UWB EMP Susceptibility Testing of General-Purpose Electronic, Radio Communication, and Industrial Equipment

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Abstract—**Technique and results of testing of general-purpose electronic, radio communication, and industrial equipment for susceptibility to powerful ultra-wideband electromagnetic (EM) pulses is presented. An example of the implementation of the developed technique is given using equipment that provides exposure in form of series of electromagnetic pulses with amplitude of up to 50 kV/m, duration of 220-250 ps, and rise time of 120-150 ps. A pulse repetition rate is from 100 Hz to 1 kHz and duration of pulse train is from 0.1 to 300 s. The test results confirm the significant effect of EM pulses impact on the performance of the set of tested radioelectronic products of general purpose for pulse amplitudes of 1...50 kV/m.**

Keywords— electromagnetic compatibility, electromagnetic pulse, ultra-wideband, high-power, protection, susceptibility

I. INTRODUCTION

Broadband and ultra-wideband (UWB) radio systems of various radio services (radar, communications, control, diagnostic, etc.) radiates pulsed electromagnetic (EM) fields with nanosecond and picosecond rise time. These EM pulses (EMPs) are the reasons of additional difficulties in ensuring EMC of these systems with other electronic and radio equipment when their joint location at small-sized objects. This is caused by the limited effectiveness of many traditional technical solutions (filters in power circuits, elements of shielding structures, etc.) used for protection against EM radiation in a relatively narrow frequency range. In addition, there is a sufficient progress in the development of compact portable generators of powerful picosecond EMP that can be sources of intentional EM impact on electronic equipment of various purposes. Despite the high amplitude (usually 1...100 kV/m) and instantaneous power, relatively low energy is required to generate pico- and nanoseconds UWB EMP, and devices for its generation are compact and lightweight.

Ultra-short ultra-wideband electromagnetic pulses with the duration of about 0.1...1 ns are one of the most dangerous types of powerful pulsed EM disturbance for the operation of radioelectronic equipment [1]-[3]. These EM exposures are characterized by a very high efficiency of impact on information, control, diagnostic, telecommunication, and computing systems. It significantly increases an interest in the analysis and testing of susceptibility of radio electronic equipment to the exposure by the powerful pulsed EM fields as well as in ensuring the required levels of protection of systems and objects against unintentional and intentional exposure by such EM fields. Examples of objects that need protection are buildings and structures necessary for the operation of authorities and media, automated control systems for objects of the fuel and energy complex and traffic, medical centers, etc. Works on the creation of national and international standard systems for the protection against intentional powerful UWB EMP are carried out in USA [4], EU [5]-[9], and Russia [10], [11].

An experimental analysis of the UWB EMP influence on the operability of electronic equipment allows determining the danger of EM exposure of this kind, as well as the required levels of their protection. Results of similar tests with separate electronic components (microcontrollers, test circuits, and microprocessor boards) in stationary laboratory conditions using open waveguide are presented in [12], [13]. These test objects are damaged at 4...17 kV/m levels of UWB EMP.

The cases and structural elements of technical devices decrease the levels of UWB EMP impact on the electronic components of the equipment under test (EUT). Equipment cases are protected against the effects of EM interference by traditional means, and for analysis of UWB EMP impact it is necessary to generate powerful test UWB EMP with levels up to 40-50 kV/m. In framework of in-situ tests and when the testing is carried out in open areas and closed premises, the impact of EMP to the power-supply and data transmission lines must be additionally taken into account.

The goal of this work is approbation of practical technique of UWB EMP susceptibility testing of general-purpose electronic, radio communication and industrial equipment and definition the levels of UWB EMP, which causes the deviations from the normal operation of equipment and equipment failures.

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II. Description of Developed Technique

The developed technique is based on standards [4]-[11] and is realized by the following stages.

