TECHNICAL REPORT

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First edition
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Electromagnetic compatibility (EMC) –

Part 1-5:
General –
High power electromagnetic (HPEM) effects on civil systems

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 1-5: General –
High power electromagnetic (HPEM) effects
on civil systems

FOREWORD

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IEC 61000-1-5, which is a technical report, has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility. This document has the status of a Basic EMC Publication in accordance with IEC Guide 107, *Electromagnetic compatibility – Guide to the drafting of electromagnetic compatibility publications*.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
77C/146/DTR	77C/152/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

IEC 61000 is published in separate parts according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts and published either as International Standards or as technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: 61000-6-1).

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 1-5: General – High power electromagnetic (HPEM) effects on civil systems

1 Scope

This part of IEC 61000 is a technical report that provides background material describing the motivation for developing IEC standards on the effects of high power electromagnetic (HPEM) fields, currents and voltages on civil systems. In the light of newly emerging transient antenna technology and the increasing use of digital electronics, the possibility of equipment being upset or damaged by these environments is of concern. This document begins with a general introduction to this subject and a listing of the pertinent definitions used. Following these clauses, the HPEM environments that are of concern are described and a discussion of the various effects that these environments can induce in civil systems is presented. Finally, techniques used to protect systems against these environments are summarised. More detailed information will be provided in separate documents in this 61000 series.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050-161, *International Electrotechnical Vocabulary (IEV) – Chapter 161: Electromagnetic compatibility*

IEC 61000-2-13, *Electromagnetic compatibility (EMC) – Part 2-13: Environment – High-power electromagnetic (HPEM) environments – Radiated and conducted* [1]

IEC 61000-4-4, *Electromagnetic compatibility (EMC) – Part 4-4: Testing and measurement techniques – Electrical fast transient/burst immunity test*

IEC 61000-4-5, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 5: Surge immunity test* [2]
Amendment 1 (2000)

IEC 61000-5-3, *Electromagnetic compatibility (EMC) – Part 5-3: Installation and mitigation guidelines – HEMP protection concepts*

IEC 61000-5-6, *Electromagnetic compatibility (EMC) – Part 5-6: Installation and mitigation guidelines – Mitigation of external EM influences*

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1 To be published.

2 A consolidated edition 1.1 exists comprising IEC 61000-4-5:1995 and its Amendment 1 (2000).

3 Terms and definitions

For the purposes of this document, the terms and definitions contained in IEC 60050-161, some of which are repeated here, and the following terms and definitions apply.

3.1
aperture
an opening in an electromagnetic barrier (shield) through which EM fields may penetrate

3.2
bandratio
br
ratio of the high and low frequencies between which there is 90 % of the energy; if the spectrum has a large d.c. content, the lower limit is nominally defined as 1 Hz

3.3
bandratio decades
brd
bandratio expressed in decades as: $brd = \log_{10}(br)$

3.4
broadband
(1) (of an emission) – an emission which has a bandwidth greater than that of a particular measuring apparatus or receiver

(IEV 161-06-11);

(2) (of a device) – a device whose bandwidth is such that it is able to accept and process all the spectral components of a particular emission

(IEV 161-06-12)

3.5
conducted susceptibility
susceptibility of a system to conducted signals on cables connected to the system

3.6
coupling
interaction of electromagnetic fields with a system to produce currents and voltages on system surfaces and cables

3.7
deliberate penetration
an intentional opening made in an electromagnetic (“EM”) shield that provides a path for the transmission of intended signals into or out of the shielded region. It can also be a consciously made opening for passing power, water, mechanical forces, or even personnel from the outside to the interior, or vice versa

3.8
disturbance
see electromagnetic disturbance

3.9
electromagnetic barrier (shield)
topologically closed surface made to prevent or limit EM fields and conducted transients from entering the enclosed space. The barrier consists of the shield surface and points-of-entry treatments, and it encloses the protected volume

3.10
electromagnetic disturbance
any electromagnetic phenomenon which may degrade the performance of a device, equipment or system

[IEV 161-01-05, modified]

3.11
electromagnetic interference
EMI
degradation of the performance of a device, transmission channel or system caused by an electromagnetic disturbance

NOTE Disturbance and interference are respectively cause and effect.

[IEV 161-01-06, modified].

3.12
electromagnetic stress
an electromagnetic stress is a voltage, current or electromagnetic field which acts on equipment. If the electromagnetic stress exceeds the vulnerability threshold of the equipment, mission-aborting damage or upset may occur. The stress may be described by characteristics such as peak amplitude, rise time, duration or impulse

3.13
electromagnetic susceptibility
inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance

NOTE Susceptibility is a lack of immunity.

[IEV 161-01-21].

3.14
environment
electromagnetic field arising from an external source that excites a system, possibly causing damage, upset or loss of function

3.15
failure level
specification of the amplitude (or other waveform attribute) of an electromagnetic field or induced current (or voltage) that, when applied to an electrical component or system, causes a failure in the device

3.16
high altitude electromagnetic pulse
HEMP
electromagnetic pulse produced by a nuclear explosion outside the earth's atmosphere

NOTE Typically above an altitude of 30 km.

3.17
high power electromagnetics
HPEM
the general area or technology involved in producing intense electromagnetic radiated fields or conducted voltages and currents which have the capability to damage or upset electronic systems. Generally these disturbances exceed those produced under normal conditions (e.g. 100 V/m and 100 V)

3.18
high power microwaves
HPM
subset of the HPEM environment, typically consisting of a narrowband signal having a pulsed peak power at the source in excess of 100 MW

NOTE This is a historical definition that depended on the strength of the source. The interest in this document is mainly on the EM field incident on an electronic system.

