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The Problems of Testing HEMP Resilience of Civil Critical Equipment on Military Guided-Wave Type Simulator

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Abstract: **Guide-wave type HEMP simulators are widely used to assess the resilience of ground-based equipment to the electromagnetic pulse from a high-altitude nuclear explosion (HEMP). These simulators were originally designed for testing military equipment according to military standards. However, recently there has been interest in testing the HEMP resilience of critical civilian infrastructure equipment as well. And such civilian equipment is being tested on the same military simulators (since there are no others). The article discusses the problems that arise in doing this and concludes that such testing is not advisable.**

Keywords: **high-altitude electromagnetic pulse, EMP, HEMP, critical civilian infrastructure, EMP test bench, guided-wave type HEMP simulator.**

1. INTRODUCTION

The ability of the powerful electromagnetic pulse, generated upon the HEMP to destroy all electronics, has been known to nuclear physicists since the first nuclear explosion was performed in 1945 on the Alamogordo range, New Mexico (project “Trinity”). Upon the explosion, all apparatus that was meant to monitor the explosion parameters became inoperative. Upon all further test explosions performed in all countries, that electromagnetic pulse was registered precisely and was followed with the analysis and study of the parameters. Beginning in the 1970s (50 years ago), that subject has been unclassified. At that time, dozens of Western scientific and technical reports, prepared by numerous military and civilian organizations (working at the military request), were devoted to different aspects of HEMP impact on electrical equipment and electronics. Since then, the electromagnetic pulse had been officially recognized as one of the damage effects of nuclear weapons, along with the detonation wave, the temperature, the light and the radioactive emission. At the same time, the first recommendations for the protection of electronic and electrical equipment from HEMP appeared, which, of course, were primarily intended for military equipment [1].

Fig. 1. Typical control cabinets at critical civil infrastructure facilities

In civil infrastructure facilities: power plants and substations, water supply and sewage systems, electric transport, communication systems, etc. highly sensitive electronic equipment based on microprocessors is widely used. This includes systems for monitoring and controlling power equipment, relay protection systems against emergency modes, SCADA systems, equipment of auxiliary DC power systems, remote control, signaling, communication systems, and so on. All of this is a crucial part of civil critical systems, without which they cannot operate. In most cases, all of this electronic equipment is housed inside control cabinets, see Fig. 1.

It is known that this kind of modern, highly sensitive electronic equipment based on microprocessors is the most vulnerable to EMI in all systems.

