Letters

Step-Response-Based Calibration Method for ESD Generators in the Air-Discharge Mode

Sen Yang, Aniket Bhandare, Hossein Rezaei, Wei Huang, and David J. Pommerenke

***Abstract*—The current IEC 61000-4-2 (2008) standard does not provide calibration specifications for electrostatic discharge (ESD) generators in the air-discharge mode. This is largely due to the well-known fact of poor repeatability in air-discharge measurements. This complicates identifying an acceptable tolerance range of a reference waveform for air discharge. The variability of the discharge waveforms is caused by variations in the spark length. A novel air-discharge calibration method is proposed, which avoids sparking. The method is based on measuring the step response of an ESD generator in the air-discharge mode using a mercury-wetted relay. Possible nonlinear effects are identified during the contact-mode ESD simulator calibration at higher voltages; thus, in combination, an air-discharge calibration method is provided. This letter explains the method and shows excellent repeatability.**

***Index Terms*—Air discharge, electrostatic discharge (ESD) generator calibration, ESD gun, step response.**

I. Introduction

ELECTRONIC products must comply with IEC [1] and/or ISO [2] electrostatic discharge (ESD) immunity standards before entering markets. Contact discharge and air discharge are considered in these standards and have been analyzed in [3]–[6]. During contact-discharge measurement, the ESD generator (also known as "ESD gun") tip contacts directly with the device under test (DUT). The discharge occurs when the internal relay of the ESD generator closes. In the air-discharge measurement, the internal relay is kept closed as the charged ESD generator approaches the DUT. The discharge in the air gap between the ESD generator tip and the DUT can occur when the distance reaches a certain length. The current-carrying charge carriers within the spark can either originate from surface processes or a result of gas discharge processes [7].

For contact discharge, the discharge current waveforms are highly repeatable because the high-voltage spark only occurs inside the ESD generator's internal relay. Thus, it is possible to specify a standard waveform for the contact-discharge measurement. On the other hand, for ESD air-discharge measurements, it is well known that the current waveforms repeat poorly due to the variations of the spark resistance, which results from the variation of the spark length. The variations of the arc length are a result of the approach speed and the statistical time lag. The statistical time lag is affected by speed of approach, humidity, surface conditions, voltage, etc. [8]. Thus, it is difficult to define a reference current waveform for the air-discharge calibration.

To produce better repeatability in the air-discharge mode discharge current, two approaches exist.

1) Discharge at a spark length given by the Paschen equation [8]–[12]. This can be realized by slowly approaching the ESD generator, possibly combined with methods that reduce the statistical time lag. Here, strong ultraviolet light, high humidity, and graphite layers on the electrodes can be used. If this method is selected, the discharge waveforms will repeat well, especially above 5 kV. However, the current rise will be rather slow (e.g., 3 ns at 10 kV), as the long arc length leads to a slow drop in the arc resistance. The current rate of changes will be for voltages above 3 kV in the range of a few amperes per meter. Thus, the arc is stabilized at a low threat level. Most fine structure of the step response of the ESD generator and high-frequency components of the current waveform and fields will be suppressed by the slow drop of the arc resistance. Thus, the test is more determining the selection of the main *RC* components of the ESD generator. In addition, Ishida *et al.* proposed an air-discharge calibration method based on fixed-gap discharge [13]. The idea is to use a fixed gap to replace the varying distance between the ESD gun tip and the ESD target of the typical air-discharge measurement. The process used spark gaps from Paschen length down to one-third of Paschen length. The shorter strongly overvoltage gaps lead to fast rise times and high peak currents. As the spark length is fixed, the waveforms are repeatable. However, they are still influenced by the time-varying spark resistance. Another condition for this method to work is that the voltage rise, which is initiated by closing the internal relay, is much faster than the statistical time lag. Otherwise, it could happen that the discharge already occurs while the voltage is rising.
2) If a low voltage is used and the ESD generator approaches the ESD target fast, the arc resistance may approach an ideal step function. One would hope that its resistance changes from infinite to nearly zero in picoseconds. Achieving this would allow capturing the step response