3.19
immunity (to a disturbance)
ability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance

[IEV 161-01-20]

3.20
immunity level
maximum level of a given electromagnetic disturbance incident on a particular device, equipment or system for which it remains capable of operating at a required degree of performance

[IEV 161-03-14]

3.21
inadvertent [EM] penetration
an opening, not deliberately made, that may provide a path for electromagnetic ("EM") energy through the EM shield. Most often inadvertent penetration is undesired. Typically, leakage through imperfectly conducting material is considered as an inadvertent penetration

3.22
intentional electromagnetic interference
IEMI
intentional malicious generation of electromagnetic energy introducing noise or signals into electric and electronic systems, thus disrupting, confusing or damaging these systems for terrorist or criminal purpose

3.23
interaction sequence diagram
ISD
graphical description of the paths that an external EM field is able to penetrate through one of more shields surrounding a system or equipment

3.24
narrowband
signal or a waveform with a *pbw* (defined in 3.27) of <1 % or a bandratio (defined in 3.2) <1.01

3.25
nuclear electromagnetic pulse
NEMP
all types of electromagnetic fields produced by a nuclear explosion

3.26
penetration
transfer of electromagnetic energy through an electromagnetic barrier from one volume to another. This can occur by field diffusion through the barrier, by field leakage through apertures, and by electrical current passing through conductors connecting the two volumes (wires, cables, conduits, pipes, ducts, etc.)

3.27
percentage bandwidth
pbw
bandwidth of a waveform, expressed as a percentage of the centre frequency of that waveform

NOTE *pbw* has a maximum value of 200 % when the centre frequency is the mean of the high and low frequencies; pbw does not apply to signals with a large d.c. content (ex: HEMP), for which the bandratio decades is used.

3.28
point/port-of-entry
PoE
physical location (point/port) on the electromagnetic barrier, where EM energy may enter or exit a topological volume, unless an adequate PoE protective device is provided

NOTE 1 A PoE is not limited to a geometrical point.

NOTE 2 PoEs are classified as aperture PoEs or conductor PoEs, according to the type of penetration. They are also classified as architectural, mechanical, structural or electrical PoEs, according to the functions they serve.

3.29
radiated susceptibility
susceptibility of a system to radiated electromagnetic fields

3.30
rebar
shortening of the words "reinforcing bar", which refers to the steel reinforcing rods located within poured concrete to enhance structural integrity

3.31
shielding
act of reducing the magnitude of an electric or magnetic field provided by a good electrical conductor such as sheet steel, reinforcing bars loops, conduit, etc. Also understood frequently as the enclosure that provides this reduction

3.32
short pulse
SP
a transient signal with a rise time and pulse duration measured in ps or ns

3.33
surge protection device
SPD
device to suppress line conducted overvoltages and currents, such as surge suppressors defined in IEC 61024-1

3.34
system
(1) collection of subsystems, assemblies and/or components that function together in a coherent way to accomplish a basic mission;

(2) collection of equipment, subsystems, skilled personnel, and techniques capable of performing or supporting a defined operational role. A complete system includes related facilities, equipment, subsystems, materials, services, and personnel required for its operation to the degree that it can be considered self sufficient within its operational or support environment.

3.35
topological control
maintaining of a closed electromagnetic shield around a system or equipment to reduce the internal EM field environment, and hence, to provide protection to the equipment

3.36
ultrawideband
UWB
signal or a waveform with a pbw value between 163,4 % and 200 % or a bandratio > 10 (also referred to as a hyperband signal)

4 General overview

Over the past 25 years, significant progress has been made in understanding and mitigating the effects of the high altitude electromagnetic pulse (HEMP) fields on electrical systems and equipment. Starting from early documents on the characteristics of HEMP [1], [2] and continuing through recent IEC committee work on developing standards for HEMP protection [3], there are clear-cut guidelines on protection methods and designs for protecting such systems [4]. Recently, such HEMP protection guidelines have been incorporated into the construction of military facilities [5, 6], and test facilities and procedures for the HEMP environments have been developed.

Recently other EM environments have been developed or postulated, including the ultrawideband (UWB) and short pulse (SP) environments [7] and the narrowband, high power microwave (HPM) environments, all of which have operating frequency spectra extending well beyond several GHz [8]. Such signals, together with conducted high-power currents and voltages, are collectively denoted as “high power electromagnetic” (HPEM) environments. Coupled with fact that modern electrical circuits and systems have used digital devices in their designs, it is now evident that we need to extend our present thinking of system protection concepts to include these new HPEM environments.

For analysing the effects of HEMP on systems, a well-developed analysis methodology has evolved. This involves the following steps: 1) definition of the system’s electromagnetic topology; 2) determination of the collectors of EM energy; 3) identification of the susceptible equipment “interface” location; 4) computation of the EM stress at the interface element(s); 5) determination of the failure levels at interface; and 6) a comparison of the stress/failure levels to estimate the system vulnerability. For modern systems subjected to HPEM excitation, a similar analysis methodology needs to be developed and tested. In particular, the following issues need to be addressed:

- modification of topological decomposition concepts to include high-frequency effects and distributed field excitations;
- extension of the EM interaction (e.g., coupling, penetration and propagation) models to the higher frequencies (faster rise times) of HPEM stresses;
- development of a better understanding of the behaviour of components and systems subjected to EM stresses, including failure mechanisms of individual components and upset, latch-up or failure of systems.

Similarly, test methods for HEMP are well established. However, these are not directly applicable for system-level testing of modern systems. Not only are there questions as to how to produce a “standard” and representative HPEM test environment, but also test procedures are lacking. A system can be in many different states, depending on its internal functioning, and its response to an external EM stimulus may depend on the “initial conditions” of the system. Moreover, in current HEMP testing, there is usually no control of the software features or changes made to the tested equipment, since only the hardware is considered of real importance. For such systems, its operating software is often changed and modified for testing, so that the real properties of the system may not be present the tested system.

Thus, we must develop a suitable test protocol for systems with rules for acceptable software flexibility.

4.1 Past experience with HPEM effects on systems

There have been several well-documented cases in the past where there have been unwanted effects on a system due to EM environments – sometimes with disastrous consequences. A report by NASA [9] examined many of these EMI events, and a few of these will be summarised here.

As has been noted in the past, damage to systems is not limited only to modern-day equipment, in 1967, the USS Forrestal was involved in perhaps the worst case of EMI ever recorded. According to [9],

> "In 1967 off the coast of Vietnam, a Navy jet landing on the aircraft carrier USS Forrestal experienced the uncommanded release of munitions that struck a fully armed and fuelled fighter on deck. The results were explosions, the deaths of 134 sailors, and severe damage to the carrier and aircraft. This accident was caused by the landing aircraft being illuminated by carrier-based radar, and the resulting EMI sent an unwanted signal to the weapons system. Investigations showed that degraded shield termination on the aircraft allowed the radar frequency to interfere with routine operations. As a result of this case, system level EMC requirements were revised to include special considerations for electro explosive devices."

