System Design and Assessment Notes

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Protection of Equipment and Electronic Systems against Electromagnetic Interference, especially NEMP

by

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Abstract

This paper outlines global E^3-aspects such as EMC but mainly focusing on EXO-NEMP. Examples of resent "EMI accidents" and equivalent trends in international EMI standards are given. Various NEMP scenarios will be briefly discussed. A limited theoretical damage/effect analysis in extensive ground based electronic systems is outlined. Experiments on protection and testing technology are demonstrated by a case study of an industrial process/control system under EXO-NEMP impact. A short overview of the West-German EMP-Defense Standards is shown. Finally a number of EMP hardened products, manufactured by Brown Boveri, is introduced.

1. Introduction

Protection against NEMP is a special aspect of the general compatibility (EMC = electromagnetic compatibility) of electronic products in a severe electromagnetic environment. Due to increased sensitivity and integration density of electronic components, in conjunction with the fact that electronics are assuming more and more functions in our modern society (process control, information transmission, electrical power supply, traffic, goods supply, medical technology etc.) that in some cases are vital, it is becoming increasingly important to ensure that this compatibility is achieved.

1.1 Actual examples of "EMI accidents"

In the event of no or limited EMC, electromagnetic interference (EMI) can have catastrophic results in systems, subsystems and/or equipment, as is shown in the following four examples:

- Crash of NATO fighter aircraft Tornado [1]
  Cause of accident: Uncontrolled electromagnetic irradiation into the electronic control system of the aircraft that has cost about DM 100 million. On July 6, 1984 it was flying at low altitude (230 meters, speed 800 km/h) in the immediate vicinity of the high power radio transmitter "Radio Free Europe" near Holzkirchen, south of Munich.

- Steelworks accident on the east coast, USA [2] in the summer of 1983
  Cause of accident: Uncontrolled electromagnetic irradiation of a walkie talkie into the microprocessor control of a crane-held ladle containing liquid steel. The ladle opened prematurely and molten steel killed one worker on the spot. Four others were seriously injured.

- Sinking of the British destroyer Sheffield in the Falkland war [3]
  Cause of accident: Inadequate EMC in the enemy aircraft detection system between radar receiver and simultaneously operated ship transmitter for data transfer via satellite, with headquarters in England. The detection system was heavily "jammed" by strong signals from the ship's own transmitters, resulting in a hit by an Argentine Exocet rocket. The losses were 20 men and the ship.

- Southern German rocket accident (American Pershing II)
  Cause of accident: Electrostatic discharge. While being brought into position the engine of this rocket was inadvertently ignited by static electricity. This incident is regrettable and surprising, insofar as it is known from open literature [4] that the rocket was subjected to an extensive analysis test program, e.g. against the effects of lightning current peaks up to 200 kA.

Problems of this kind and similar have been known to the technical world for a long time. Attempts are being made to avoid such incidents by means of appropriate design, or by the standardization of protection measures that in many cases are also internationally recognized.

1.2 International development of EMC standards and trends

At the very inception of telegraphy and telephony (1850 - 1875) interference problems such as crosstalk on cables and transmission lines became known. Increasing interference to radio and television communications from the operation of electrical appliances finally led to the founding of international technical committees such as the CISPR (= Comité international spécial des perturbations radioélectriques) (1934). Since 1945 American military circles have increasingly concerned themselves with the EMC problems of the army, air force and navy, which in 1968 led to the issuing of the well-known standard MIL-Std 461 (Electromagnetic Interference Characteristics, Requirements) by the Department of Defense that is still valid today. Further developments in technology from black-and-white television, the invention of the transistor, of color television, extending to modern-day informatics and microelectronics is marked by a continuous reduction in the interference thresholds.

That is the reason why worldwide more than 20 major standardization organizations such as the IEC (International Electrotechnical Commission) are increasingly concerned with matters of EMC. This circumstance has resulted in a immense number of consistently stricter standards, guidelines and recommendations, and even laws. (At Seequa Computer Corporation, on 24 July 1985 US marshals impounded manufactured material of a value of US$ 1 million due to violation of an American FCC EMC interference regulation that was legally in force.) In this context it is increasingly being realized that greater attention must be devoted to the interaction of individual components in system complexes. Since it is only recently that greater efforts have been made to coordinate the work of these various organizations, the standards themselves are not always compatible and cannot always be meaningfully interpreted according to the laws of physics [5]. These standards deal with six different fields (Fig. 1).

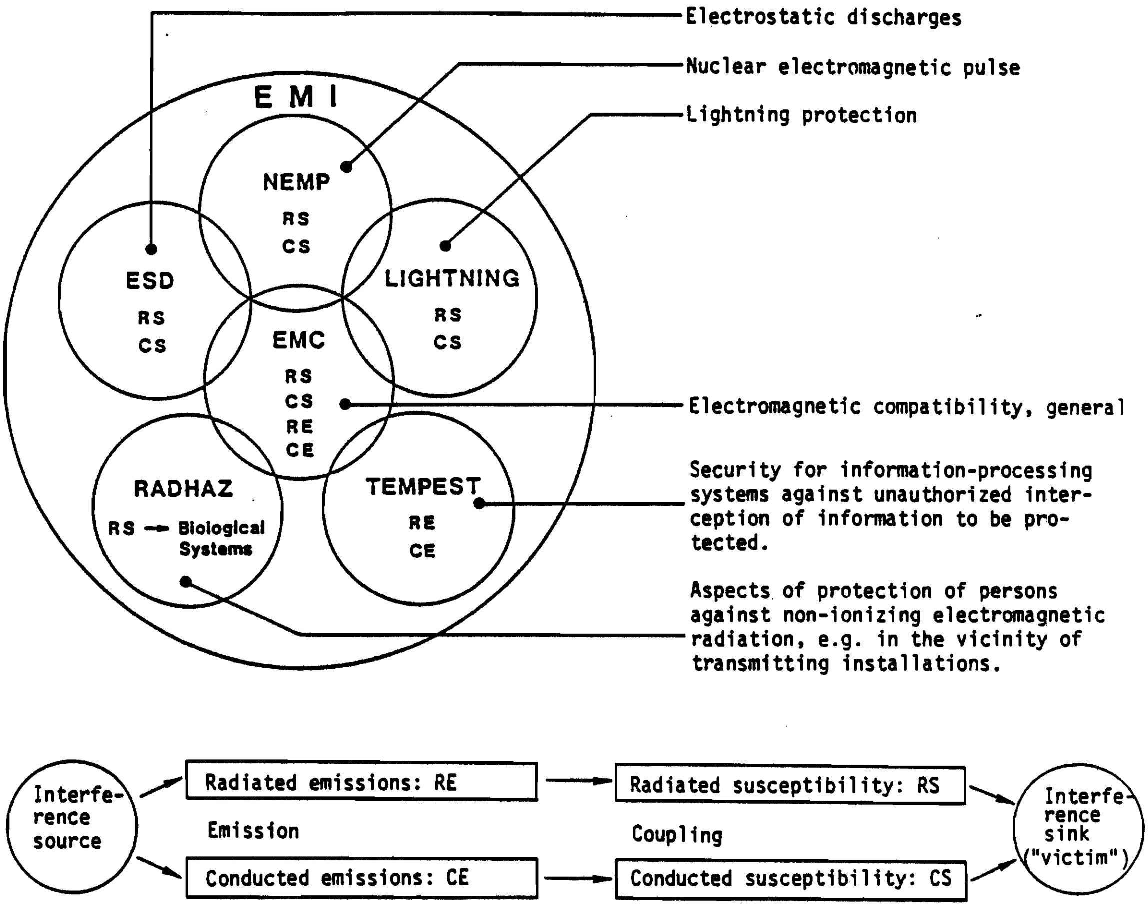


Fig. 1 Interrelationships of the different EMI fields

1.3 Interrelationships of the EMI fields

In the course of time it has become increasingly evident in the treatment of EMI problems that all these fields, while appearing to be very different, have a common denominator: similar electromagnetic characteristics that in the end behave according to Maxwell's equations.

In the case of an electronic system susceptible to interference, e.g. a computer, as a general rule only two types of interference are possible:

- the machine/system is the source of the interference (E = emission)

- the machine/system is the victim (sink) of the interference (S = susceptibility).

In both cases differentiation is made between radiated and conducted processes.

The high-frequency, digital clock signals of such systems generate a wide-band frequency spectrum, which e.g. is radiated and conducted through the cabling that act as an antenna. On the other hand, the cabling or the electronic PC boards equipped with components act as receivers of interferences. Field coupling and conducted interference occur. If this computer is to be protected, as a first step EMC protection measures should be installed. If TEMPEST is required in addition, the emission of the equipment must be strongly attenuated. In the case of lightning protection, protection must be provided particularly against the coupling of higher energy (current carrying capacity etc.).

