

# Measurement of the electric field radiated by electrostatic discharges

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## Abstract

The aim of this work is the investigation of the transient electric field radiated by two different commercial generators of electrostatic discharges for various charging voltages. Measurements of the electric field generated by contact electrostatic discharges have been conducted a few centimetres away from the discharge point. In this paper the current transducer, which is used for the measurement of the discharge current, is mounted on a grounded metal plane. It is the first time that measurements of the electric field have been conducted along three different directions in relation to the electrostatic discharge generator. Measurements prove that each generator produces a different transient electric field, which affects the equipment that is tested in a different way. Also, each generator produces a different electric field depending on the orientation of the generator. Finally, comparisons of the electric field for both generators and useful conclusions for the decrease of the electric field are presented.

**Keywords:** electrostatic discharges, electrostatic discharge generators, electric field sensors, IEC 61000-4-2, electric field, grounded metal plane, Pellegrini target

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Thales of Miletus was the first to observe the phenomenon of static electricity around 600 BC. Electrostatic discharge is very common to our lives, since it happens many times during a day. It occurs when a transfer of electric charge takes place between conducting bodies that have different electrostatic potentials. The danger for humans is something that needs further investigation and there have been studies that attempt to study the effect of electrostatic discharges on human health [1–3]. The phenomenon of electrostatic discharge is more crucial for electronics. Due to the small size of semiconductor devices, the amount of energy that is deposited in the elements can be so high that the semiconductor material can suffer local melting. ESD (electrostatic discharge) and its associated high electric field can cause electric breakdown of the sensitive isolation layers, especially the thin gate oxides in CMOS (complementary metal oxide semiconductor) technologies [4–6]. To sum up, these effects can result in latent damage or

even a breakdown of the whole IC (integrated circuit), which is in some cases a relevant safety issue.

Due to the importance of the phenomenon the IEC (International Electrotechnical Committee) prescribed the Standard 61000-4-2 [7] in order to define the procedure that must be followed during tests on electrical or electronic equipment against electrostatic discharges. The ESD generator is also specified by this Standard, defining the parameters of the discharge current as the rise time, the peak current and the current at 30 ns and 60 ns. Although different ESD generators fulfil the criteria of the Standard [7], they produce different electromagnetic fields. Wilson and Ma [8] were the first to simultaneously measure the current and the electric field during electrostatic discharges at a distance of 1.5 m, using a broadband, TEM (transverse electromagnetic) horn antenna. Pommerenke [9, 10] found that the electromagnetic field produced by various ESD generators is different although they fulfil the Standard's criteria. Pommerenke and Frei [11] measured the electromagnetic field

for various ESD generators, proving that the field is higher, where the discharges take place, when the metal plane is in the vertical position rather than horizontal.

Leuchtmann and Sroka [12, 13] investigated the simulation of the phenomenon of ESD in order to calculate the electromagnetic field produced. A comparison with experimental data showed a very good agreement for the magnetic field but worse for the electric field. The two different probes that were used gave different results, proving that the measurement of the electromagnetic field is a very challenging task. It should be noted that in [13] the authors tried to put the gun in aluminium foil in order to make the inside of the gun electrically isolated so as to improve its rotational symmetry. They intended to propose to the IEC Committee to build the ESD generators in a rotatable metal case in order to have rotational symmetry of the field.

Bendjamin *et al* [14] presented measurements of the electromagnetic field radiated by electrostatic discharges 1–3 cm from the discharge point. They found that the peak of the electric field reduces as the distance from the discharge point increases, while the magnetic field is proportional to the current. There have also been studies [15, 16] where the ESD current waveform can be calculated by measuring the electromagnetic field.

A recent publication from Pommerenke's research team [17] investigates what the next revision of the Standard should include. They make it obvious that the four parameters defined by the Standard are deficient and therefore the electromagnetic field produced by the ESD generators should be taken into account, in order to define limits and specifications.