Manuscript received October 24, 2017; accepted October 30, 2017. Date of publication December 5, 2017; date of current version May 29, 2018. *(Corresponding author: David J. Pommerenke.)*

S. Yang, A. Bhandare, H. Rezaei, and D. J. Pommerenke are with the Electromagnetic Compatibility Laboratory, Department of Electrical and Computer Engineering, Missouri University of Science and Technology, Rolla, MO 65409 USA (e-mail: sydgf@mst.edu; anbwx7@mst.edu; hrr7d@mst.edu; davidjp@mst.edu).

W. Huang is with ESDEMC Technology LLC, Rolla, MO 65409 USA (e-mail: whuang@esdemc.com).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TEMC.2017.2776749

0018-9375 © 2017 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

Authorized licensed use limited to: Missouri University of Science and Technology. Downloaded on March 01,2022 at 07:46:07 UTC from IEEE Xplore. Restrictions apply.

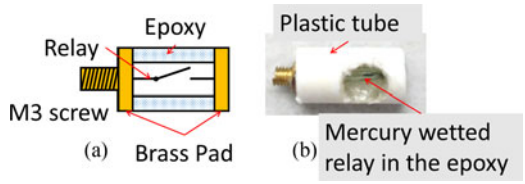

Fig. 1. (a) Diagram and (b) photo of the mercury relay tube.

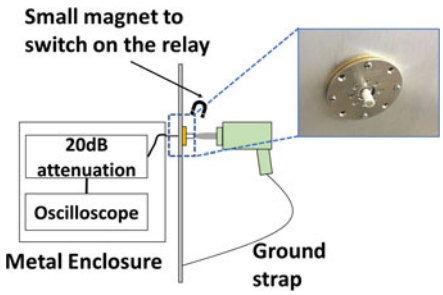

Fig. 2. Mercury-wetted relay attachment screwed into the center conductor of the ESD current target.

of the ESD generator. The problem is that the spark gap formed between the ESD target and the ESD generator tip does not act as an ideal switch even at fast approach speeds. Here, the method suggested in this letter improves this concept by using a mercury-wetted relay that approaches an ideal switch much better.

The approach presented in this letter avoids testing ESD generators in the actual air-discharge mode that have a spark at the tip. The proposed method measures the step response of the ESD generator in the air-discharge mode using a mercury-wetted relay. The details of the structure and the measurement setup are explained in the following sections. Human body discharge step response was also measured using the same mercury relay setup. In this measurement, the tester is first charged to certain voltage (1 kV) and then discharges with the mercury relay. The measured human body discharge waveform can serve as a reference for the air-discharge mode waveform for the air-discharge calibration.

II. Step Response Method

A. Mercury-Wetted Relay

To measure a good approximation of the step response of the ESD generator, a mercury-wetted relay is mounted between the tip and the ESD current target. The additional structure has a length of 16.4 mm. It substitutes the actual spark (see Fig. 1). ESD current targets have a discharge pad at their center [1]. In this measurement, the discharge pad is replaced with the mercury relay, which is enclosed into an epoxy filled tube to ensure mechanical stability. The relay is activated once a permanent magnet is brought into its proximity.

B. Step Response Measurement for the ESD Gun

The mercury relay tube is screwed onto the center of the ESD target (see Fig. 2). The selected relay cannot withstand voltage higher than 2 kV, so measurements were performed at 1 kV.

An Agilent DSO81304A Oscilloscope was used in the measurement. Three ESD generators from different manufacturers were tested. They will be labeled as "ESDGUN1," "ESDGUN2," and "ESDGUN3" in the measurement results section.

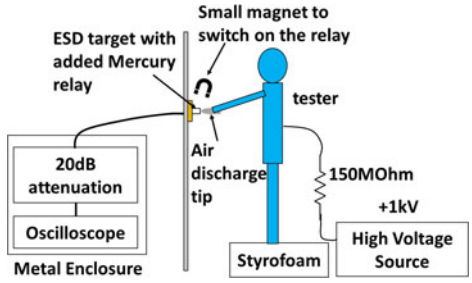

Fig. 3. Illustration of human metal discharge step response measurement.