NEMP or ESD aspects eventually require protection against steep-front interferences of very high amplitudes. Hence, it appears to be expedient to realize an NEMP protection based on a sound EMC concept.

However, also included in the peripheral areas of the EMI discipline and no less important is the protection against non-ionizing EM radiation [6], it being an important design criterion of transmitting antennas or in experimental radiation susceptibility measurement setups.

In the following, the aspects which are important for NEMP protection are dealt with in more detail since in recent years this topic has become of greater interest to the general public as well.

2. NEMP threat scenarios

At this point reference is made to the paper already held by Dr .J. Gut (FMB) in the last series of lectures (see collection of colloquium papers "Krieg in Aether", No. XXIV). Only the three most important scenarios are dealt with briefly, and I propose to limit all further subsequent delibera-tions and analyses exclusively to the case of exoatmospheric EMP.

2.1 EMP at ground level (endoatmospheric EMP)

If a nuclear charge detonates on the ground or at a low altitude, the effects known from Nagasaki and Hiroshima such as fireball, gamma rays, X-rays, neutrons, pressure wave and heat stand in the foreground. A zone of ionized air is produced, the magnitude of which is dependent upon the caliber of the weapon (Fig. 2, applicable for about 1 MT). This zone contains large magnetic and electrical fields (generation mechanism: asymmetry at ground/air interface), which however as the distance increases decrease much more quickly than high-altitude EMP acting upon a large area.

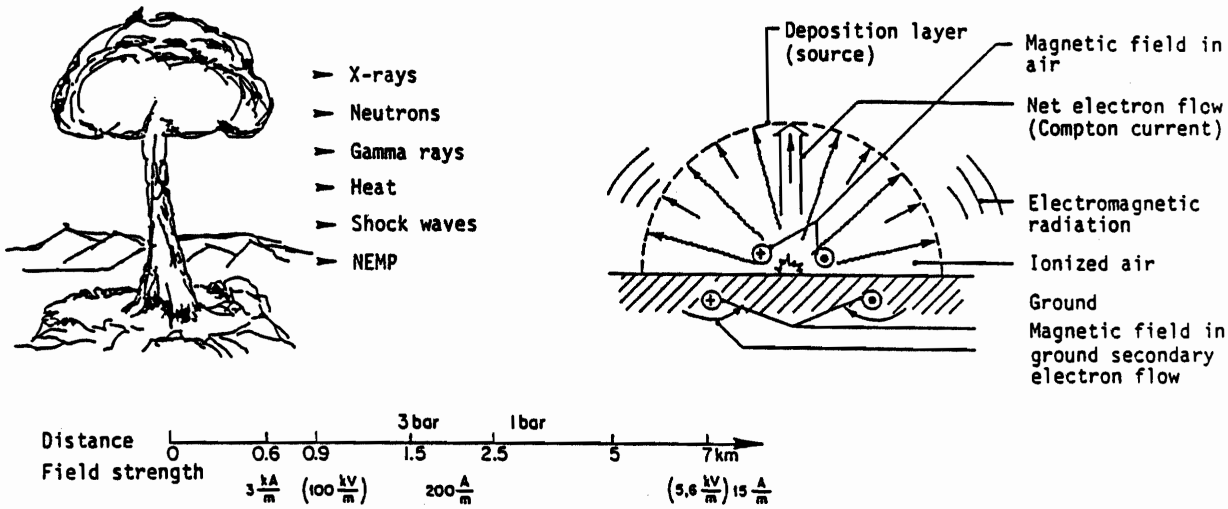


Fig. 2 Effects of EMP at ground level (endoatmospheric EMP)

2.2 EMP resulting from detonation at high altitude (exoatmospheric EMP)

Detonations of nuclear charges at high altitudes achieve their intensive, continent-covering field effects via a transformation (Compton) effect, whereby electrons are released by the collision of X-rays produced by the explosion with the neutral molecules located in the lower air layers. Under the influence of the lines of force of the earth's geomagnetic field the punctiform gamma source is converted into a large-area source of single-shot, synchronously radiating "radio waves" [7]. The steep-fronted change in field intensity occurring on the ground is given as typically 50 kV/m after 5 ns. (Fig. 3) Local variations in field intensity of up to a factor of two can occur.

By comparison with the endoatmospheric EMP, in the case of which the amplitude density spectrum has already dropped to 1% at a frequency of about 200 kHz, the exoatmospheric EMP reaches 1% at about 80 MHz, so that even high frequency receiving systems can still be affected. The exoatmospheric EMP produces destructive induction effects particularly in systems and metal structures of large dimensions.

2.3 Magnetohydrodynamic EMP (MHD-EMP)

For many years these destructive side effects of an exoatmospheric EMP [8], in particular in long (many kilometers) energy and telecommunications lines, was not mentioned in open literature.

Expansion phenomena of the bomb plasma "pushes" the earth's magnetic lines of force upward or downward (Fig. 4). This slow effect, which occurs in the seconds range, induces small electrical field intensity changes on the ground, which can result in dangerous energy couplings similar to those of geomagnetic storm effects in northern countries. The slow equalizing currents thereby produced, especially in public power systems with neutral earthing (star configuration) can destroy components such as power transformers (which constitute items of power supply equipment that are indispensible at short notice) as a result of saturation effects in the core. Under these circum-stances the part of the system which is perhaps not yet damaged by the effects of exoatmospheric EMP could now fail and cause total collapse of a network. This is exactly the point at which e.g. theoretical damage/effect analysis with its predictive estimates is implemented.

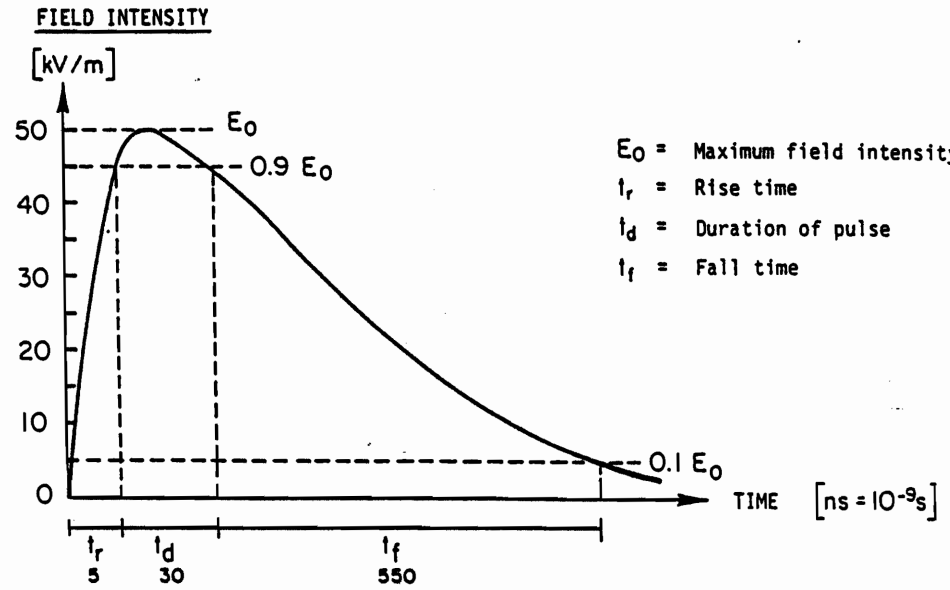


Fig. 3 Field intensity curve of an exoatmospheric EMP on the ground (MIL standard 461B)