From the above it is obvious that the study of transient fields is very important. This work aims to contribute to the forthcoming revision of the Standard through the experiments that have been carried out. In the High Voltage Laboratory of the National Technical University it has been observed for years that an EUT (equipment under test) may pass with one generator and yet fail with another for the same charging voltage and for the same discharge current. The reason for this is that each generator produces a different electromagnetic field and therefore the induced voltages are different. These observations are made clear through the results of the work presented here. But the most important result of this work and something that has not been presented elsewhere is that each generator may have a different effect on the EUT depending on its orientation. Consequently, the next revision of the Standard should take this observation into consideration. In this way the construction of each generator (internal circuits, capacitors, etc) will be defined and the radiating electromagnetic field will be the same in all directions.

## 2. Measurement system

### 2.1. Experimental set-up

Figure 1 shows the ESD current experimental set-up. The current and the electric field (*E*-field) for charging voltage levels of  $\pm 2$  kV were measured simultaneously, by the four-channel Tektronix oscilloscope model TDS 7254B, whose bandwidth ranged from dc to 2.5 GHz. The electrostatic discharges were contact discharges and they were conducted

using two Schaffner's ESD generators. The experiment was made only for contact discharges, because there is a reproducibility problem for air discharges; during air discharges the electric arcs produced are different. Therefore, the electric fields produced can be compared only if the electric arcs of the air discharges are the same. After all, the verification of the ESD generators is done only for contact discharges.

The ESD generators used were the NSG-433 and the NSG-438. The NSG-438 is newer in construction than the NSG-433. It has a touch screen for the selection of the charging voltage and the discharge type (contact or air). They also differ in their inner circuits, since the charging resistance is 100 M $\Omega$  for the NSG-433 and 50 M $\Omega$  for the NSG-438. This difference is in accordance with the Standard since it defines that the value of the charging resistance must be between 50 and 100 M $\Omega$ . It must be mentioned that the NSG 438 had a basic station, something that the NSG-433 did not have. The basic station of the NSG-438 was on the floor of the anechoic chamber and its horizontal distance from the edge of the grounded metal plane was 40 cm. The positioning of the high voltage cable was kept constant during the whole experiment. The high voltage cable positioning of the station was very important and this is a basic difference between the two ESD generators, which have different effects on the electric field produced.

The temperature and relative humidity were measured and found to be in the ranges  $23 \pm 2$  °C and  $40\% \pm 5\%$ , respectively. In order to measure the current a resistive load was used, as the IEC defines. This resistive load (Pellegrini target MD 101) [18, 19] was designed to measure discharge currents created by ESD events on the target area and its bandwidth ranges from dc to above 1 GHz. The Pellegrini target was placed on a horizontal grounded metal plane. The dimensions of the horizontal metal plane were 1.5 m  $\times$  1.5 m. In order for the measurement set-up to be unaffected by surrounding systems, the experiment was conducted in an anechoic chamber.

The sensor that was used for the experiment was an *E*-field sensor constructed by D Pommerenke. The sensor was placed at various distances (20, 35, 50 and 65 cm) on the metal plane and in three perpendicular directions (directions A, C and D) on the horizontal plane as can be seen in figures 2 and 3. Measurements in direction B were not conducted due to the interference that the ground strap of the ESD generator was causing. It is known that the position of the ground strap affects the falling edge of the current's waveform. In order to minimize the uncertainty that this introduces into the measurement of the electric field, the ground strap was at a distance of 1 m from the target, as the Standard defines, and its loop was as large as possible. At each point, as shown in figure 2(a), six measurements were made, each time measuring 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. Figure 2(b) shows the position of the *E*-field sensor in relation to the Pellegrini target on the grounded metal plane.

