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Measurement of the electromagnetic field radiating by commercial ESD generators with the Pellegrini target on insulating material

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ABSTRACT

The aim of this work is the investigation of the transient electromagnetic field radiating by two different commercial generators of electrostatic discharges. Measurements of both magnetic and electric field generated by contact electrostatic discharges have been carried out a few centimeters away from the discharge point. In this paper the current transducer, which is used for the measurement of the discharge current is not mounted on a grounded metal plate, but on an insulating material. With this aberration to the Standard a closer simulation to the electromagnetic field produced by the electrostatic discharge generators on the equipment under test is obtained. This experiment is closer to real conditions of electrostatic discharges, which do not involve a metal plate. It is proved by measurements that each generator produces a different transient electromagnetic field, which has different repercussions on the equipment that is tested. Comparisons of the radiating field between the two generators and useful conclusions for the variation of the electromagnetic field are also presented.

1. Introduction

Electrostatic discharge (ESD) may be destructive for electronic or integrated circuits, which are very sensitive to these discharge currents even though the ESD phenomenon lasts a few hundred nanoseconds. Therefore, the International Electrotechnical Committee (IEC) prescribed the 61000-4-2 [1] in order to define the procedure, which must be followed for the tests on electrical or electronic equipment against electrostatic discharges.

Little attention has been paid to the measurement of the electromagnetic field less until the end of the 1980s. Wilson and Ma [2] were the first, who simultaneously measured the current and the electric field during electrostatic discharges at a distance of 1.5 m, using a broadband, TEM horn antenna. Many researchers have conducted measurements of the electromagnetic fields associated with the ESD event. Pommerenke [3] measured the electric and the magnetic field at a distance between 0.1 and 1 m, for both air and contact discharges. He found that the magnitude of the magnetic field strongly depends on the $1/R$ factor (where R is the distance from the point where the ESD occurs). He also found that after a period of decrease, the magnitude of the electric field increases.

Studies have also been conducted [4,5] which involve calculation of the electromagnetic field waveform, using analytical formulas. In order to improve the repeatability of the ESD generator, in [6,7] the current waveforms and the produced electromagnetic fields have been investigated by taking into consideration, correlated parameters to the ESD event. This work depicts that the most important factor, which affects an equipment under test (EUT) is the transient field. In [8,9] measurements of the

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produced electromagnetic field during electrostatic discharge at the calibration set-up have been carried out, proving that the field measurement is a challenging task and its results may vary depending on the field probes and the measurement system.

Bendjamin et al. [10] measured the optical radiation, the magnetic field generated by electrostatic discharges and their ESD current. They found that the peak current is linearly correlated to the peak of the optical radiation. In another work [11] they measured the magnetic field in the time domain very close to an ESD event.

In another recent publication [12] the transient magnetic field radiating by two different commercial generators of electrostatic discharges for various charging voltages was investigated, when the current transducer was mounted on the center of a grounded metal plane. Measurements proved that each generator produces a different transient magnetic field, which affects on the equipment that is tested in a different way. Also, each generator produces different magnetic field depending on the orientation of the generator.

2. The problem

The study presented in this paper is conducted with the aim of contributing the upcoming version of the Standard through experiments that have been carried out at the facilities of the High Voltage Laboratory of the National Technical University of Athens, Greece. It was observed that there is a strong probability that the EUT will pass a test, when conducting measurements using a certain 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. These observations are made clear through the results of this work. The experimental data demonstrate that each generator may result in a different way on the EUT, depending on its orientation. Such an observation has not been made until today and should be taken into consideration in the next revision of the Standard, in order to define the construction of each generator, in order the radiating electromagnetic fields to be the same in all directions. The validity of this is proved by the experiments presented in this work.

This work attempts to investigate the electromagnetic field radiating by contact electrostatic discharges for two different types of commercial ESD generators. The current transducer (Pellegrini target) is not mounted on a grounded metal plate, but on an insulating material. Thus, it is attempted to investigate both the radiating electric and magnetic field in a state closer to reality, since the current transducer affects the electromagnetic field, when it is mounted on a metal plate. The produced electromagnetic fields and their induced voltages on the equipment that is usually tested are produced without the presence of grounded metal plates, which alter the radiating electromagnetic fields. The presence of an insulating material instead of a grounded metal plate, where the Pellegrini target is mounted has smaller effect on the produced electromagnetic field. The presence of the metal plate produces reflected waves, which distort the field produced by the ESD generator, which happens to a lesser extend with the insulating material.

