A METHODOLOGY TO ASSESS EXO-NEMP IMPACT ON A REAL SYSTEM - CASE STUDIES

D.Hansen, H. Schaer, D. Koenigstein, H. Garbe, H. Hoitink
Asea Brown Boveri Ltd.
Corporate Research
ABB EMI Control Center CRBE.4
CH 5405-Baden / Switzerland

ABSTRACT

A systematical, theoretical as well as experimental approach to assess EMP-impact on real systems is outlined. The systems considered are an electromechanical locomotive, a private telephone branch exchange system, and a small digital encryption unit.

In spite of the different sizes of the systems the same simulation techniques - field excitation and current injection - are used, resulting in different system responses (upset - damage). Some of these results are presented and analyzed in light of the weighting between conducted and radiated interference phenomena to help establish realistic and economical test methods.

1. INTRODUCTION

The effects of a nuclear electromagnetic pulse (NEMP), generated by a detonation 20 - 40 km above ground, have been investigated in a number of experiments at special test sites since the early 60's, and in the literature [1,3].
NEMP effects upon electronic systems can be simulated nowadays to a great level of accuracy without detonating nuclear devices, using various types of NEMP simulators. Especially in the case of a large test object (system) a theoretical analysis is very helpful for defining the threat levels at the interfaces to the smaller subsystems, which may then be tested and hardened in a laboratory.

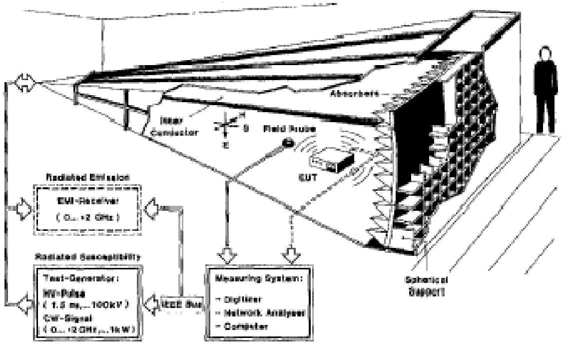


Fig. 1 Broadband Tem Cell "GTEM 1500" for pulse and CW experiments.

Real systems under the impact of Exo NEMP have been analyzed theoretically and investigated experimentally, using both large and laboratory sized NEMP simulators, such as "MEMPS" (Mobile Electromagnetic Pulse Simulator), which is capable of producing about 80 kV/m electric field strength directly below the pulser. Other types of NEMP simulators, e.g. "MIGUS" of the technical university Stuttgart [9], the EMP pulser NP 100 [5] and a broadband TEM cell, the "GTEM-1500" [2] (see figure 1), have also been used. In spite of the different sizes of the test objects and the simulators, the same simulation techniques - field excitation and current injection - were applied.

Three examples of real systems covering the range from power electronics (MW range) to telecommunication units (400 MHz range) are presented, i.e.

- a Swiss electromechanical locomotive (4.6 MW; 80 tons weight, 15 kV, 16 2/3 Hz) including some control electronics (late 60's) and a new UHF-radio system (400 MHz),
- a private telephone branch exchange system (CMOS), and
- a small digital encryption/telecommunication unit (CMOS, TTL, analogue).

The paper describes in which manner the different test objects were analyzed, theoretically and experimentally. The scope of this paper is to show the following.
Good knowledge and experience in solving the technical problems on a subsystem level are necessary, but do not guarantee a proper and economical solution on a system level.
To achieve system level NEMP hardening, certain rules concerning the system topology and the project management guidelines have to be observed as well.

Rough experiments and a first analysis are necessary to set up the final test and analysis plan.
The topology approach shows that larger objects must be analyzed "from outside to inside" in several steps, where experiments and theory are used alternately to get an overview of "what is going on" and to define the threat levels at the interface between system and subsystem. Statistical aspects have also to be considered.
Subsystem equipment can then be investigated and hardened in a laboratory.
A final integration test (laboratory or big simulator) makes sure that the electronics is working without damage or upset.

2. ASSESSMENT OF EXO-NEMP IMPACT

In accordance with the West German Defense Standard VG 96 901, Part 4 [10] and the GRD handbook [8] a double exponential 5/200 ns, 50 kV/m pulse incident on the system under test was assumed. According to the

different test object sizes different experimental procedures in conjunction with theoretical system analysis had to be used.
The systems/subsystems under test and the simulators will first be presented briefly, then a more detailed analysis will be described.