### 2.2. Reconstruction of the current

In the oscilloscope the measured magnitude is voltage. Therefore the reconstruction of the measured voltage into

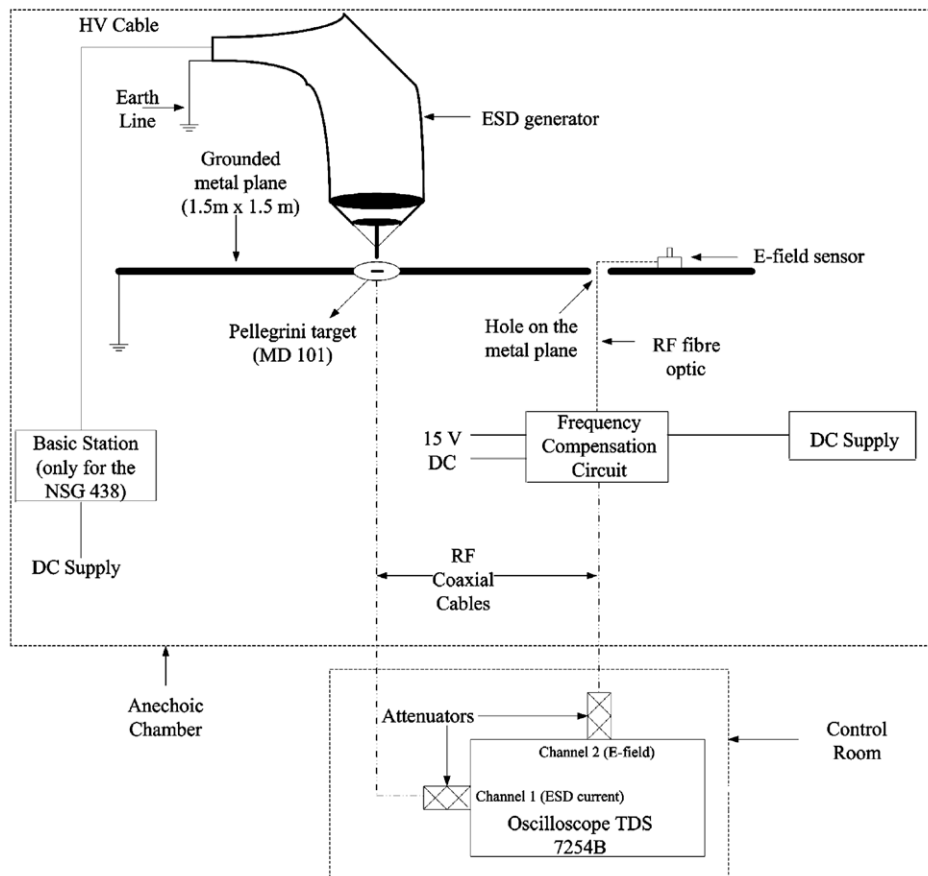


Figure 1. Experimental set-up.

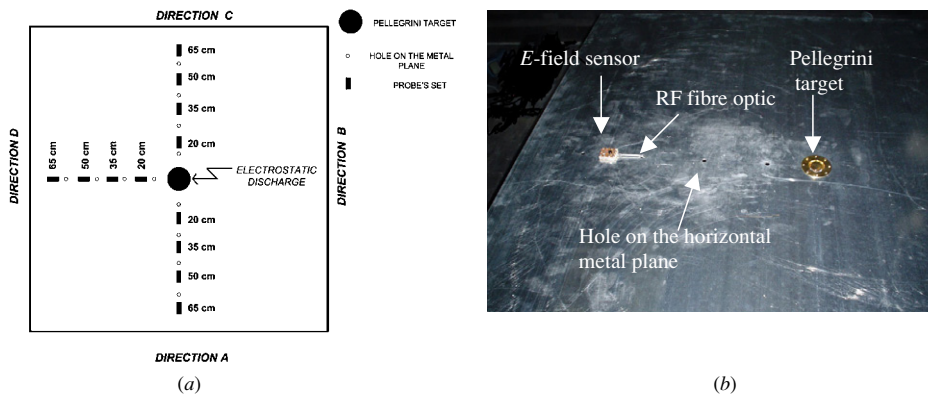


Figure 2. (a) The measurement points where the E-field sensor was placed. (b) Position of the E-field sensor on the grounded metal plane.

