Tomasz Kossowski[1], **Paweł Szczupak**[1]

Rzeszow University of Technology, Faculty of Electrical Engineering and Computer Science (1)
ORCID: 1. 0000-0001-5420-3629;
ORCID: 2. **0000-0002-5715-3492**;

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Analysis of the electric field distribution in the parallel-plate capacitor designed for testing the immunity of electrical devices to lightning electromagnetic pulse.

***Abstract**. The article verifies the actual voltage distribution inside a 2x2x1m capacitor. It is used to test objects an order of magnitude smaller, e.g.: unmanned aerial vehicles and determine the influence of the electrical component on the resulting surges in the circuits of these devices. The theoretical field distribution for an ideal capacitor is uniform, but for a real one, it can deviate significantly from the assumptions. This is affected by a number of factors, including conductive objects in the immediate vicinity, electrical wiring in walls, or water pipes. This is because each real capacitor has a different distribution of the electric field inside as well as near the ends of its covers. The uniformity of this distribution is therefore significantly altered, and it is necessary to determine in which cross-sectional area it is constant and provides the right conditions for reliable measurements. To determine these parameters, time-varying signals of low (a sinusoidal waveform with a frequency of 50 Hz) and medium frequency (a lightning surge pulse with rise/fall times of 6.4/69 μs) were used. The results of the analysis are presented in this article.*

***Streszczenie.** W artykule weryfikowano rzeczywisty rozkład napięcia wewnątrz kondensatora o wymiarach 2x2x1m. Służy do badania obiektów o rząd wielkości mniejszych np. bezzałogowych statków powietrznych i określania wpływu elementu elektrycznego na powstałe przepięcia w obwodach tych urządzeń. Teoretyczny rozkład pola dla idealnego kondensatora jest równomierny, ale dla rzeczywistego może znacznie odbiegać od założeń. Wpływ na to ma wiele czynników, w tym przewodzące obiekty w bezpośrednim sąsiedztwie, przewody elektryczne w ścianach lub rury wodociągowe. Dzieje się tak, ponieważ każdy rzeczywisty kondensator ma inny rozkład pola elektrycznego wewnątrz i na końcach jego osłon. Jednorodność tego rozkładu zostaje zatem znacząco zmieniona i konieczne jest określenie, w jakim obszarze przekroju jest on stały i zapewnia odpowiednie warunki do wiarygodnych pomiarów. Do wyznaczenia tych parametrów wykorzystano zmienne w czasie sygnały o niskiej (przebieg sinusoidalny o częstotliwości 50 Hz) i średniej częstotliwości (impuls udarowy piorunowy o czasach narastania/opadania 6,4/69 μs). Wyniki analizy przedstawiono w tym artykule. (**Analiza rozkładu pola elektrycznego w kondensatorze płytowym, równoległym przeznaczonym do badania odporności urządzeń elektrycznych na piorunowy impuls elektromagnetyczny**)*

Keywords: surge voltage generator, drone’s immunity, lightning discharge, electric field distribution.
Słowa kluczowe: impulsy piorunowe, kondensator płytowy

Introduction

For the analysis of surge protection (from lightning) of flying devices, which include both aircraft and unmanned aerial vehicles, EMP (ElectroMagnetic Pulse) [1-6] pulses are used. Irradiating a machine with an electromagnetic pulse is comprehensive and yields a result of the magnitude of interference that is created in the drone's circuits. As previous studies have shown [7, 8] the electronics of small devices such as a drone are more affected by the magnetic component, and overvoltages are induced in long conductors such as motor winding, antennas and power cables. However, the electrical component has a different form of impact on electronic devices and its separate impact has also been studied [9]. To prove the validity of the tests carried out, it is necessary to consider the uniformity of the field and the stability of the test stand. Repeatability of surge pulses in accordance with international standards RTCA DO-160 [10] related to surge protection in aviation is provided by the surge pulse generator MIG0618SS [5, 8]. Pulses with pulse rise/fall times of 6.4/69 μs, respectively, were used for the study. This shape is a normalized waveform [3, 4, 10] that is used for a wide variety of applications and reflects the phenomena of magnetic field penetration resulting from a nearby discharge, inside the aircraft through "structural gaps" such as windows [8].