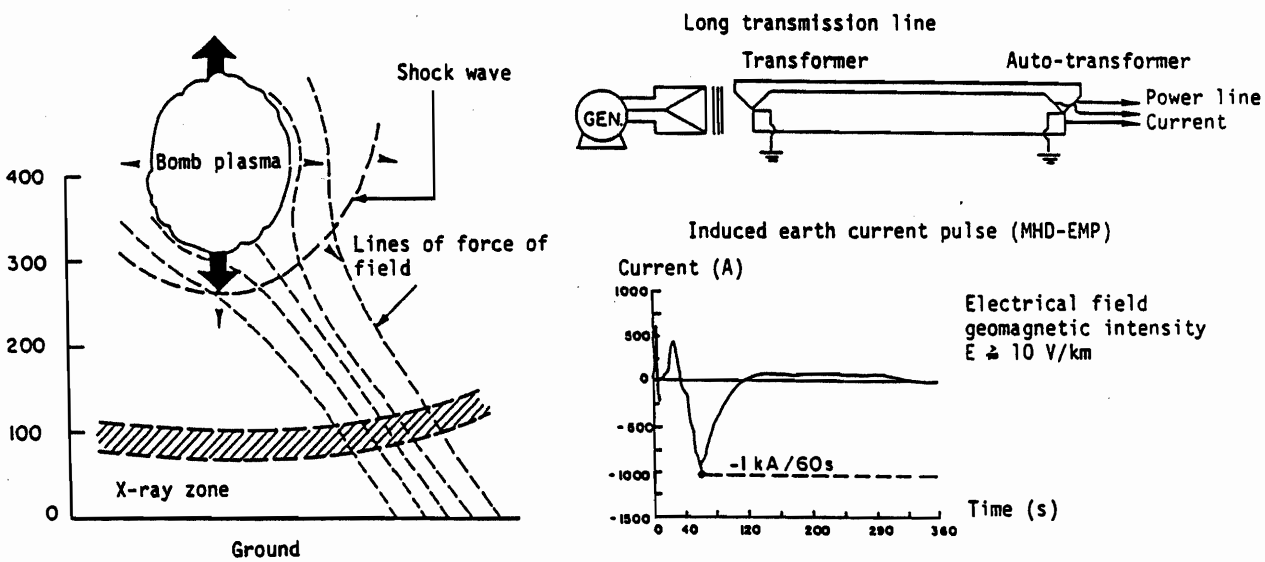


Fig. 4 Magnetohydrodynamic EMP effect (MHD-EMP)

3. Theoretical damage/effect analysis in extensive electronic systems

The most important theoretical fundamentals have already been presented by Dr. J. Gut and W. Blumer in the paper cited above, so that only the industrial aspect important for us is dealt with here.

3.1 Objective, planning, project management

The objective of such an analysis is to establish initial guideline estimates before the project is started of the threat in the form of voltages, currents and fields (Fig. 5) expected at the interfaces by computation, which are required in the technical specification phase.

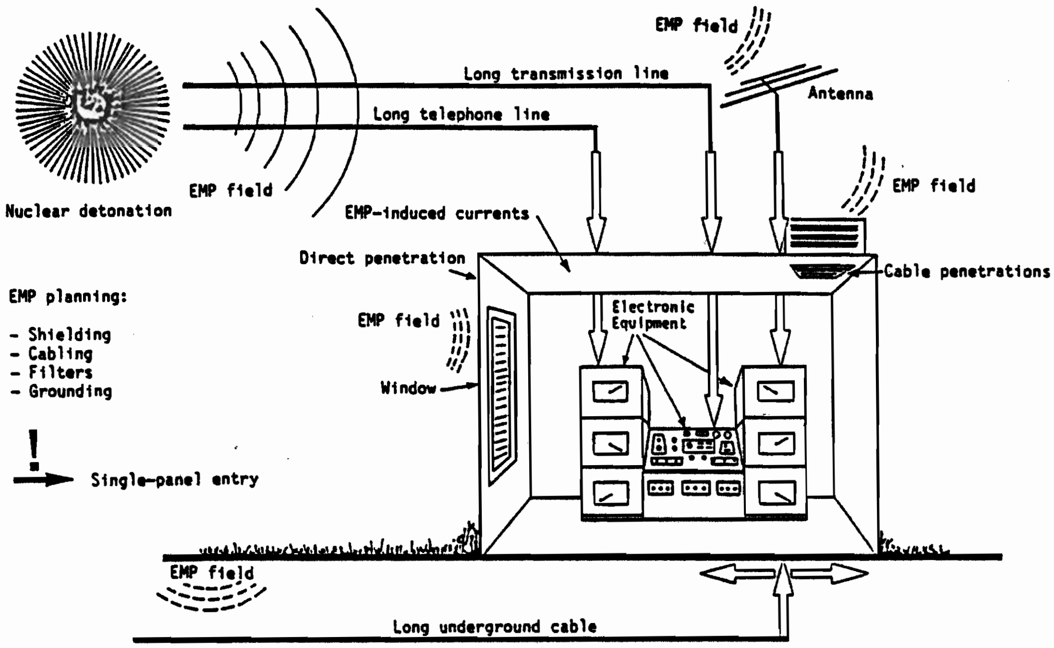


Fig. 5 Penetration of EMP energy into an electronic system

A large-area system is analytically divided into subsystems that can be handled by testing technology. In Fig. 6 the entire analysis, planning and testing procedures, including project management, is shown in simplified form. It is important that these measures be incorporated into the project procedures at the earliest possible stage to avoid cost-intensive and in some cases unsatisfactory retrofitting measures at a later time.

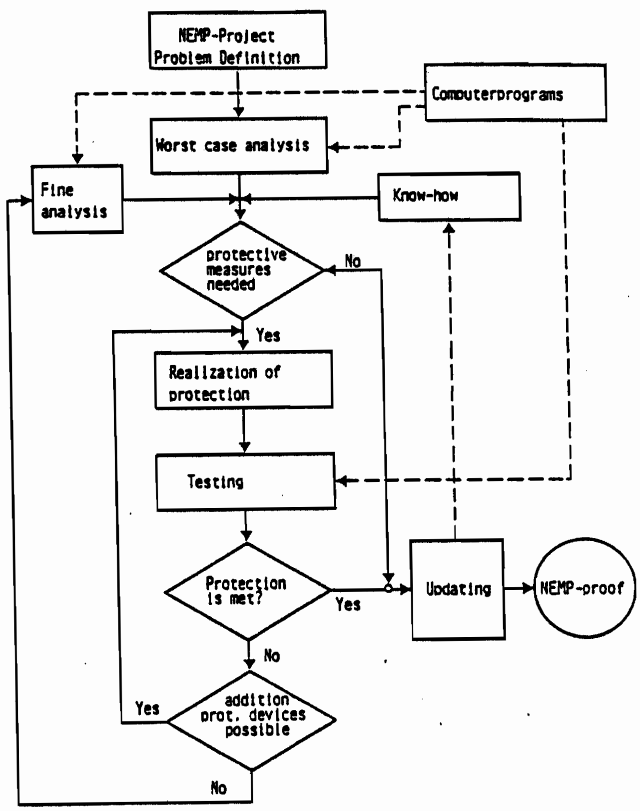


Fig. 6 Typical NEMP project procedures

3.2 Computation programs

In the BBC Research Center special computer program packages were developed [9], [10], [11] that constitute analysis/engineering tools. These programs comprise several, usually modular sub-programs, thereby enabling fast and cost-effective problem solving. Large and hence unwieldy computer codes as are used in some cases in the USA frequently result in long data input and processing times; in addition they are expensive or often not even available on the market due to being classified.

3.3 Case study (problems, limits)

First case: Microwave tower under exoatmospheric EMP impact. An approximately 50 m high microwave tower conducts EMP-induced currents of up to 9 kA. An interesting fact is that in all extensive structures of this type natural resonances of the system are excited by the short field excitation pulse.

Second case: In long energy or communications lines, as is shown in Fig. 7, substantial currents are induced (worst case).