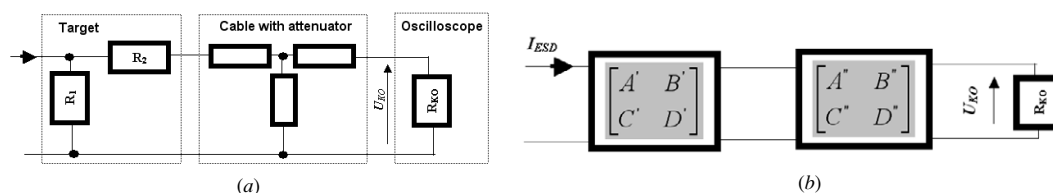
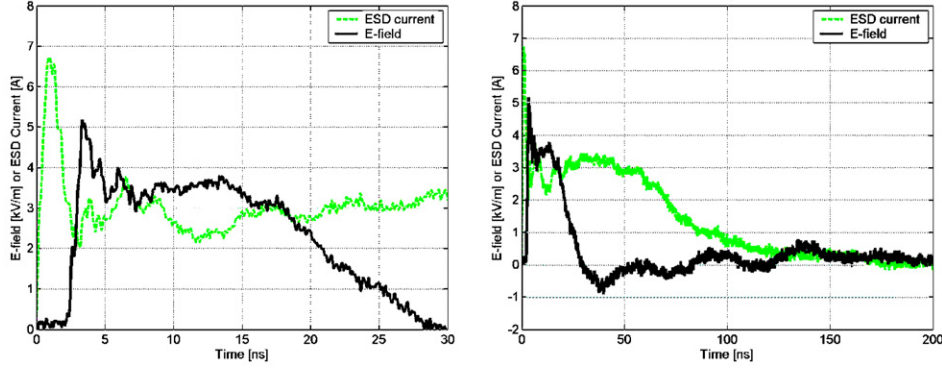


Figure 3. The equivalent circuit of the ESD generator in DC analysis.

current is necessary. The most accurate way to reconstruct the current is described by Sroka [20] using the measurement chain as shown in figure 3. The low frequency transfer impedance of

a target/attenuator/cable chain is defined as the ratio between the current injected at the front face of the target and the voltage across a precision 50 Ω load at the output end of the cable.



**Figure 4.** ESD current and  $E$ -field for the NSG-438 ESD generator at 20 cm from the discharge point, in direction A (charging voltage = +2 kV).

$P_{\text{cable}}$  and  $P_{\text{target}}$  are chain matrices. By cascade connection of two two-ports (in our case the target and cable with attenuator) they enable the calculation of the equivalent chain matrix.

For the chain matrix of the target the following formula is valid:

$$P_{\text{target}} = \begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} = \begin{bmatrix} 1 & R_2 \\ \frac{1}{R_1} & 1 + \frac{R_2}{R_1} \end{bmatrix} \quad (1)$$

where  $R_1$  is the target resistance to ground and  $R_2$  is the target resistance between input and output. For the chain matrix of the cable with the attenuator the following formula is valid:

$$P_{\text{cable}} = \begin{bmatrix} A'' & B'' \\ C'' & D'' \end{bmatrix} = \begin{bmatrix} \frac{1+d^2}{2 \cdot d} & \frac{25}{d} \cdot (1-d^2) \\ \frac{1-d^2}{100 \cdot d} & \frac{1+d^2}{2 \cdot d} \end{bmatrix} \quad (2)$$

where  $d$  is rated attenuation of the attenuator on a linear scale:

$$d = \frac{1}{10^{\frac{A}{20}}} \quad (3)$$

and  $A$  is the attenuation in dB. In our case since  $A = 20$  dB,  $d = 0.1$ .