Test Object 1:

system under test: a Swiss electromechanical locomotive (Re 4/4"), see figure 2.

subsystem: a new UHF-radio system, implemented into the locomotive

Simulators:

MEMPS --> field illumination: 25 kV/m; current injection: up to 2.4 kA.

GTEM --> CW field illumination: 10 V/m (1-500 MHz).

NP-100 --> current injection: up to 2.0 kA (power on/power off).

System analysis:

- Evaluation of threat levels at the interface system/ subsystem (e.g. field coupling through apertures).
- Weighting conducted versus radiated threat level.
- Integration test of UHF radio system (no hardening of the locomotive).

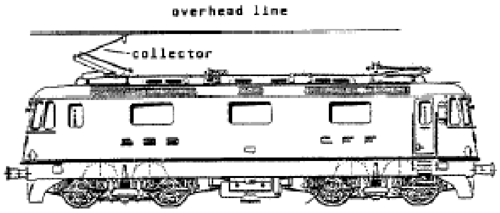


Fig. 2 Test object 1. Electromechanical locomotive of the Swiss Federal Railways (SBB).

Test Object 2:

System: A private telephone branch system, see fig. 3.

Simulators:

MIGUS --> field illumination: 50 kV/m; indirect current injection: 50 A.

GTEM --> CW field illumination 10 V/m (0.01-220 MHz).

NP-100 --> current injection: up to 13 kA.

System analysis:

- Evaluation of threat levels within the system (field coupling).
- Evaluation of cost-effective hardening measures.
- Topology/zoning approach.
- Comparison to EMI levels (conducted/radiated)
- Integration test.

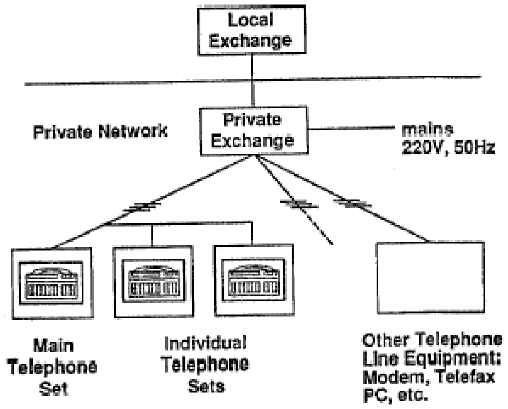


Fig. 3 Telephone branch exchange (system configuration).

Test Object 3:

System under test: A small digital encryption unit.

Simulators:

GTEM--> NEMP field illumination: 50 kV/m;

NP-100 --> current injection: up to 5.6 kA; direct pin injection: 2.2 kA.

System analysis:

- Current injection values for critical connections.
- Integration test.

3. SYSTEMS UNDER TEST / ANALYSIS

3.1 Test Object 1

Figure 4 shows a horizontally polarized dipole (HPD) simulator (resistively loaded elliptical loop structure with a 4-MV-generator 20 m above ground) and a transmission line system formed by an overhead wire connected through two impedances to the rails on the ground. The power of the overhead line is for the time being switched off. The locomotive (system test object) is shown in figure 2. It can be disconnected from the overhead wire by a collector, which is either up or down.

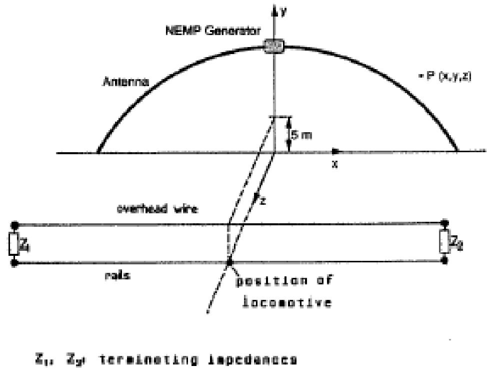


Fig. 4 Geometry of the simulator - overhead wire in a rectangular coordinate system

Step 4:

Once the threat levels at the boundary between system and subsystem were known, the subsystem NEMP test (and also subsystem hardening) could be done in our laboratory.