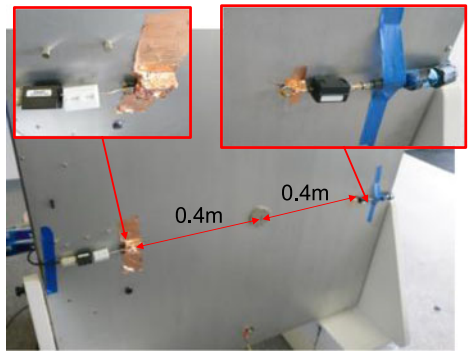

Fig. 4. E- and H-field measurement setup, based on the IEC ESD generator calibration standard. The frequency response of the E-field probe is flat from about 2 MHz to 2 GHz.

C. Step Response Measurement for Human Metal Discharge

The event of human discharging via a hand-held metal (human metal model, HMM) forms the reference event for the IEC 61000-4-2 standard, and it can be tested how similar the step response of the air-discharge mode generators is to the HMM events. As shown in Fig. 3, the person is standing on an insulator and is connected to a high-voltage supply. The tester holds the air-discharge tip against the mercury relay when the step response is measured. The discharge current and transient field of two testers were measured; the text refers to them as "Person1" and "Person2."

D. Transient Field Measurement

Previous research has shown that the transient fields of ESD generators in the contact mode differ strongly, especially in the higher frequency region [14]. The variation in the transient field often causes different equipment under test failure levels when using different ESD generators. Thus, the transient fields during a step response excitation were captured. Fig. 4 shows the setup of the transient field measurement. A shielded loop probe having a loop diameter of 1 cm is used for H-field measurement. The E-field sensor, which was shown in [15], is used in the measurement. The E-field sensor has a flat response from 2 MHz to 2 GHz. On the other hand, waveform deconvolution [16] is needed for the H-field data as the sensitivity of the loop probe drops at lower frequencies by 20 dB/dec. The H-field probe is good for up to 2 GHz. The transient fields at 10 and 40 cm distance from the ESD target center were measured. The discharge current, E-field, and H-field are recorded simultaneously. It should be noted that the transient field of the ESD generator discharge event is not rotationally symmetric [14]. The E/H fields in this setup were measured at different locations (see Fig. 4).

Authorized licensed use limited to: Missouri University of Science and Technology. Downloaded on March 01,2022 at 07:46:07 UTC from IEEE Xplore. Restrictions apply.

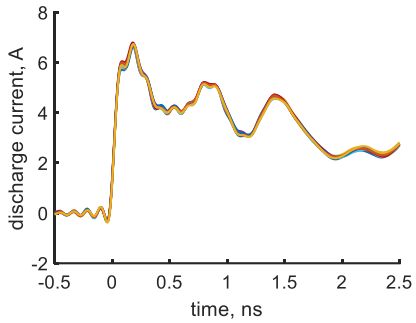

Fig. 5. Ten discharge waveforms of the ESDGUN1 in the air-discharge mode showing excellent measurement repeatability.

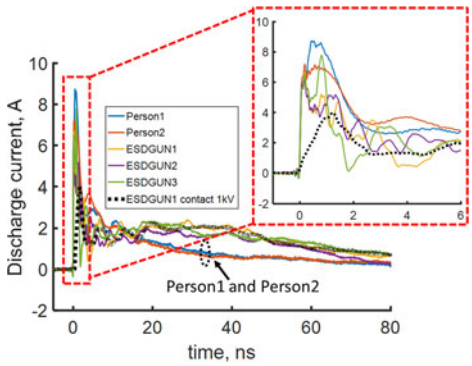

Fig. 6. Step response currents for three ESD generators and two people.