3. Measurement system

Fig. 1 shows the experimental set-up. The current and the magnetic field strength (H-field) or 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 2.5 GHz. 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 5 cm. 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 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 °C and $40 \pm 4\%$, 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 and this material was placed on a wooden surface. 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

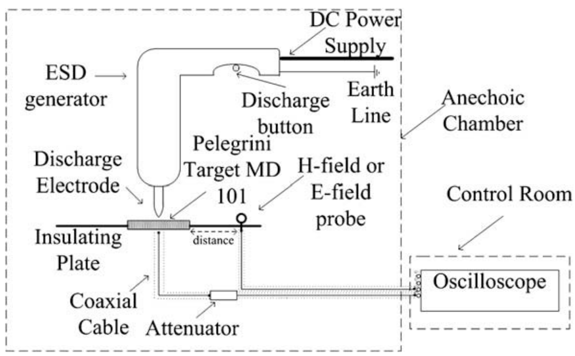


Fig. 1. Experimental set-up.

insulating material. Moreover, charging effects cannot happen due to the fact that the Pellegrini target is grounded.

The probes that were used for the experiment were the loop probe of 3 cm in diameter and the sphere probe of 3.6 cm in diameter of the HZ-11 set of Rohde and Schwarz, for the measurement of the magnetic and electric field, respectively. The HZ-11 set consists of five passive near field probes. The probes were 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 Figs. 1 and 2. At each point six measurements were conducted measuring each time the discharge current and the electric or magnetic field. This was done in order to calculate the average and the standard deviation of the electric or magnetic 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 1 GHz in order to measure accurately the very fast transient phenomenon of ESD. The equipment used fulfills this criterion with the oscilloscope having higher bandwidth.

4. Experimental results

4.1. Measurements of the H-field

The ESD current has different waveforms depending on the type and dimensions of the material on which the target is mounted. Experiments where the Pellegrini target was mounted on different materials have been conducted at the High Voltage Laboratory of NTUA [13] and in Fig. 4 three different ESD currents using the NSG-438 are depicted depending on the material the target is mounted on for 2 kV charging voltage. These different materials are a 1 m × 1 m grounded metal plate (horizontal position), a 0.5 m × 0.5 m grounded metal plate on the wall of the anechoic chamber (vertical position) and an insulating material. Observing Fig. 3 it can be concluded that the

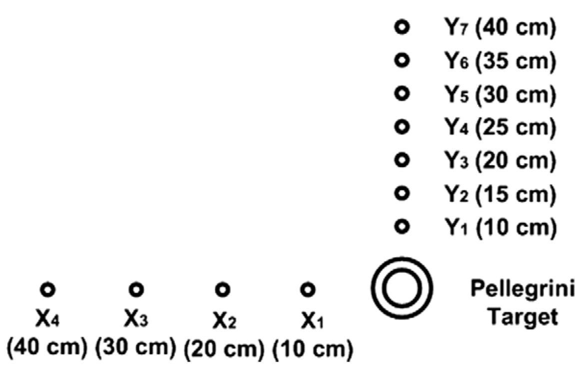


Fig. 2. The measurement points in the two perpendicular directions on the HCP (horizontal coupling plane) where the two field probes were placed.

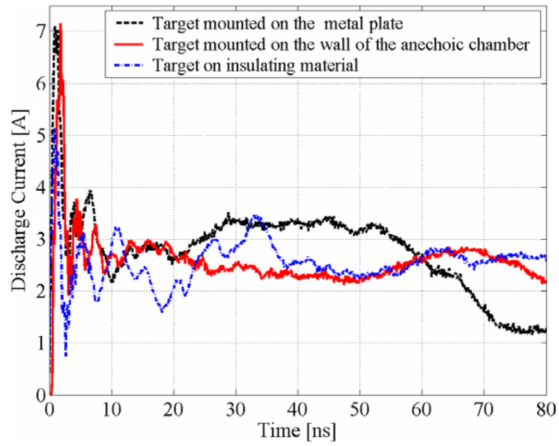


Fig. 3. Comparison of the ESD current for 2 kV charging voltage and for three different cases of contact discharges, where the target is mounted for the NSG-438.