From measurements it can easily be found that  $R_1 = 2.018 \Omega$  and  $R_2 = 48.964 \Omega$ . Multiplying (1) with (2), the chain matrix of a cascade junction of two two-ports is easily found:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = P_{\text{target}} \cdot P_{\text{cable}} \approx \begin{bmatrix} 9.8974 & 494.7682 \\ 5.0034 & 250.2174 \end{bmatrix}. \quad (4)$$

The transfer admittance as a recalculation coefficient between the voltage displayed on the oscilloscope and the discharge current is given by (5). Also, assuming that  $R_{\text{KO}} = 50 \Omega$ , the discharge current is found as a function of the output voltage.

$$Y_{\text{TRAN}} = \frac{i_{\text{ESD}}(t)}{u_{\text{KO}}(t)} = C + \frac{D}{R_{\text{KO}}} \Rightarrow I_{\text{ESD}} = 10.0077 \cdot V_{\text{out}}. \quad (5)$$

Taking all the above into consideration, a voltage reading of 1 V on the oscilloscope corresponds to a discharge current of approximately 10 A.

### 2.3. $E$ -field sensors

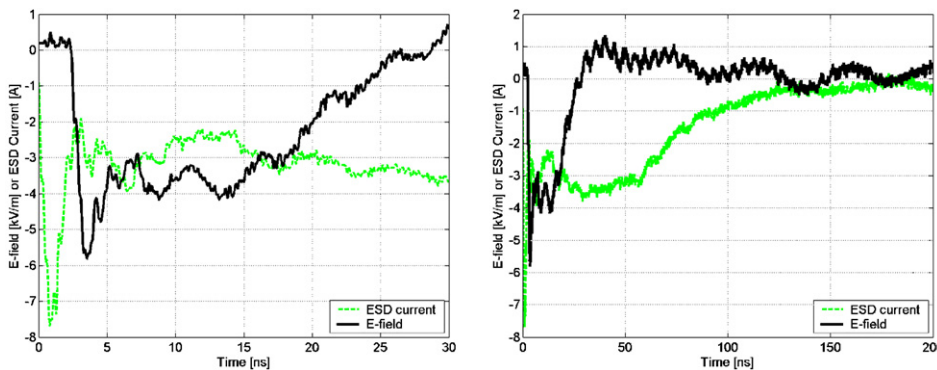
The  $E$ -field sensor is a ground-based field sensor with active integration using a GaAs impedance converter for the sensor. It is rectangular in shape and it is about 4 cm by 3 cm by 1 cm. The  $E$ -field sensor covers an area of  $0.0012 \text{ m}^2$  on

the metal plane, when the metal plane has a total surface of  $2.25 \text{ m}^2$ . The dynamic range of the  $E$ -field sensor is  $20 \text{ V m}^{-1}$  to  $20 \text{ kV m}^{-1}$ . When measured in an open strip line the sensor exhibits a  $\pm 1.5$  dB frequency response from 2.5 MHz to 2 GHz. The sensor's sensitivity, which is  $194 \mu\text{V}/(\text{V m}^{-1})$  can be determined by calibration using frequency response set-up. The set-up for the sensor's calibration includes the sensor placed in a strip line and a network analyser. A detailed analysis of this sensor and its calibration can be seen in [21]. This sensor has been constructed by Pommerenke and is not available commercially.