III. Experiment Results

A. Repeatability

Achieving repeatability is the main challenge for every air-discharge calibration method. The mercury-wetted relay is the best possible approximation of an ideal switch; thus, it has achieved excellent repeatability in both human metal and ESD generator discharges. Fig. 5 illustrates the repeatability of the current measurement. The variation in the peak values are within $\pm 1\%$ with respect to the average peak value.

B. Discharge Current

The data shown in Fig. 6 compare ESD generators and discharges from people holding the air-discharge tip in their hand. The waveforms represent the step responses and the initial rise of all waveforms is similar. The rise time is determined by the "ideal switch" formed by the mercury relay, and it is also limited by the bandwidth of the oscilloscope. Since the ESD target shows ideal impedance up to 5 GHz, the measured discharge current data will be filtered by a 5-GHz first-order low-pass filter. The discharge current of ESDGUN1 in the contact-discharge mode (black dotted line) is also shown in Fig. 6.

Core findings from the discharge current comparison in Fig. 6 are the following.

1) The measurement method gives repeatable step response information that allows characterization of the ESD generators in the air-discharge mode without having any effect of an arc.
2) The peak values of these three generators varied between 6.4 and 7.8 A, which are well within $\pm 15\%$ of the average measured ESD generator peak values for a charge voltage of 1 kV (a larger sample size of ESD generators may show higher variations between ESD generators).

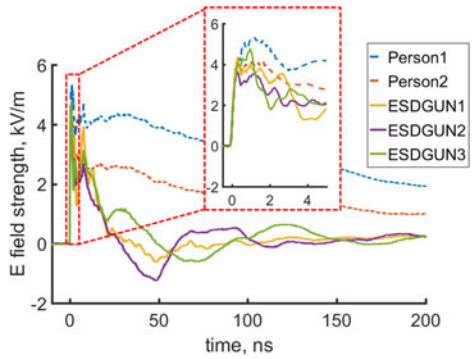

Fig. 7. E-field of the step response measurement result at 10 cm at +1 kV for three ESD generators and two human metal discharges, the measurement bandwidth is limited to 2 GHz (E-field sensor) at 1 kV charge voltage.

3) Comparing the 1 kV ESDGUN1 air-discharge step response (yellow solid line) to the contact-mode discharge (black dotted line) reveals a 2.6 A larger peak current value, which is partially explained by the difference in rise time. There is also significantly more charge in the initial peak of the step response. This agrees with the observation in [9]. The authors reported that the total charge of the air discharge is higher than the contact discharge in the same level. This can be explained by the fact that all metal parts downstream of the relay are not charged in the contact mode, but in the air-discharge mode, they are charged to the set voltage. The later parts of waveforms (after 10 ns) almost overlap. This results from having the same *RC* network for the contact mode and the step response.
4) The human metal ESD ("Person1" and "Person2") showed larger current values of 7–8.2 A. This is caused by the local capacitance of the hand that is close to the grounded wall. This structure is bulkier than the tip region of most of the ESD generators leading to a higher current in the step response (see Fig. 3). The total charge of the human metal ESD was less than the total charge of the ESD generators. This is to be expected as in most of the cases, the capacitance of a human to ground is less than the 150 pF as specified in the ESD standard. Human-to-ground capacitances can be as low as 70 pF in a wood frame house [17]. For a given tribo charge value, the voltage on a human may reach double the value in a wooden frame house relative to the human standing (insulated) on a conductive floor.
5) All air-discharge ESD generators showed some ringing; each shows ringing at a different frequency. The human metal ESD does not show the double peak structure, which is (for historical reasons) part of the IEC standard's reference waveform. It is known and has been reported many times that the human metal ESD only rarely shows the clear double-peak structure [18].

C. Transient Field Results

The setup of the field measurement is shown in Fig. 4. The following conclusions can be drawn from Fig. 7.

1) The peak field strength at 10 cm is between 4.5 and 5.5 kV/m at a 1 kV charge voltage. In a real air-discharge situation, one could not expect that the field strength increases linearly with voltage, as the rise time would typically increase with voltage.