UHF Radio System

In order to implement a recently inhouse developed UHF communication system into the locomotive (fig. 2), an EMI/EMP analysis focusing on the electromagnetic environment had to be performed. Measurements of conducted and radiated signals included both time and frequency domain. The frequencies of interest ranged from 10 kHz up to 500 MHz, the time domain measurements covered the region between nano- and milliseconds.

Typical values for EMI-threats were up to 120 dB µ V/m for field ambients and more than 100 V for conducted EMI due to switching operations, while an EMP-field threat could lead to values of 250 V at the 50-Ohm antenna system. This is less than the well known protection device (C<<) on set limits and consequently dangerous. Other project objectives included an experimental simulation of an EXO-NEMP field illumination in a GTEM cell [2], and susceptibility measurements according to IEC 571 [6]. Some tests went up to 1 GHz. (mod. IEC 801-3). In conjunction with the associated IEC 801-5 [7] surge withstand capability test, practical hardening measures were tested.

Two measured transfer functions are compared in figure 9. The full line corresponds to MEMPS measurements (time domain), the dotted line to CW-measurements in the GTEM-1500. The transfer functions have their maxima between 80 - 200 MHz, the operating frequency of the subsystem is 400 MHz. Typical transfer function values are 1 mV/(V/m) at 1 MHz, and 1 V/(V/m) at 100 MHz.

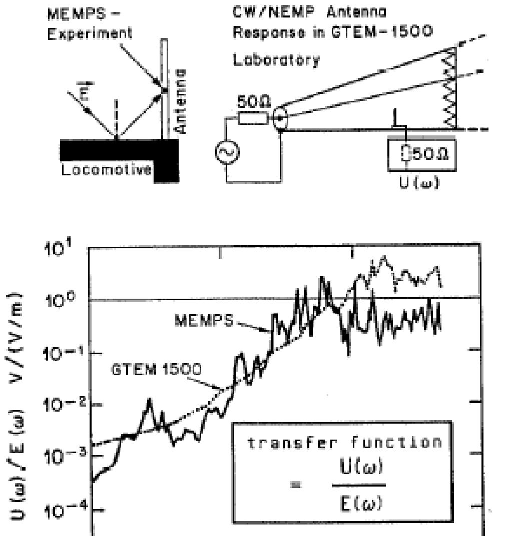


Fig. 9 Transfer function of UHF antenna system measured at 50-Ohm-terminator. Comparison of MEMPS vs GTEM 1500.

System Analysis Aspect

Take small equipment of locomotive (UHF radio system) into the laboratory and test it according to the threat values calculated and found inside the locomotive. Field illumination tests can be done in the time and in the frequency domain (hardening measures). Full threat-level experiments include non-linear effects.

Step 5:

The final system integration test was a "power on" experiment without NEMP field illumination. The locomotive was powered by 15 kV, 16 2/3 Hz, and a current injection experiment was performed with the ABB NEMP pulser NP-100 [5], which is a high voltage/high current generator (it delivers short circuit currents up to 80 kA at 100 kV charging voltage).
Currents up to 2 kA were injected at different interfaces of the locomotive (power entrance on the roof/control wires between locomotive and carriages/heating circuitry) while the power was either switched on or off, see fig.10. Power-on experiments showed that the injected test current damaged a cable insulation, causing a large follow current destroying parts of the heating circuitry (figure 11) and introducing a potential threat to the unprotected transformer, a key element of the vehicle.

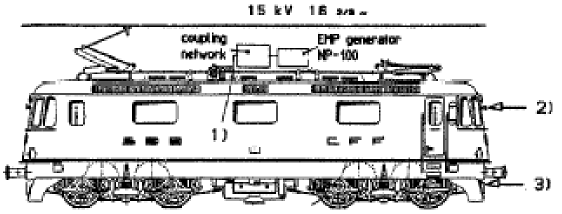


Fig. 10 Power-on current injection experiments with EMP Pulser NP 100 and coupling network.
1. injection into main transformer
2. injection into UIC line
3. injection into heating circuitry (1 kV).

