Resilience of Digital Protection Relays to Electromagnetic Pulse (HEMP)

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***Abstract* - This article addresses the issues of resilience of digital protection relays (DPR) to High Altitude Electromagnetic Pulse of nuclear explosion (HEMP). The article performs the critical analysis of some articles presented by a well-known American company SEL and shows that the publications contain many inaccuracies and lapses. Thus, this proves that SEL relays have not advantages over those offered by other manufacturers. The article shows that reliable information pertaining to DPR's resistance to HEMP can be obtained on a basis of correctly set-up tests; key principles of these tests and stages of preparation are also offered.**

***Keywords* - Digital protection relays, DPR, High Altitude Electromagnetic Pulse, of nuclear explosion, HEMP, Resilience, Tests, SEL.**

I. Introduction

Explosion of nuclear ammunition at high altitude (30 - 400 km) results in occurrence of electromagnetic pulse near the earth surface with the field strength up to 50 kV/m. This pulse can impact electric and electronic devices and equipment over a vast territory. This type of non-lethal (due to high altitude of blasting) weapon is perceived as a rather perspective trend in various countries, and thus it is rapidly developing. Consequently, development of protection measures against it has recently become very relevant [1].

As for the electric power industry (representing the No. 1 target for this weapon), microelectronic and microprocessor-based systems, particularly, digital protection relays (DPR) are the most susceptible to High Altitude Electromagnetic Pulse of nuclear explosion (HEMP). That is why producers of DPR are concerned about the problem and their efforts to research the DPR's resistance to HEMP are more than welcome. One of the largest DPR producers that performs a deep research of this problem is an American company, Schweitzer Engineering Laboratories **(**SEL**).** Thus, the experience gained by the SEL could have been extremely important for protection engineers.

II. CRITICAL ANALYSIS OF SEL's PUBLICATIONS

Unfortunately, one of the first publications of SEL in this area [2] provokes many baffled questions, Fig. 1. It discusses testing of commercial relay SEL-311C on the test benches of the US army's Picatinny Arsenal in New-Jersey.

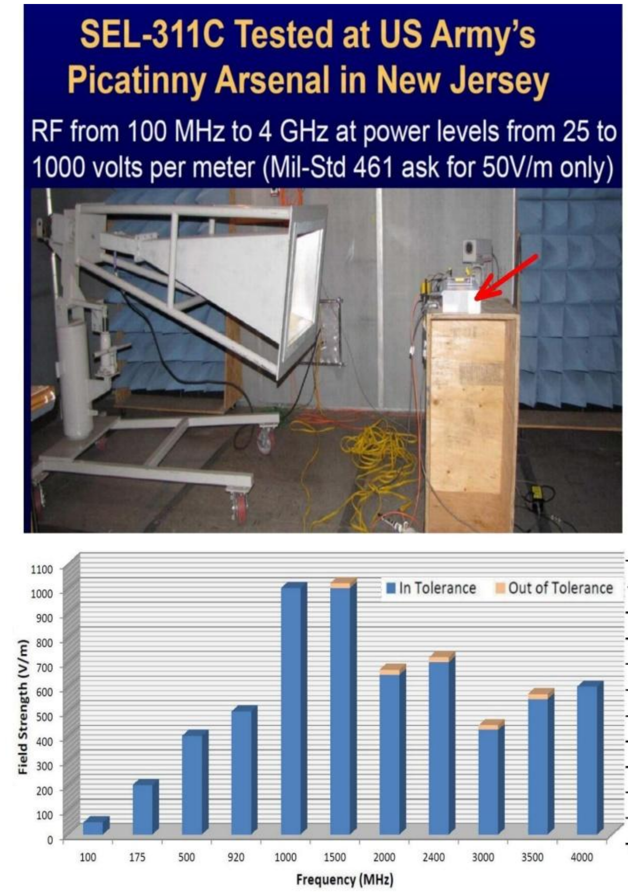

Fig. 1. Adapted from images enclosed to test report of SEC-311C relay [2].

The specialists of SEL have demonstrated a rather strange ignorance in this document [2], considering that the standard (MIL-STD-461), shown in Fig. 1, measures field strengths corresponding to HEMP in kilovolts rather than in volts, and the number "50" referred to in the standard is mentioned as 50 kV/m, rather than 50 V/m.

The bar diagram illustrated in Fig. 1 is even more strange. It shows that in reality the field strength of 1000 V/m was implemented for testing at 1000-1500 MHz frequencies, while at another frequency, it was almost two times lower. Furthermore, the dependence of amplitude on the frequency does not correspond to MIL-STD-461.