The response of the tested capacitor to impulse excitations, was compared with the results obtained for an excitation with a sinusoidal signal of 50 Hz frequency (line voltage with amplitude increased to 250 V). A real capacitor is characterized by a homogeneous electric field in a certain area, in its interior. The case is different with the edges of the covers, because there, the field distribution is no longer homogeneous [11, 12]. In the article, a structure with covers 2 m wide and 2 m high is considered. The distance between the covers of the capacitor is 1 m. Such a large structure can interact with electrical/ telecommunications/ water infrastructure located in the walls. The influence of the floor and especially its reinforcement is also not insignificant. The distance to the ceiling lighting can also have an impact on disturbing the uniformity of the field inside the capacitor. All these factors make mathematical analysis difficult. An example of the electric field distribution for the DC component using a simulation model in the Matlab environment is presented in Figure 1. It is based on a two-dimensional model using the finite difference method [13]. However, it refers to an ideal situation, which is not the case here. The presented bulbs do not refer to standard electromagnetic compatibility measurements in TEM chambers. The presented research stand is a completely different solution.

The aim of the work is to determine whether it is possible to test very small (10 times smaller than the size of the capacitor) objects in a uniform electric field. The research was intended to show how much of the surface does not meet the discussed assumptions due to the presence of floor, walls and other elements in the laboratory. For electromagnetic immunity tests, TEM Cells are typically used. Thanks to them it is possible for example to carry out durability tests of electronics for far electromagnetic fields in the range from zero to several hundred MHz. In this solution, however, due to the 50 Ohm termination located at the end of the TEM cell, the magnetic component is significantly higher than in the case of the parallel-plate capacitor used by the authors. There are many methods to tests lightning indirect effects on electronic such as pin injection, transformer injection, capacitive injection, ground-circuit injection, and field immersion techniques. These methods are defined in IEEE, ANSI, SAE, RTCA, EUROCAE, U.S. MIL-STDs and many industry and company standards and specifications.

Measurement setup description

The size of the capacitor's plates (2x2 m) allows to calculate its capacitance using the formula [2, 11]:

$$C = \frac{\varepsilon_0 \varepsilon_r S}{d} \text{ [F]} \quad (1)$$

Where: ε_0, ε_r – electrical permeability of vacuum and medium [F/m], S - surface area of covers [m^2], d - distance between covers [m].

Its capacitance is 35 pF. This is a very small value, and it is of no significance in the case of cooperation with the generator in question (the generator can operate both at the opening of the output terminals and at a short circuit).

The shape of the electric field corresponds to the shape of the voltage applied to its covers. For low-frequency excitations, there are still no phenomena as in the high-frequency range, or their influence is negligible. The electric field is therefore described as follows, without taking into account additional factors:

$$E = \frac{U}{d} \text{[V/m]} \quad (2)$$

where: E - Electric field, U - Set voltage [V], d - distance between covers [m]

The power generator was the MIG0618SS, dedicated to avionics testing in accordance with DO - 160G section 22. It allows testing the effects of indirect lightning, using two methods of pulse exposure so-called "pin injection", i.e. direct pulse injection, and "cable bundle" - using a coupling transformer in addition. Among other things, this generator allows for single repetitive 6.4/69 μs pulses with an amplitude of up to 3400 V. In the conducted tests, the surge voltage was limited to 2500 V [7, 8]. The theoretical distribution of the field, along with the marked lines, is presented in Figure 1. This is the result of a simulation for the capacitor shown in the Matlab environment, using the 2D Poisson equation (Praveen Ranganath Matlab code) [13,14].

