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# Basic experimental set-ups for the characterization of emission from electrical discharge events

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## Abstract

We address the phenomenon of the electrostatic discharge from the point of view of its implications in the field of electromagnetic compatibility. Conducted and radiated emissions from electrical discharges are considered. We investigate how the main parameters of an electrical or electronic system participating in a discharge process contribute to the production of electromagnetic interferences. Here we report a summary of the results that we have previously obtained, as well as some new data on the specific topic of discharges between two isolated spheres. We have been involved in an extensive experimental study of the emission from discharge events, and several specific experimental set-ups have been implemented for their phenomenological characterization. We discuss also the application of simplified numerical models, based on parameters extracted from the experiments. Particular attention is given to the role of the arc in the electromagnetic radiation associated with electrostatic discharges. We discuss the contribution of the arc channel to the total radiated emission from the circuit, and present experimental evidence that this contribution is negligible compared to that of the rest of the circuit. Finally, we present some remarks on the modelling of the discharge formation.

## 1 Introduction

Electrical discharges are of scientific and practical interest. In particular, from an electromagnetic interference (EMI) point of view, electrical discharges represent an important challenge both for the conducted and radiated susceptibility. A complete description of such phenomena involves a very large parameter space; as a consequence, an exact simulation of the discharge process would not only require an extremely long computation time but it would pose an overwhelming problem in the exact boundary condition definitions. Therefore it is important to pursue the development of simplified models, capable of providing reasonably accurate results. First, we will discuss the characterization of the main parameters influencing the conducted and radiated emission from an electrical discharge event. We summarize here results obtained in previous papers (Giannetti [1]), (Tellini [2]), (Giannetti [3]), (Tellini [4]), which were the outcome of an extensive experimental activity. Next, we will move on to experiments aimed at the study of electrical discharges from a phenomenological point of view. In particular, measurements were performed, with the purpose of estimating the contribution of the arc channel to the total radiated emission from an electric circuit since several ambiguities on this issue have surfaced in the literature during the last decade. A further analysis was carried out of how the arc switching behaviour influences the discharge process formation (Giannetti [3]). Most of our experimental set-ups use simple electrode geometries, in order to allow direct comparisons with theoretical calculations.

For example, we discuss the discharge event between two conducting spheres connected through a capacitor characterized by a capacitance large in comparison with that between the spheres (Giannetti [1]), between two isolated spheres, and between a sphere and a ground plane. We investigate also the discharge of a circuit connected to an element with high radiation efficiency, in our case a wire antenna. Finally, we discuss the possible application of simplified models for the estimation of the discharge current and of the radiated emission, validated on the basis of the experimental results.

As expected from considerations in basic electromagnetism, our models confirm that the radiated field is the result of contributions from the whole circuit, in which the discharge current is flowing (Mardiguian [5]), (Taillet [6]). In our measurements, we proved that whenever the arc length is small in comparison with the relevant dimensions of the discharge circuit, the contribution from the arc to the emission phenomenon is negligible, except for the emission in the visible and UV spectrum due to thermal effects. The arc plays the role of a switch, while the radiation is mainly the result of the rapid variation of the electrical quantities in conductors, which have a relevant geometrical extension that makes them much more efficient radiators than the arc itself. This is the situation found in the vast majority of practical cases; as a consequence, it is possible to simulate the radiation phenomenon modelling the arc as a localized current source to be applied to the rest of the system. The experimental results have also shown that the radiation effect does not influence the discharge current in the arc in a significant way; in other words, we have verified that the emission phenomenon does not load the circuit in most of the practical situations, as better described in the next sections. On the other hand, the radiated power is a small fraction of the global involved discharge power and the emission is simply an electromagnetic image of the radiating behaviour of the elements with the largest radiation efficiency.