It is obvious from the diagram that the levels of field strength are limited by the beginning of the instability of relay functioning (yellow areas on the tops of the bars). In other words, the diagram shows the area of steady operation of a separately installed (outside the relay protection system) SEL terminal. This implies that the relay does not allow for steady operation outside the area of values represented in this diagram, with its extremely low levels of electromagnetic field strength. In fact, it is not clear where the frequency range 100 MHz to 4 GHz came from, as it has nothing to do with the HEMP's frequency range (see below).

Thus, considering the awkwardness of the parameters selection and the testing procedure of SEL-311L's resistance to HEMP, can we be serious about the manufacturer's declaration that these products are HEMP-resistant?

Another issue is concerned with selection of a single DPR terminal as a test specimen. As a rule, these terminals are produced in metal enclosures, which weaken the electromagnetic emission.

Thus, testing resilience of an individual terminal to electromagnetic emission impact may expect positive results. In reality, DPR hosts many cables acting as antennas, absorbing electromagnetic energy and delivering it to the DPR's internal elements. Various DPR units can be connected to each other through corresponding communication equipment that is very susceptible to HEMP. Consequently, the test should embrace the whole relay protection system (which should be operational during the test with all the currents and voltages applied to its inputs) rather than a separate terminal used in the actual test.

The most recent comprehensive work presented at the Relay Protection Conference in Washington (October, 2017) [3], and published under the auspices of IEEE, shows the results of a recent research conducted by SEL. The paper was expected to deal with lapses and mistakes of the previous paper and to provide correct and true data of DPR resilience to HEMP. Unfortunately, the expectations fell short. The pretentious 18-page paper written by one of SEL's engineers (who has no previously HEMP-related publications) and co-authored by the Director of Quality, Director of Government Affairs and Vice-President of R&D of the company, contains even more lapses than in the previous article. Since the criticism should always be substantiated and supported by specific arguments and evidences, the arguments are given below.

1. The authors do not distinguish between electromagnetic pulses of lightning (LEMP) and the high altitude electromagnetic pulses of nuclear explosion (HEMP), and thus they transfer their experience on lightning protection gained in the electric power industry to protection from HEMP. In reality, these are absolutely different physical phenomena that have different specifications, impacting the equipment in different ways. For instance, the lightning EMP represents the localized impact, while HEMP covers a vast area. When lightning is an electric air disruption between two electrodes (charged cloud with high potential relatively to the earth and the grounding system with zero potential), there are no electrodes, between which high voltage would have been applied and air breakdown would have happened during HEMP. Moreover, the earth (grounding system) does not represent a zero potential area for HEMP. Furthermore, HEMP features both vertical and horizontal components, whereas part of the electromagnetic energy falling on the earth is reflected from its surface. Parameters of a nuclear explosion's pulse are significantly different from lightning's EMP parameters, so some widely-used protecting elements (such as gas discharge tubes – GDT, widely used for electronic equipment protection) are not acceptable as HEMP protection due to their long response time. Finally, it is worthy to cite an unambiguous statement, mentioned in Section 3 of IEC 61000-6-6 standard: "Lightning protection will not assure protection against HEMP… Lightning protection will not provide adequate HEMP protection…".

2. LC-filters recommended in the discussed paper as an efficient HEMP-protection measure are not efficient in practice as most of them (with some rare exceptions) are intended to divert the energy of high-voltage pulse (applied to the filter's input) to the grounding system (i.e. to zero potential area), which actually does not represent zero potential for HEMP [4]. It should also be noted that in case of HEMP impact, the grounding system will turn into a huge antenna absorbing the energy from a large area and delivering it directly onto the internal sensitive components of DPR [5, 6]. Thus, recommendations given in the article about common methods employed for proper DPR grounding (approved for lightning protection or high voltages produced by short circuit currents) are not acceptable for HEMP protection.

3. The article suggests that the frequency range of HEMP is 100 kHz – 100 MHz, which does not correspond to MIL-STD-188-125-1 [7] in terms of efficient protection (shielding) of equipment from HEMP, Fig. 2. Moreover, the specifications shown in Fig. 2 suggest that the requirements to shielding efficiency are maximum in the range from 100 MHz and up to 1 GHz (80 dB). The value mentioned in the standard does not correspond to the frequency range mentioned in SEL's reports, either in the first (4 GHz) or in the second (100 MHz) publications.