Problems with the flight control system on the F-16 fighter were reported:

> "An F-16 fighter jet crashed in the vicinity of a Voice of America (VOA) radio transmitter because its fly-by-wire flight control system was susceptible to the HIRF transmitted. Since the F-16 is inherently unstable, the pilot must rely on the flight computer to fly the aircraft. Subsequently, many of the F-16's were modified to prevent this type EMI, caused by inadequate military specifications on that particular electronics system. This F-16 case history was one of the drivers for institution by the Federal Aviation Administration (FAA) of the HIRF certification program."

A more recent occurrence involved a UH-60 Blackhawk helicopter being affected by nearby radio transmitters:

> "An Army Sikorsky UH-6O Blackhawk helicopter, while flying past a radio broadcast tower in West Germany in 1987, experienced an uncommanded stabiliser movement. Spurious warning light indications and false cockpit warnings were also reported. Subsequent investigation and testing showed that the stabiliser system was affected by EMI from high intensity radiated fields (HIRF). The Blackhawk has a conventional mechanically linked flight control system with hydraulic assist. The stabiliser system, however, uses transmitted digital signals (fly-by-wire) to automatically adjust its position relative to control and flight parameters. These digital signals are highly susceptible to HIRF. When the Blackhawk was initially designed, the Army did not routinely fly near large RF emitters. The Navy version of the Blackhawk, the SB-60 Seahawk, however, has not experienced similar EMI problems because it is hardened against the severe EME aboard modern ships. Despite the Army identifying several hundred worldwide emitters that could cause problems and instructing its pilots to observe proper clearance distances, between 1981 and 1987 five Blackhawk helicopters crashed and killed or injured all on board. In each crash, the helicopter flew too near radio transmitters. The long-term solution was to increase shielding of sensitive electronics and provide as a backup some automatic control resets."

Such occurrences of EMI are not limited to the military, as evidenced in the following case involving an automobile:

> "During the early years of the antilock braking system (ABS), automobiles equipped with ABS had severe braking problems along a certain stretch of the German autobahn. The brakes where affected by a near-by radio transmitter as drivers applied them on the curved section of highway. The near-term solution was to erect a mesh screen along the roadway to attenuate the EMI. This enabled the brakes to function properly when drivers applied them."

The medical care sector also has been affected by EMI, as noted in the following account:

> "Susceptibility of medical equipment to conducted or radiated emission is a concern (in an ambulance heart monitor/defibrillator unit.) In this case, a 93-year-old heart attack victim was being taken to the hospital and the medical technician had attached a monitor/defibrillator to the patient. Because the machine shut down every time the technicians turned on the radio transmitter to request medical advice, the patient died. An investigation showed that the monitor/defibrillator was exposed to exceptionally high radiated emissions because the ambulance roof had been changed from metal to fibreglass and fitted with a long-range radio antenna. Reduced shielding combined with the strong radiated radio signal resulted in EMI to the vital machine."

These instances of HPEM fields affecting electrical systems were inadvertent consequences of a poor system design, abnormally large EM fields, or both. It is possible, however, to envision the use of HPEM sources to deliberately cause upset or damage in a system. Such an occurrence could occur in a military setting, where the HPEM environment could be directed towards an enemy missile, aircraft, or other system containing susceptible electronics. Similarly, this attack concept could be used by hackers, terrorists or similar organizations against civil systems in what has been referred to as "EM terrorism" [10], [11] or more recently Intentional Electromagnetic Interference (IEMI).

Such possibilities have been the subject of technical sessions in recent scientific symposia [12], [13], [14], and [15], and continue to be discussed in the popular press [16], [17]. Although there are several unconfirmed accounts of instances where such (EM) weapons have been used against civil and military systems [18], [19], obtaining clear, convincing and documented evidence as to this HPEM environment remains elusive.

Notwithstanding the lack of indisputable proof linking the use of such HPEM sources to attack civil facilities, several governments continue with research programs into the assessment of the possible effects of HPEM environments on their systems and infrastructure. For example, there has been one effort in Sweden [20]. Also, the possibility of using radio frequency (RF) weapons was recently described [21] to the U.S. Congress.

For further information concerning the intentional use of HPEM environments, the reader is invited to consult the special issue of the IEEE Transactions on Electromagnetic Compatibility covering Intentional EMI (IEMI) [50].

4.2 General EM protection techniques as applied to civil systems

Significant work has been conducted in developing protection concepts for both military and civil systems against the nuclear high-altitude electromagnetic pulse (HEMP) environment [22]. Protection measures include global shielding (e.g., system topological control [23]), installation of filters and surge protection on incoming power or signal lines [24], and the protection of individual pieces of equipment that may be especially sensitive to the HEMP environments [25], [26].

Much of this past HEMP work is directly applicable to the protection of electrical systems and facilities against the higher frequency HPEM environments. As in the HEMP case, the most significant coupling paths for an external HPEM stress are the long lines entering into the facility. However, because of the higher frequency content in the HPEM environment, the induced signals in these lines typically exhibit a larger attenuation with distance than does the HEMP-induced signal. Thus, in some cases, the requirements placed on protection elements for the HPEM signals on "deliberate" EM penetrations into the facility may not be as strict as for HEMP.

For the HPEM environment, there are other penetrations that are of concern, however. These are the so-called "inadvertent" penetrations[3)], which occur through EM field penetration through imperfections in the system shield. Typically, as the frequency of the external EM environment increases, the penetration efficiency of the fields also increases through these inadvertent (and undesired) paths, and the system interior can be excited more strongly. Improving the global (topological) shielding of the system under consideration will help to mitigate this problem.

Because many of the electronic systems of interest are digital, there is an additional dimension to the HPEM field interaction phenomenon. Because the HPEM environment can be repetitive, such a periodic pulsing of the electrical stress on the system can interfere with the clock cycles in digital circuitry. Thus, there may be system upset at certain critical pulse rates – even though the EM field intensity is below the threshold for permanent component damage. This suggests that an additional EM protection concept is the careful design of the digital electronics to be impervious to such periodic disruptions. Such an approach is commonly called "circumvention" in the HEMP community.

Further details and specifications of recommended HPEM protection concepts and their realisations will be forthcoming in future standards in this 61000 series.