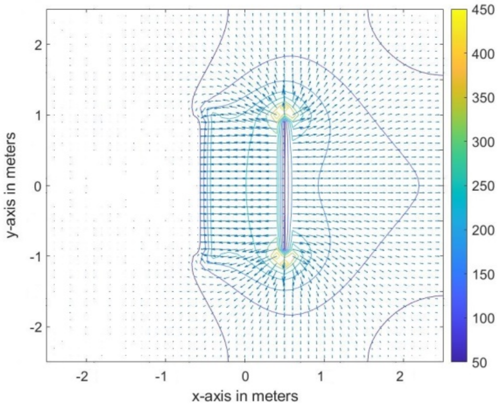

Fig.1. Simulated electric field distribution [V/m] for the capacitor under test by Praveen Ranganath Matlab code [13] - view from the top

The Poisson distribution in maths is used to determine the discrete probability distribution of the number of events in time or space (distance, area, volume), that is, regardless of the number of axes [13,14]. In our case, we are performing a 2D analysis, so the graph shown in Figure 1, is formed using the relationship described by equation 3 [14].

$$P(N(D) = k) = \frac{(\lambda|D|)^k \, e^{-\lambda|D|}}{k!} \quad (3)$$

where: D - 2D area, |D| - area of 2D area, N(D) - number of points in area, k - probability given by function, λ - expected number of events

The discussed MIG0618SS pulse generator (interchangeable with a 50Hz alternating voltage source) was connected to both capacitor plates. The negative plate has been grounded. Measurements were made inside the capacitor by manually placing the measurement probe at equal distances from each other, creating a grid of results (accuracy 1 cm). The sampler was a system of open connectors, connected to the Rigol 1054Z oscilloscope using a coaxial cable (for the pulse generator). The generator is designed to operate in open terminal conditions, so it was possible to connect it directly to the capacitor under test. The analysis of the voltage on its plates reflected the perfectly generated impulse (also regardless of the changes taking place inside the capacitor - its stability was tested). Measurements of the 50 Hz field were made using a Maschek meter, described later. Experimental setup was shown in Figure 2.

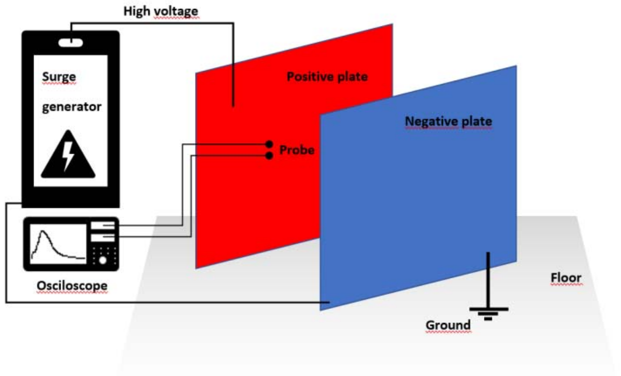

Fig.2. Experimental setup

Experimental results

A. For a sinusoidal forcing with a frequency of 50 Hz

First, measurements were taken for low-frequency signals. Since the measurement system was to be used to study time-varying pulses, measurements were not undertaken for the constant component.

For this purpose, results were collected for three different locations:

- 10 cm from the positive cover of the capacitor
- halfway between the covers
- 10 cm from the grounded cover

Since the signal was periodic, it was decided to measure the value of the electric potential using a professional electric and magnetic field meter Maschek ESM-100. It enables single (as in this results) and serial measurements with the possibility of presenting the results in 3D. Its operating parameters allow the analysis of signals up to 400 kHz in the range of 0.1 V/m to 100 kV/m in three planes simultaneously. The results of the measurements are shown in the graphs below (Figures 3-5). Graphs present sliced parallel to capacitor plates where floor is in the bottom of figures (for all).

The measurements show a clear effect of the floor on the distribution of the electric field. The potential at this edge is clearly higher than at other points. However, this does not affect the central part of the capacitor, where the fields maintain a similar uniformity.

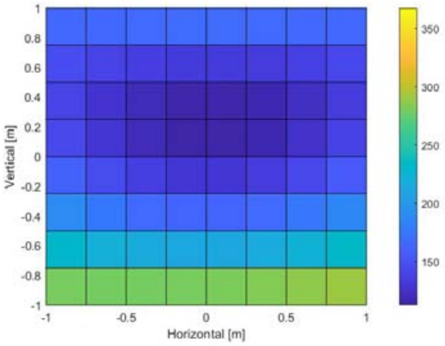

Fig.3. The amplitude [V/m] of the electric field at a distance of 10 cm from the capacitor cover to which the voltage was applied.