## 2 Experimental set-ups

Different set-ups have been assembled for investigating fast electromagnetic transients related to electrical discharge events. The first set-up, shown in Fig. 1, has been used for measuring the discharge current between a sphere and a ground plane. In order to be able to measure the discharge current, the spark takes place between the sphere and a small rod, which is held, by means of a plastic cylinder, in the middle of a hole in the metal ground plane. The rod is connected to the ground plane with a non-inductive 50 Ω resistor, and the voltage across this resistor (proportional to the arc current) is fed to the oscilloscope input by means of a 50 Ω coaxial cable and a cascade of wide-band attenuators. A more accurate description of this set-up is reported in (Tellini [4]). In Fig. 2 the second set-up is shown, which is useful to test electrical quantities in an extended circuit, and is based on a 2.2 nF capacitor that can be discharged via a spark gap obtained moving a sphere close to a grounded conducting plane (Giannetti [1]). The shielding effectiveness of the box enclosing the spark gap has been estimated at a frequency of 150 MHz, by placing a battery powered Colpitts oscillator (together with the battery) inside the box, and measuring the signal which can be received outside, at a distance of 1 m, with and without the box cover. In this way, a 40 dB difference was measured, thus corresponding to an attenuation of at least 40 dB. The capacitor is charged by temporarily connecting it, through a 10 MΩ resistor, to a high voltage DC power supply. Before lowering the sphere and therefore producing the spark, all connections to the power supply are removed, so that only well-known and controlled elements are present during the discharge transient. Both the radiated field and the arc current of the previous set-up are measured in the time domain, using a Tektronix TDS680B digitising oscilloscope, with a sampling rate of 5Gsa/s. The third experimental set-up has been assembled similarly to the previous one; the only difference being the connection of an extended element, a rod antenna with a length of 50 cm and a diameter of 5 mm. Figure 3 shows a photograph of the cited set-up. This set-up has been tested in a semi anechoic chamber in order to collect reference data for the validation of numerical models we are currently developing. The fourth set-up we have used is shown in Fig. 4: it consists of two spheres between which a potential difference is kept by means of a 2.2 nF capacitor that is charged via removable electrodes. Once the capacitor has been charged, the spark is obtained moving the spheres closer together, by means of an insulating rod. For this experimental set-up, the radiated field is the only quantity being detected, using the same measurement equipment as in the previous cases. The fifth and sixth experimental set-ups contain a capacitor system made up of two isolated spheres and a capacitor system consisting in a sphere located in the proximity of a ground plane, respectively. The spheres have been mounted on insulating holders and have been charged with a high voltage DC power supply via removable electrodes.

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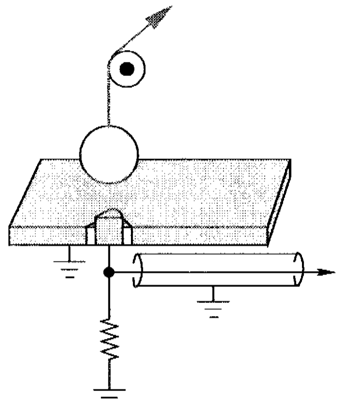

Figure 1: Discharge current measurement set-up.

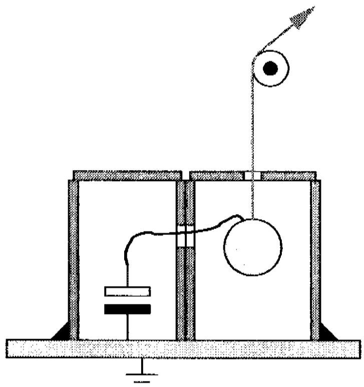

Figure 2: Schematic representation of experimental set-up used for electrostatic discharge of a single-sphere in an extended circuit.

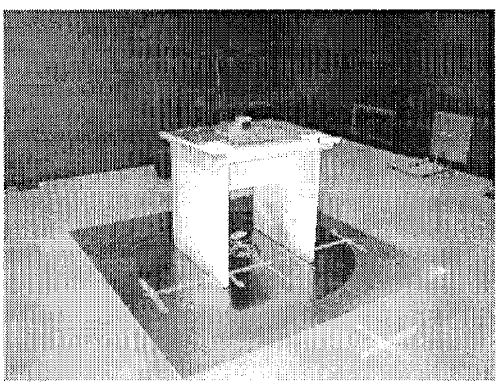

Figure 3: Photograph of the set-up with the rod antenna in a semi anechoic chamber.

