Measurement of the electric field at the near field radiating by electrostatic discharges

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Abstract: This work aims to study the transient electric field radiating by two different generators of electrostatic discharges, which are constructed according to the Standard related to electrostatic discharges. Measurements of the electric field generated by contact electrostatic discharges a few centimetres away from the discharge point are presented. With the aberration to the Standard that the current transducer is mounted on an insulating material instead of a metal plate a closer simulation to real electrostatic discharges is obtained. Measurements proved that there are differences from generator to generator and also differences at the same generator, depending on its orientation.

Key-Words: Electrostatic Discharge (ESD), Equipment Under Test (EUT), Electric Field, Pellegrini Target, International Standard IEC 61000-4-2, ESD generators, ESD measurement system

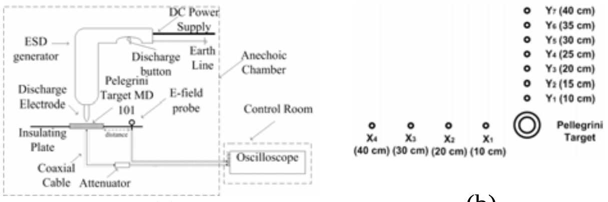
1. Introduction

This paper presents measurements of the electric field using E-field probes, with the aim of contributing the upcoming version of the Standard [1]. Many researchers have been involved in the study of the transient electromagnetic field radiating by electrostatic discharges [2-13]. It was observed that there is a strong probability that the Equipment Under Test (EUT) will pass a test, when conducting measurements using a certain Electrostatic Discharge (ESD) generator and fail when using another, both cases referring to the same charging voltage and to the same discharge current. This rises from the fact that each ESD generator produces a different electromagnetic field, causing the induced voltage to differ. This work aims to study the produced electric field, when the Pellegrini target is mounted on an insulating material instead of a metal plate as the Standard defines, because this way there is a closer approach to the real ESD event.

2. Experimental setup

Fig.1a shows the experimental set-up. The current and the electric field strength (E-field) for various charging voltage levels were measured simultaneously, by the 4-channel Tektronix oscilloscope model TDS 7254B, whose bandwidth ranged from dc to 2.5GHz. The electrostatic discharges were contact discharges and they were conducted using two Schaffner's ESD generators. The experiment was conducted only for contact discharges, because air discharges are difficult to be reproduced. In air discharges the produced electric arcs are different. Therefore the produced electromagnetic fields can be compared only if the electric arcs of the air discharges are the same. This is also the reason why the verification of the ESD generators is made only for contact discharges.

The ESD generators used were the NSG-433 and the NSG-438. The discharge electrode in both generators had the same length and it was equal to 5cm. In order for the measurement set-up to be unaffected by surrounding systems, the experiment was conducted in an anechoic chamber. The generator's capacitance was charged at ±2 kV and ± 4kV the discharge electrode of the ESD generator used for the contact discharge measurements had a sharp point. The temperature and relative humidity were 23±1^{o}C and 40±4%, respectively. For the current measurement a resistive load was used, as the IEC defines. This resistive load (Pellegrini target MD 101) was designed to measure discharge currents by ESD events on the target area and its bandwidth ranged from dc to above 1 GHz. The Pellegrini target was mounted on an insulating material made of plastic. This material was placed on a wooden surface, as it can be seen in Fig. 1b. The pulses that the ESD generators produce are reproducible, as it was found by the palm graphs of the ESD current for many electrostatic discharges for the same charging voltage and for both the ESD generators. The calibration certificates of the ESD generators can also prove their reproducibility. Therefore, the pulses are reproducible in spite of the fact that the Pellegrini target is on an insulating material. Moreover, charging effects cannot happen due to the fact that the Pellegrini target is grounded.



(a) (b)

Fig. 1: a) Experimental set-up. b) The measurement points in the two perpendicular directions on the HCP (Horizontal Coupling Plane) where the two field probes were placed.

