.77	17.75	8.11
Slow	1.1	20.02	17.26	7.75
Very Slow	1.1	21.17	17.98	7.78

TABLE II. RESULTS WITH A 6 KV VOLTAGE

6 kV	t_r [ns]	I_P [A]	I_{30ns} [A]	I_{60ns} [A]
Very Fast	1.6	38.10	29.30	12.62
Fast	1.6	35.52	29.46	12.80
Normal	1.3	31.54	27.16	12.24
Slow	1.3	29.97	21.17	11.57
Very Slow	1.3	27.93	26.98	12.44

TABLE III. RESULTS WITH A 8 KV VOLTAGE

8 kV	t_r [ns]	I_P [A]	I_{30ns} [A]	I_{60ns} [A]
Very Fast	1.8	47.10	39.59	17.28
Fast	1.8	46.96	39.76	17.28
Normal	1.8	43.60	39.40	16.16
Slow	1.7	37.89	35.61	16.15
Very Slow	1.7	35.39	37.02	17.33

The tables confirm the strong dependence of the current values on the ESD gun speed. For instance, in the case of the peak current, an I_P reduction of 21.2, 26.7, 24.4 % is observed by reducing the speed from "very fast" to "very slow", for the cases of 4, 6, 8 kV respectively. On the contrary, smaller differences can be observed for the other parameters, where the obtained values appear more independent of the chosen gun speed.

The fact that the speed of the gun influences the first peak of the discharge current is due to the different instant at which the arc occurs. In fact the time required for the air ionization is comparable with the path-time of the gun during the approach. As a consequence, with a high speed the arc occurs at shorter distance than that occurring with a slow speed. Moreover, the parasitic capacitance between the body of the ESD gun and the object where the discharge occurs should be taken into account, as shown in [8]. For the high frequency components of the ESD current this capacitance (typically some picofarad) offers an alternative path with respect to the strap used for grounding the ESD gun. When approaching the gun to the object with a faster speed, the ESD event occurs at a smaller distance and consequently higher is the parasitic capacitance causing "more" current. Further details about this point will be provided in the subsequent simulation section.

B. *Angle effects*

A possible effect of the angle between the ESD gun tip and the target plane (β) is the reduction of the speed component perpendicular to the target. Referring to Fig. 7, the approach speed (S_{APP}) is decomposed into two components: $S_{//}$ and $S_{\perp}$. The latter is the speed proportional to the *sin β* and responsible for the discharge. The best case is for β = 90°, at which the gun is orthogonal to the target plane.

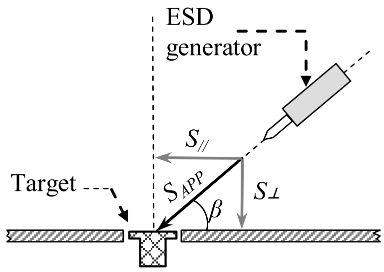

Figure 7. Effect of the angle between the gun and the target

Some tests have been done with different β values: *i)* 90°, *i.e.* the ideal case, *ii)* 75°, and *iii)* 60°. Results of the mean values for the case of 4 kV voltage with the "normal" approach speed are summarized in Fig. 8, where it can be noted an important reduction of the discharge waveform when the gun is not orthogonal to the metallic plate.

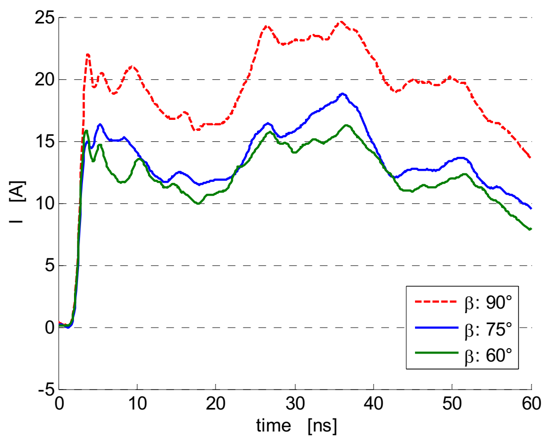

Figure 8. Angle effects: 4 kV voltage, "normal" approach speed

Other tests have been performed with the gun oriented as well as possible orthogonal to the plate. This measure proofs that for small variations of the gun angle (below 2°) the uncertainty discharge trend is very close to that obtained during the normal test.