Photographs of such set-ups are shown in Figs. 5 and 6.

With reference to the first, fifth and sixth experimental set-ups, spheres with different diameters have been adopted, in order to show the influence of the electrode geometry in characterizing the electromagnetic transient associated with the electrical discharge.

## 3 Measurements and discussion

Highly reproducible results have been obtained, although confirming the intrinsic random nature of the discharge: i.e., for each measurement slight deviations have been observed around a substantially repetitive behaviour.

With reference to the set-up of Fig. 1 results are consistent with theory and with experimental data obtained by other authors, (Maier W. B. II [7]); i.e. longer current rise time and larger maximum in the discharge current for larger spheres. The set-up of Fig. 2 allows for testing the radiated emission in different conditions, by independently removing the cover of each box. Results are reported in (Giannetti [1]) where it was concluded that the relative contributions to the radiated emission from the different sections of the circuit strongly depend on their radiation efficiency. New data are reported in this paper about the voltage waveform between the electrodes; in particular the high-frequency components of the voltage across the main capacitor are measured. To this purpose, we have used a CR filter assembled directly on the terminals of the capacitor itself. The time constant of the CR filter is 2.75 ns, obtained with a 110 pF capacitor and a 25 Ohm resistor. The value of such a time constant is the result of a tradeoff between preventing an excessive perturbation of the circuit and obtaining a signal that is a reasonable representation of the relevant high-frequency components of the voltage on the main capacitor. At any rate, since the CR filter is exactly known, it is always possible to compute the actual behaviour of the main capacitor voltage from the measured data. This filter is needed also to prevent the high DC voltage on the main capacitor from damaging the attenuators and the digitising oscilloscope. Voltage and current transient waveforms are substantially unaffected by the presence of the covers.

With this set-up, we expect that a significant increase in the emission will occur if we add to the circuit an antenna operating at frequencies within the spectrum of the voltage transient. The voltage transients across the main capacitor in the absence of any antenna is shown in Fig. 7(a), while that in the presence of a wire antenna connected to the "hot" terminal is reported in Fig. 7(b).

It is apparent that there is no significant difference between the two transients, and that, therefore, the loading effect of the antenna is negligible, except for a narrow band of frequencies near its resonance. We are currently still investigating this issue, in order to develop a simplified numerical model able to characterise both the radiated and the conducted emission from such systems. The main objective of our work is to create a model in which electrical quantities such as the arc channel current or voltage can be calculated using a simple equivalent circuit with lumped parameters.

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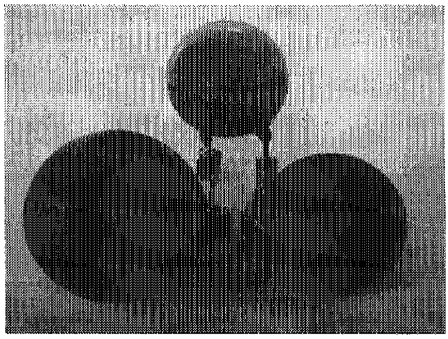

Figure 4: Photograph of two spheres connected together with a capacitor having a large capacitance in comparison with that between the spheres.

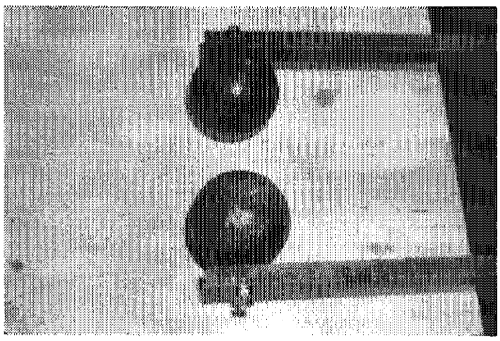

Figure 5: Two insulated spheres system.

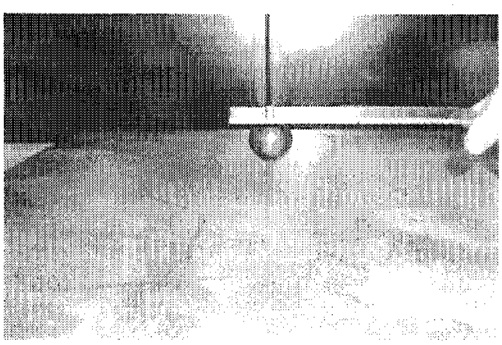

Figure 6: Insulated sphere close to the ground plane system.