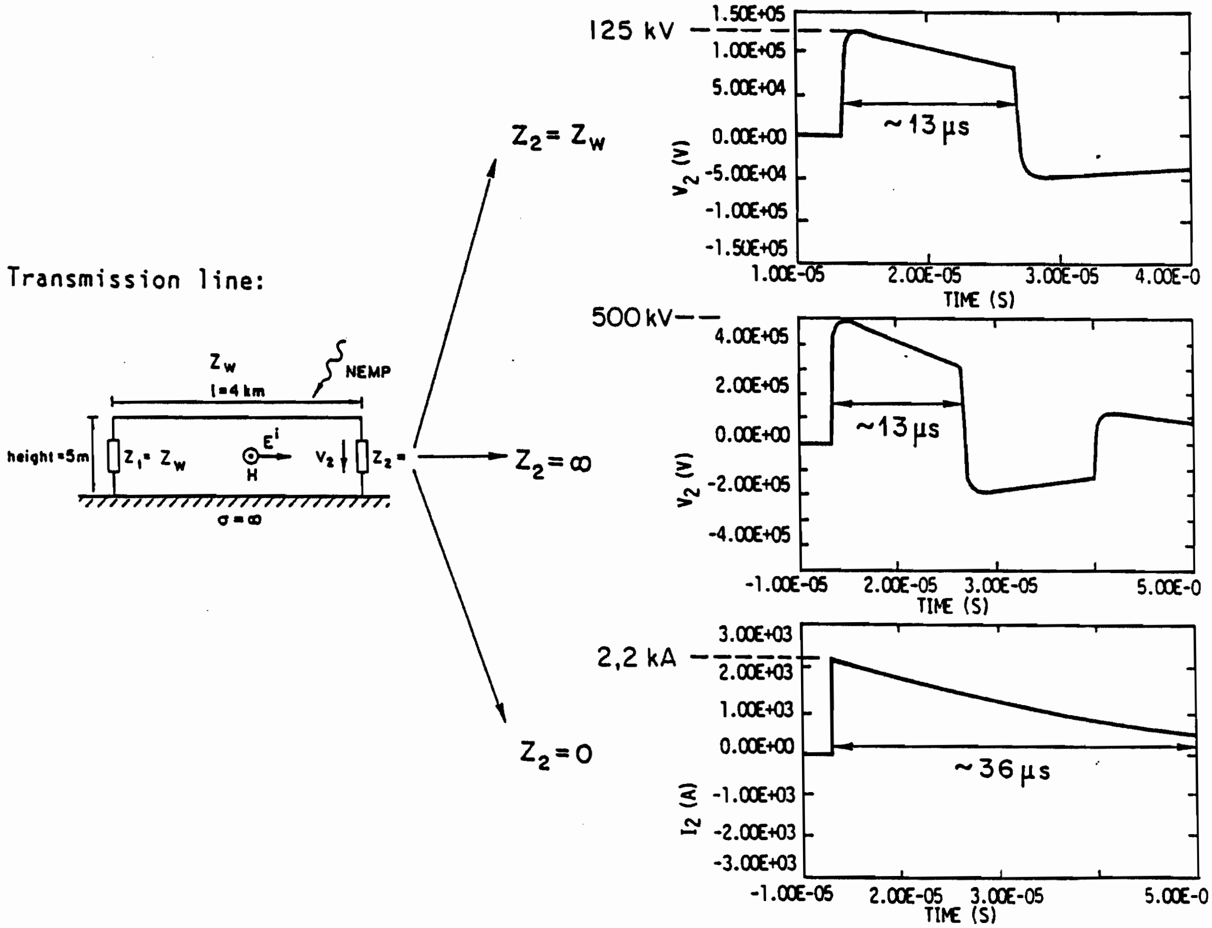


Fig. 7 Case study: Exoatmospheric EMP coupling into long power line (Z_w = 120 ohms)

This second case also serves well to indicate the problems and limits of such a procedure:

- A physical model makes idealized assumptions: σ = ∞, line loss-free etc.
- In practice e.g. natural, dielectric voltage limitations occur over the isolation distances so that coupling values (MV) that have been obtained by computation should be scrutinized critically.

4. Experiments on protection and testing technology

4.1 Protection philosophy

Reputed American NEMP specialists divide the protection concept for "ground-based systems" into the fields [12], [13]:

- topology (division into zones)
- penetrating conductors
- aperture control

reference justifiably being made to the great importance of the shield-penetrating conductors. Here, decisive improvements can often be achieved by simple means, e.g. by bonding the cable shields at the instrument input.
Differentiation is made generally between protection against radiated interference (protection measures: shielding, grounding, bonding) and conducted interference (protection measures: e.g. surge arresters, filters).

This zone concept (Fig. 8) contains inlaid zones of protection. In this way 20 - 30 dB can be reached in steps against radiated interferences to reduce the interference to an acceptable EMI level (zone 3). The same applies generally for conducted interferences, except that due to other coupling mechanisms in lines the same stepping of the protection is not necessarily expedient.

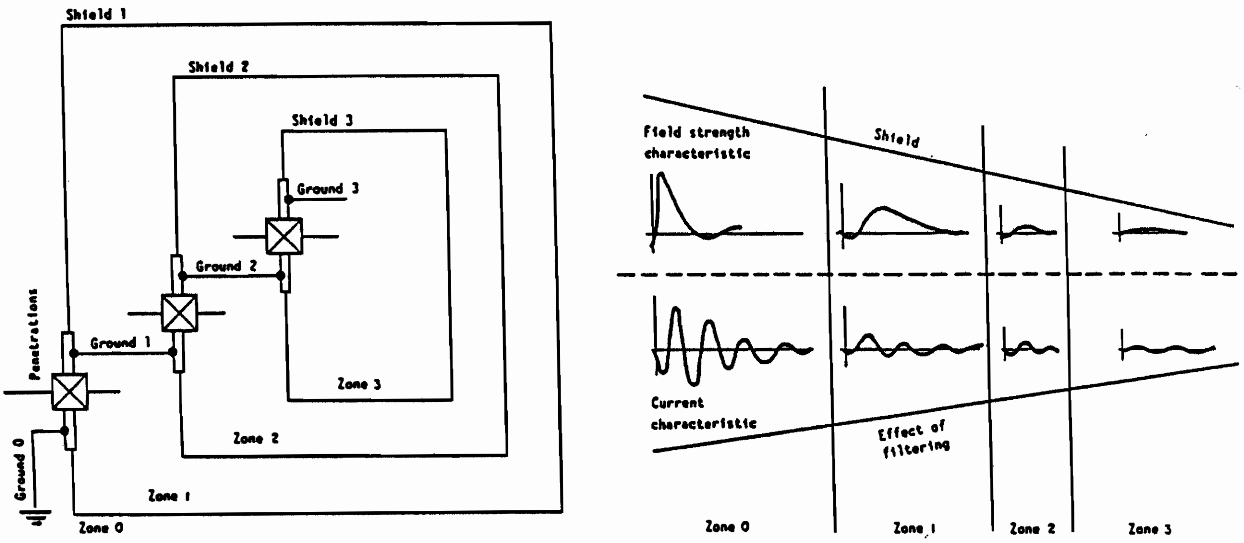
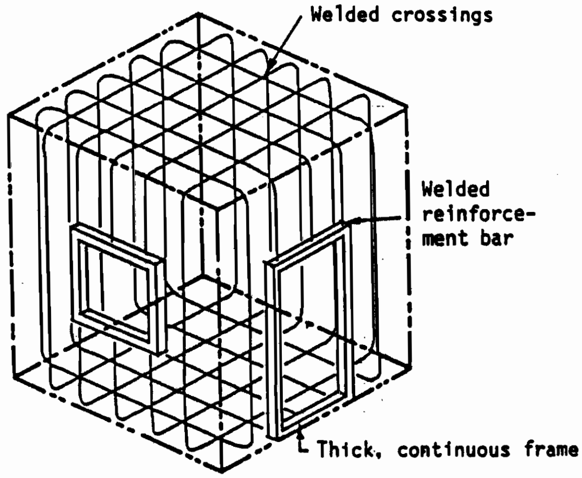


Fig. 8 NEMP protection zone concept

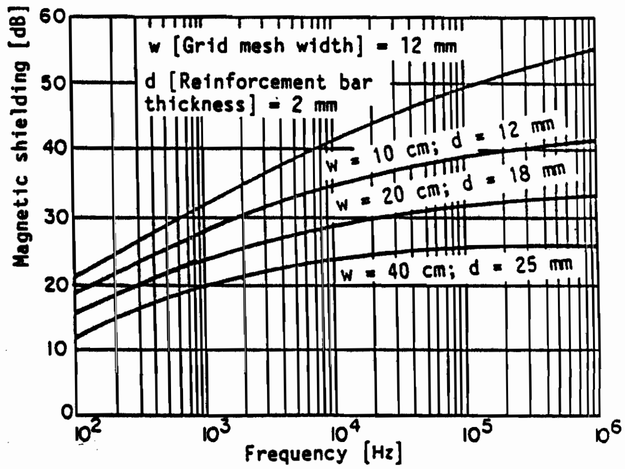
4.2 Example of protection measures

Field damping

When designing new EMP-protected installations which are e.g. covered by additional greater amounts of earth it might be advantageous to include the steel reinforcement skeleton in the zone concept. In the low frequency range (10 kHz, Fig. 9) particularly, approx. 20 dB magnetic shielding effectiveness can be gained. A prerequisite however, is correct welding of the reinforcement bar crossings.



Diagram



Shielding quality

Fig. 9 Cost-effective shielding concept

Line damping

In order to render transient conducted interference harmless the level that would lead to the destruction of the electronic components (connected to the lines) must first be known [13]. The spread for current/voltage level of such a susceptibility measurement for short stressing times on TTL line drivers and receivers is shown in Fig. 10. In the time range < 100 ns shown, in particular dielectric defects predominate as failure mechanisms. In the case of longer periods of time energy effects in the component are the governing factor.