Authorized licensed use limited to: Missouri University of Science and Technology. Downloaded on March 01,2022 at 07:46:07 UTC from IEEE Xplore. Restrictions apply.

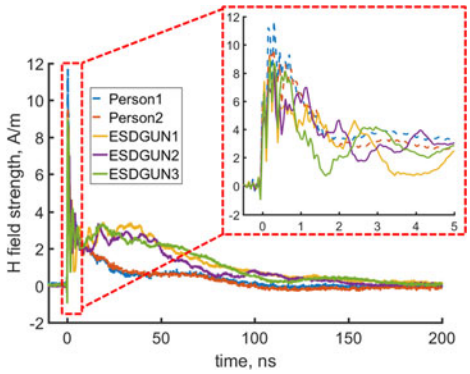

Fig. 8. H-field of the current step response measurement at 10 cm at 1 kV for three ESD generators and two human metal discharges.

2) The human metal ESD shows a much larger electric field in the later time of the waveform as a result of having a charged body. The ESD generators store the energy of the charged body in a discrete capacitor. Thus, these fields are not visible outside the ESD generator. Furthermore, the ground return path for an ESD generator and that of a charged human body is quite different. This may also contribute to the differences in Fig. 7.
3) The rise time is determined by the relay and the field sensors' bandwidth (about 2 GHz); thus, it cannot be attributed to properties of the ESD generator.

The magnetic field data in Fig. 8 show that the peak values are in the range 9–11 A/m for the cases investigated at 1 kV, the rising edge is determined by the mercury relay, not by the ESD generators, and the H-field waveform shapes are similar to the corresponding discharge current waveforms at this distance.

IV. Discussion

The air discharge is well known for its poor repeatability due to the variation of the spark length for approaching electrodes. Several attempts have been made in the hope of defining a calibration method for ESD generators in the air-discharge mode. Greatly improved repeatability can be achieved either by a fixed gap [13] or by only considering discharges at spark lengths defined by Paschen's law. Although carefully controlling the experimental parameters such as approaching speed, humidity, and air pressure can improve repeatability, it is not possible to achieve the repeatability of the contact mode as long as a spark is part of the testing. The proposed method overcomes this by avoiding the arc and capturing the step response of the linear ESD generator. The measured currents and fields repeat well in the contact mode, such that differences between different brands of ESD generators become clearly visible. The data also indicate that the peak current variation between different brand ESD generators (sample size of only three) is in the same range (within $\pm 15\%$) as accepted for the contact mode. As the spark is substituted by a relay, no useful rise-time measurement can be performed. We do not consider this as a disadvantage, as the rise time in air discharge is determined by the drop of the arc resistance, and the arc physics is independent of the specific model of the ESD generator used. Another concern is nonlinearity. If there are nonlinear elements in the system, such as a saturating ferrite, sparking to some floating metal, or simply a wrong high-voltage supply value, this will be detected in the contact-mode calibration. For that reason, we believe that the air-discharge calibration does not need to repeat the high-voltage testing. A description by step response is sufficient, as nonlinear problems would be detected during the contact-mode calibration.

V. Conclusion

A calibration method is proposed in this letter for ESD generator air-discharge measurement. The method is based on the step response, which is realized by using a mercury-wetted relay. The mercury relay measurements are highly repeatable, and it excludes any arc effects. Thus, the data show the effect of the ESD generator structure. This method has the potential to be a calibration method of the ESD generator in the air-discharge mode.