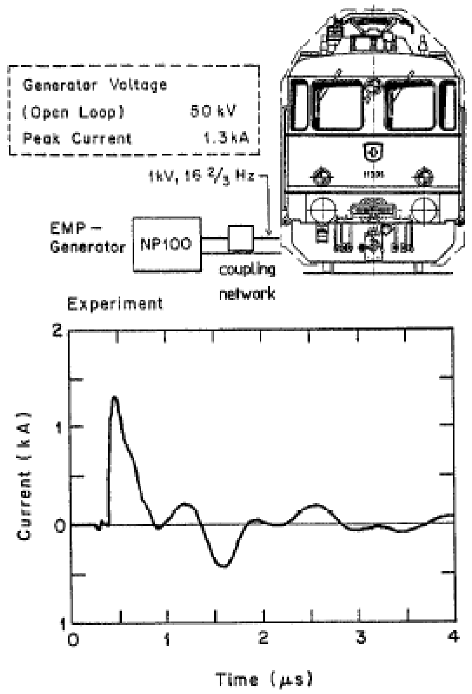


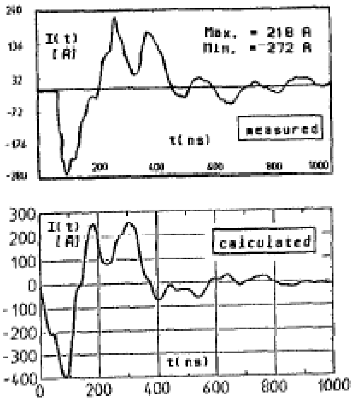
Fig. 11 Power-on current injection (heating circuitry).

System Topology/Project Management

It is always a good practice to check the data acquisition system and to map the field components of the simulator at various points without any test object. The availability of the locomotive had to be integrated into the time schedule of the test plan.

Step 1: Field illumination (25 kV/m)

The test object was located in the middle of the overhead transmission line (collector positioned down), and the induced currents in the line at various locations and with various terminating impedances were measured and analyzed theoretically. Figure 5 shows an example of measured and calculated currents in the overhead line.
Next induced currents and field components were measured outside and within the locomotive. Important analog / digital control electronics, deep inside the PC-boards was repeatedly burnt out.
In order to understand quantitatively the threat levels within the locomotive, special "sensors" (transmission lines) were installed.
The currents were measured and compared to theory (field coupling through apertures, see figure 6).



The values of the terminating impedances are
$Z_1 = \infty$; $Z_2 = 600\ \Omega + j\omega L$ ($L = 5\ \mu H$),
the location x is = -7 m.

Fig. 5 Measured and calculated current response in the overhead transmission line.

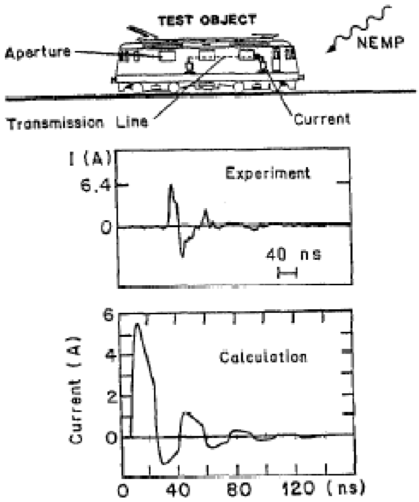


Fig. 6 Measured and calculated currents in an internal transmission line behind apertures.

This enabled us to confirm the experimental results by theoretical calculations. The measured currents are also in good compliance with MIL-Std-461 C, which states that the upper current limit (frequency domain) is 10 A. The shielding effectiveness and threat values within different topological zones inside the locomotive are thus known, especially the threat-levels for the subsystem test (UHF radio system).

The system analysis aspect is that induced currents in simple structures outside or within the locomotive (e.g. transmission lines) can fairly accurately be predicted by theory. Moreover, this gives the possibility to perform different numerical analysis in order to determine the influence of such parameters which may hardly be varied during the experiment (e.g. soil conductivity or pulser data) upon the interface threat levels.

Step 2:

The collector of the locomotive was raised (figure 7), the field illumination experiment was repeated. A part of the overhead transmission line current thus contributed to the field induced currents within the locomotive.

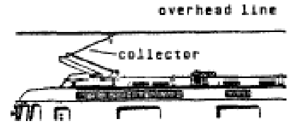


Fig. 7 Test object 1, step 2. Collector contacts the overhead line.