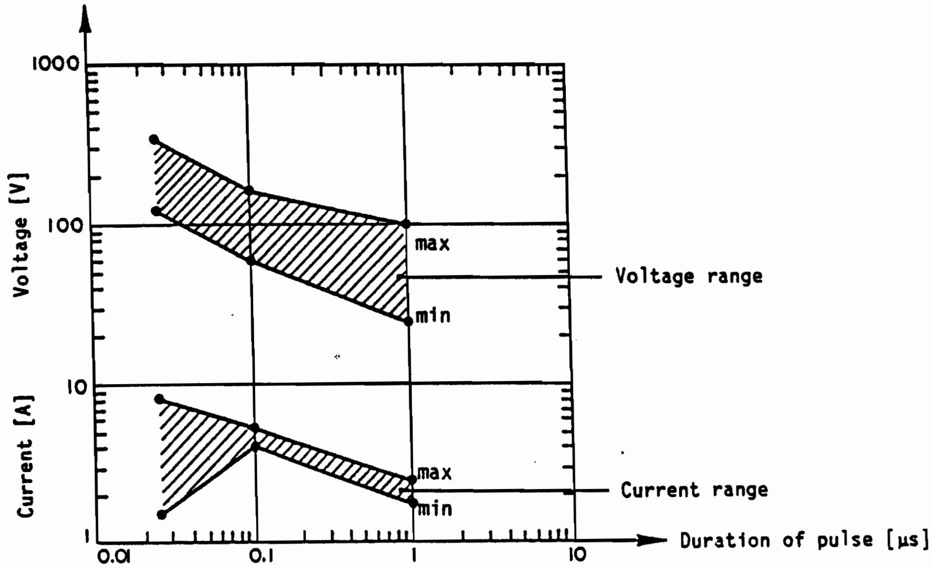


Fig. 10 Destruction limit values of electronic components

The interference level can now be matched to the respective protection zones by means of overvoltage protection (spark gaps, noble gas surge arresters, metal-oxide varistors, high-speed clamping diodes) or by lowpass filters (Fig. 11).

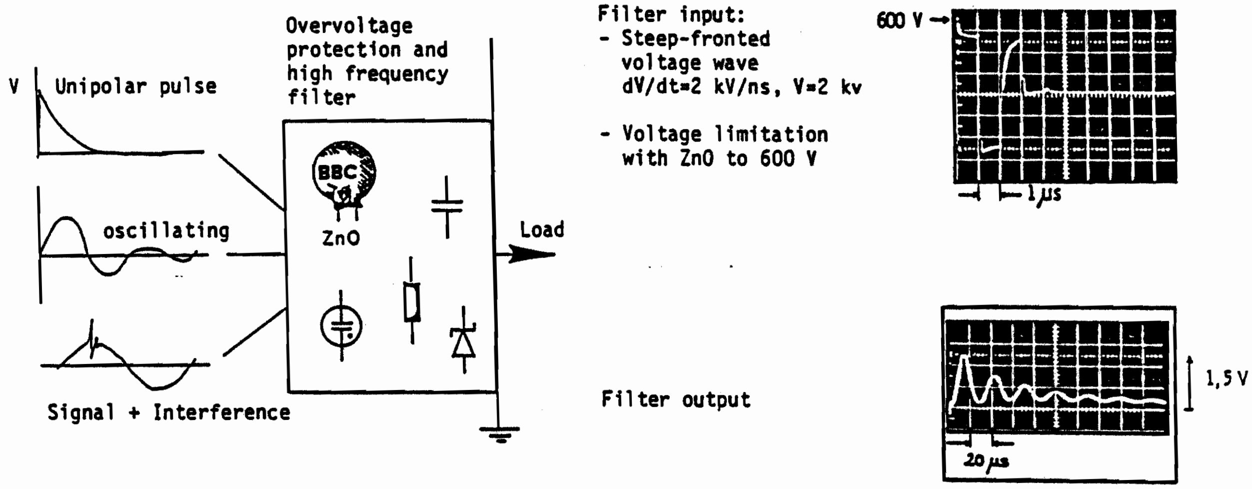


Fig. 11 Pulse damping by overvoltage limitation and filtering

These power line filters have good high-frequency characteristics, which can be verified by the measurement with a steep-fronted voltage wave (600 V ---> 1.5 V). However, with an improper filter/protection design problems can be encountered, especially in the case of interferences comprising pulses of long duration, because the filters may possibly fail in the low frequency range due to inadequate damping characteristics. In this case the voltage-limited input pulse will appear undamped at the filter output.

Fig. 12 shows a case of total failure. The output pulse behind the filter has been "amplified" to 1,300 V! This amplification effect, including the uncontrolled resonances in the filter interacting with the load circuit, can also be proven by computation. It must therefore be noted that- measured in 50 Ω test circuits - selecting a filter from the catalog is problematic. These problematics [14], [15] lie inter alia in the frequency-dependent power line impedance, particularly in the common mode at low frequencies which strongly deviates from the setpoint value of 50 ohms.

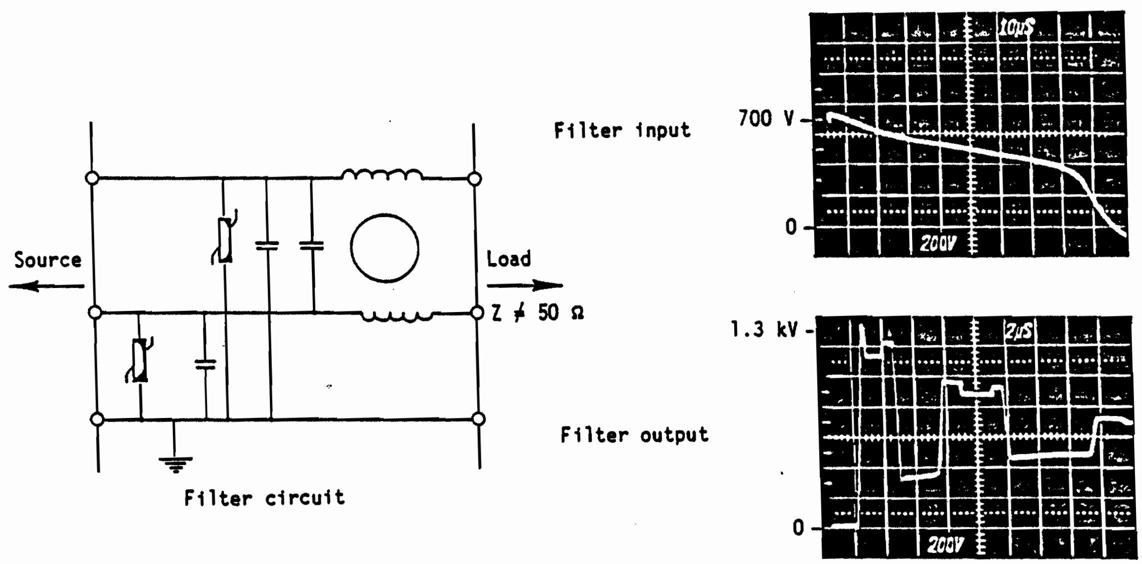


Fig. 12 "Amplification effect" of power line filters

4.3 Testing philosophy

Primarily for reasons of cost we are presently not advocating the procurement of a large field simulator (such as the AC-Spiez Working Group EMP). However, in addition to the development work EMP tests of equipment and installation parts will be performed according to the test schedule. For this reason e.g. the current injection method or the test in a larger TEM cell lends itself to EMP tests being carried out in the laboratory. By employing the results from research and development measurements in external large EMP simulators it will be attempted to bring theory and practice into harmony.

4.4 Case study: NEMP system test

A BBC control system, including the associated cabling, was subjected to tests in the simulator of the university of Stuttgart, professorate of Prof. K. Feser. The simulator principle, the antenna (presently 6 meters high), as well as the test pulse data achieved are shown in Fig. 13.