References

[1] *Electromagnetic Compatibility (EMC), Part 4: Testing and Measurement Techniques—Section 2: Electrostatic Discharge Immunity Test*, IEC Standard 61000-4-2, 2001.
[2] *Road Vehicles—Test Methods for Electrical Disturbances from Electrostatic Discharge*, ISO Standard 10605, 2001.
[3] G. Shen *et al.*, "Simple D flip-flop behavioral model of ESD immunity for use in the ISO 10605 standard," in *Proc. IEEE Int. Symp. Electromagn. Compat.*, Raleigh, NC, USA, 2014, pp. 455–459.
[4] G. Shen *et al.*, "ESD immunity prediction of D flip-flop in the ISO 10605 standard using a behavioral modeling methodology," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 4, pp. 651–659, Aug. 2015.
[5] J. Zhou *et al.*, "IEC 61000-4-2 ESD test in display down configuration for cell phones," in *Proc. IEEE Int. Symp. Electromagn. Compat.*, 2016, pp. 713–718.
[6] D. Liu *et al.*, "Full-wave simulation of an electrostatic discharge generator discharging in air-discharge mode into a product," *IEEE Trans. Electromagn. Compat.*, vol. 53, no. 1, pp. 28–37, Feb. 2011.
[7] S. Bönisch, D. Pommerenke, and W. Kalkner, "Broadband measurement of ESD risetimes to distinguish between different discharge mechanisms," *J. Electrostatics*, vol. 56, no. 3, pp. 363–383, 2002.
[8] D. Pommerenke, "On the influence of the speed of approach, humidity and arc length on ESD breakdown," in *Proc. ESD Forum*, Grainau, Germany, 1993, pp. 103–111.
[9] H. M. Ritter, L. Koch, M. Schneider, and G. Notermans, "Air-discharge testing of single components," in *Proc. 37th Elect. Overstress/Electrostatic Discharge Symp.*, Reno, NV, USA, 2015, pp. 1–7.
[10] J. Zhou *et al.*, "ESD spark behavior and modeling for geometries having spark lengths greater than the value predicted by Paschen's law," *IEEE Trans. Electromagn. Compat.*, vol. 60, no. 1, pp. 115–121, Feb. 2018.
[11] Q. Yuan, S. Liu, X. Zhang, Z. Wu, and M. Wei, "The effect of approach speed and charge voltage on an air discharge," *IEEE Trans. Electromagn. Compat.*, vol. 52, no. 4, pp. 985–993, Nov. 2010.
[12] M. Borsero, S. Caniggia, A. Sona, M. Stellini, and A. Zuccato, "A new proposal for the uncertainty evaluation and reduction in air electrostatic discharge tests," in *Proc. Int. Symp. Electromagn. Compat.*, Hamburg, Germany, 2008, pp. 1–6.
[13] T. Ishida, F. Xiao, Y. Kami, O. Fujiwara, and S. Nitta, "An alternative air discharge test in contact discharge of ESD generator through fixed gap," in *Proc. IEEE Int. Symp. Electromagn. Compat.*, Ottawa, ON, Canada, 2016, pp. 46–50.
[14] J. Koo *et al.*, "Correlation between EUT failure levels and ESD generator parameters," *IEEE Trans. Electromagn. Compat.*, vol. 50, no. 4, pp. 794–801, Nov. 2008.
[15] R. Chundru, D. Pommerenke, K. Wang, T. Van Doren, F. P. Centola, and J. Sheng Huang, "Characterization of human Metal ESD reference discharge event and correlation of generator parameters to failure levels—Part I: Reference event," *IEEE Trans. Electromagn. Compat.*, vol. 46, no. 4, pp. 498–504, Nov. 2004.
[16] S. Yang, J. Zhou, D. Liu, and D. Pommerenke, "A simple frequency response compensation method for current probe measurements of ESD currents," in *Proc. IEEE Int. Symp. Electromagn. Compat.*, 2017, pp. 158–163.
[17] A. Talebzadeh, M. Moradian, Y. Han, D. E. Swenson, and D. Pommerenke, "Effect of human activities and environmental conditions on electrostatic charging," *IEEE Trans. Electromagn. Compat.*, vol. 58, no. 4, pp. 1266–1273, Aug. 2016.
[18] D. Pommerenke and M. Aidam, "ESD: Waveform calculation, field and current of human and simulator ESD," *J. Electrostatics*, vol. 38, nos. 1/2, pp. 33–51, Oct. 1996.

Authorized licensed use limited to: Missouri University of Science and Technology. Downloaded on March 01,2022 at 07:46:07 UTC from IEEE Xplore. Restrictions apply.