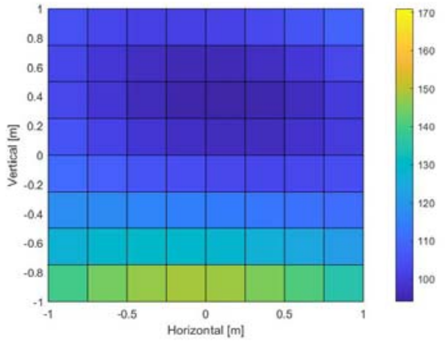

Fig.4. The amplitude [V/m] of the electric field between the capacitor covers.

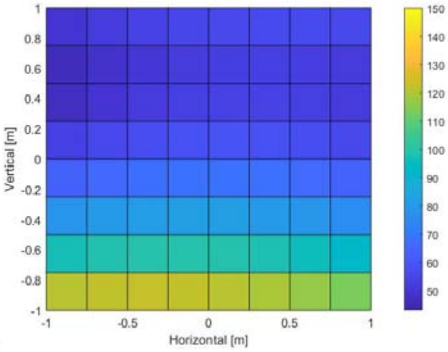

Fig.5. The amplitude [V/m] of the electric field at a distance of 10 cm from the grounded capacitor cover.

B. For 6.4/69 µs pulse

Figure 6 shows sample waveforms of the recorded signal. Every fourth sample was selected, for each position to increase the readability of the graph. It can be determined from this that the shape of the measured surge pulse is preserved for each measured point between the covers. However, it is very difficult to determine the exact distribution of voltages at each location.

For this purpose, results were collected for three different locations:

- 10 cm from the positive cover of the capacitor
- halfway between the covers
- 10 cm from the grounded cover

The distribution of potentials (the peak value of the measured shock pulse) on the planes described above, which are cross sections, are presented in Figures 7-9, respectively. Graphs present sliced parallel to capacitor plates where floor is in the bottom of figures (for all).

From the results presented in these figures, it can be concluded that the distribution of the electric field inside the capacitor differs from the assumptions. One can clearly see the influence of the laboratory floor on the reduced value of potentials for all three cross sections. The underestimated value also occurs at the corners, which is correct and in accordance with the simulation model. From the results, it can also be determined that the central section exhibits the properties of a homogeneous field.

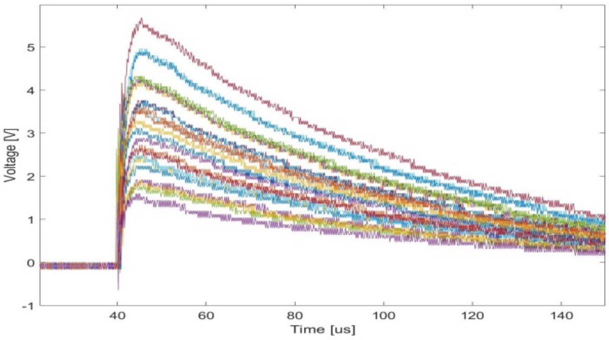

Fig.6. Shape of the waveform of selected pulses at different measured points (every fourth sample).

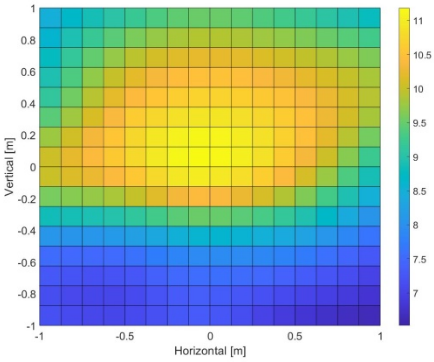

Fig.7. The peak value [V] of the Voltage at a distance of 10 cm from the nagative cover of the capacitor.

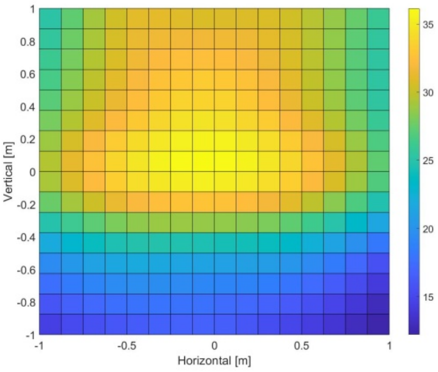

Fig.8. The peak value [V] of the Voltage after the center of the capacitor.