5 Classification of HPEM environments

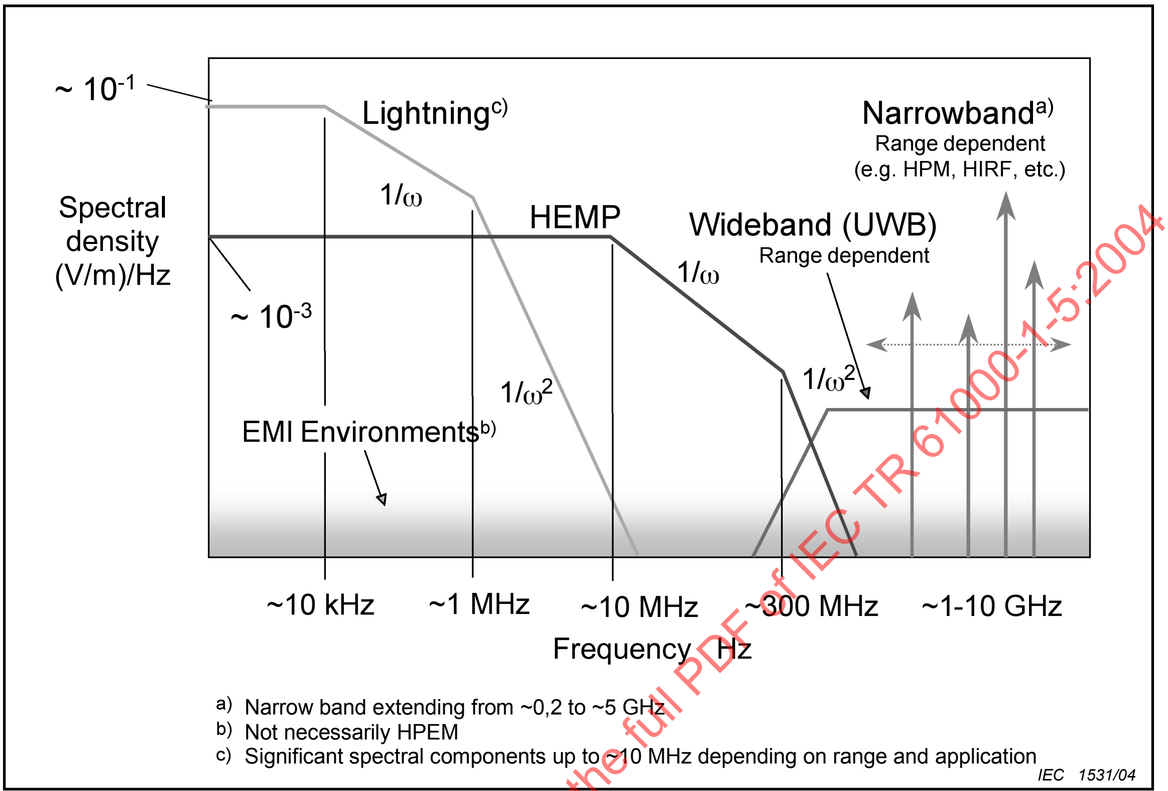
HPEM is a term used to refer to a man-made electromagnetic environment that can adversely affect the operation of electrical systems. It can occur in the form of a pulsed waveform of microwave energy, and in this form, it is often referred to as high power microwave (HPM) signal. Alternatively, this excitation can also occur in the form of a broadband pulse of EM energy, commonly referred to as an ultrawideband (UWB) pulse. Typically, this HPEM energy arrives at the system in the form of an incident electromagnetic field.

One way to illustrate the difference between the HPM and UWB environments is to examine their frequency domain spectra, as shown qualitatively in Figure 1. This figure illustrates the magnitude of the spectral density for typical lightning and the high altitude electromagnetic pulse (HEMP), together with HPM and UWB short pulse (SP) signals. Note that the both the UWB and HPM environments are significant for frequencies greater than about 300 MHz. The broadband nature of the UWB environment is evident, and the HPM spectra are seen to resemble nearly single frequency signals. It should be noted that the UWB frequency content will often decrease above 3 - 5 GHz and the narrowband "arrows" in Figure 1 are intended to indicate large values.

Also shown in this figure is a low-level continuum of signals denoted as "EMI environments", which represents the ambient level of electromagnetic noise environment due to the operation of nearby electrical equipment or distant EM emitters, and which may cause EMI in equipment.

3) The terms "front-door" and "back-door" penetrations are often used to describe how HPEM energy is able to penetrate into a system. These are non-technical descriptive terms, and for this IEC document we chose to define the HPEM penetration mechanisms as "deliberate" and "inadvertent", respectively, since these latter terms more adequately characterize the reason for the external HPEM energy being able to penetrate into the system.

Electrical systems are generally protected against some level of interference to achieve EMC according to the applicable standard. However in most cases HPEM environment levels are considerably higher than typical civil protection levels.



Note that both scales are logarithmic.

Figure 1 – Illustration of the spectral content of HPM and UWB signals, together with other EM signals [8]

The production, radiation, coupling and damage/upset possibilities of each of these EM environments can be very different; however, their effects on electrical systems can be the same – upset or physical damage of the system.

Depending on its design, a high power microwave source typically produces a waveform that appears like a gated sinusoidal signal [27] as in Figure 2. Frequencies between 0,2 GHz – 5 GHz are typical, with pulse durations lasting up to several microseconds. Other important features of this type of signal, and its effects on systems, are as follows.

- Waveform pulses can be repetitive; pulse frequency can vary with time and be modulated.
  - Maximum coupling occurs if tuned to significant resonance in the system's transfer function.
  - A hundred cycles or so are necessary to ring up resonance.
  - Likely to cause interference through the inadvertent coupling and penetration paths, and even permanent damage through the deliberate penetration paths.
- Many illuminated systems have significant resonance susceptibilities at particular frequencies.
  - This suggests the possibility of "tuning" a source for causing a particular effect on a system.

- Sources for this EM environment are typically radar or microwave oven tubes, relativistic magnetrons, vircators or super-reltrons.

The fast transient UWB pulse excitation is different, in that it produces frequency and energy content over a wide range of frequencies, and in this regard it is similar to that of HEMP. Salient features are as follows.

