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doi:10.15199/48.2017.10.07

Nanosecond EMP simulator using a new high voltage pulse generator

Abstract. *In this paper, a prototype of an electromagnetic pulse generator (EMP) is presented. It is designed to test electrical systems and equipment in electromagnetic hostile environments according to military standards. It consists of a high voltage pulse generator connected directly to a helical antenna in order to convert the electrical energy into an electromagnetic wave. Two types of simulations were developed in order to predict the behaviour of the simulator: the first one using Matlab Simulink for the electrical part, and the second using FEKO to figure out the parameters of the designed antenna. A reduced model has been built and tested. The generated electrical field of the generated EMP was measured using a free field D-dot probe.*

Streszczenie. *W artykule przedstawiono projekt systemu generującego nanosekundowe impulsy elektromagnetyczne. System taki może być zastosowany do testowania (zgodnie z normami wojskowymi) odporności urządzeń i systemów elektronicznych na impulsowe zaburzenia generowane na przykład przez broń elektromagnetyczną. System składa się z autorskiego generatora szybkich impulsów wysokiego napięcia podłączonego bezpośrednio do anteny śrubowej. W celu zaprojektowania urządzenia wykonano symulator generatora w programie Matlab Simulink i model anteny w oprogramowaniu FEKO. Na podstawie wyników symulacji wykonano i zbadano pomniejszony prototyp urządzenia.* ***(symulator impulsów nemp z autorskim generatorem impulsów wysokiego napięcia)***

Keywords: Electromagnetic pulse (EMP); High voltage pulse generator (HVPG); Dipole antennas; D-dot probe.
Słowa kluczowe: impuls elektromagnetyczny; generator impulsów wysokiego napięcia; anteny dipolowe; sonda D-dot

Introduction

The design of reliable electrical systems is not a simple task, especially in some sensitive domains which demand high-security level like aeronautics and aerospace or for those working in very severe conditions such as the military equipment. Therefore, several standards and norms have been elaborated in order to normalise the tests' conditions that the system should sustain in order to be approved, in particular, those tests connected with the electromagnetic compatibility (EMC). In our case, we are interested in the checking of the susceptibility of a designed system to the electromagnetic radiated pulses (EMPs) like those created by nuclear explosions or some electromagnetic weapons in order to confirm its ability to work in electromagnetic hostile environments. For that purpose, it's very important to reproduce, in the lab, artificial conditions where the tests could be carried out.

The presented paper is a part of a general project of developing a test bench (simulator) capable of producing EMPs. It's devoted to explain the primary designed solution, present the constructed prototype, discuss the experimental results and measurements done in the lab and comparing them with the results obtained from simulation. In this work, we mainly focus on the connection between the high voltage pulse generator and the antenna, which can be done using different alternatives such as a direct connection without any intermediate or using some kind of pulse forming networks or transmission lines to adjust the impedance between the generator and the antennas. The chosen solution depends on several parameters like the generator impedance, the distance between the generator and the antennas, the frequency range (i.e wavelength)...etc. The second point discussed in this paper is the measurement of the radiated EMP.using a fast free field D-dot probe, which is a convenient way to measure the high amplitude electrical field contained in the EMP. In the last part of this section, some similar works from the literature are presented.

SUN Qi-Zhi et al. constructed an EMP generator capable of producing an electrical field of 35kV/m at a distance of 3 meters from the antenna. The design is based on 570kV/1.5ns Marx generator discharging in a helical antenna through a transmission line used for impedance matching and for pulse compression in the same time. The used Marx generator has got 10 stages, charged using inductors in order to raise the repetition rate and to create voltage oscillations on the output of the generator [1].

In [2], L. Pecastaing et al. presented an UBW radiation source based on a 250kV/300ps Marx generator connected to a broadband Valentine antenna through a pulse forming device. The measured electrical field using Michelson technique was 436 kV/m peak to peak.

In [3], T. A. Holt et al. presented an Impulse Radiating Antenna developed by APELC which consists of a TEM-horn-fed parabolic reflector that is directly driven by a 22-J, 400-kV Marx generator. The radiated field exceed the 200 kV/m with a central frequency of 210 MHz at 1m distance from the antenna.

Another EMP Simulator with horizontal polarised dipole antenna was fabricated by L-3 Pulse Sciences. It was driven by a 6-MV biconical pulse generator. It can produce pulses from 60 to 117.5-kV/m peak [4].