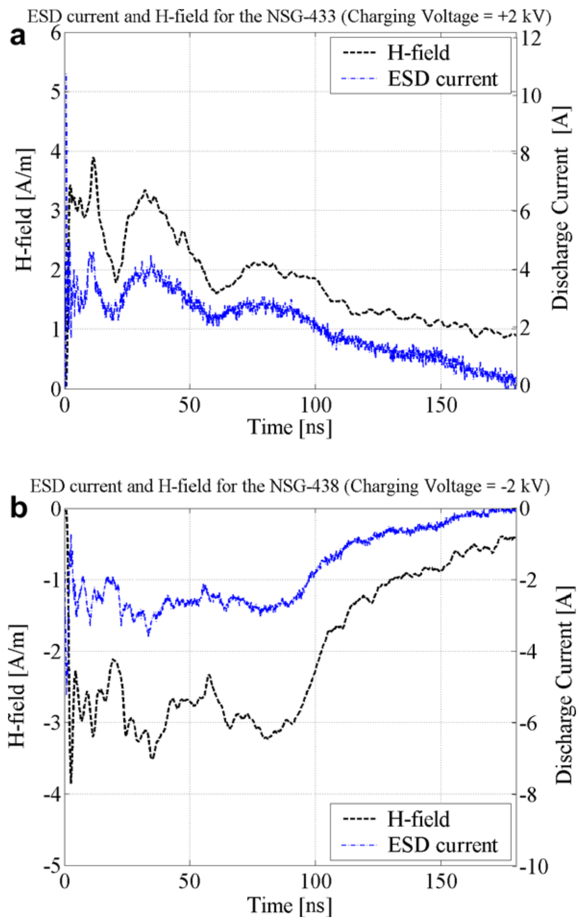


Fig. 4. ESD current and H-field for the two ESD generators at 10 cm (Y1 point) from the discharge point.

current's values, when the target is mounted on an insulating material are lower than those obtained, when the target is mounted on a metal plate (either on the vertical or the horizontal position). That explains the aberration between the values of the discharge current, when the current transducer is mounted on an insulating material and those defined by the Standard.

Measurements of the produced by two ESD generators magnetic field, were taken by following the procedure described previously. Integration of the time derivative of the B-field gives the B-field. The H-field can be calculated by the equation:

$$B = \mu_0 \cdot H \tag{1}$$

where μ_0 is the magnetic permeability and it is equal to $4\pi \times 10^{-7}$ Tesla m/A.

As it was presented in Fig. 3, the maximum value of the ESD current, when the Pellegrini target is mounted on an insulating material is lower than the value obtained when the target is mounted on a metal plate. In the latter case the value of the magnetic flux density is also lower given the fact that the magnetic flux density is proportional to the ESD current. Fig. 4 proves that the magnetic flux density at a distance of 10 cm from the discharge point is proportional to the current whether the charging voltage is positive or negative. The H-field changes in the same

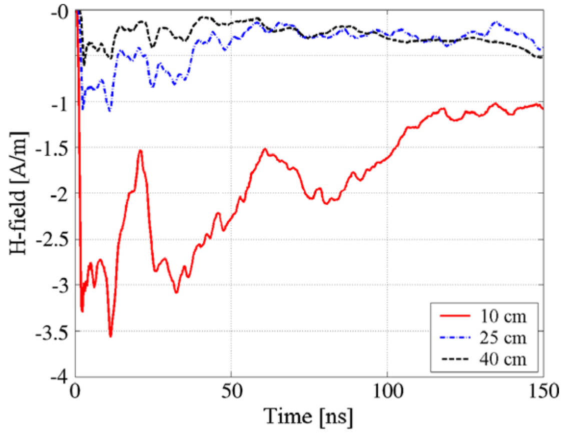


Fig. 6. Comparison of the H-field for the NSG-433 ESD generator and for three different distances from the discharge point (charging voltage = −2 kV).