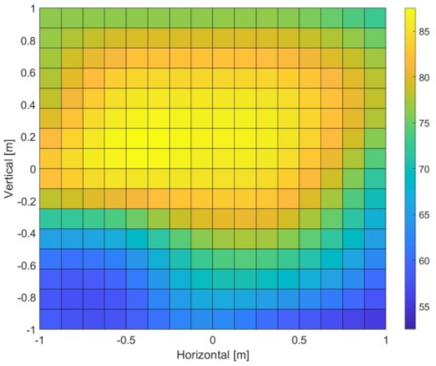

Fig.9. The peak value [V] of the Voltage at a distance of 10 cm from the positive cover of the capacitor.

The behavior of the same distribution occurs within 50 cm in each direction from the center of the capacitor. This means that objects smaller than the specified area will be in a homogeneous electric field of equal potential for any distance from the capacitor's covers. Tests conducted in this zone will therefore provide a meaningful result.

Conclusion

The primary objective of the published experiments was to determine to what extent the physical model of a large-scale capacitor differs from the mathematical model. The main problem of the case at hand is the size of the covers (2x2 m), since such a large scale combined with high voltage (2.5 kV) causes anomalies. This is primarily due to the distance to the surrounding objects, primarily the walls, floor, or ceiling, where the electrical, water, or central heating pipes of the building are located. Since they are grounded in different ways, they affect the field distribution around such a large object, which by its own dimensions cannot be further separated from them. In the graphs shown, it is clear that the influence of the factors in question is clear and significant for areas near the edges of the covers. The central part of the capacitor, on the other hand, shows stability and uniformity of the electric field. This means that it is possible to carry out measurements inside the covers, assuming that the tested object is of dimensions no larger than 0.5x0.5 m and is located in a central position. For this location, it is possible to speak of analyzing the objects under study in a homogeneous electric field. As you can see, the area is larger, but limiting it to the mentioned dimension of 0.5x0.5 m ensures correct analysis and reliable results during testing. The center of the capacitor was chosen as the starting point, hence the distances given. If this central point were moved higher (above the center of the capacitor), the area of the uniform field would be much larger. To determine its size, it was assumed that the voltage drop did not exceed 10% compared to the maximum value in its center. Of course, it is possible to make completely different assumptions. However, the aim of this article was to determine whether small objects (10 times smaller than a capacitor) can be examined inside it in a uniform field. However, the results allowed us to determine their size, twice as large as expected. It should also be remembered that the resolution of the measurements limits the ability to precisely determine this area. Performing the analysis with a higher resolution could further increase the area in question. However, the goal was to determine the range of uniformity and not to precisely draw the electric field lines throughout its entire volume.

Based on the results of the above experiments, it is proven that such a large capacitor placed near conductive elements has an electric field distribution that is definitely deformed from the mathematical assumptions. It would be very difficult to carry out simulations, since it would be necessary to know the exact location of each installation inside the walls/ceilings, as well as measurement data informing about their characteristics. Thus, it can be seen that the only way to determine whether the proposed testbed for testing small unmanned flying objects meets the requirements for measurements in a homogeneous electric field is to conduct actual measurements, as presented in this article. Thus, it has been proven that the tests and analyses carried out with the described test stand are carried out reliably and in an appropriate manner, for objects that meet the discussed criteria for their size.

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***Authors**: mgr inż. Paweł Szczupak, Politechnika Rzeszowska, Katedra Elektrotechniki i Podstaw Informatyki, ul. Wincentego Pola 2 , 35-959 Rzeszów, E-mail: pszczup@prz.edu.pl; dr inż. Tomasz Kossowski, Politechnika Rzeszowska, Katedra Elektrotechniki i Podstaw Informatyki, ul. Wincentego Pola 2, 35-959 Rzeszów, E-mail: tkossowski@prz.edu.pl;*

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