A series of works were done by Dr. M. M. Kekez within the High Energy Frequency Tesla Inc. HEFTI (which was established by him on March 28, 2002). The main subject of his studies is the radiation produced by gas discharges. He has built several EMP with very high frequencies reaching gigahertz and also with high amplitude [7, 8, 9, 10, 11].

General description

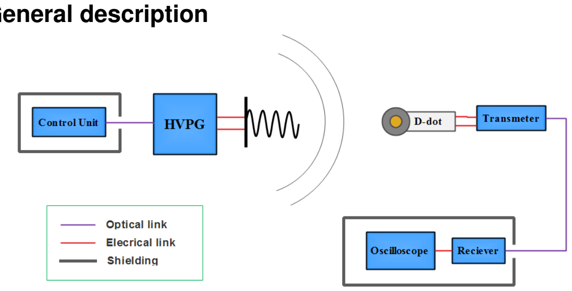

Fig. 1. Schema describing the general structure of the test-bench

The system described in this section (see Fig. 1) is a prototype of an EMP simulator. It consists of a high voltage generator (HPVG), supplied by a DC source, connected directly to a helical antenna. The HVPG is triggered using a control unit connected to the generator using an optical fibre. The control unit is based on a microcontroller which provides low voltage pulses with a specified repetition rate and pulse width. The user can continuously change these two parameters using a keypad and an LCD. The comtrol impulses are sent using a transmitter and an optical fibre to the HVPG, to set on the triggering system. The discharge of the capacitors in form of high voltage pulse rich of high frequency harmonics forces antenna to radiate an impulse of EM field.

The electromagnetic pulses created by the antenna are measured using a fast free field D-dot probe connected to the oscilloscope through an optical link. Both the control unit and the oscilloscope are shielded in order to protect them from the EMPs and to minimise the perturbation. The choice of D-dot probe as a sensor for electrical field was done basing on several reasons such as the wide range of measured frequencies, the high amplitude range of the sustained electrical field and the most important is the ultrashort time response (rise time) which allows as to measure the fastest variations of the electrical field.

It is worth to be mentioned that the use of optical links to connect the different parts of our system provides several advantages. For instance, it offers more immunity from the noises created by the electromagnetic radiations, it ensures a galvanic insolation between the control and the power circuits and of course it makes the system easier to operate (mount and dismount).

Simulations

The simulation of the system has been divided into two parts: the model of antenna with FEKO software, the purpose behind it is to calculate the parameters of the designed antenna; and the HVPG model using Matlab Simulink.

Electrical part

The simulation of the electrical part consists of implementing the model of the high voltage generator connected to a resistive load which represents the impedance of the antenna.

This simulation was done using Matlab (Simulink). It allows us to understand the behaviour of the generator and to get a first idea about the output voltage waveform and its harmonics content shown in Fig. 2 and Fig. 3 respectively.

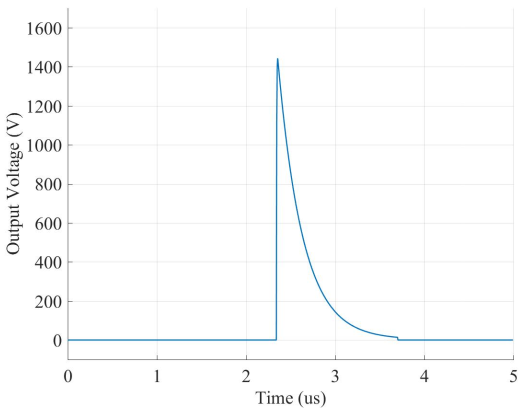

Fig. 2. Simulated output voltage waveform of the HVPG

Estimation of the output voltage spectrum using the fast Fourier transformer (FFT) can give an idea about the harmonics content of output signal.

The simulation was done using a fixed step solving technique. Basing on the time plot of the signal shown in Fig. 2, the sampling step of FFT was chosen as 1 nanosecond. Thus, the maximum detectable frequency is 500 MHz (according to Shannon law).

From Fig. 3, it is clear that 90% of the signal power is distributed from the DC component until 30 MHz. This information is fundamental for the choice and the design of the antenna, even though in this simulation the antenna was approximated by a resistor which simplifies the model, because the impedance of the antenna depends fundamentally on the frequency. At resonant frequencies the antenna is seen as a better conductor, which means that the discharge of the capacitor is adjusted according to resonance modes of the antenna (frequencies where the antenna impedance is minimal).