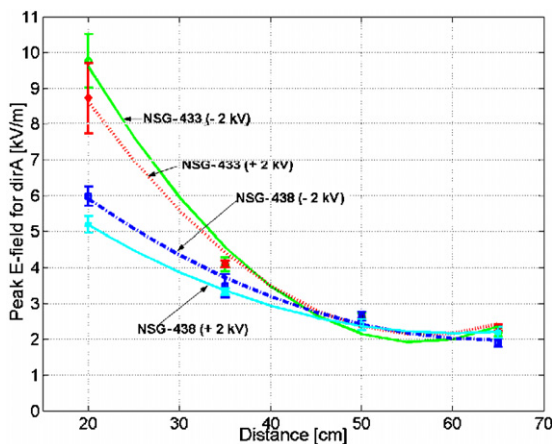
### 3. Experimental results

The electric field strength ( $E$ -field) produced by the two ESD generators was measured using the experimental set-up as previously described in section 2.1. Figures 4 and 5 depict representative  $E$ -field waveforms in relation to the discharge current for the first 30 ns and 200 ns, respectively, when the  $E$ -field sensor is placed at a distance of 20 cm from the discharge point. It can be observed that the polarity of the  $E$ -field is similar to the polarity of the discharge current (positive or negative), although there are periods (e.g. around 50 ns), where the  $E$ -field receives negative values. The maximum power in both polarities of the  $E$ -field's signal is reached during the first 30 ns. Therefore, the damage that may be caused in electronic equipment due to the voltages induced by the electric field will take place in these first few nanoseconds. After 30 ns the value of the electric field is stabilized around  $0 \text{ kV m}^{-1}$ . The electric field starts with a flat line for approximately the first 3 ns. The electromagnetic wave covers the distance of 20 cm in about 0.7 ns. The other 2 ns are due to the delay of the field sensor. The superposition of wave delay and probe results in a total delay of about 3 ns.

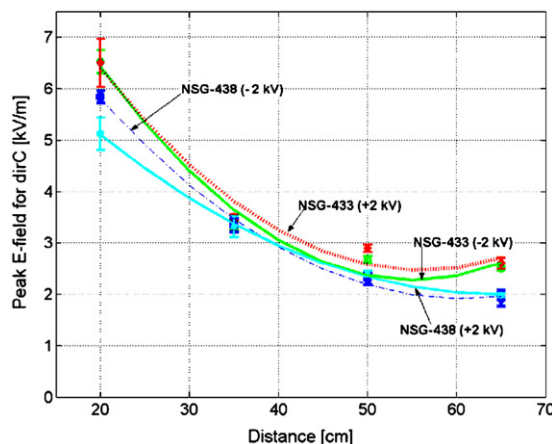
The peaks of the electric field's strength ( $E_{\text{max}}$ ) for both the NSG-433 and the NSG-438 and for the three different directions are presented in figures 6–8. Initially, as can be observed from these three figures, the amplitude of the peak  $E$ -field decreases. Also, it can be observed that for both polarities and in all three directions the NSG-433 ESD generator produces higher electric field than the NSG-438. This fact can be explained by the different construction of the two ESD generators and probably from the different relay they



**Figure 5.** ESD current and  $E$ -field for the NSG-438 ESD generator at 20 cm from the discharge point, in direction A (charging voltage =  $-2$  kV).



**Figure 6.** Peak of the  $E$ -field for various distances from the discharge point in direction A, using the NSG-433 and NSG-438 ESD generators.

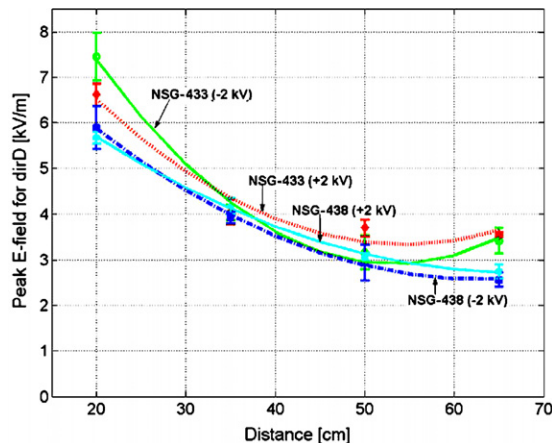


**Figure 7.** Peak of the  $E$ -field for various distances from the discharge point in direction C, using the NSG-433 and NSG-438 ESD generators.

have. Consequently, the electric field produced is different for the two ESD generators.