Step 3:

Current was injected directly from the MEMPS simulator. But a field simulator such as the "MEMPS" still radiates a transient electromagnetic field while it is acting a a current injector. Steps 1 and 2+3 , however, suffice to distinguish between the contributions due to an electromagnetic field or due to a conducted interference. Figure 8 shows an example (speedometer sensor cable), where the contributions due to a field of 25 kV/m and due to a total current of 1 kA are roughly equal above 1 MHz, but differ by almost a decade (17.5 dB) below 1 MHz.

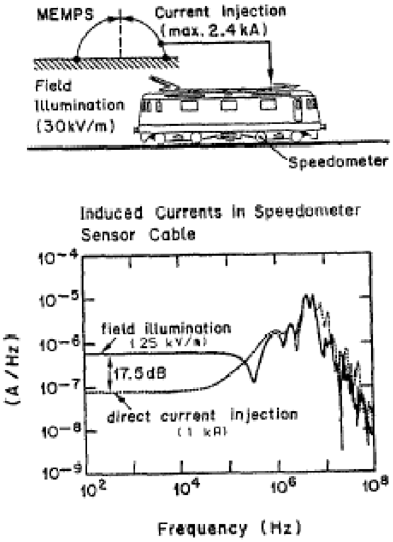


Fig. 8 Comparison of conducted versus radiated threat levels. Example: speedometer sensor cable.

Summary for test object 1

Good agreement between the theoretical system analysis and the experiments could be achieved. The results could be extrapolated numerically to boundary conditions which could not be simulated by the experiment (simulator characteristics such as pulse rise time, soil conductivity, etc.). By choosing between different types of NEMP simulators, we got an economical procedure to determine the threat values and to select a cost-effective hardening measure (subsystem).

Moreover, a weighting between conducted and radiated interference was obtained.

Systems have to be tested while power is on , because a NEMP coupled transient can act as a trigger for a large follow current which is a really dangerous threat. Power on tests are not always required for LRUs by standards such as MIL 461 C. Considering the coupled energy content, even robust systems may be vulnerable to an Exo NEMP threat.

3.2 Test object 2: private telephone branch exchange system

Topology approach

The NEMP simulator "MIGUS" of the technical university Stuttgart (bounded wave type simulator) was used. The system configuration is shown in figures 3 and 12. A typical current waveform is given in figure 13.

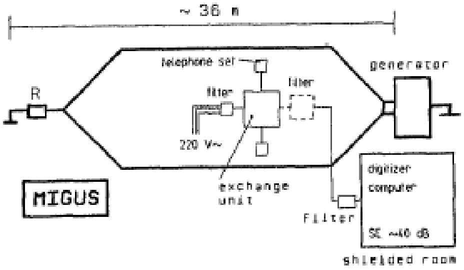


Fig. 12 Telephone system under NEMP test at MIGUS (top view).

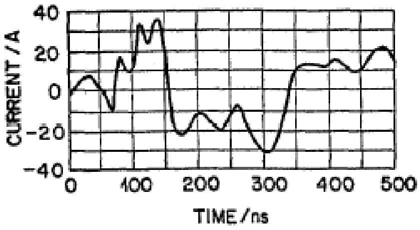


Fig. 13 Current in connection loop between telephone set and exchange.

The following hardening measures were taken:

telephone set:	line filters (data and voice), handset unprotected;
exchange unit:	mains surge protection and filter; voice and data line protection unit.

The test results are summarized in table 1. Laboratory generators were used for the generation of the threat-level currents on the lines.

Telephone Set

Original	Modified
NEMP field induced functional upset	
30 kV/m	70 kV/m
Damaging pin injection voltage 0.1/50 µs (@ 47 Ohm)	
> 1 kV	> 11 kV

Exchange Unit

Original	Modified
30 A (30 kV/m) voltage regulator 5/12 V burnt out	same configuration 70 kV/m o.k.
Damaging pin injection voltage (IEC 801/4 Burst)	
1 kV CPU upset	> 4 kV

Table 1 Unhardened and hardened telephone system.

The conclusions for this test system are:

1) Unprotected telephone systems (CMOS technology) will be damaged by NEMP impact.

2) EMC measures are a good platform for optional EMP protection.

3) NEMP hardening should focus on line effects.