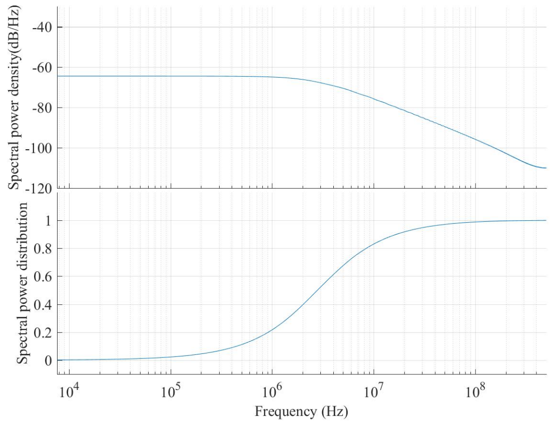

Fig. 3. Spectral power density and distribution of the HVPG output voltage

For that range of frequencies, the direct connection between the HVPG and the antenna is very convenient, because the dimensions of the system are very small comparing to the wavelength.

Antenna model

The helical antenna is one of the most popular antennas. It was invented by John D. Kraus in 1947 [13]. And since then, it has been widely covered by studies and researches. This type of antennas has two main radiation modes: the axial mode where the wavelength equals the circumference of the antenna and the normal mode where the wavelength is much larger than the antenna circumference.

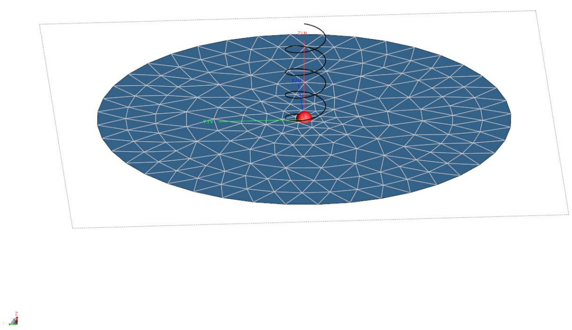

Fig. 4. 3D model of helical antenna using FEKO software

In our work we are interested in the normal radiation mode. It's clear from the previous simulations of the generator that the maximal frequency contained in our signal cannot exceed some tens of megahertz, so it's very difficult to build a helical antenna with a circumference in the range of that wavelength because it'll be too big (condition of the axial mode radiation), and that's why the normal mode of radiation is more convenient for us.

Before building the antenna, a 3D model of it was developed using a commercial software FEKO as shown in Fig. 4. The calculated radiation pattern of the antenna for the frequency of 17 MHz is shown in Fig. 5. It's very similar to the radiation pattern of a quarter wavelength monopole antenna for the same frequency.

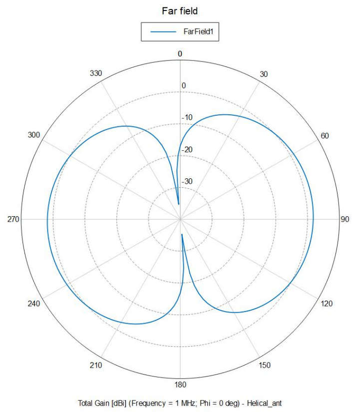

Fig. 5. Calculated far field gain in dBi in a normal plane

Practical experiments and results

The first prototype of the EMP simulator, shown in Fig. 6, was built and tested in the high voltage laboratory of the Electrical Engineering Faculty at Warsaw University of Technology.

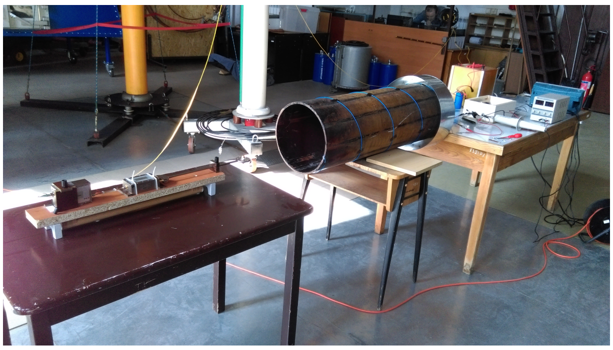

Fig. 6. Calculated far field gain in dBi in a normal plane

The constructed HVPG has the following characteristics: output voltage 1.5 kV, rise time 2 ns and a repetition rate of 100 pps. The erected capacitance of the generator is 4 nF and the total inductance is 4 nH. The output voltage waveform is shown in Fig. 7 (the upper inset).