- Rise time typically on the order of 100 ps and the pulse width on the order of 1 ns.
  - The major frequency content and power is spread over a very broad spectrum, approximately within the 0,2 GHz – 5 GHz frequency range.
- Pulses can be repetitive.
  - Resonances of different systems can be stimulated simultaneously.
  - However, energy produced in a single pulse is spread over many frequencies.
  - Thus power density is lower than for than the high power microwave sources
- More likely to cause interference from the inadvertent coupling paths than permanent damage.

To better understand the effects on systems, one can conduct an analysis or perform an experiment on the system of interest. This requires, among other things, a specification of the HPEM environment that excites the system. Important aspects of these environments are discussed further in 5.1.

5.1 Radiated and conducted HPEM environments

As discussed [3], the transient HEMP stress on a system can be divided into a *radiated* EM field component, and a *conducted* current component. The same partitioning can be done for the HPEM environments. The radiated environment will be specified by an electric (or possibly magnetic) field strength, together with information about the waveform characteristics of the field and the polarisation, angle of incidence, spatial extent and illumination location of the system. This radiated environment is specified at the system exterior as an incident HPEM field.

The conducted environment is generally in the form of a current waveform or spectrum on one or more electrical conductors in the system of concern. Usually, this specification is at a penetration point in the system, where a conductor having an externally produced current is able to penetrate the system envelope and inject the current into the interior.

5.2 Narrowband (CW) waveform

Narrowband radiated and/or conducted HPM environments are usually represented in the time domain by a modulated sinusoid waveform. One such waveform is the Gaussian modulated sine wave, which is given by the following analytical expression:

$$g(t) = A_o \cos(2\pi f_o (t - t_s))\, e^{-\left(\frac{2(t-t_s)}{\alpha}\right)^2} \qquad (1)$$

This waveform, *g(t)*, is defined by the following parameters:

A_o = peak value of transient E-field (in appropriate units)

f_o = frequency of carrier signal (in Hz)

t_o = period of the carrier signal (in s), and is equal to 1/ f_o

t_s = arbitrary time shift of the waveform (in s)

α = effective width of the Gaussian pulse from 1/e points (in s)

Many different envelope shapes of this waveform are found in practice, depending on the type of source producing the radiated fields and the location in the system where the waveform is observed. As an example, Figure 2a illustrates an amplitude-normalised waveform for the Gaussian width parameter $\alpha = 10t_o$ and a time shift $t_s = 2\alpha$, plotted as a function of normalised time t/t_o.

The modulated sinusoidal waveform of Figure 2a is inherently narrowband. The spectral magnitude for the waveform is illustrated in Figure 2b. This waveform is a simple example of this type of HPEM environment. Additional detailed information about this HPEM environment and the expected amplitude, centre frequency, etc., is provided in IEC 61000-2-13 [28].

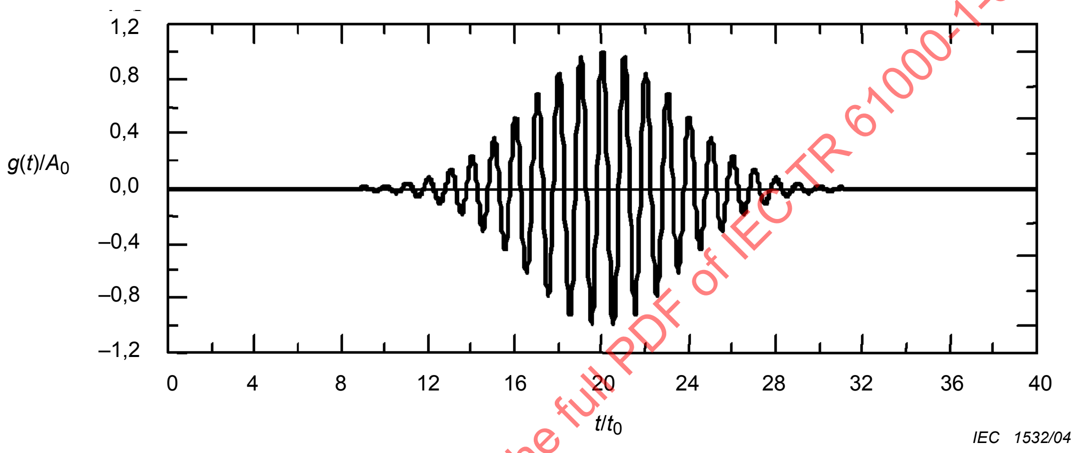


Figure 2a – Transient waveform

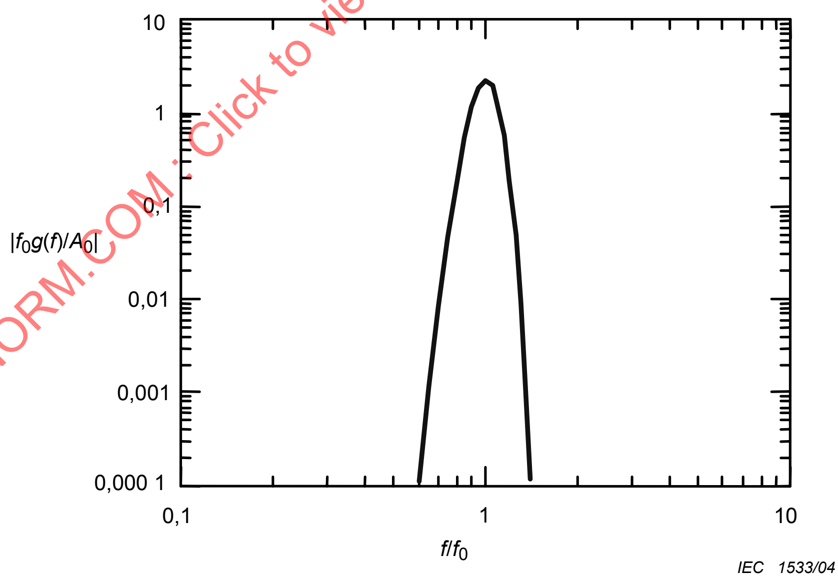


Figure 2b – Spectral magnitude

Figure 2a illustrates the transient waveform, and Figure 2b the normalised spectral magnitude.

Figure 2 – Plot of a normalised Gaussian modulated sine wave, serving as a simple representation of a narrowband HPEM waveform

5.3 Ultrawideband/short pulse transient environment

Another possible HPEM excitation is in the form of an ultrawideband (or short-pulse) transient signal, as shown in Figure 3. Unlike the narrowband HPM excitation, this waveform appears more like a bi-polar pulse, and as a consequence, its spectral representation contains contributions over a very wide band of frequencies.