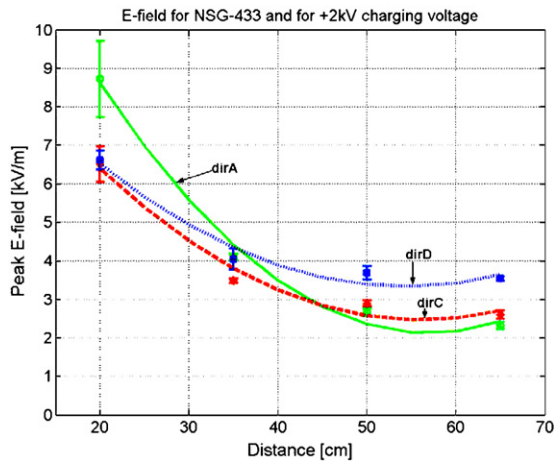
Measuring the electric field produced by the two ESD generators, it was found that this field was different for the same horizontal grounded plane, the same charging voltage and the same distance but in perpendicular directions from the ESD generator. Comparisons of the absolute value of the electric field’s peak for the three directions, for each generator and for the different charging voltages can be seen in figures 9–12.

Figures 10 and 12 depict the peak  $E$ -field for charging voltages of  $+2$  kV and  $-2$  kV, respectively, in all three directions for the NSG-438 ESD generator. The directions can be sorted as follows: direction D  $\rightarrow$  direction A  $\rightarrow$  direction C, with direction D having the higher  $E$ -field. Likewise, observing figures 9 and 11 for the NSG-433 ESD generator and in both polarities ( $\pm 2$  kV) the directions in which the peak  $E$ -field is higher can be sorted as follows: direction A  $\rightarrow$  direction D  $\rightarrow$  direction C. Direction D for distances greater than 50 cm from the discharge point has the higher  $E$ -field. A possible cause of the differences in the electric field produced in different directions may be the circuit’s construction, which produces a different electric field around it. This is something that should be carefully examined, because the orientation of

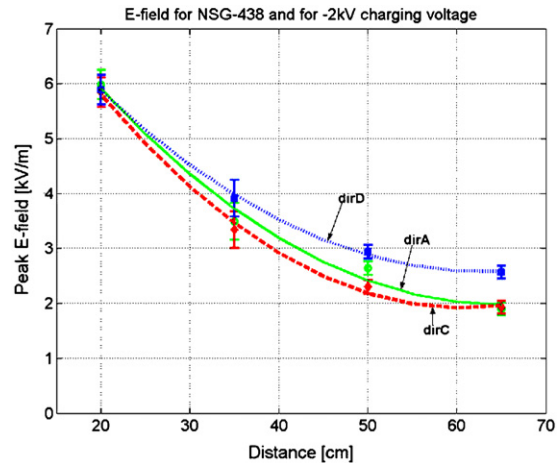


**Figure 8.** Peak of the  $E$ -field for various distances from the discharge point in direction D, using the NSG-433 and NSG-438 ESD generators.

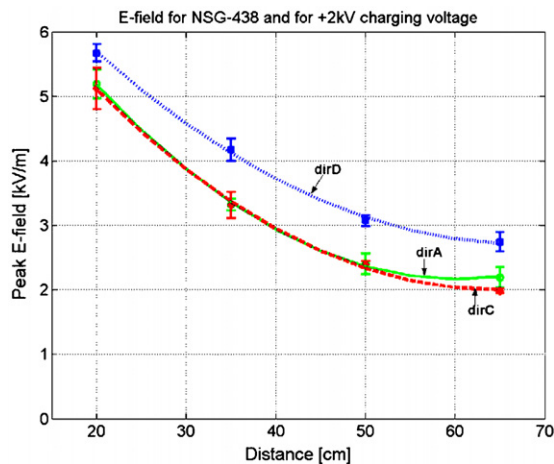
the ESD generator may give different results for the equipment that is tested. For example, if a test is carried out with the NSG-438 and the EUT is placed in direction C, it may pass the test yet fail with the same generator and for the same charging voltage if placed in direction D, because in this direction the peak field is higher.