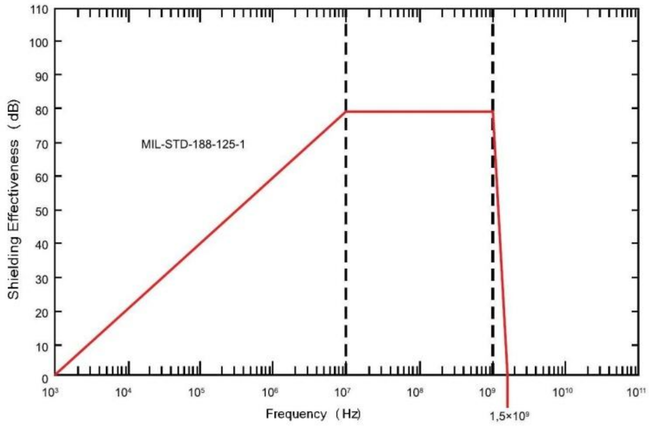

Fig. 2. Required shielding efficiency for HEMP protection at various frequencies [7].

4. The article continually claims that the reinforced concrete building, in which DPRs are usually located, can weaken the HEMP's electric field by 20 dB (i.e. 10 times) and thus further on the electric field is taken as 5 kV/m instead of the initial value of 50 kV/m. Indeed, IEC 61000-2-11 [8] and IEC 61000-5-3 [9] standards really suggest that the concrete building with rebar can weaken the electromagnetic emission by 20 dB in the range from 100 kHz to 30 MHz. They also conclude that it can also weaken the HEMP's electric field up to 5 kV/m. However, the problem is that these standards do not provide any definition of "concrete building with rebar". It is noteworthy that the shielding efficiency of reinforced concrete against electromagnetic emission is largely dependent on the mesh size of the internal steel net, the number of net layers, the thickness of reinforced concrete and the availability of windows and doors in the building, their size and number, etc. Another problem is related to the frequency range for which this 20 dB decrease has been determined and which is too far from that of HEMP. Thus, the field intensity of 5 kV/m can be assumed on certain conditions and very tentatively, and it does not allow to draw the far reaching conclusions about DPR's resistance to HEMP.

5. The authors of the above mentioned article make a strange transition from the value of field intensity (5 kV/m) to the voltage applied to DPR (5 kV). But 5 kV/m and 5 kV are absolutely different values. For instance, theoretically the voltage at the ends of a 10-meter cable can reach as high as 50 kV at 5 kV/m field intensity. So, where did they take 5 kV from?

6. The article provides confusing information regarding testing of DPR's resistance to so called electrical fast transients (EFT)**.** First of all, there are three tables in the article, which provide different values of EFT amplitudes (in kilovolts) for three different conditions, which have not been determined in the article, Table 1.

TABLE 1
ELECTRICAL FAST TRANSIENT (EFT) IMMUNITY LEVELS FOR DIFFERENT DPR CIRCUITS AND CONDITIONS ACCORDING TO [3]

Circuits of DPR, intended for testing by EFT Immunity levels (kV)	Table XIII [3] DPR	Table XIV [3] DPR on new substation design	Table XV [3] DPR on legacy substation design
Signal (PT, CT, I/O)	4	2	8
Signal (serial comm.)	2	2	-
Power (DC)	4	2	4 - 16
Power (AC)	4	2	-
Telecommunication	2	1	-
Antenna	2	1	-

What does strange distinguishing between conditions for each of the tables mentioned in [3] mean and what about the phrase: "*The EMC electrical transient immunity levels for DPR are higher than the HEMP resiliency levels for new substation design (compare Table XIII and Table XIV respectively)*". What is the difference between a typical substation and a new substation? Why should a new substation be less resistant than the legacy substation? Unfortunately, the reader will not find any answer to these questions in the article.

It would be fair to note that some standards also provide such puzzling information regarding testing. For instance, ITU-T K.78 [10] suggests the same value of field strength for internal space of a reinforced concrete building, i.e. 5 kV/m (with a reference to IEC standards mentioned above), while Table 6 in [10] provides amplitude values of test EFT pulse – 1 kV for "signal ports" and Table 8 in [10] - 8 kV for "signal ports (telecommunication)". Additionally, both cases deal with telecommunication equipment (see the standard's name) and deal with 10-meter long cables connected to its ports installed inside of the above mentioned building. Moreover, clause 3.1.12 of this standard takes "telecommunication port" as an example of "signal port". So, where does the 8-fold difference between test pulse amplitudes (intended for testing of the same equipment under the same conditions) come from? It is difficult to follow the logics of the authors of this standard.

Secondly, the note under Table XV recommends to test resistance to electrostatic discharge (ESD) instead of EFT, and further in the text, the authors provide data regarding DPR's testing for ESD resistance without even mentioning the EFT.