As discussed in 61000-2-13, there are several simple analytical expressions that can be used to represent such wideband waveforms[4]. These include a Gaussian pulse and the double exponential transient that is often used to model the fields from a high altitude nuclear detonation. This latter waveform is discussed further in an IEC standard [25].

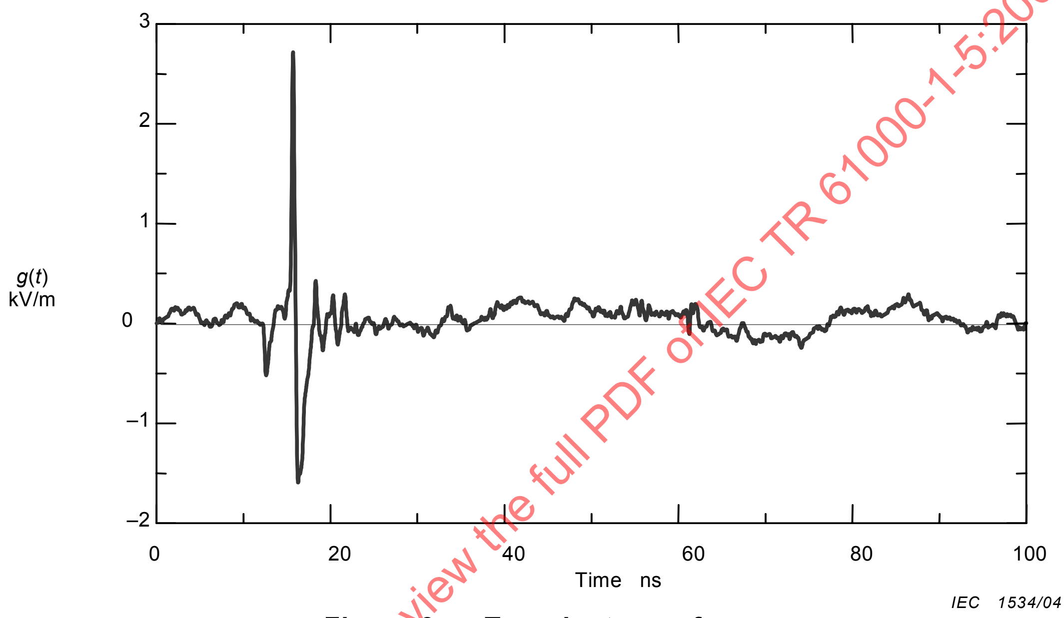


Figure 3a – Transient waveform

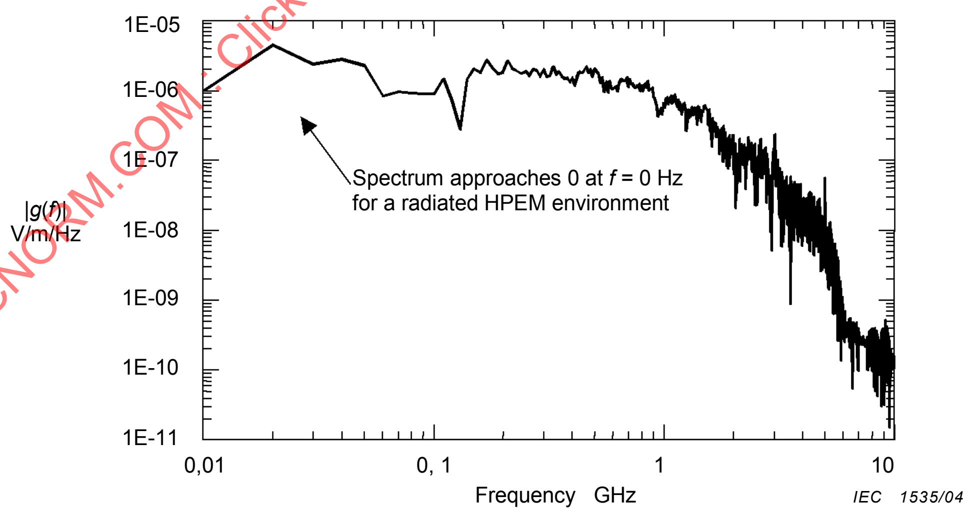


Figure 3b – Spectral magnitude

Figure 3 – Illustration of a wideband transient HPEM waveform together with its spectral magnitude

4) For radiated HPEM fields of this type, there is a requirement that there be no dc component in the spectrum. This implies that the integrated area under the waveform shown in Figure 3a) or any analytically constructed waveform representing this environment must be zero.

5.4 Repetitive excitations

The preceding discussion has assumed that the HPEM waveform is a single waveform event – either a modulated sinusoidal waveform or a single broadband pulse. It is possible, however, to envision a periodic replication of the waveform, in the form of a pulse train, as shown in Figure 4a. In this figure, the waveform of Figure 2a with fundamental time period t_o, is repeated periodically, with an assumed period $T_p = 40t_o$.

This type of waveform will provide more energy to an illuminated system, and since it has been shown that upset effects are a strong function of the signal repetition rate (from between 100 Hz to 1 000 Hz), this type of HPEM environment can pose serious problems for systems. Due to the repetitive nature of the signal, the Fourier spectrum of the waveform is also different. Figure 4b illustrates the Fourier spectral magnitude for the pulse train, and it is seen that the continuous spectrum of the single waveform pulse of Figure 2b is now converted into a discrete spectrum, with spectral components occurring at a normalised frequency interval of $\Delta f = 0{,}025\ f_o$. If the pulse train itself is not of infinite duration, then the individual impulse functions in the spectrum also become discrete functions of frequency.

It is clear that there can be many different parameters entering into the definition of the HPEM waveform. Further detailed specifications of these environments are provided in IEC 61000-2-13.