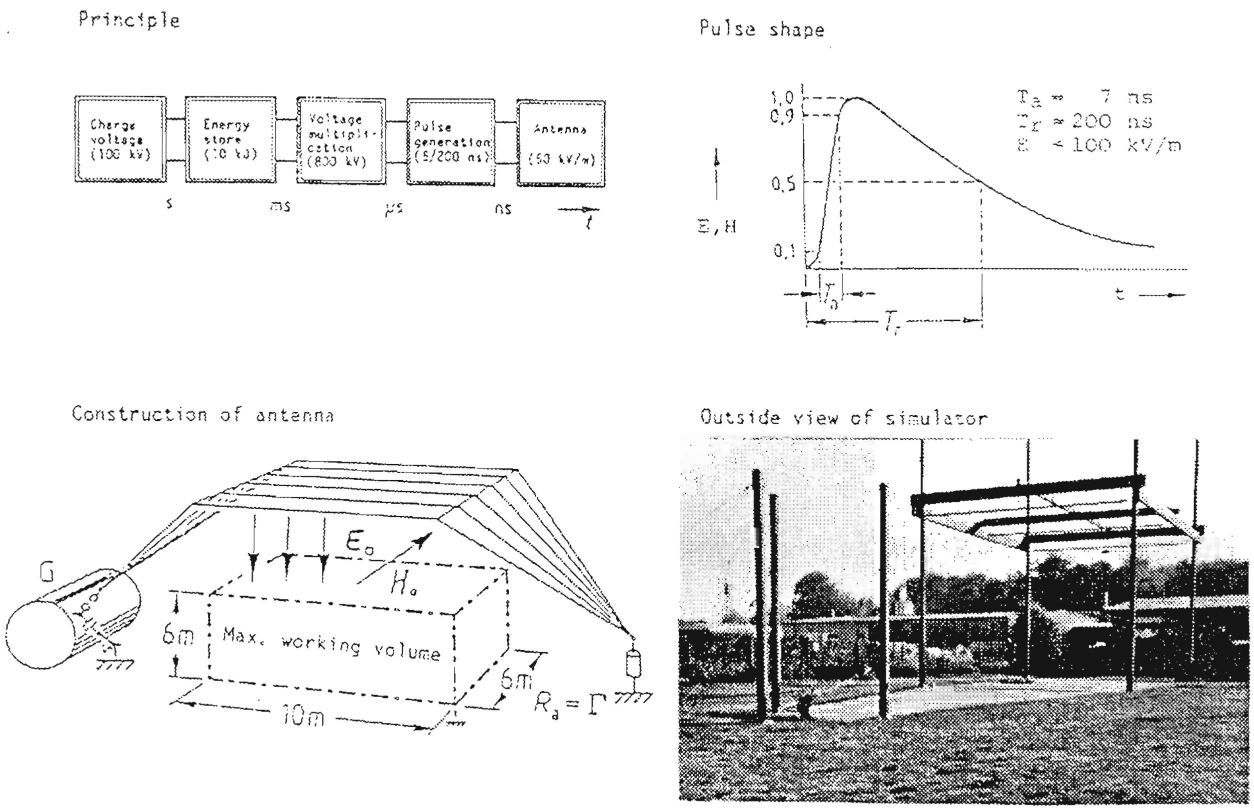


Fig. 13 Principle and setup of MIGUS EMP simulator

Fig. 14 shows the shielded location of the 800 kV EMP generator with Marx generator and peaking circuit. The interference phenomena coupled into the test object below the antenna are conducted to the shielded room by means of highly shielded cables or fiber optic links (Fig. 14). Here, digital or analog signals from several channels can be recorded simultaneously, in some cases with band-widths of up to several hundred megahertz. Since the field probes usually supply the derived signals (E —> D, H —> B) of the physically interesting measured values, integration is effected by means of a computer. The measuring principle and data of the H or E field probes used are given in Fig. 15, taking into account the wide range of change in measurement sensitivity by matching the active area of the probe to the respective application.

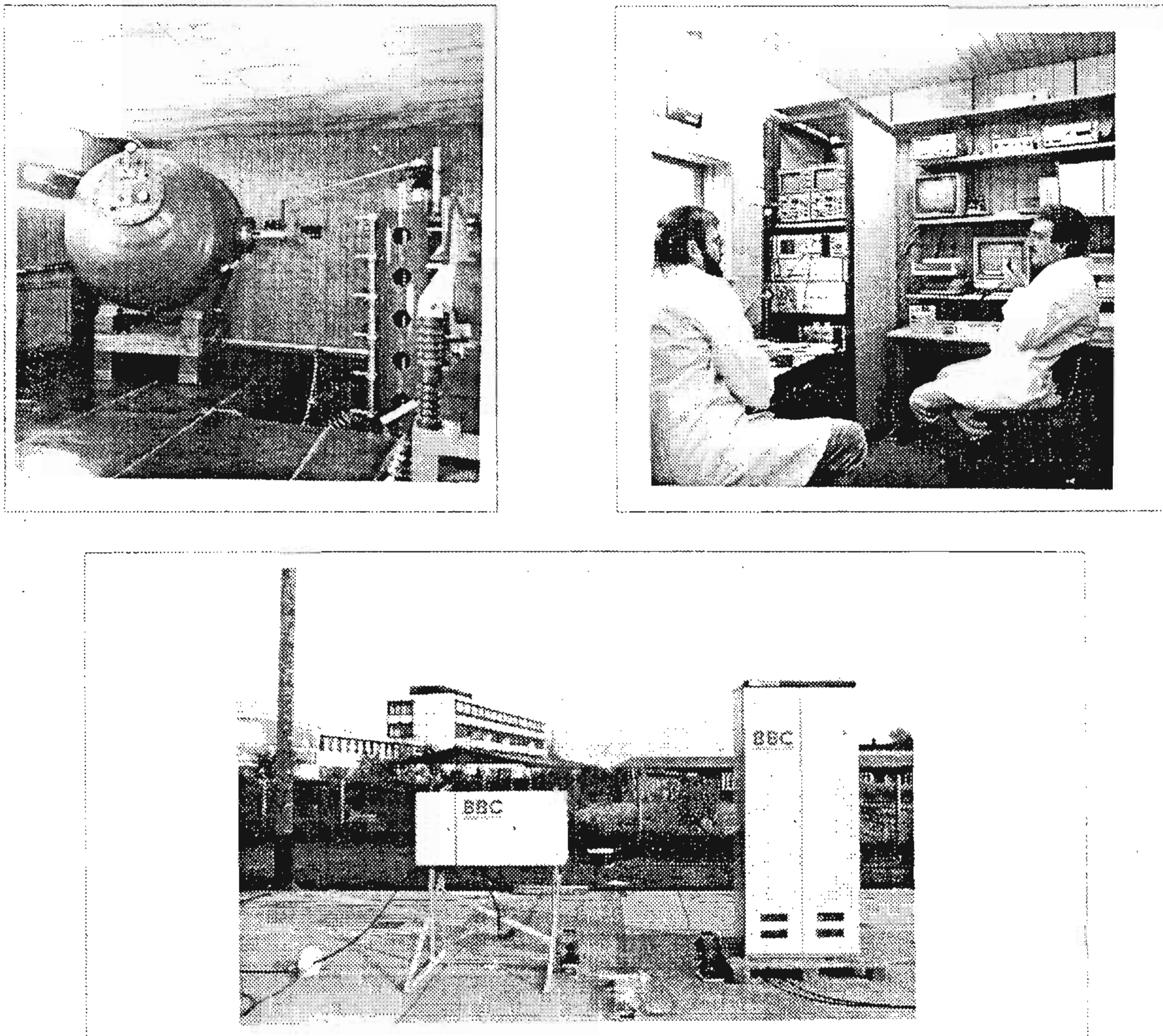
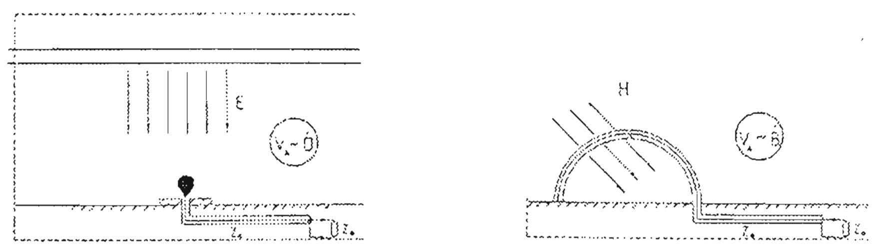


Fig. 14 View of MIGUS generator, data acquisition system and BBC-Control System under test



$$V_A = Z_0 \cdot \varepsilon_0 \, A_{eff} \, \frac{dE}{dt}$$

$$V_A = A_{eff} \cdot \mu_0 \, \frac{dH}{dt}$$

$\dot{D}$ - 12	$\dot{D}$ - 122	$\dot{B}$ - 4	$\dot{B}$ - 20
A_{eff} = 12,4 cm^2	A_{eff} = 122,6 cm^2	A_{eff} = 4 cm^2	A_{eff} = 20 cm^2
f_{gr} = 5 GHz	f_{gr} = 1 GHz	f_{gr} = 1 GHz	f_{gr} ~ 500 MHz
t_a = 0,12 ns	t_a = 0,35 ns	t_a = 0,35 ns	t_a = 0,7 ns
V_A = 548 mV $\frac{dE}{dt}\frac{ns}{kV/m}$	V_A = 5,43 V $\frac{dE}{dt}\frac{ns}{kV/m}$	V_A = 505 mV $\frac{dH}{dt}\frac{ns}{A/m}$	V_A = 2,5 V $\frac{dH}{dt}\frac{ns}{A/m}$

Fig. 15 Measurement principles: $\dot{D}$ probe for electrical field, $\dot{B}$ probe for magnetic field

A special rugged fiber optoelectrical, wide-band transmission link as shown in Fig. 16. has been developed by BBC for such extremely high requirements. The battery powered head amplifiers are calibrated, fully automatic and remotely controlled.