1) First stage is an analysis of EUT, which includes the definition of its main and auxiliary functions; definitions of EUT state (normal operation, interference, degradation of characteristics and breakdown). The indicators of the EUT state are defined, which visualize the quality of performing of main and other EUT functions. The behavior of indicators must be recordable by the means of objective control. The etalon behavior of indicator and possible deviations from them are established before the testing. The most vulnerable system elements and most dangerous orientations of EUT relative the EMP incidence are estimated based on the available information about the internal structure of EUT, configuration of transmission lines connected to it, and parameters of EUT antennas (if they are present).

2) The infrastructure of test site is prepared in dependence of the features of EUT (dimensions, power supply characteristics, climatic conditions, useful signal receiving and processing, etc.). The test site must satisfy the following requirements. It must provide the irradiation of EUT by the testing pulses with the defined EMP amplitude in predefined orientations. The waves reflected from elements of infrastructure must be eliminated in the working area where EUT is placed. Equipment of test site must provide to control and record the EMP amplitude as well as the behavior of EUT indicators during the testing. The impact of EMP disturbance and high voltage on personnel and means of objective control must be minimized.

3) Testing is carried out with the purpose to establish the minimum level of EMP amplitude and corresponding orientation of EUT, for which the deviation of EUT state from normal operation occurs. The type of deviation must be identified based on the indicator behavior. At first, the calibration procedure of test site is performed for proving that only waves irradiated by the antenna of testing complex (TC) are present in working area and reflected waves and other unintended disturbances are eliminated. It is proved by the coincidence of measurement results obtained in test site with the result obtained during the certification of TC. Than the EUT is installed in the working area and connected with power-supply sources and interfaces needed for its normal operation; etalon behavior of EUT indicators is established before irradiation. The initial orientation of EUT is the orientation, which was estimated as minimum susceptible by preliminary analysis (see item 1). The testing begins from the minimum values of EMP amplitude, pulse train (burst) duration, and frequency of pulses in the train. The EUT is irradiated and the behavior of indicators are recorded and analyzed. If the level of EUT damage due to irradiation is not the breakdown, then the parameters of EMP disturbance are changed to increase the probability of EUT damage in the following sequence: increase the duration of burst; increase the frequency of pulses in the train; change the orientation to more vulnerable. Finally, if the breakdown of EUT is not achieved, the EMP amplitude is increased by the changing of generator or by the decreasing of distance between antenna of TC and EUT (all other settings are established in initial states). The testing stops when the breakdown is achieved or all possible variants of settings are implemented.

4) The analysis of EUT damage is performed. The damaged element is established and the corresponding influence path causing this damage is defined.

5) The recommendations deals with the protection of EUT are formulated (using shielding and/or absorbing materials, changing the working frequency range of equipment, changing the type and layout of transmission lines, etc.).

III. Test System

A comparative analysis of possible types of testing equipment [6], [14], [15] allow selection a technical solution [15] based on the use of the protected TEM-horn array as a source of test UWB EMP for using both in open area and in laboratory conditions.

The Test System (TS) includes (Fig. 1) an antenna-feeder system (AFS), two generators of high-voltage electric pulses, digital field indicator (DFI) for measuring the UWB EMP field strength. The TS provides UWB EMP generation with pulse amplitude up to 50 kV/m, duration of 240 ps ±30%, pulse rise time of 130 ps ±30%, repetition rate of 0.1…10 kHz, and pulse train duration from 0.1 to 300 s. The dimension of the irradiation area with level of 3 dB from pulse amplitude is 1.2×0.8 m at the distance corresponding to beginning of the working zone.

Fig. 1. TS equipment: AFS (left), pulse high-voltage generators (PVGs) 50 kV and 5 kV, high-voltage feeders, DFI (right).

Oscillogram of UWB EMP generated by TS demonstrates a good stability and repeatability of the test EMP parameters (see Fig. 2 and 3). Cumulative function of energy flow (energy fluence) of EMP is shown in Fig. 4.