C. *Humidity effects*

In order to investigate the effects of the humidity variation, tests have been carried out within a calibrated climatic chamber. In particular, a different gun has been used equipped with an external control apparatus EMC-Partner ESD 2000, as shown in Fig. 9. Tests have been accomplished with a constant chamber temperature of 20°.

In this scenario, quite the same results in terms of current waveforms have been obtained with respect to the case discussed in Section IIIA.

Figure 9. ESD test into climatic chamber

Some results from the performed tests are summarized in Table IV in terms of peak current values I_P. Different relative humidity (RH) levels (35 and 50%), tip peak voltages (4 and 8 kV), and gun speeds have been considered in the tests.

TABLE IV. RESULTS WITH HUMIDITY VARIATION

I_P [A]	4 kV		8 kV	
	35% RH	50% RH	35% RH	50% RH
Very Fast	21.52	16.80	39.48	26.80
Fast	21.16	16.35	37.51	26.32
Normal	20.80	15.75	35.20	24.91
Slow	19.75	15.27	31.33	24.26
Very Slow	18.50	12.96	28.85	24.12

The results highlight a visible dependence of the current peak values on the humidity variations (from 20% up to 30%). This is due to the fact that the air itself, being dry, becomes a part of the electrostatic build-up mechanism. These results can be considered in good agreement with those documented in [8], where a strong correlation between RH and the peak current is shown. In [8], it is also shown that the peak current is approximately related to the inverse cube of RH. Therefore, given a same probability of ESD events, the current values at RH=15% are expected to be 20 through 40 times higher than at RH=45%.

IV. SIMULATION ANALYSIS

The model used in the simulations, sketched in Fig. 10, is based on the circuit described in [9]. Some modifications have been purposely introduced in order to better approximate the experimental waveforms of Fig. 4. The main parameters causing the different discharge current peak are the inductance associated to the tip (*pLtip*), and the stray capacitance between the ESD gun body and the target, or EUT (*pCgb*). These parameters change when an air discharge occurs and are function of the approaching speed of the ESD gun to the object. This means a greater stray capacitance *pCgb* and a lower inductance *pLtip* associated to the tip in the fast approach. The values considered for the simulations are: *pCgb* = 7.5 pF, *pLtip* = 0.14 µH for "very slow" case; *pCgb* = 15 pF, *pLtip* = 0.1 µH for "very fast" case. No intermediate speeds have been investigated. The length of the strap was 2 m.

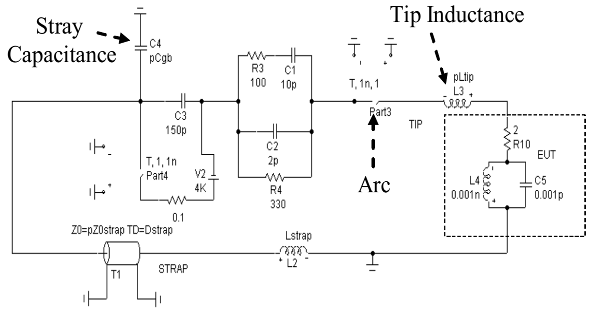

Figure 10. Equivalent circuit used for simulations

Fig. 11 shows the simulation results of the discharge trend both for the very slow and very fast approach. The figure confirms, once again, that the fast approach is the cause of a higher current peak. It is also important to emphasize that the ESD discharge generates a radiated field around and within the EUT. This field is the major responsible for failures in the victim apparatuses and its value is directly related to the current peak trend.