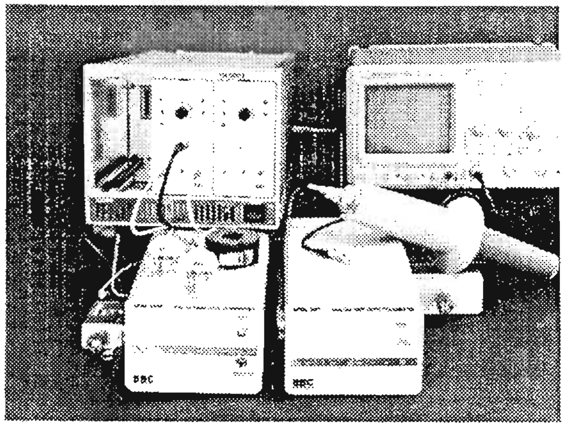


Fig. 16 Fiber optic link with probes

Comparison of a typical field intensity characteristic in the working volume measured with this system and the analogical comparison with a standard pulse are shown in Fig. 17. Relative close agreement between the present pulse shape and the test pulse in the time and frequency domain, defined recently by the VG standard (VG 96 901 T4 10/85), is demonstrated.

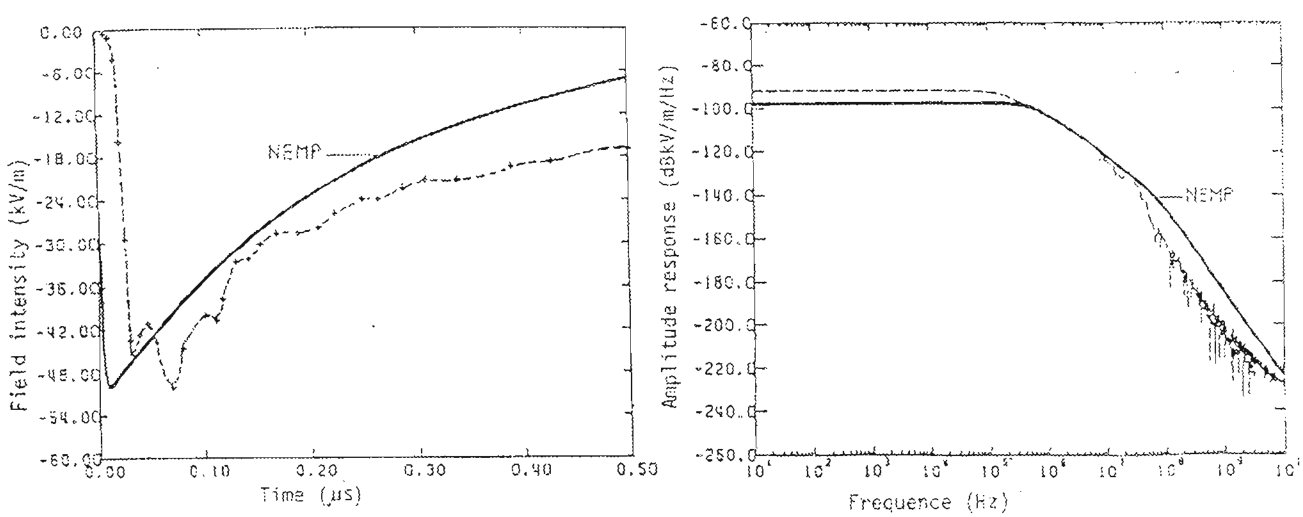


Fig. 17 Pulse shape and spectrum: Comparison MIGUS and standard NEMP

The shielding effectiveness of a small cabinet containing electronic equipment is measured by means of field sensors arranged inside and outside. Here, high-speed optoelectric data transmission is absolutely essential to prevent falsification of measured data, e.g. by cable resonances.

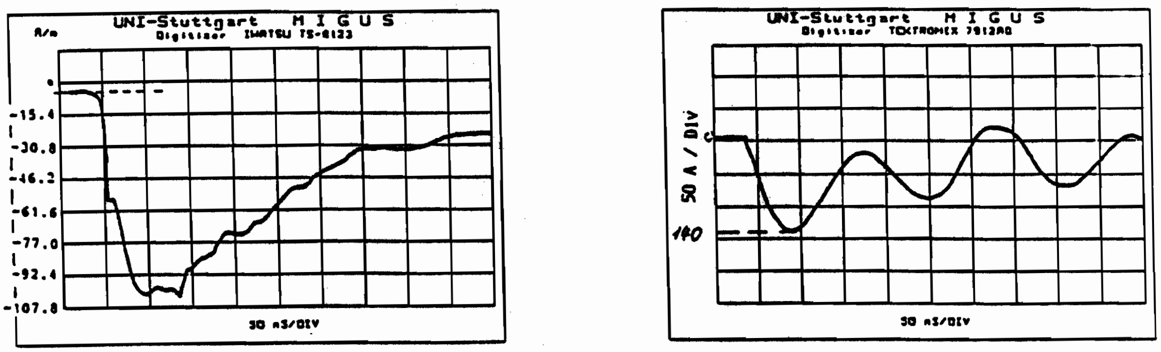


Fig. 18 Comparison H field characteristic (left) with induced sheath current (right) (remote bus cable)

Measured coupling values for a laid-out coaxial cable for digital data transmission in the test unit is shown in Fig. 18. The left picture shows the time characteristic of the magnetic field H measured near the cable, and in the right picture the associated induced cable sheath current I_m is given, showing the typically occurring oscillations. If the current I_i coupled in the inner conductor of the coaxial cable is also simultaneously determined, as shown in Fig. 19, the shielding effectiveness SE of various cables can also be determined. This simple theoretical estimate indicates quite good agreement with the measured value.

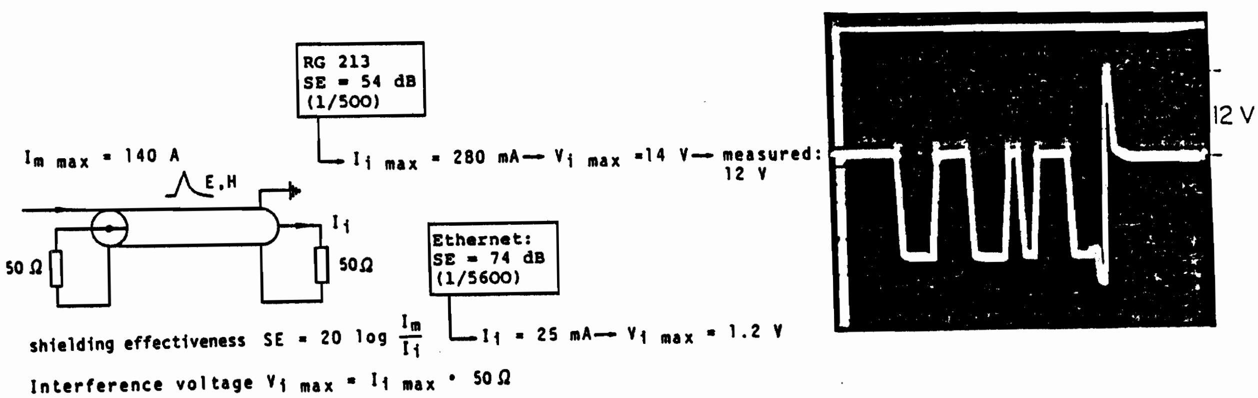


Fig. 19 Coupled interference signal on the inner conductor of a remote bus coaxial cable (sheath current coupling)

Current injection measurements in the laboratory can then be conducted in order to test the effects of the coupling values expected based on the theoretical threat assessment, but not achievable in this simulator on the system.