3.3 Test object 3: military encryption unit
(to be connected to a radio/telecommunication unit)

The pulse field tests were performed with a NEMP field strength of 50 kV/m resp. 133 A/m (risetime 5 ns) in the laboratory test simulator GTEM 1500 [2] in different system configurations (e.g. figure 1).

Current injection values for critical system connections were measured during field tests and evaluated from system analysis and computation, see figures 14 and 15.

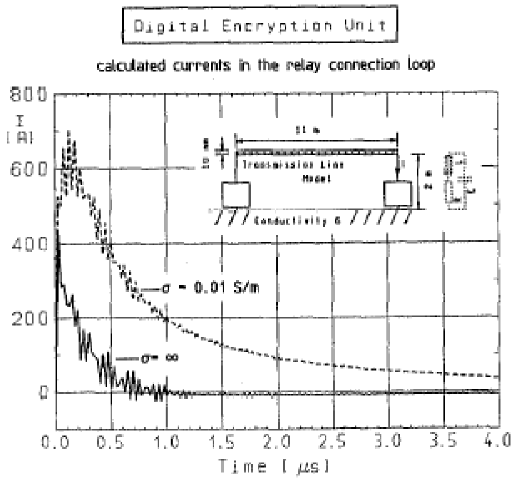


Fig. 14 NEMP field induced currents

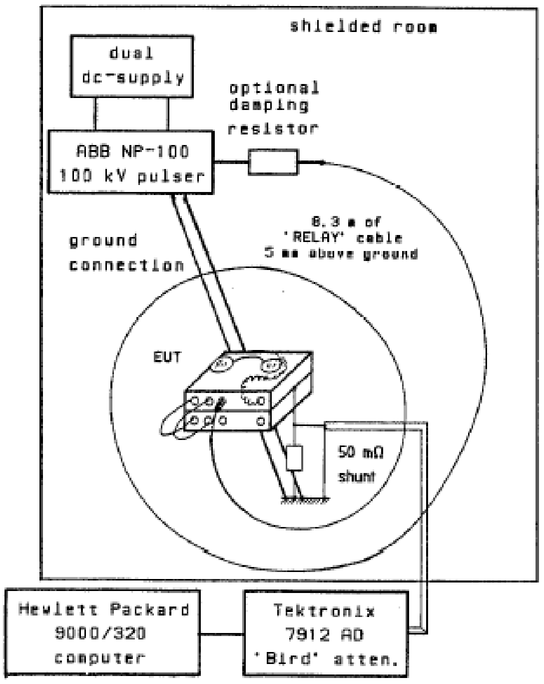


Fig. 15 Setup for direct current injection tests

Bulk current injection was performed with currents up to a peak value of 5.6 kA, using an ABB NEMP generator [5]. This method is a more system related test than MIL Std. 461 C (pin injection test), because it includes the cable/connector transfer impedance and nonlinearities like suppressor elements, dielectric breakdown and saturation effects.

All tests were performed with an electrically active ciphering unit connected to a dummy unit for voltage supply. A full function test after each single test and a detailed laboratory analysis after the end of the tests showed no defect and generally no malfunction. Only with a direct pin injection test using 2.2 kA peak current (specification 50 A) there was a loss of codes without permanent damage provoked.

Surprisingly, a prototype failed EMI-test CS01 as rated by MIL-Std 461 C Part 2. The short EMP impact is not critical in this case. However, there is more energy coupled into the system by CW excitation leading to upset levels on the order of volts.

4. CONCLUSIONS

EMI hardening is a good basis for NEMP hardening. Test object 2 (telephone system) essentially shows that the conducted interference has to be suppressed by filters and voltage limiters, in order to avoid upset (latch up) or damage.But the opposite is not always true. A NEMP hardened system (test object 3: encryption unit) may fail EMC tests without additional protection measures (CW) being taken.

The test object 1 (locomotive) shows that the contributions of conducted and radiated interference can clearly be separated. The radiated interference contribution must not be neglected. This means that other types of locomotives which do not need an overhead wire (e.g. diesel electrical locomotives) could also be vulnerable to Exo NEMP.

Systems have to be tested while power is on , because a NEMP coupled transient often acts as a trigger for a large follow current / power which is the real dangerous threat. Early into the project implemented NEMP protection can somestimes be achieved for just a few percent of the overall project cost.

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