But these are absolutely different treatments (Figs. 3 and 4), which should be realized under different procedures and which have an absolutely different impact on DPR! The 8 kV electrostatic discharge applied to a surface of grounded metal casing of DPR is not equivalent to 8 kV pulse voltage applied directly to DPR's terminals!

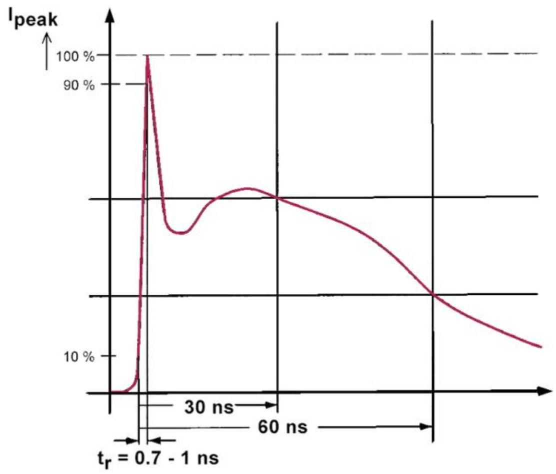

Fig. 3. Shape and time parameters of ESD test pulse according to IEC 61000-4-2 [11].

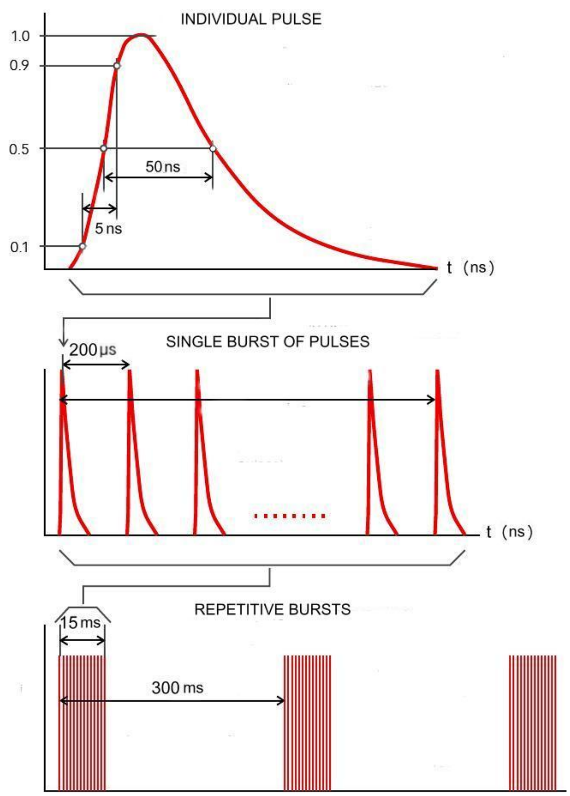

Fig. 4. Shape and time parameters of EFT test pulse according to IEC 61000-4-4 [12].

7. The authors' statement that the shields of control cables need to be grounded on both sides to ensure higher shielding efficiency is not confirmed in practice. The reasons for that are covered in [13] in full details.

8. For some unclear reasons, the authors start using IEC 60255 standards group in the second half of the article in order to evaluate the DPR's resilience to HEMP. However, these standards suggest the requirements for protection relays' resilience to ordinary electromagnetic interference, which has nothing to do with HEMP.

9. The authors easily discuss such a "simple" problem as protection of a telecommunication system (which ensures communication in relay protection) from HEMP. They have no knowledge about a comprehensive aggregate of complex problems [14, 15] that persist in protecting of communication systems (which are very susceptible to HEMP) and many other problems.

10. The article provides a rather strange representation of testing results of SEL's protection relays. For example, the article says that due to 20 dB weakening achieved by the typical substation building, the field intensity inside this building will be 5 kV/m. Further on, the article says that DPRs were tested in a certified laboratory, which mimics the environment of a typical substation, whereas in the next sentence, we read that based on those tests SEL's relays (obviously, they mean all types of SEL's relays?) could resist a 50 kV/m pulse and they refer to some inaccessible internal unpublished corporate document. What should be the reader's conclusion based on this description?

11. The article makes a reference to another internal unpublished document and claims that the test of an individual printed circuit board of DPR "*of the same SEL's relay*" without casing and any metal shielding covers, exposed to electric field pulse of 25 kV/m, confirmed resistance of SEL's relays to HEMP.