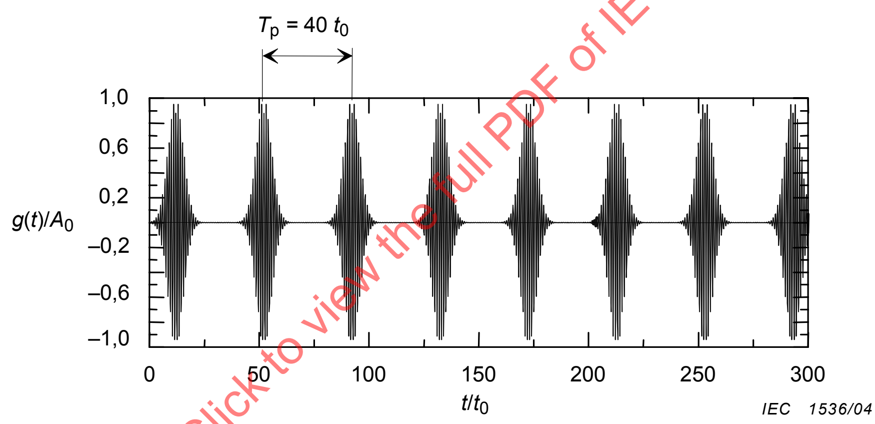


Figure 4a – Transient waveform

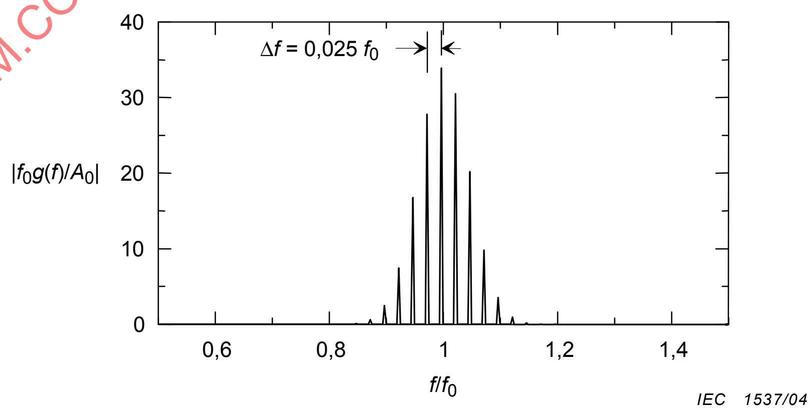


Figure 4b – Spectral magnitude

Figure 4 – Illustration of a repetitive waveform of pulses similar to that of Figure 2

6 HPEM effects on systems

As in other areas of EMC technology, the effects of HPEM on a system can be categorised into radiated susceptibility and conducted susceptibility.

For radiated susceptibility, externally produced HPEM fields propagate through air and will couple directly to outside cables and antennas attached to a piece of equipment. Fields will also propagate through apertures to enclosures and couple inside where damage or upset to system operations will occur.

Electrical disturbances also can be injected directly (galvanic), capacitively, or inductively onto power, telecommunication and signal cables. These disturbances can propagate until they reach equipment connected to the cables. One should note that cable and wire transfer functions may limit the propagation of high frequency content. For example, electrical wiring inside of a building significantly attenuates disturbances above several megahertz. Other cables (e.g., category 5 cables) are designed to operate at much higher frequencies (~1 GHz).

In this clause, we will examine in more detail these mechanisms of system excitation, how the system can be represented using the concepts of electromagnetic topology, and the various effects that these HPEM stresses can have on electrical subsystems and components.

6.1 Topological representation of the system

A key aspect in estimating the effects of HPEM fields on a complex system is understanding how to incorporate the excitation in the analysis and how to represent the electromagnetic interactions among the various constituents of the system. Characterising the various barriers within the facility, together with the possible paths that the EM energy can take, results in a description of the *electromagnetic topology* of the system. Such a concept has been discussed in IEC 61000-5-6. This approach involves viewing the system as a collection of EM barriers (or shields) that impede, to a certain degree, or facilitate the passage of HPEM energy from point to point. The sources of the HPEM fields can be outside the system, as in the case of lightning, radio frequency interference, or HEMP.

No practical EM barrier is perfectly closed, and as a consequence, there will be several openings through which energy can pass. The EM field strength inside an arbitrary enclosure will be lower than the external field, due to the attenuation of the conducting walls and to the tenuous path through which a signal must travel. However this attenuation is finite because there may be openings (apertures) in the shield, and the imperfectly conducting shield material may permit EM fields to diffuse through walls.

As an example, Figure 5 shows a simple drawing of a shielded facility excited by an external electromagnetic field. Clearly, there will be EM field penetrations at discrete locations in the EM barrier, such as at the door gasket, at the access panel, at air vent apertures, and at the seams and cracks in the shield. Furthermore, the incoming power line, insulated from the shield wall, provides a path through which energy from the outside environment may pass to the internal regions of the facility.

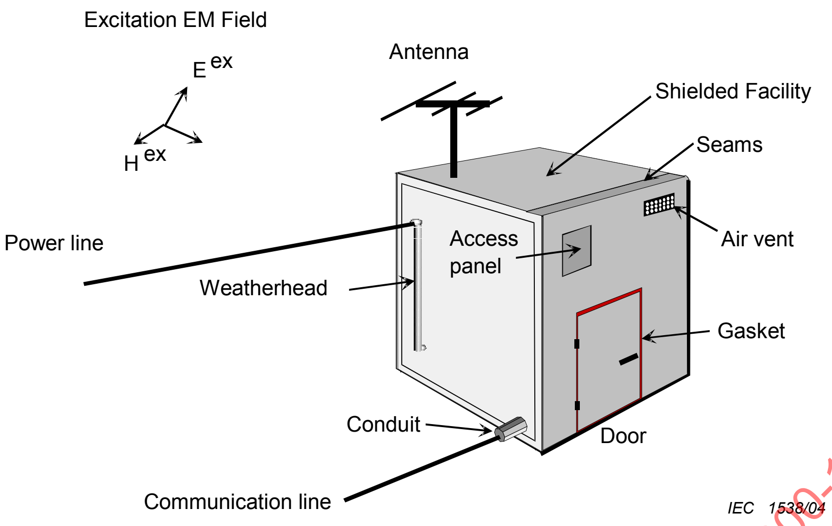


Figure 5 – Simplified illustration of a hypothetical facility excited by an external electromagnetic field

The above discussion has been made in the context of a shielded facility. Of course, not all facilities are well shielded: in fact in some cases like an ordinary house, business establishment, or automobile there may be no attempt to provide EM shielding in the "system." Nevertheless, there can be fortuitous shielding in the form of rebar or steel beams in building construction and in the form of the metal skin of an automobile, etc. Furthermore, in many parts of the world, lightning protection for incoming power or signal lines may be encountered. In all such cases and in many others, the EM topological concept is a useful tool in defining regions of "protection" in which the induced EM stress is less than that outside the facility.