2. GUIDED-WAVE TYPE HEMP SIMULATORS

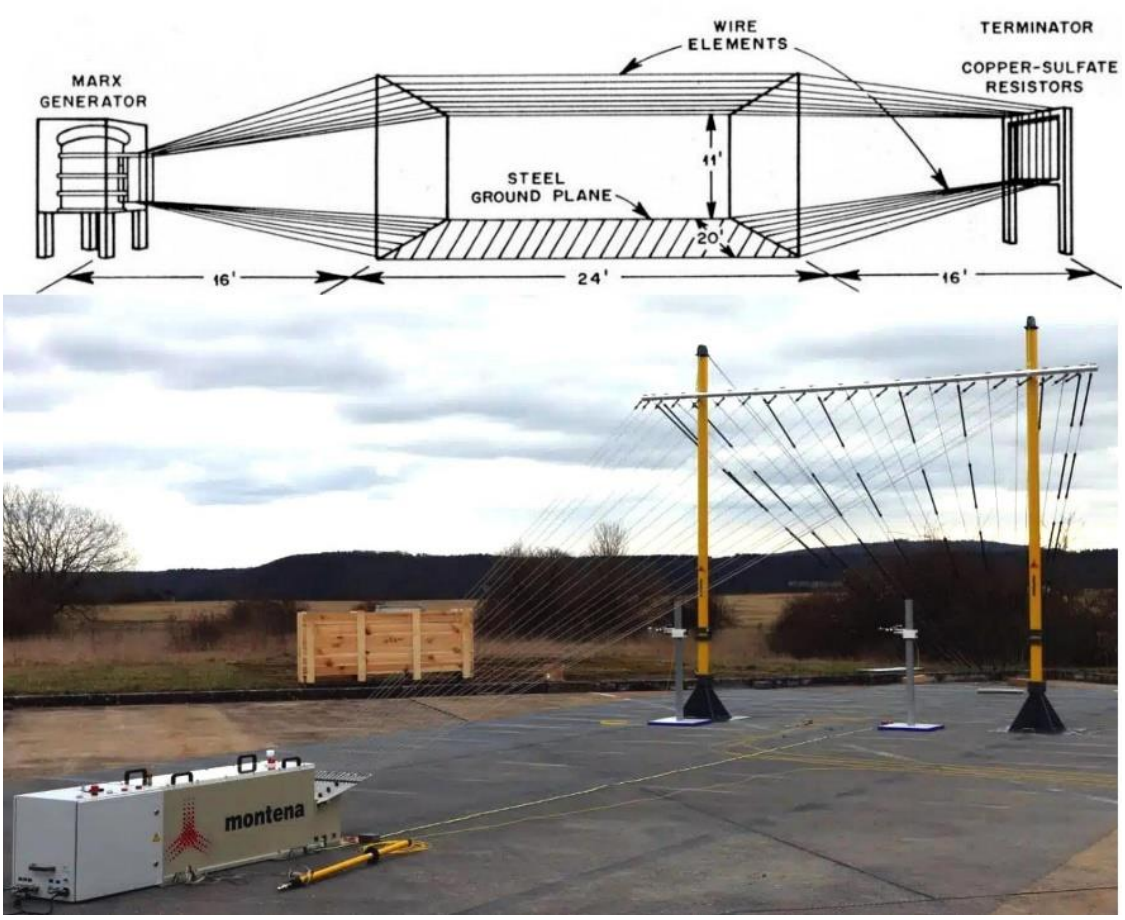

Fig. 2. Typical design of HEMP simulator guided-wave type

A modern typical HEMP simulator consists of two major parts: a source of high-voltage pulses and an antenna system, which creates electric field pulse (matching E1 component) within the operational volume of the simulator, where a test object is placed (Fig. 2).

Usually, a source of high-voltage pulses is represented by a pulse voltage generator (PVG) assembled according to Marx design, Fig. 3.

This generator consists of a set of high-voltage capacitors, parallel charged from an external power supply and controlled discharge spark gapes, connected in such a way that upon their internal breakdown, the capacitors become connected in series and the output electrodes of the generator receive voltage equal to the sum of all voltage rates from all capacitors. The picture of a Marx generator (Fig. 3) shows small sparks on multiple discharge gaps and one total powerful electric arc between major electrodes.

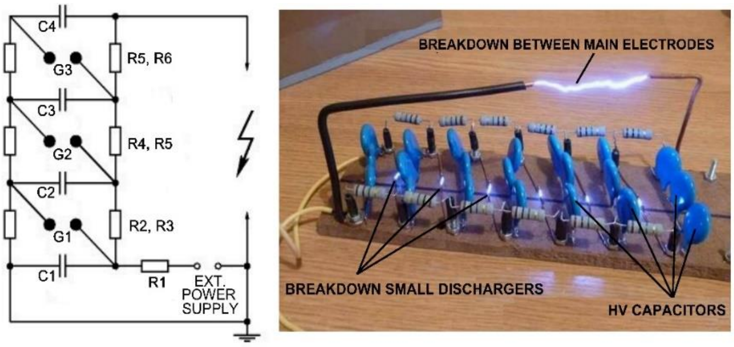

Fig. 3. Simplified circuit diagram and desktop experimental working model of Marx generator. C1-C4 – capacitors; G1-G3 – discharge spark gapes; R2-R6 – resistors, equalizing voltage distribution on capacitors.

Real full-size Marx PVGs is built based on the same design, but obviously employ much larger and more expensive elements (Fig. 4).