The induced voltage in the E-field probe was calibrated to get the electric displacement vector $\frac{dD}{dt}$ using Gauss's law:

$$V_0 = RA_{eq} \cdot \frac{dD}{dt} = RA_{eq} \cdot \frac{d(\varepsilon_0 E)}{dt} \qquad (1)$$

where R is the resistor's characteristic load impendence which is 50 Ohms, D is the magnitude of the electric displacement vector and ε_0=8.854×10^{-12} F·m^{-1}.

By numerically integrating the derivative of the electric field strength, using either the Tektronix oscilloscope or Matlab, the electric field strength (E) is obtained.

The probes that were used for the experiment was the sphere probe of 3.6 cm in diameter of the HZ-11 set of Rohde & Schwarz, for the measurement of the electric field. The HZ-11 set consists of five passive near field probes. The probe was placed at various distances and in two perpendicular directions (X and Y axis) at the horizontal plane from the discharge point, as it can be seen in Fig. 1b. At each point as it can be seen in Fig.1b six measurements were conducted measuring each time the discharge current and the electric field. This was done in order to calculate the average and the standard deviation of the electric field at each point. The presence of the probe itself affects the near field measurement altering the measured quantity. There is capacitance and inductance between the circuit being measured and the probe with its associated cabling. The probe becomes part of the circuit when conducting near field measurements. In the present measurements these problems are minimal. In the case of the electromagnetic field measurements, probes of different sizes and geometry were used giving similar fields, showing that the probe does not seriously affect field measurements. The Standard defines that the equipment for the verification procedure should have a range from dc to 1GHz in order to measure accurately the very fast transient phenomenon of ESD. The equipment used fulfills this criterion with the oscilloscope having higher bandwidth.

3.2 Current's reconstruction

The equivalent circuit of the measurement system at DC analysis is illustrated in Fig.2 and it includes the ESD generator, the current transducer and the oscilloscope [14]. In this figure R_L, R_b and Z_0 are the load resistance of the current transducer (CT), the backward matching resistance of the CT and the nominal input impedance (50 Ohms) of the measurement system including the oscilloscope, respectively.

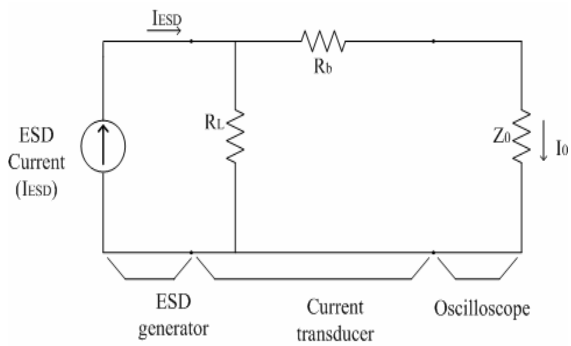


Fig.2: The equivalent circuit of the ESD generator in DC analysis.

The discharge current can be given by the following equations:

$$I_{ESD} = \frac{C \cdot V_R}{Z_0} \qquad (2)$$

$$C = C_{CT} \cdot C_A \qquad (3)$$

$$C_{CT} = \frac{I_{ESD}}{I_0} = \frac{R_L + R_b + Z_0}{R_L} \qquad (4)$$

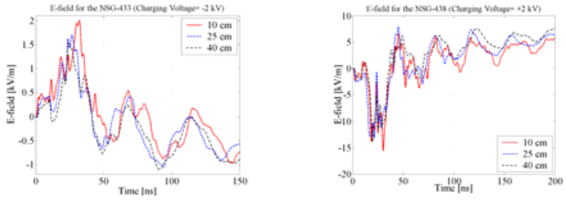
where I_{ESD} is the amplitude of the discharge current, V_R is the voltage measured by the oscilloscope due to the output current I_0. C is a current conversion factor; C_{CT} and C_A are the conversion factors of the CT and the attenuator, respectively. Equations from 2 to 4 are approximate with assuming matching on the output i.e. exactly 50 Ohms.