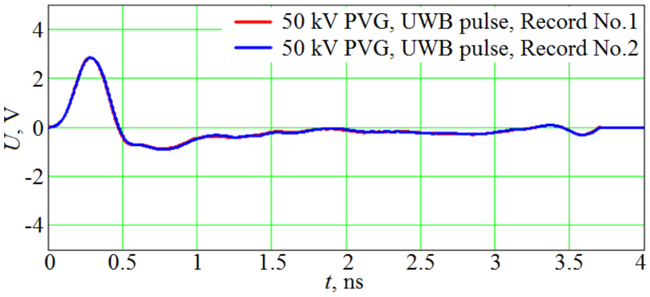

Fig. 2. Oscillograms of the pulse voltage obtained when 50 kV generator is connected to the AFS. Two series for the same conditions and time window 3.7 ns were carried out: record No1 (red line) and record No2 (blue line). UWB EMP rise time (defined by relative levels of 0.1 and 0.9) is 145 ps ± 4 %; full width at half maximum (FWHM) is 230 ps ± 4 % [16]

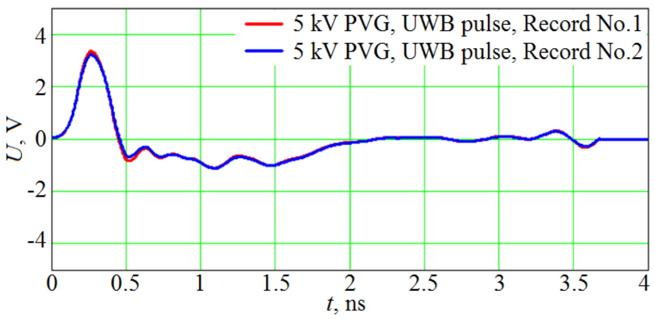

Fig. 3. Oscillograms of the pulse voltage obtained when 5 kV generator is connected to the AFS. Two series for the same conditions and time window 3.7 ns were carried out: record No1 (red line) and record No2 (blue line). UWB EMP rise time (defined by relative levels of 0.1 and 0.9) is 129 ps ± 4 %; full width at half maximum (FWHM) is 226 ps ± 4 % [16]

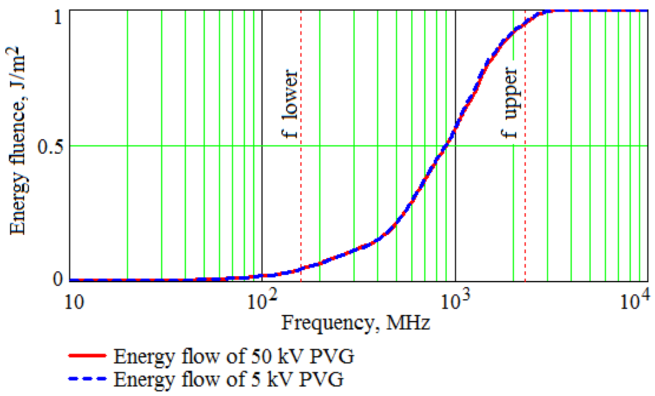

Fig. 4. Cumulative function of energy flow for 50 kV PVG (red solid line) and for 5 kV PVG (blue dashed line). Lower limit of effective frequency range is 170 MHz, upper limit is 2.31 GHz [16].

Test site and equipment layout satisfying the necessary requirements for UWB EMP testing (see Section II) is presented in Fig.5.

The fundamental difference of used TS from the traditional ones is the absence of such measuring equipment as an oscilloscope with different field probes and fiber optical links. To increase productivity and reduce the cost of testing, as well as to limit the required dimensions of the experimental hall, the DFI is used, which consists of the field probe (of strip-line type) and build-in measuring system. The DFI provides the measurement of UWB EMP amplitudes within 2…20 kV/m. It was established in calibration procedure that the results of measurement obtained by the use DFI in experimental hall coincides with the results obtained during certification of testing complex.