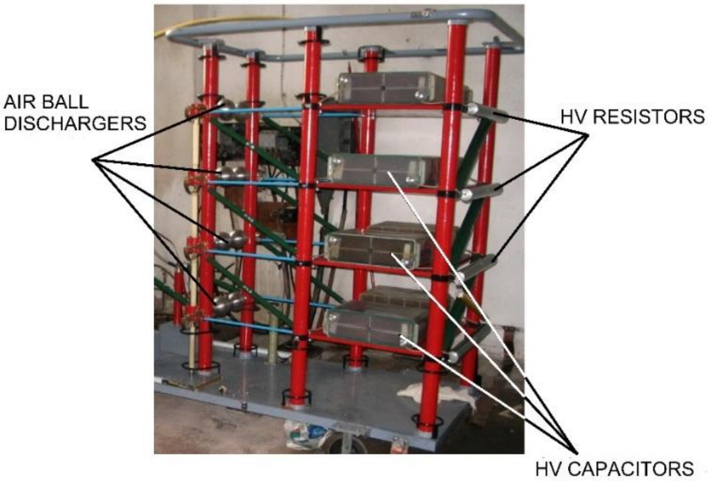

Fig. 4. Real full-size Marx PVGs

PVGs rated for several million Volts are rather massive (Fig. 5).

In order to obtain a PVG of a reduced size, they are sometimes placed into large basins made of insulation material and filled with insulating mineral oil, or into special air-tight chambers filled with sulfur hexafluoride gas (SF_6), Fig. 6.

Fig. 5. PVGs rated for several million Volts

Fig. 6. Compact PVG, manufactured by the company Montena.

The traditional design of the test-bed radiating antenna on the typical guided-wave test bench Fig. 2, includes the central section, where two parallel meshes are located at a fixed distance to each other, and two side sections, where the distance between the top and the bottom meshes is decreasing. There is also a simplified antenna system design that doesn't have parallel sections with a fixed distance in the central part.

Despite the impressive size of the antenna system, there is only a relatively small area for placing the equipment under test (EUT). For example, in an antenna system with a total length of 27 m and a maximum height of 5 m, the space allocated for the test object is just 2 m x 2 m x 2 m. True, in an antenna system with a horizontal section in the center, the area for EUT can be larger, but for full and correct testing of EUT in such a design, it would need to be installed at a certain angle to the horizontal.

3. THE PROBLEMS

The Problem No. 1.

As a rule, the power system electronic equipment is installed in the metal cabinets located in all-brick or concrete buildings significantly attenuating the HEMP impact, while other devices, such as grounding system, various sensors, measuring current and voltage transformers connected to very long high-voltage overhead lines, and numerous outgoing control cables, are located in a HEMP exposed area. Therefore, in real life, the different components of the common system are exposed to the electromagnetic impacts of different energy.

In general, the situation can be summarized briefly as follows (detailed description can be found in [2, 3]):

1. The parameters of a HEMP and the intensity of its effects heavily depend on the power of the nuclear charge, the explosion altitude, the location of the target relative to the blast epicenter, etc., and therefore cannot be predetermined. For military equipment, the maximum possible electric field strength in open areas is taken to be 50 kV/m. But such a maximalist approach is unacceptable for civilian infrastructure.

2. Critical electronic equipment at stations and substations is placed in different buildings made from various construction materials, with different interior designs, different window and door arrangements, and in cabinets of different designs... All of this results in varying degrees of attenuation of external HEMP.

3. Electronic equipment used in the power industry and other critical sectors of civil infrastructure facilities already has a certain level of protection against electromagnetic effects according to current standards, which needs to be taken into account.

4. Dozens of civilian and military standards in this area, often referencing each other and filled with dozens of data tables, are too complicated for staff at civilian critical infrastructure facilities who aren't HEMP specialists to use. And the tips and recommendations presented in hundreds of scientific reports on this topic often contradict each other or suggest protection measures that are theoretically correct but impractical for real-world (not just theoretical) use in actual electrical installations.

This list of problems could be continued further, but discussing them is not the topic of this article, especially since a detailed review of them, as well as the proposed solutions, is covered in [3].

In the context of this issue, it's *just important to note that the field intensity value used in military equipment testing isn't really suitable for civilian equipment and should be significantly reduced during testing*.

Unfortunately, in most cases, this is impossible to do on modern test benches designed for military equipment, where there's no need for it. Unlike modern compact PVGs, in old large stationary PVGs this capability was achieved by adjusting the gap between the intermediate arresters using a pneumatic drive, but in the modern compact PVG described above, there's no way to adjust the pulse field strength. For example, it's impossible to set the field strength to 10%, 25%, 50%, or even 75% of the maximum value of 50 kV/m. Meanwhile, when an ordinary reinforced concrete building weakens an external electromagnetic field by 20 dB, the remaining electric field strength inside such a building will be only 5 kV/m (that is, 10% of the maximum value).