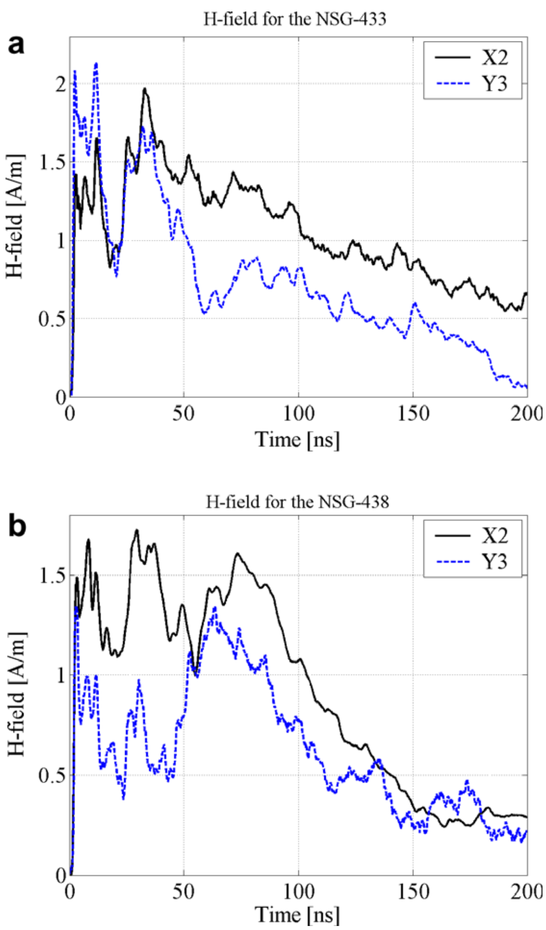


Fig. 5. Magnetic field strength for the two ESD generators 20 cm from the discharge point but for two perpendicular directions on the horizontal plane (charging voltage = +2 kV).

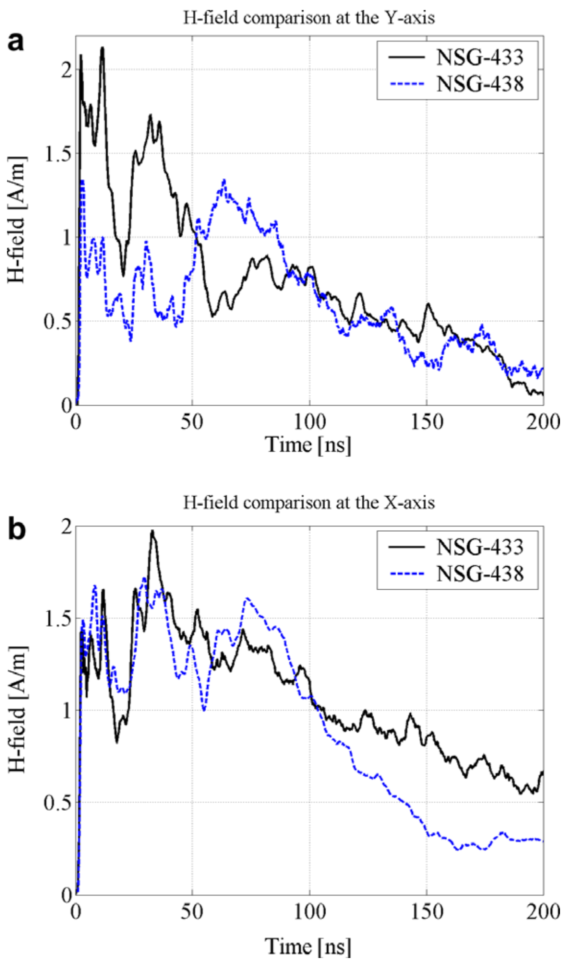


Fig. 7. Magnetic field strength produced at 20 cm from the discharge point by the two different ESD generators (charging voltage = +2 kV).

way as the discharge current with a slight delay, which can be interpreted as the time needed for the magnetic wave to travel in space.

Someone would expect that the ESD generators produce the same magnetic field in all directions. However, such a thing actually does not happen. 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 magnetic field was different, as it is shown in Fig. 5. Measurements of the magnetic field at a distance of 20 cm from the discharge point on both *X*- and *Y*-axis, proved that each generator produces a different magnetic field (Fig. 5).

Fig. 6 presents a comparison of the H-field produced by the NSG-433 ESD generator for three different distances. It can be observed that the magnetic flux density decreases as the distance from the discharge point increases. Also, in all three distances the magnetic field strength is proportional to the discharge current.