The obtained values could then be used as an input for a second, distributed-parameter simulation, in which it would be sufficient to take into account just the elements with the highest radiation efficiency. Simulations have been done through a simple lumped parameter model reproducing a typical *RLC* series (Maier W. B II [8]), with values consistent with the results of impedance measurements on a wide frequency range. The equivalent inductance of the discharge branch has been computed on the basis of the loop length. The arc formation has been modelled with the equivalent network model proposed in (Giannetti [3]). Numerical results are in good agreement with measurements. Such agreement demonstrates the validity of the circuit model for the interpretation of the discharge current and voltage transient, as long as the radiated energy is not a significant fraction of the overall energy involved in the transient, which is the condition found in most practical situations. When this is not the case, or for a more refined evaluation of the electrical quantities, radiation has to be taken into account with a full-blown electromagnetic simulation, including the detailed geometry of the circuit and of all conducting structures connected to it.

Electric field measurements have been performed in the semi-anechoic chamber of GSD s.r.l confirming that the presence of a high-efficiency radiator, like the rod antenna in our case, leads to a large increase in the radiated emission from the circuit. A calibrated antenna at a distance of three meters has been used for measuring the emission from the system of Fig. 3: the electric field is reported in Fig. 8. A preliminary discussion on the emission from the system described in the fourth set-up of the previous section has already been published in (Giannetti [1]). Here we report, in addition, a typical electric field measured in the time domain for two different pairs of spheres; results are reported in arbitrary units, because a non-calibrated antenna was used (Fig. 9). It can be easily observed that the electric field levels are higher for larger spheres; but the current transient through the arc is substantially the same, regardless of sphere size, so that any difference observed in the emission is due to the different antenna behaviour of the different spheres.

In Fig. 10 the electric field obtained from a discharge between an isolated sphere placed on a ground plane is reported, in arbitrary units. The upper diagram refers to larger spheres, with a diameter of 7 cm, while the bottom plot refers to smaller spheres, with a diameter of 3 cm. Higher emission levels are therefore registered for larger spheres; substantially analogous results are obtained for the system presented in Fig. 5, consisting of two isolated spheres.

Results seem to be in agreement with the previous considerations, but at this stage of the work, it is not yet possible for this particular set-up, to perform an accurate analysis of the relative importance of the contributions to the emission from the arc and from the spheres. Two results are indeed established: i) the quantity of charge involved in the discharge processes shown in Fig. 10(a) is different from that of Fig. 10(b), ii) the discharge currents present different maxima and different rise times.

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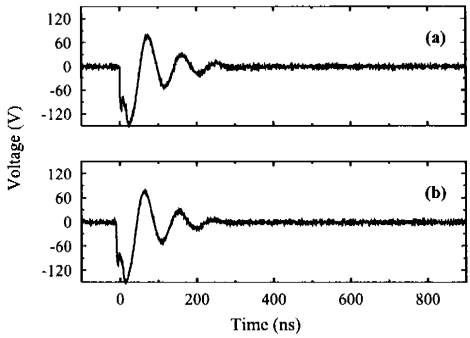


Figure 7: Plots of high-frequency components of the voltage transient of the main capacitor, for an electrostatic discharge without (a) and with (b) thc additional vertical rod antenna.

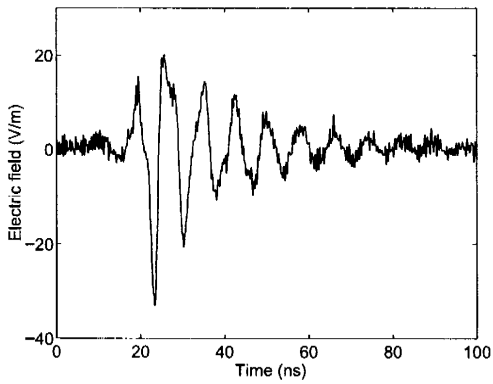


Figure 8: Electric field due to the discharge from the set-up of Fig. 3.