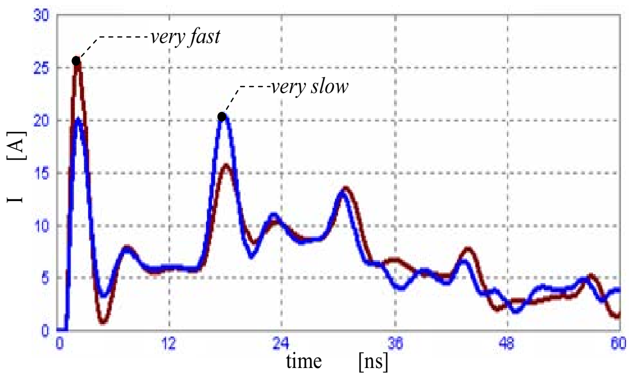

Figure 11. Simulation results for different approach speed

V. UNCERTAINTY BUDGET

As defined in the ISO GUM [6], the type A uncertainty contribution of the performed current amplitude measurements is just the standard deviation of the obtained observations. In the previous tests, a visible variability of such observations has been noted upon the varying of the approach speed. In Table V the standard deviation of the current peak I_P is shown for the different speed cases previously analyzed.

TABLE V. STANDARD DEVIATION OF I_P

Ip [A]	*4 kV*	*6 kV*	*8 kV*
Very Fast	2.34	1.08	7.85
Fast	3.15	10.76	2.47
Normal	1.87	11.45	6.05
Slow	3.65	6.65	8.27
Very Slow	2.04	5.99	11.75

It can be observed that the variability does not seem to be related to the speed. This confirms that such tests are not very repeatable, although a same speed has been used during the test.

However, the uncertainty of the discharge current also depends on the repeatability of the cable/adaptor connection, the measuring instrument errors, the current conversion factor of the target, the mismatch error between the input port of the DSO and the current transducer. In [4] an expanded uncertainty with confidence level of 95.5% is computed with a coverage factor $k = 2$. The relative uncertainty (U_{RE} %) is obtained by dividing the expanded uncertainty by the corresponding current parameter. A comparison between the combined uncertainty due to the different contributions and the uncertainty due to the only speed and humidity variation is now considered.

In Table VI the relative uncertainty for the current peak I_P is shown. In the case *A*, all the contributions obtained without approach speed and humidity effects [4] are considered, which corresponds to type B uncertainty. In the other cases, the uncertainties U_{RE} are computed using the mean values for each voltage level as a function of the speed variation, which corresponds to the type A uncertainty contributions. In the case *B*, all the intervals between "very slow" and "very fast" are considered; in the case *C* all the intervals between "normal" and "very fast" are taken into account; in the case *D* all the intervals between "very slow" and "normal" are instead accounted for. Indeed, in the case in which many repeated measurements are performed, a higher possibility to have a non-constant speed from one test to another is possible: in this circumstance, cases *C* or *D* are more likely. Finally the effects of humidity variation are summarized in the case *E* for a normal speed and 15% humidity variation.

TABLE VI. RELATIVE SPEED UNCERTAINTY OF *IP*

U_{RE} [%]	*4 kV*	*6 kV*	*8 kV*
case A	6.07	5.05	6.14
case B	21.39	25.40	24.93
case C	8.63	18.85	20.74
case D	21.13	12.14	5.65
case E	39.07	28.76	48.41

Since the effects of the other physical parameters on the uncertainty of repeated measurements are negligible, the errors due to the different speeds or humidity used during the test could reduce the effectiveness of any solution adopted to improve the test repeatability.

The effects of the angle can instead be contained by maintaining the gun as orthogonal as possible with respect to the target plane.

VI. CONCLUSIONS

In this paper, the repeatability contribution on the evaluation of uncertainty in air discharge tests has been analyzed. It has been shown that the type A uncertainty, not so important for contact ESD tests, becomes essential in the case of air ESD tests. In fact, if not adequately controlled, it may lead to a relevant degradation of the test repeatability in an ESD generator. About this issue, quite opposite requirements are provided in the available standards. This means that lab technicians might interpret such requirements in different ways, to the detriment of the test repeatability. To this aim, a proposal has been reported in the paper, aimed at improving the repeatability of the test, and suggesting new requirements for future versions of the standards. The proposal is also based on a specific device, to be used for the control of the gun speed in air discharge tests. Finally, from measurements performed within the climatic chamber, it has been found that the uncertainty contribution associated to the humidity variation during the tests must be below 2% with humidity variations lower than 1%.

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