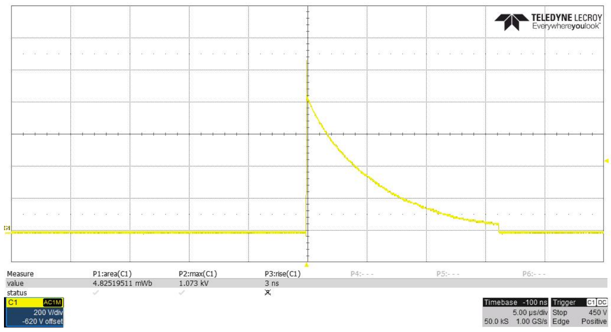

Fig. 7. The output voltage of the HVPG with a resistor charge

The constructed antenna has the same dimensions as those used in the simulation:

- Diameter 32 cm;
- Number of turns 4;
- Turn spacing 24cm;
- Shallow cupped ground plan diameter 42cm;

The normal mode radiation frequency is 17MHz. It can be calculated theoretically using the monopole formula (the frequency corresponding to a wavelength which equals four times the length of the wire of the antenna). The obtained result was confirmed experimentally by measuring the impedance of the antenna using a network analyser. The measured impedance of the antenna shows a well around this frequency (the same as the reflexion coefficient Γ).

The measurement of the electrical field was done using a SGE3-5G free field D-dot probe, a product of Montena company. The probe was placed at distance of 90 cm from the antenna in the normal direction.

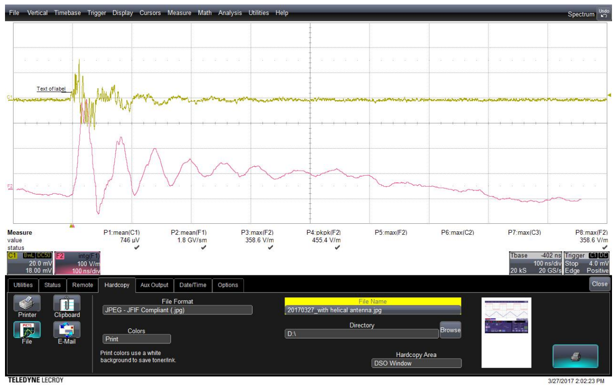

Fig. 8. The electrical field measured using free field D-Dot probe

Fig. 8 shows simultaneously the voltage provided by the D-dot probe which represent the derivative of the electrical. The reconstitution of the electrical field is done automatically using the mathematical tools provided by the oscilloscope (integration + scaling).

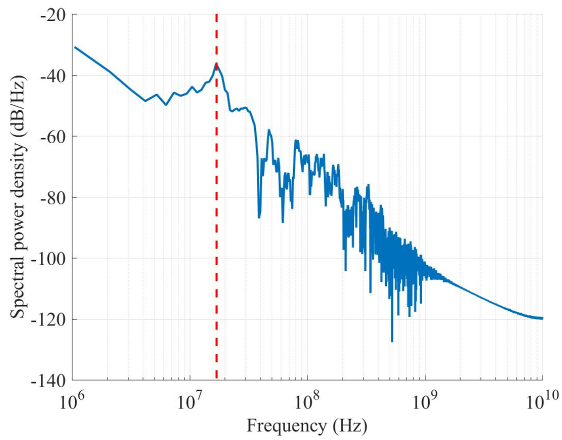

Fig. 9. Spectral power density of the measured electrical field

The results shows a peak to peak electrical field of 455.4 V/m. The calculation of the spectral power density of the measured electrical field was done using Matlab, the result is presented in Fig. 9 It shows a peak at the frequency of 17 MHz as predicted before by the theory and the simulation.

Conclusion

A prototype of an EMP simulator has been presented. It consists of a high voltage pulse generator connected directly to a helical antenna. Two types of simulation were done in order to get the best performance of the simulator. The obtained results show the feasibility of such systems and the possibility to build real EMP simulators with better performance basing on the discussed structure.

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