Measuring the DC resistance of the Pellegrini target the values of R_L and R_b can be found. Although available data of the target could be used this was avoided in order for the measurement results to be more accurate. The DC load resistance of the target (R_L) is the resistance between the inner electrode (disc) and the outer electrode of the CT. R_L was found 2.005 Ohms. The DC backward matching resistance of the CT (R_b) is the resistance between the input and the output of the inner electrode of the target. It was found that R_b was 48.246 Ohms. The calculation of these two values (R_L and R_b) was made by taking the average value of 20 measurements in order to minimize the measurement uncertainty. Taking all the above into consideration the voltage reading of 1V at the oscilloscope corresponds to the discharge current of approximately 10A. The attenuator was 20dB (C_A=10).

3. Measurement of the Electric Field

In Fig. 3 comparisons of the E-field produced by the NSG-438 and the NSG-433 ESD generators for three different distances and different charging polarities can be seen. It can be concluded that the produced electric field strength has a strong dip or a strong rise for positive or negative charge respectively, at the first ns. Also, the electric field strength decreases with the time receiving both negative and positive values. It can be observed that as the distance from the discharge point increases the E-field decreases but not dramatically. Another observation is that the electric field corresponds to the time derivative of the magnetic field.

It was found that for the same horizontal plane, the same charging voltage and the same distance but in perpendicular directions from the ESD generator, the produced electric field for each ESD generator is different. Figs 4-5 prove this conclusion. Measurements of the electric field at a distance of 20 cm from the discharge point on both X and Y axis, proved that each generator produces a different electric field.



(a) **(b)**

Fig. 3: Comparison of the E-field for the two ESD generators and for 3 different distances from the discharge point at Y-axis.

Fig. 4 depicts the electric field strength for the two different ESD generators at 20 cm on both the X and Y-axis and for the two different charging voltages. Comparing the produced transient electric fields differences can be found, although their behaviour in the time domain is similar. The NSG-433 produces higher E-field than the one produced by the NSG-438.

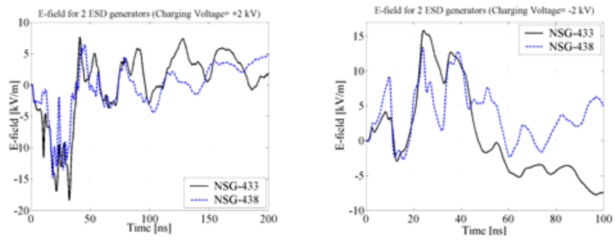


Fig. 4 Comparison of the E-field for the two ESD generators 20 cm from the discharge point and for two charging voltages.

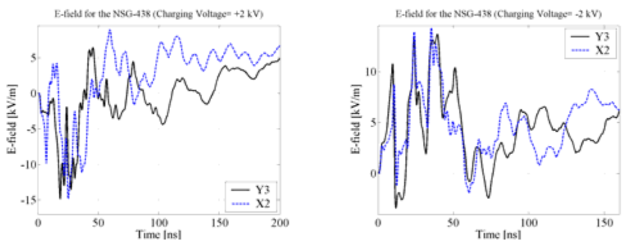
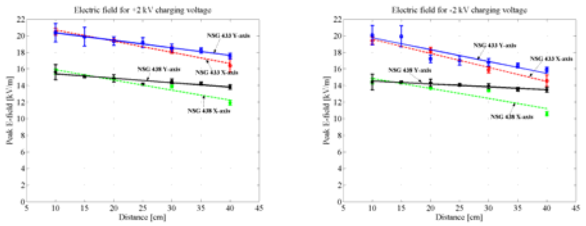


Fig. 5: Electric field strength for the NSG-438 ESD generator 20 cm from the discharge point, for two perpendicular directions on the horizontal plane and for two charging voltages.