The UWB EMP amplitude E_{EUT} at the point of EUT center placement at a given distance from the AFS aperture is calculated according to the relation

$$E_{EUT} = E_0 d_0 / d_{EUT} \text{ kV/m}, \qquad (1)$$

where E_O is the UWB EMP amplitude in reference point, located at a distance d_0 from the AFS aperture on the antenna radiation axis, which is measured by DFI, E_{EUT} is the estimated UWB EMP amplitude on antenna radiation axis at the point corresponding to the EUT center, which is placed at a distance d_{EUT} from the aperture of AFS.

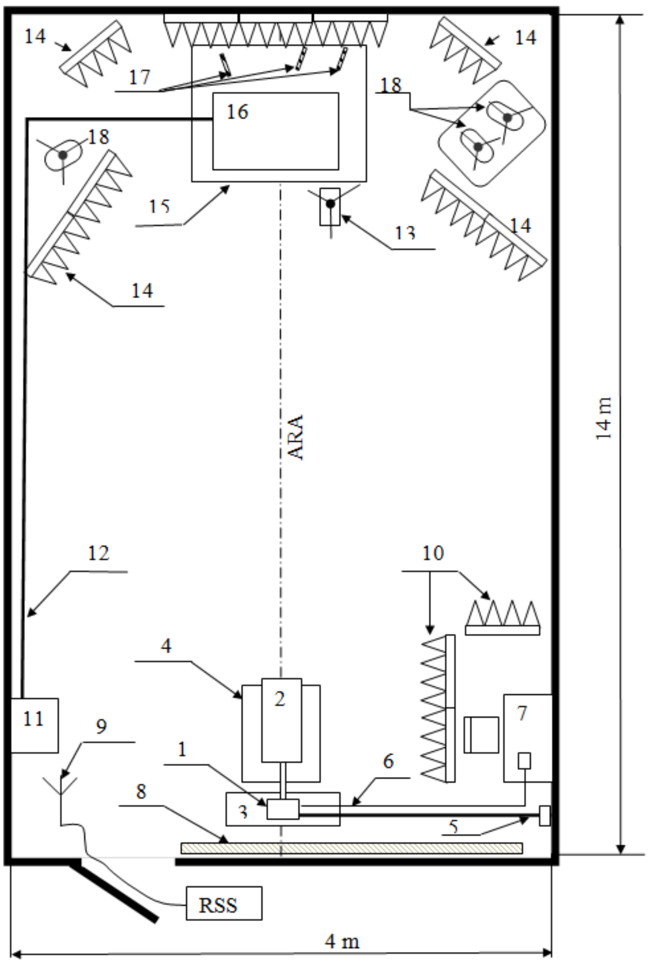

Fig. 5. Typical test site equipment layout (experimental hall) for UWB EMP testing The notations are as follows: 1 - PVG, 2 - AFS, 3 - support for PVG, 4 - support for AFS, 5 - power supply cable with plug, 6 - remote control coaxial cable with Start button, 7 - working place of operator, 8 - shielding panel (steel plate), 9 - antenna generating the Reference Signal (RSS), 10 & 14 - panels of radio absorbing material (RAM); 11 - power supply unit for EUT, 12 - power supply cables of EUT (shielded by copper braid and grounded), 13 - DFI on dielectric support, 15 - instrumental table for EUT placing, 16 - EUT, 17 - auxiliary equipment for control of EUT state, 18 - equipment for registration of behavior of EUT indicators (for example, photo and video cameras, oscilloscopes or computers with additional shields protecting against EMP impact). Antenna radiation axis is marked as "ARA".