Figs. 7 and 8 depict the magnetic field strength for the two different ESD generators at 20 cm on both *X*- and *Y*-axis and for the two different charging voltages (± 2 kV). By observing the graphs, useful conclusions can derive. Comparing the produced transient magnetic fields differences can be traced. The NSG-433 produces higher H-field than the NSG-438, which means that the induced voltages from each generator are different. Therefore, when an EUT is tested, for the same charging voltage and following the same experimental procedure, it may pass the test using one ESD generator and fail using another.

The maximum or minimum values of the magnetic field strength (H-field) for both the NSG-433 and the NSG-438 are presented in Fig. 9. The maximum absolute values of the magnetic field strength of the NSG-433 are higher than those of the NSG-438, either for negative or positive discharges. Also, the maximum absolute values of the magnetic field produced by the two ESD generators are higher on the *X*-axis than *Y*-axis either for positive or negative discharges. For a charging voltage of -2 kV the maximum absolute values of the magnetic field produced by the NSG-433 on the *X*-axis are greater than those of the NSG-438. However, these values on the *Y*-axis are very close. In [9] it has been explained that there are two dominating causes for the related magnetic field. The first is the inner

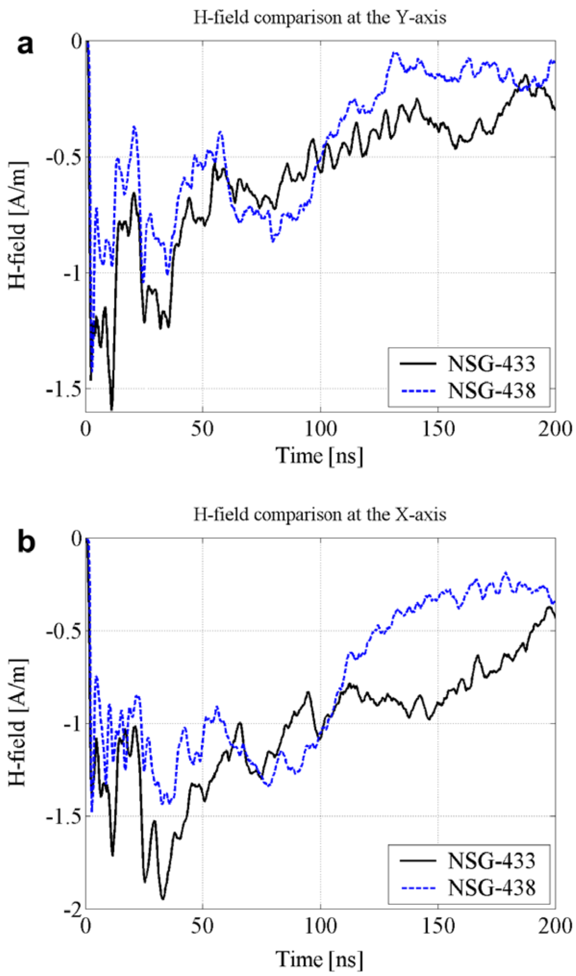


Fig. 8. Magnetic field strength produced at 20 cm from the discharge point by the two different ESD generators (charging voltage = -2 kV).

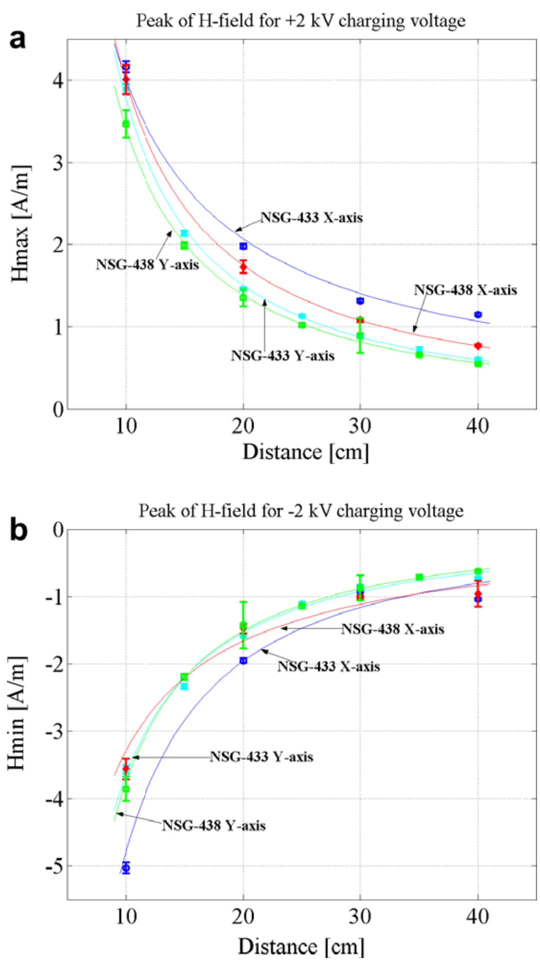


Fig. 9. Peak of H-field for various distances in the two perpendicular directions from the discharge point, using the NSG-433 and NSG-438 ESD generators and for two different charging voltages.