Induced voltage in loop:

$$\boxed{V_A = A \cdot \mu_0 \cdot \frac{dH}{dt}}$$

$A \approx 0{,}1\ m^2 \quad \mu_0 = 4\pi \quad 10^{-7}\ \frac{Vs}{Am}$

$\frac{dH}{dt}$ max. about $\frac{60\ A/m}{10\ ns}$ (field undamped)

$V_{A\ max} \approx 800\ V$

Measurement: magnetic field pulse damping about 30 dB

then $V_{A\ max} \approx 25\ V$

Measurement: $V\ max = 19\ V$

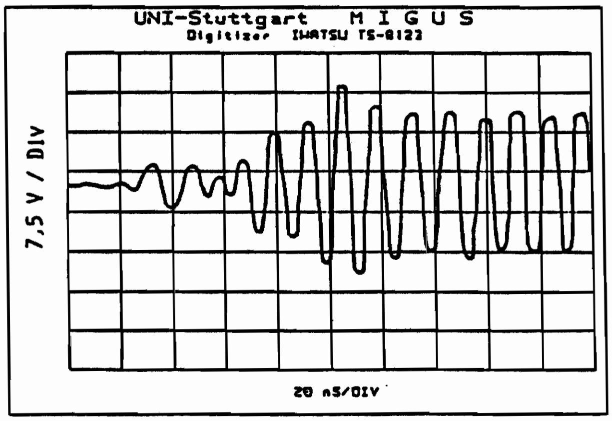


Fig. 20 Induced loop voltage in the cabinet (comparison theory/experiment)

As the last example on measurement technology the induced loop voltage determined in a partially open test cabinet at a certain point in the wiring is also cited. With the same theoretical simplification, as in the case of the magnetic field probe, coupling is done here with an area of 0.1 m^2 (Fig. 20) without cabinet damping 800 V. If 30 dB shield damping (partially open test cabinet) is assumed, a peak voltage value of 25 V is obtained; in magnitude this agrees well with the measured 19 V. This and similar measuring experience already gained at other locations then form the basis for the definition of typical limit values, e.g. in the preparation of standards and specifications.

5. NEMP standards

Existing standards and trends

In Switzerland guidelines of the Federal Civil Defense Office and of the Armaments Group have been in existence for some time. In the Federal Republic of Germany the defense standard (VG) for NEMP and lightning protection (Fig. 21) is in preparation.

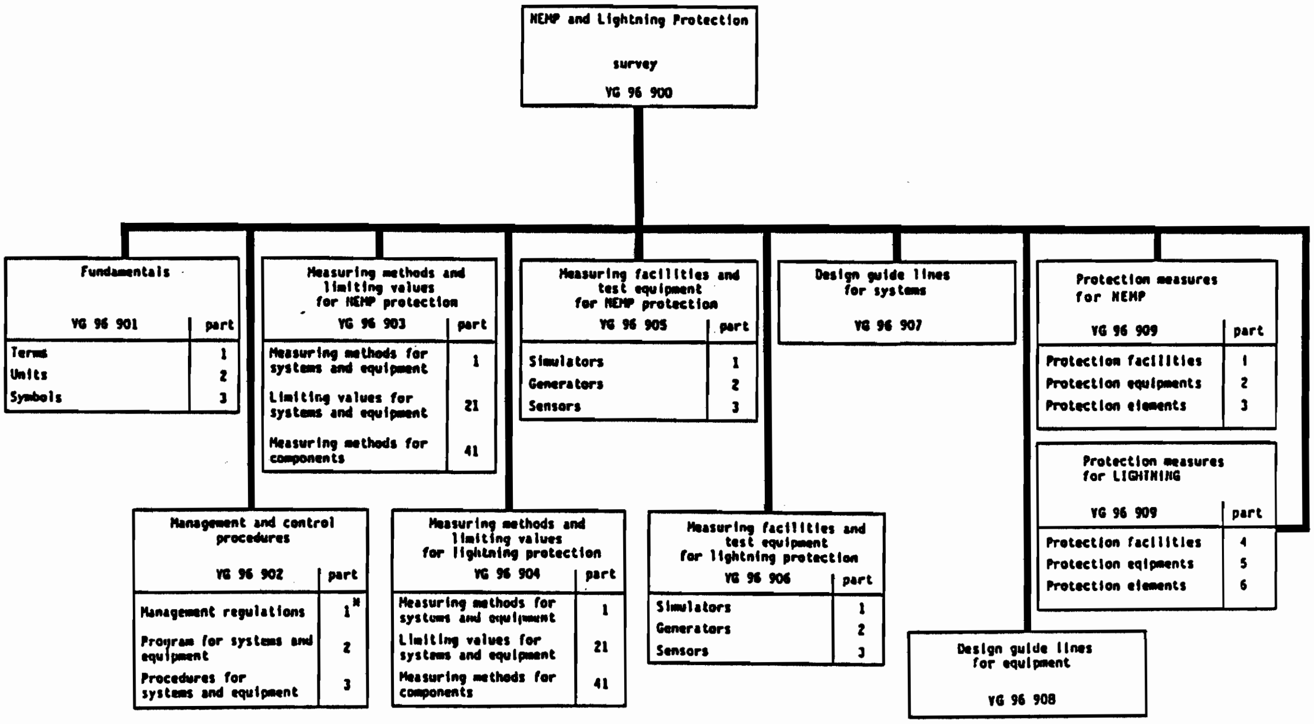


Fig. 21 German defense standard

*This standard is published
Status February 1982

In this context the concept of a theoretical threat assessment for the entire system to be performed at the beginning of the project is defined. In the committees and working groups of the DIN Standard Committee (NEA 760) representatives of industry and the federal authorities have been consulting since 1976. In addition to organizational procedures, limits, measurement methods, measuring equipment, protection equipment and guidelines are discussed and resolved. The current status of publications is as follows (source: Beuth Publishers, Cologne):

- VG 96 900 (March 1982): Protection against NEMP and lightning

- VG 96 901, part 4 (October 1985): Protection against NEMP and lightning, fundamentals, threat data

- VG 96 902, part 2 (beginning of 1986): Protection against NEMP and lightning, program for systems and equipment

- VG 96 907, part 1 (beginning of 1986): Protection against NEMP and lightning, design measures and protection equipment, general.

IN the USA the well-known EMC-Mil-Standard 461 B for equipment has been supplemented by the following EMP requirements:

- RS 05: Radiated susceptibility, field pulse

- CS 10: Conducted susceptibility, interface pin voltage/current.

The field pulse of an exoatmospheric NEMP detonation is given as a maximum amplitude value of 50 kV/m and a rise time (10 - 90%) of 5 ns. Equipment inputs and outputs must withstand up to 1,000 V and 10 A in function of the respective working frequency range of the unit. The current/voltage loading is assumed as having a damped sinusoidal waveshape. After 15 oscillations the voltage or current amplitude has dropped below 5% of its initial value. The oscillation therefore decays faster with increasing frequency. According to [16] the shape of the limit curve can be construed as a convolution of crosstalk transfer function and NEMP amplitude density spectrum.

6 Presentation of some NEMP-hardened electronic products of telecommunications technology

In addition to some military telecommunications devices (e.g. radio relay link R 902) BBC also supplies portable radio transceivers such as the Veriphone Comet (900 MHz) of exoatmospheric EMP-protected design. Local radio transmitters and civil defense shelter receivers have also been manufactured for some time. These units serve to ensure communications between command posts and shelters. With their typical cable configurations such as power and antenna the units have been successfully tested by the Spiez GRD-AC Laboratory, Working Group EMP. In the transmitter the protection against conducted interference in the power supply is achieved primarily by appropriate application of BBC ZnO surge arresters. The antenna input has a specially developed, coaxial filter circuit ($\lambda/4$ - quarter wave stub).

It is emphasized that NEMP protection measures need not necessarily be expensive. They are also not necessarily readily noticeable on an item of equipment. However, the requirements must be formulated by the user in his technical specifications for the equipment in order that they can be accounted for in the overall development. Retrofit measures to existing equipment are considerably more expensive to realize.

7. Summary, outlook

In the previous chapters I have attempted to show how the protection of equipment and electronic systems can be realized generally, and especially NEMP in a systematic and cost-conscious manner. In conclusion I would like to mention one aspect that is peculiar to this field. Despite the recent increasing NEMP activity in many European countries recently may I make the following remarks:

- As always, first-hand information (USA or France) is only difficult to obtain because it has a predominately military character. Always classified are the exact weapon data (NEMP generation), as well as the system data (effects of EMP on weapon systems or telecommunications systems). An exception is the current EMP study for the civilian US power grid [17].

- The realization of a stepped, low-cost protection against all types of electromagnetic threat such as EMI, ESD and/or lightning and NEMP corresponds to a trend that is also starting to manifest itself in the form of standards, but which at this time has been put into practice in only a few cases.

In the future designing a reliable protection system economically - by measurement and calculation - will surely pose even greater challenges for researchers and developers, especially in complex, expansive systems. In this work international cooperation is of great importance.

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