The Problem No. 2.

The problem is that it is impossible to simulate HEMP impact on hundred-meter-long control cables using a test-bench with 2 x 2 m or even 20 x 20 meters bottom plate in the system with parallel central section. How would you accommodate very long cables in such a restricted area? If a zigzag pattern is used, the pulse induced in oppositely directed parts of the zigzag will be mutually compensated. If they are placed in concentric circles, the impact of the test-bench's electric field onto this cable will be significantly higher compared to the real situation. Combination of the two is both too complicated for calculations and almost unpredictable. If the object being tested features short cables, sometimes the way out would be to increase the intensity of the simulator's electric field (determined theoretically) in order to obtain the outcome similar to long cables.

METRIC

MIL-STD-461H
17 APRIL 2026
SUPERSEDING
MIL-STD-461G
11 DECEMBER 2015

DEPARTMENT OF DEFENSE
INTERFACE STANDARD

REQUIREMENTS FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS OF SUBSYSTEMS AND EQUIPMENT

5.22 RS105, radiated susceptibility, transient electromagnetic field.

5.22.1 RS105 applicability.
This requirement is applicable to equipment and subsystem enclosures which are exposed to the external electromagnetic environment and have an electromagnetic pulse (EMP) requirement. For surface ships, this includes external, above deck and exposed below deck installations. The requirement is applicable to Army aircraft for safety critical equipment and subsystems located in an external installation.

5.22.2 RS105 limit.
The EUT shall not exhibit any malfunction, degradation of performance, or deviation from specified indications, beyond the tolerances indicated in the individual equipment or subsystem specification, when subjected to a test signal having the waveform and amplitude shown on Figure RS105-1. At least five pulses shall be applied at the rate of not more than one pulse per minute.

5.22.3 RS105 test procedures.

5.22.3.1 Purpose.
This test procedure is used to verify the ability of the EUT enclosure to withstand a transient electromagnetic field.

Fig. 7. Extraction from MIL-STD-461 (RS105)

It should be noted though that excessively intense electric field will impact both short cables and all other items placed in the working space, e.g. control cabinets, and this is unacceptable. Placement of short cables outside the working area of the simulator (in the area of stronger fields) is also not a solution to the problem, since outside the working area the electric field is not equivalent at different points.

If we turn to the standard that describes the procedure for testing objects on such a test bench (MIL-STD-461, part RS105), we find something surprising, Fig. 7.

It turns out that this test bench is only meant for evaluates the shielding effectiveness of the equipment’s enclosure or box. And no long wires and cables sticking out beyond the protective enclosures (that is, control cabinets with electronic equipment inside). An example of such equipment could be, for instance, a tank, see Fig. 8.

Fig. 8. A battle tank mounted on a HEMP test stand.

Of course, the tank also has external devices and instruments, but all of them are arranged compactly and do not exceed the tank's external dimensions or the size of the test area, unlike the control cabinet cables.

Well, okay, if this test setup is meant only for testing the protective properties of enclosures (or, more precisely, fully complete modular-type equipment that can be entirely set up on the test stand site) and can't be used for testing equipment with long cables coming out of it, then let's at least test the control cabinets only, without any cables attached (as simple enclosure or modular-type equipment). The impact of EMI on long cables can be tested separately on different test equipment and according to a different standard.

However, even on this path, a problem awaits us.

The Problem No. 3

Since we are talking about a very short pulse (2.5/25 ns), which affects electric circuits similar to a high-frequency signal with a frequency of up to 100 MHz, obviously variations of internal layout and external cables, as well as different types of equipment used in cabinets and different combinations of this equipment, will heavily influence high-frequency properties, and consequently equipment sensitivity to HEMP and efficiency of protection elements [1, 2], that it does not make any sense to extrapolate the findings obtained for one cabinet to other cabinets. As was shown in [1, 2], changing the positioning (distance) in different cabinet designs between two conductors inside the cabinet by just 25-50 cm can drastically change the high-frequency characteristics of the entire internal cabinet setup and significantly alter the resilience of internal electronic equipment.