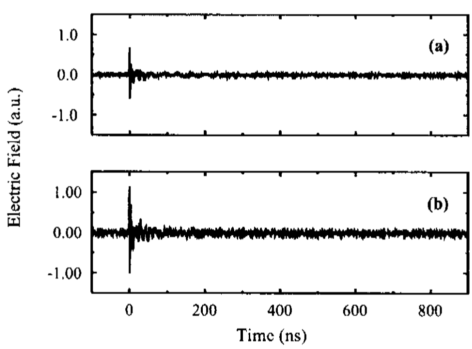


Figure 9: Electric field vs. time, measured for a discharge between two smaller spheres (a) and two larger spheres (b).

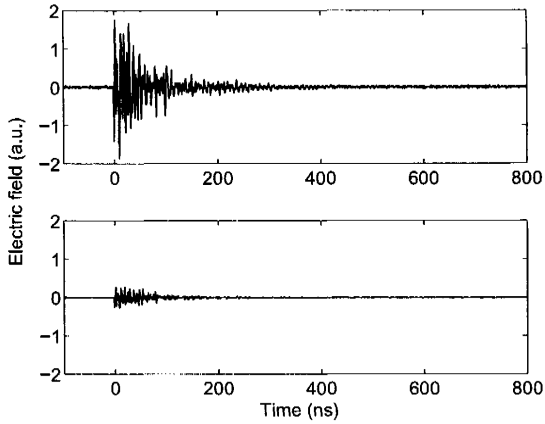


Figure 10: Electric field vs. time due to an electric discharge in the system of Fig. 6 for two small spheres (a) and two large spheres (b).

Further work is in progress to define a more accurate set-up for a better understanding of this type of transients, and, in particular, to determine whether in this case the radiation from the arc (which is usually negligible compared to that from other parts of the circuit) plays a relevant role. Under the hypothesis of the same arc length, size and resistance for the systems with large and small spheres, from the theory of the short dipole it is possible to evaluate, with a relatively simple analytical computation, the radiated field, in the hypothesis that only the arc (short-dipole) acts as a radiating element. With the aid of experiments in a semi-anechoic chamber, or in a suitable open-range test site, it should be possible to measure the actual electric field emitted. A comparison between numerical and experimental results should indicate the actual contribution from the arc to the total emission.

We have shown that whenever the arc length is small in comparison with the rest of the circuit the arc plays the role of a switch and, in practice, does not contribute significantly to the electromagnetic radiation. It would be important to find a tradeoff between an accurate model of such a switch and the computation cost. Assuming an ideal switch may be too much of an approximation for some situations, such as, for example, those corresponding to the last three set-ups that we have discussed. In such configurations an over-damped transient of the current has been measured and usage of an ideal switch in the model would yield a double exponential solution that is not consistent with the observed phenomenon.

In particular the current for the double exponential solution predicts a concave waveform at the beginning of the transient, while measurements show a convex form.

We proposed in (Giannetti [3]) an equivalent network model for representing arc formation. Results were encouraging and applications have been done for electrodes of different geometries.

## 4 Conclusions

In this paper we have presented the main results of an extensive experimental effort for the prediction of the discharge current and of the radiated emission from electrical or electronic circuits characterized by electrical discharge events. Basic experimental set-ups have been used to analyse the phenomenology of the electrical discharge transient and to determine the main parameters taking part in the discharge process. Our main purpose has been that of clarifying the role of the arc in the determination of the discharge current and of the radiated emission. Results show that the arc plays the role of a non-ideal switch, and therefore it influences the current transient as well as the radiation. However, the direct contribution of the arc to the electromagnetic emission is, in most practical situations, negligible compared to that from the rest of the conductors forming the circuit, which, just as a consequence of the much larger physical extension, have a much more efficient antenna action. Further work is currently in progress for the accurate evaluation, in a semi-anechoic chamber, of the contribution of the arc to the emission in structures in which discharge currents are expected to be very localized, such as those in the last three described set-ups.

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