current of the ESD generators and the RC circuit that produce the first component of the magnetic field. The other component is produced by the discharge current. Consequently, different shield on two ESD generators may produce different magnetic field even though the discharge current is the same.

Comparing each ESD generator for two different charging voltages, it is obvious that maximum values of the H-field are observed for a −2 kV charge. Someone would expect that for the same charge in absolute value and for the same distance, the produced magnetic field should be the same. This does not happen probably due to differences in the construction of the RC circuit for the production of the same discharges with different polarity. It is obvious that H_{max} approximately varies inversely to the distance ($1/R$) from the discharge point.

4.2. Measurements of the E-field

Using the same experimental set-up and an E-field probe, the electric field produced by the two ESD generators was measured. In Fig. 10 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.

Fig. 11 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 behavior in the time domain is similar. The NSG-433 produces higher E-field than the one produced by the NSG-438.

Similar to the magnetic field, it was found that for the same horizontal plane, the same charging voltage and the

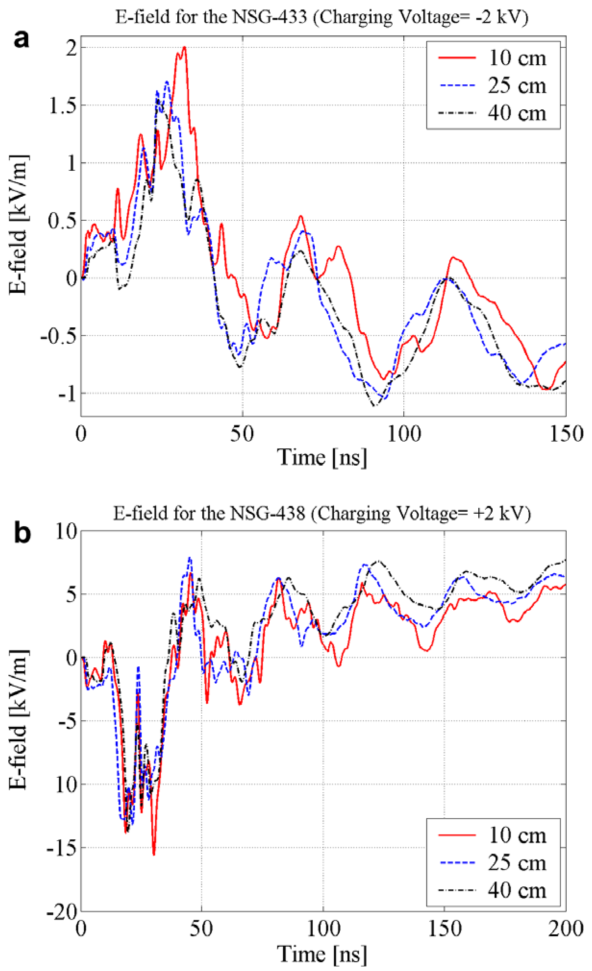


Fig. 10. Comparison of the E-field for the two ESD generators and for three different distances from the discharge point at Y-axis.