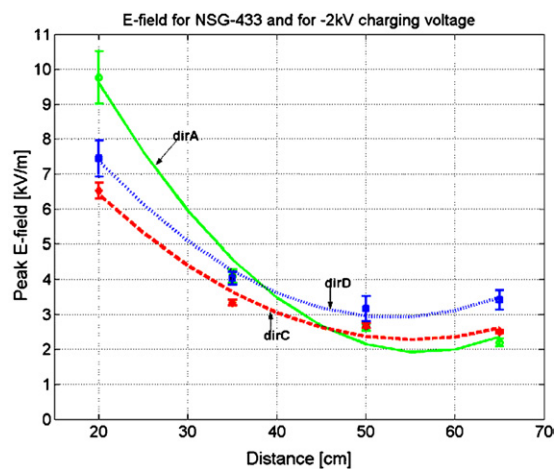
**Figure 9.** Peak of electric field strength for the NSG-433 ESD generator for three perpendicular directions on the horizontal plane (charging voltage = +2 kV).



**Figure 12.** Peak of electric field strength in absolute value for the NSG-438 ESD generator for three perpendicular directions on the horizontal plane (charging voltage = -2 kV).



**Figure 10.** Peak of electric field strength for the NSG-438 ESD generator for three perpendicular directions on the horizontal plane (charging voltage = +2 kV).



**Figure 11.** Peak of electric field strength in absolute value for the NSG-433 ESD generator for three perpendicular directions on the horizontal plane (charging voltage = -2 kV).

#### 4. Conclusions

An experimental approach has been carried out in order to investigate the transient electric field radiated by electrostatic discharges. The transient electric field, which was produced by two different ESD generators and for charging voltages at  $\pm 2$  kV, was measured when the Pellegrini target was mounted on a grounded metal plane. The comparisons showed that each generator produces a different electric field, and due to this fact, there are different results when an EUT is tested. Therefore, there is a need for the next revision of the IEC 61000-4-2 [7] to take this remark into consideration, in order to define and unify the limits of the transient fields produced. Also, it was found that each ESD generator produces different electric fields depending on the direction in which the measurement is carried out. Not only does this mean that there are differences in the electric field produced from generator to generator, but for the same generator as well. Therefore, depending on the orientation of the ESD generator, the induced voltages are different, and therefore an EUT may pass the test for one orientation of the ESD generator yet fail for another. In general, it was also concluded that the electric field decreases as the distance from the discharge point increases.

There is rotational asymmetry of the field distribution around the ESD generators, which may affect an EUT differently. Two possible reasons for this phenomenon are: (a) inside the ESD generator the high voltage relays do not have rotational symmetry; (b) the positioning of the return path and additionally the high voltage cable of the NSG 438 have an influence on it. It should also be mentioned that the positioning of these cables in the calibration set-up can be defined and the field measurements can be reproducible, but when testing an EUT the positioning of these cables is not defined and the reproducibility of the field distribution is much weaker. In the future revision of the Standard the IEC Committee should take into consideration that the ESD generators should be marked with the direction in which the field is highest. Also, during the verification the ESD generators should be tested on the produced electromagnetic field around 360°.

Future work must include measurements for the magnetic field for contact discharges for the same experimental setup and also measurements for the electric and magnetic field, when the grounded metal plane is vertical in order to make comparisons. Furthermore, a computational method for the calculation of the electromagnetic field radiated by electrostatic discharges must be applied and a comparison with the measured data has to be made.

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