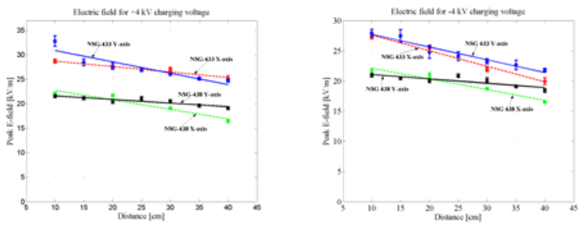
The maximum absolute values of the electric field strength (E-field) for the two ESD generators and for the four different charging voltages are presented in Fig. 6 and 7. From these figures it can be concluded that the amplitude of the E-field decreases with the distance. Also, observing these figures it is obvious that the absolute value of the electric field strength of the NSG-433 is higher than this of the NSG-438 for the four charging voltages and for the two perpendicular directions.

It could be said that the electric field strength has higher values at the Y-axis and lower at the X-axis, probably due to the fact that each generator has a different internal circuit that depending on its orientation produces different electric field.



(a) (b)

Fig. 6: Peak of E-field for various distances from the discharge point at the X and Y-axis using the ESD generators NSG-433 and NSG-438 for charging voltages of: a) +2 kV and b) –2 kV.



(a) (b)

Fig. 7: Peak of E-field for various distances from the discharge point at the X and Y-axis using the ESD generators NSG-433 and NSG-438 for charging voltages of: a) +4 kV and b) –4 kV.

4. Conclusions

An experiment has been carried out to investigate the transient electromagnetic field produced by contact electrostatic discharges. The transient electric field produced by two (2) different ESD generators for both positive and negative discharges were measured; having the Pellegrini target mounted on an insulating material. The comparisons indicate that each generator produces a different electric field.

The electric field corresponds to the time derivative of the magnetic field. It also decreases with the distance following an almost linear decrease. It was found that each ESD generator produces different electric field depending on the direction that the measurement is carried out. Also, electrostatic discharges with different polarities but equal in absolute value produce different electromagnetic field.

There is rotational asymmetry of the field distribution around the ESD generators, which may affect differently an EUT. Two possible reasons for this phenomenon are: a) Inside of the ESD generator the high voltage relays have not rotational symmetry, b) The positioning of the return path and, additionally, the high voltage cable of the NSG 438 have influence on it. It must also be mentioned that in the calibration set-up the positioning of these cables can be defined and the field measurements can be reproducible, but during the test on an EUT the position of these cables is not defined and the reproducibility of the field distribution is much weaker.

The above observations make it clear that there are differences in the produced field not only from generator to generator but also at the same generator. This means that, depending on the orientation of the ESD generator, the induced voltages are different and therefore an EUT may pass the test with one orientation of the ESD generator and fail with another. Therefore, it is essential that the next revision of the IEC 61000-4-2 to take into consideration this remark, in order for the limits of the produced transient fields to be defined and unified. The IEC Committee should take into consideration, in the future revision of the Standard, that the ESD generators should be marked on the direction that the field is highest. Also, during the verification, the produced electric field of the ESD generators should be tested around 360^o. The next revision of the Standard should include typical waveforms of the electric field that is produced by electrostatic discharges. It should also define the range of values for several magnitudes of the electric field (such as E_{max}, the rise time and perhaps values for the derivatives of the produced electric field). Should the above remarks be taken into consideration in the next revision of the Standard and particularly in the specifications for the design of the ESD generators, the test result uncertainty will be reduced.

A future work should examine measurements of the electric field in greater distances. In [16] the variations of the electric field have been explained and it has been analyzed that although there is an initial decrease of the electric field strength after a certain distance it increases again. Also, field measurements on metal plates with different dimensions should be carried out since the discharge current depends on where the target is mounted on.