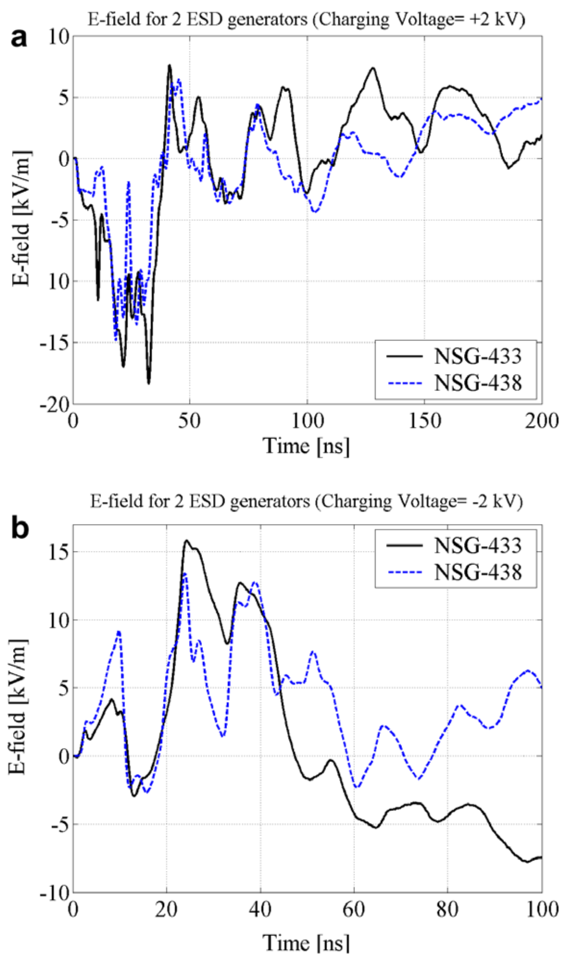


Fig. 11. Comparison of the E-field for the two ESD generators 20 cm from the discharge point and for two charging voltages.

same distance but in perpendicular directions from the ESD generator, the produced electric field for each ESD generator is different. Figs. 12 and 13 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.

The maximum absolute values of the electric field strength (E-field) for the two ESD generators and for the two different charging voltages are presented in Fig. 14. From these figures it can be concluded that the amplitude of the E-field decreases with the distance. Also, observing Fig. 14 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 two charging voltages and for the two perpendicular directions.

Another crucial observation is that, in addition to the magnetic field, the absolute values of the peak values of the electric field strength for the discharges of negative polarity are lower than those measured for the positive polarity.

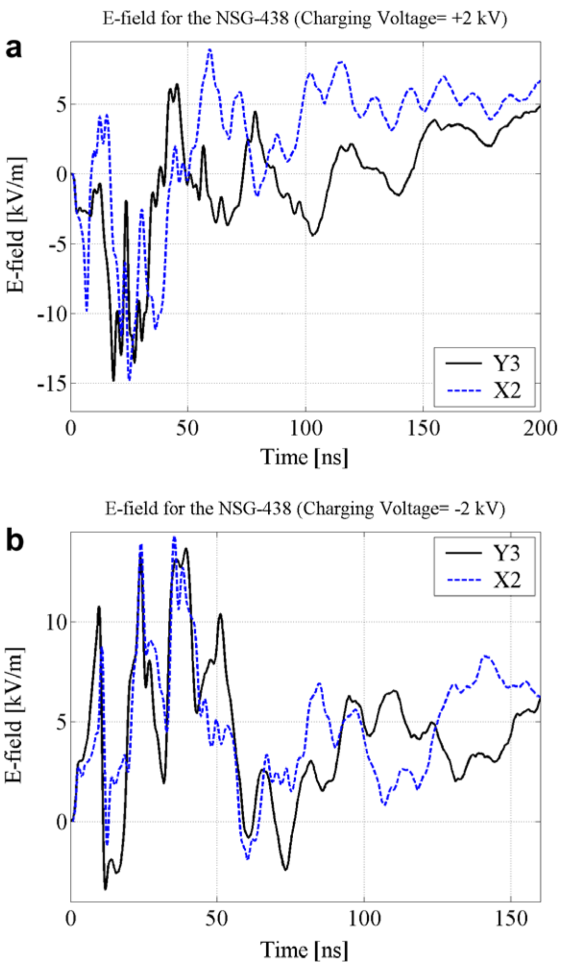


Fig. 12. Electric field strength for the ESD generator NSG-438 20 cm from the discharge point, for two perpendicular directions on the horizontal plane and for two charging voltages.