It should be noted that resistance of a passive set of electronic components (installed on an individual printed circuit board without any connection) to a pulse of external electric field with the intensity of 25 kV/m does not prove anything to anybody. On the other hand, according to data presented at the Symposium [16] organized by serious American organizations, such as North American Electric Reliability Corporation (NERC), Department of Energy (DOE), Department of Defense (DOD), Department of Homeland Security (DHS), Federal Energy Regulatory Commission (FERC) etc., the following figures were repeatedly mentioned:

- programmable controllers, PCs and communication ports of equipment can be damaged by applied voltage of 0.5 – 0.6 kV;
- failures and operational disorders of DPR occur at 3.2 – 3.3 kV;

- voltage occurring on the cable ends running inside typical buildings and connected to electronic equipment of power systems can reach as high as 10 kV upon HEMP impact.

Conclusions of [16]:

- "*The direct coupling of E1 HEMP fields inside the building is strongly influenced by construction type of the building*";
- "*Given that ordinary building protection level will typically allow up to 10 kV to be coupled to internal cables… leading to the electronics…, this indicated a potential problem".*
- *"…upsets on relays begin at 3.2 kV and damage to programmable logic controllers and personal computers begin at approximately 0.5 kV, indicates a serious concern for the continued reliable operation of substations."*

How can we determine the actual level of DPR resistance to HEMP? Obviously, valid results can be obtained during real tests on HEMP simulators due to a broad range of DPR's parameters, differences in the environments of their installations, as well as inaccuracies in standards and reports.

III. TESTING OF DPR RESILIENCE TO HEMP

The test procedure of power systems' electronic equipment and a variety of test impact parameters (using DPR as an example) is given in [17] in full detail. Thus, this article provides just a short list of main stages of preparation to these tests and their principles:

1. Determine critical facilities and select critical types of equipment at these facilities that need to be tested.
2. Establish the aim of testing and condition of equipment under test ("as is", partially protected equipment, completely protected equipment).
3. Establish the structure of equipment considering connections between its individual elements and the schedule of operation according to which it will be tested.
4. Establish performance criteria for functioning of equipment under test, as well as a selection of auxiliary testing equipment, which will control the condition of equipment under test during and after the test impact.
5. Determine requirements to types and parameters of testing impacts. Furthermore, the real level of electromagnetic emission weakening by the premises, where EUT is used in normal conditions, should be measured in advance according to the procedure provided in [18].
6. Develop a detailed test plan including a general test setup. An example of a test setup to check the resilience of a relay protection system to a pulse of HEMP electromagnetic field is shown in Figure 5.
7. Coordinate the test plan and test setup with the company that owns the testing equipment.
8. Design and assemble equipment that will be tested considering the requirements to its transportation to a test bench and upon it, the assembly of equipment.

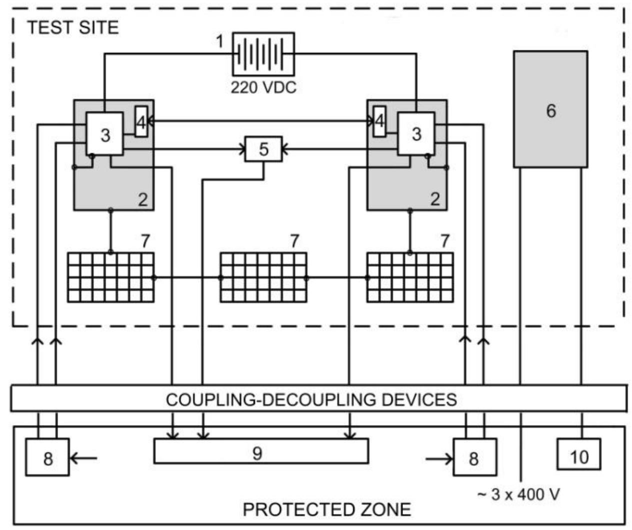

Fig. 5. Arrangement of EUT in the test-bed. 1 – Mobile battery 220V, 2 – Electrical cabinets distanced from one another; 3 – Tested electronics (such as Digital Protective Relays - DPR); 4 – Communication devices; 5 – Lockout relay controlled via DPR output circuits; 6 – Battery charger; 7 – Set of metal meshes comprising the ground system model; 8 - simulators of different modes of EUT operation synchronized with HEMP initiation system; 9 – EUT status recorders; 10 – Load with battery charger output voltage control unit.

IV. CONCLUSIONS

The data published by SEL Company does not demonstrate advantages of its relays compared to those manufactured elsewhere. The data does not prove the resilience of digital protection relays to HEMP, the materials are rather promotional that contain technical lapses and inaccuracies, which can mislead the readers. The valid data regarding resilience of relay protection system to HEMP can be obtained based on properly setup tests, requiring performance of preliminary and rather difficult and responsible work, the main stages of which are discussed in this article.

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