Acknowledgments

The authors would like to thank Professor David Pommerenke of the Missouri-Rolla University in the USA and Dr Jan Sroka of Schaffner EMC for their very useful comments and support of the work presented here.

References:

[1] IEC 61000-4-2, Electromagnetic Compatibility (EMC), Part 4: Testing and measurement techniques, Section 2: Electrostatic discharge immunity test – Basic EMC Publication.

[2] D. Pommerenke, ESD: transient fields, arc simulation and rise time limit, *Journal of Electrostatics*, 1995, Vol. 36, pp. 31-54

[3] D. Pommerenke, M. Aidam, ESD: Waveform calculation, field and current of human and simulator ESD, *Journal of Electrostatics*, 1996, Vol. 38, pp. 33-51

[4] P.F. Wilson, M.T. Ma, Field radiated by electrostatic discharges, *IEEE Trans on Electromagnetic Compatibility*, 1991, Vol. 33, no. 1, pp. 10-18

[5] Ki-Chai Kim, Kwang-Sik Lee, Dong-In Lee, Estimation of ESD current waveshapes by radiated electromagnetic fields, *IEICE Trans on Communications*, 2000, Vol. E83-B, No. 3, pp. 608-612

[6] S. Ishigami, R. Gokita, Y. Nishiyama, I. Yokoshima, Measurements of Fast Transient Fields in the vicinity of Short Gap Discharges, *IEICE Trans on Communications*, 1995, Vol. E78-B, No. 2, pp. 199-206

[7] R. Chundru, D. Pommerenke, K. Wang, T.V. Doren, F. Centola, J. Huang, Characterization of human metal ESD reference discharge event and correlation of generator parameters to failure levels-Part I: Reference event, *IEEE Trans on Electromagnetic Compatibility*, 2004, Vol. 46, No. 4, pp. 498-504

[8] K. Wang, D. Pommerenke, R. Chundru, T.V. Doren, F. Centola, J. Huang, Characterization of human metal ESD reference discharge event and correlation of generator parameters to failure levels-Part II: Correlation of generator parameters to failure levels, *IEEE Trans on Electromagnetic Compatibility*, 2004, Vol. 46, No. 4, pp. 505-511

[9] P. Leuchtmann, J. Sroka, Transient field simulation of electrostatic discharge (ESD) in the calibration setup (ace. IEC 61000-4-2), *International Symposium on EMC*, 21-25 August, 2000, pp. 443-448

[10] P. Leuchtmann, J. Sroka, Enhanced field simulations and measurements of the ESD calibration setup, *International Symposium on EMC*, 13-17 August 2001, pp. 1273-1278

[11] J. Bendjamin, C. Gomes, V. Cooray, Remote sensing of ESD through optical and magnetic radiation fields, *IEEE Trans on Dielectrics and Electrical Insulation*, Vol. 6, No. 6, December 1999, pp. 896-899.

[12] J. Bendjamin, R. Thottappillil, V. Scuka, Time varying magnetic fields generated by human metal (ESD) electrostatic discharges, Journal of Electrostatics, Vol. 46, No. 4, May 1999, pp. 259-269.

[13] D. Pommerenke, ESD: What has been achieved, what is less well understood, *IEEE Symposium on EMC*, Minneapolis, August 2002, pp. 895-900

[14] T.W. Kang, Y.C. Chung, S.H. Won, H.T. Kim, On the uncertainty in the current waveform measurement of an ESD generator, *IEEE Trans on Electromagnetic Compatibility*, 2000, Vol. 42, No. 4, pp. 405-413

[15] J. Sroka, Target influence on the calibration uncertainty of ESD simulators, *14th International symposium on Electromagnetic Compatibility*, Zurich, Switzerland, Feb 2001, pp. 189-192

[16] S. Frei, D. Pommerenke, Fields on the horizontal coupling plane excited by direct ESD and discharges to the vertical coupling plane, 1998, *Journal of Electrostatics*, Vol. 44, pp. 177-190