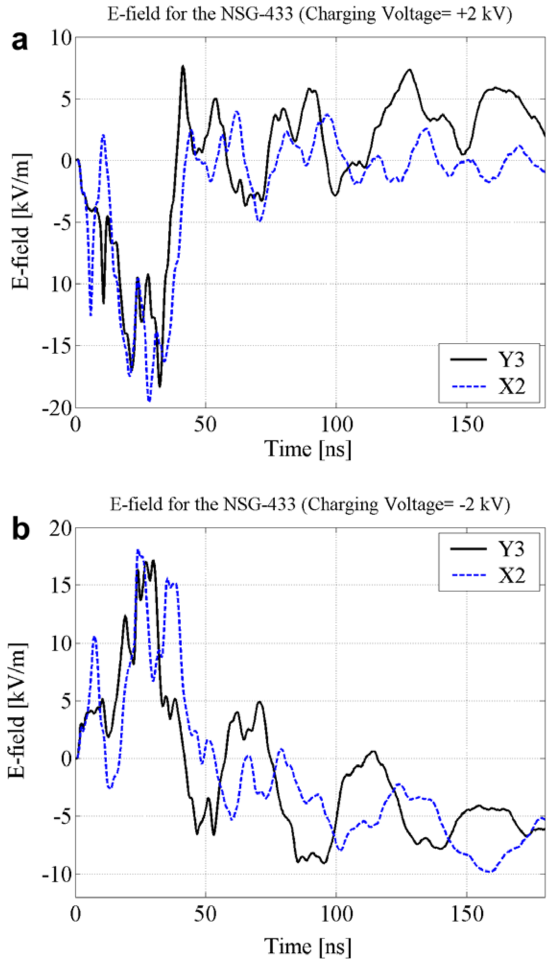


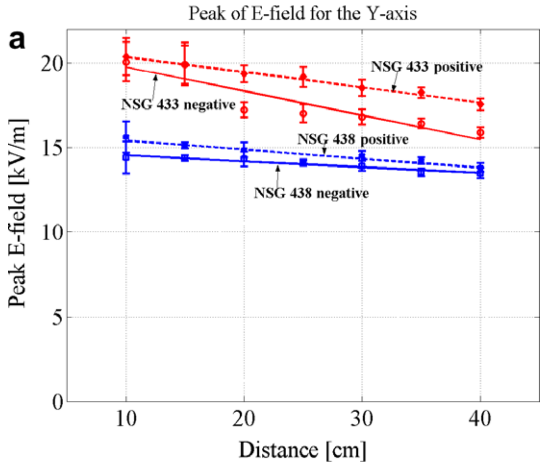
Fig. 13. Electric field strength for the ESD generator NSG-433 20 cm from the discharge point, for two perpendicular directions on the horizontal plane and for two charging voltages.

5. Conclusions

An experiment has been carried out to investigate the transient electromagnetic field produced by contact electrostatic discharges. The transient electric and magnetic fields 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 electromagnetic field.

The magnetic field depends on the ESD current and it is inversely proportional to the distance from the discharge point (R). Within a few centimeters the field is governed by Ampere's law and can be estimated by the discharge current. As the distance from the discharge point increases the magnetic field is also determined by the current distribution of the ESD generator (fields from the discharge current + fields from the inner currents of the generator).

The electric field has a different behavior compared to the magnetic field. It corresponds to the time derivative of the magnetic field. It also decreases with the distance following an almost linear decrease.



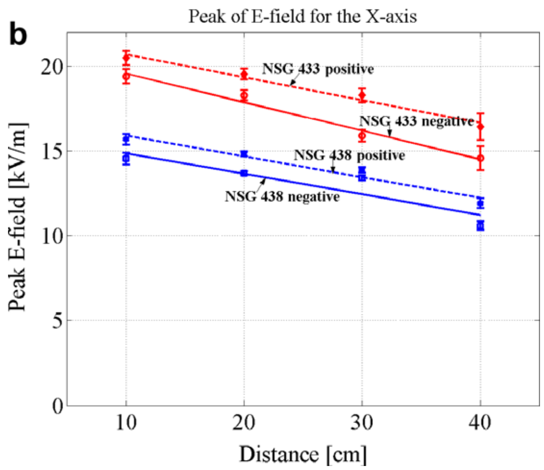


Fig. 14. Peak of E-field for various distances from the discharge point at the *X*- and *Y*-axis using the ESD generators NSG-433 and NSG-438.

It was found that each ESD generator produces different electromagnetic 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 electromagnetic field of the ESD generators should be tested around 360°. The next revision of the Standard should include typical waveforms of the electric and magnetic fields that are produced by electrostatic discharges. It should also define the range of values for several magnitudes of the electric or magnetic field (such as E_{max}, H_{max}, the rise time and perhaps values for the derivatives of the produced electromagnetic fields). 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 electromagnetic field in greater distances. In [14] 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

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