The use of two PVGs with output pulse amplitudes of 50 kV and 5 kV allows a decade change in the amplitude of the UWB EMP on the EUT (50-5 kV/m and 5-1 kV/m respectively) in experimental hall of limited dimensions (14×4 m) schematically shown in Fig. 5 that provides a dynamic range of TS of about 34 dB. As it was established by calibration, the field amplitude measured by DFI at distance 1.9 m from the marker point of AFS is 5 kV/m when PVG-5 kV is used. This value coincides with the value obtained by certification, so the distances to the points, in which the EMP amplitude can not be measured by DFI (is less than minimum measurable value 2 kV/m) can be calculated by formula (1). For example, the value of field strength of 1 kV/m corresponds to the distance of 9 m when PVG-5 kV is used. The same approach is used when PVG-50 kV is connected to AFS. Measured by DFI value of 10 kV/m corresponds to the distance 8.7 m between marker point of AFS and DFI, so the distance from AFC to the center of EUT, which provides the value of field strength

50 kV/m, (it can not be directly measured by DFI), is 1.7 m in accordance with (1). Note that value 1.7 m coincides in limits of instrumental error with the value specified by the manufacturer's certificate as the beginning of working zone for testing complex. The amplitude values used in testing are changed discretely and correspond to known E6 Series of preferred numbers (the values of E6 are slightly changed in order to obtain the value of 5 and 50 kV/m).

IV. TEST RESULTS

A significant number of kinds of electronic equipment for general and industrial purposes were tested (personal computers, laptops, tablets, video cameras, wireless communication devices (cellular phones 2G/3G/4G, FM radio stations, Wi-Fi and WiMAX equipment, etc.), GPS-navigators, technological equipment, diesel and petrol engines with electronic control, etc.

The following results were obtained.

1) Even at relatively low levels of exposure (UWB EMP amplitude of 1...5 kV/m), the interference was often observed, for example, a decrease in the speed of data transmission rate in communication channels. This interference can cause malfunctioning of complex control and monitoring systems. Such exposure levels can lead to the failure of unprotected electronic devices and general-purposes equipment (personal computers, laptops, tablets, video cameras, etc.).

2) With an increase in the level of UWB EMP exposure to 10...20 kV/m, loss and/or distortion of the received information is often observed for a long time: the duration of the observed effects can significantly exceed the duration of UWB EMP exposure on the EUT. Such effects can lead not only to malfunctions in the system, but also to the failure of the executive devices.

3) As result of UWB EMP impacts with a high pulse amplitudes (more than 20 kV/m), the equipment breaks down due to irreversible processes in electronic components and nodes (primarily due to thermal breakdown of semiconductor elements). Such effects are observed even in protected devices of vehicles and in various industrial systems owing to UWB EMP exposure on the power supply lines, control and signal cables, as well as through the apertures in a shield.

4) The impact of UWB EMP on control systems for complex technological processes can lead to the failure of these systems with a high probability.

V. CONCLUSION

UWB EMP exposure with levels of 5-20 kV/m can lead to the interference, to malfunction of general-purpose and industrial equipment associated with loss/distortion of received information, and to failure of executive devices. These results correlate with results in [13]. High-amplitude pulses (level is 20 kV/m and more) lead to the breakdown of equipment due to irreversible processes in electronic components and nodes, which are realized even in protected industrial devices. These results show the necessity of development of protection measures against the effects of UWB EMP on critical radio-electronic systems.

The test results allow us to conclude that, as a rule, the using of traditional means of protecting of different equipment and objects from the effects of microwave EM fields (high-quality microwave shielding, the use of filters in power supply circuits, etc.) can ensure effective protection against UWB EMP with rise times more than 100 ps. The UWB EMP with levels of more than 10 kV/m are capable to disrupt the serviceability of general-purposes electronic equipment. These levels of disturbance can realize only near the sources of the EMP, and one of the solutions of the problem is a safe spatial separation of UWB EMP sources and other equipment. For a compact UWB EMP sources similar to the TC used in the TS described above, the safety distance is about 50 m, but for more powerful UWB EMP sources (multi-element TEM-horn arrays, powerful ultra-high-resolution radars, etc.), a protective area with a radius of up to 0.5 -1 km may be required.

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