Is it really possible to maintain strongly identical wiring and short connecting wires in all the civil control cabinets with different electronic equipment inside? The answer is pretty straightforward: not at all.

Therefore, it doesn't make any sense to extrapolate the findings obtained for one control cabinet to other cabinets. But if you can't test each of the thousands of such cabinets in the power system, and you can't extrapolate the test result from one cabinet to other cabinets, then the question arises: so why was it necessary to test this particular cabinet at all?

What should we do with testing of military systems on such benches? The fundamental difference of military systems (tanks, armored fighting vehicles, aircrafts, missiles), which are obligatory subjected to such tests, is that all copies of the same type are manufactured based on the same drawings with strict adherence to the same technology. They feature negligibly small differences both in terms of component parts and in terms of assembly, which is performed using the same wire harness that has been previously prepared on a special's templates.

Of course, if you want and purely theoretically, you could test the resilience of civilian equipment on this stand too, which is then planned to be widely *used without any design changes*. As well as special types of protected equipment and protective means, which will later be *replicated without changes to their design* and are suitable for such tests according to standard MIL-STD-461 (RS105). Only in doing so, you should take into account the existence of Problem No. 1, described above.

The Problem No. 4.

This issue is determined on the one hand by the difference between electromagnetic pulse of lightning (LEMP) and that of a high-altitude nuclear explosion (HEMP), and on the other hand, by the design of the test-bench with an earthed bottom plate (as bottom electrode).

The thing is, the actual HEMP from a high-altitude nuclear explosion doesn't have a potential relative to the ground; it's a distributed electromagnetic wave in space. Unlike a lightning LEMP, where there's a high potential difference relative to the ground. So, if equipment is grounded, like a cabinet with devices inside, a lightning strike will flow from the surface of that cabinet to the ground through an external grounding system, and the equipment inside the cabinet won't be damaged. But a real nuclear EMP doesn't have potential relative to the ground, whereas an EMP inside a test stand happens exactly between the antenna and the lower grounded panel. That is, the impact of a EMP on a test object inside a test stand differs from reality, even if the pulse parameters themselves perfectly match reality. If the test object is completely isolated from the bottom plate (i.e., from the ground), there's no problem. But if it's grounded, the picture changes, Fig. 9. All internal circuits of the civil electronic equipment inside the control cabinets are connected to the chassis, and the chassis is grounded. If such a cabinet is grounded on a test stand (that is, if all its external and internal circuits are connected to the bottom electrode (plate)), the effect of the electromagnetic pulse can be completely neutralized, just as the effect of a lightning pulse on grounded equipment is nullified. But in reality, the impact of a HEMP on equipment will be different.

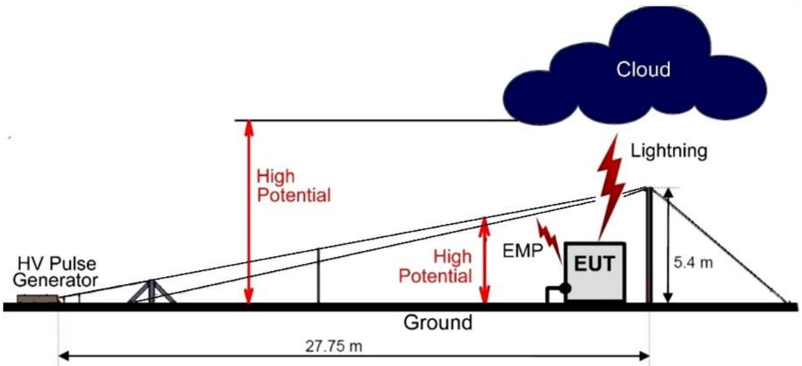

Fig. 9. The EMP inside the test stand affects a grounded equipment under test (EUT) the same way lightning (LEMP) does, not like a real HEMP, which has no potential relative to the ground.

This issue requires separate consideration, but raises additional doubts about the feasibility of testing such cabinets on military test stands.

4. CONCLUSION

From all of the above, it can be concluded that testing civilian equipment of critical infrastructure on standard HEMP simulators doesn't make sense, since these simulators are designed for testing military equipment according to military standard, while civilian equipment is significantly different from military equipment in terms of parameters, characteristics, and resilience requirements. Buying such simulators for personal use by some power systems is just a waste of a lot of money.

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