The use of the EM topological concept is straightforward. The system is regarded as a collection of one or more EM barriers or surfaces, as shown in Figure 6. The interconnections of these surfaces and all penetration points for EM energy are identified and categorised. Conducting penetrations are the most serious, e.g., insulated power supply wires through a hole in a conducting wall, as they usually produce the largest internal responses within the system. Aperture penetrations are next in importance, with the diffusive penetrations usually being of least importance. There are other entry mechanisms such as through (usually, out of band) antennas and other devices, which must couple to the outside environment.

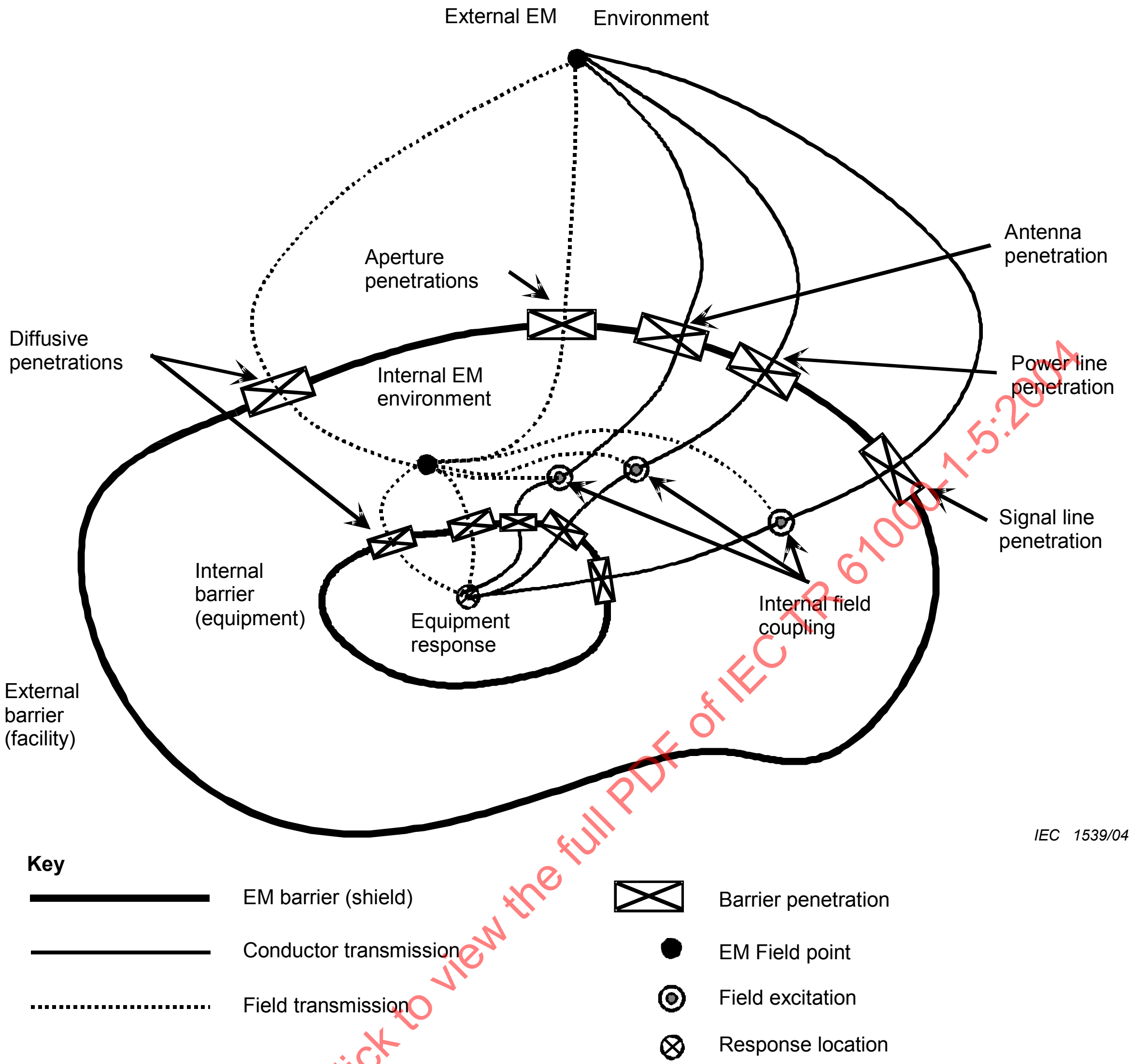


Figure 6 – The topological diagram for the simple system shown in Figure 5

The overall effect that an externally generated HPEM environment can have on a system is determined by the interaction sequence diagram. This diagram illustrates the various aspects of the EM signal production, propagation, interaction and response on the system. For the hypothetical system shown in Figure 5, this diagram is presented in a very elementary form in Figure 7.

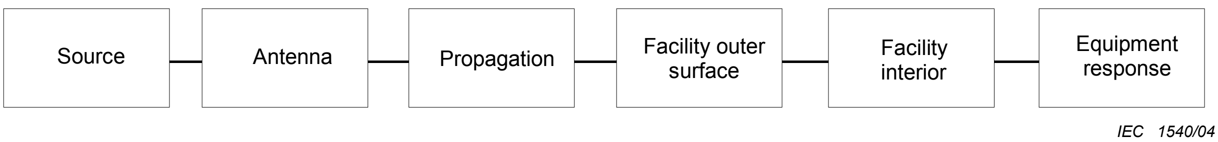


Figure 7 – General interaction sequence diagram for the facility of Figure 5

6.2 Examples of HPEM effects on electronic systems and components

While the conceptual representation of a system by its topological model assists in understanding how the HPEM field can enter into a system and affect its internal electrical components, it is difficult to use this tool for the accurate prediction of upset or damage. This is due to the large uncertainty in the details of the coupling, penetration and propagation mechanisms, and to the uncertainties as to how the electrical components will respond to the electrical stress. The benefit of this topological modelling, however, is that it allows one to design and conduct appropriate experiments to evaluate system responses to the HPEM stresses.

While the results of many HPEM test programs are closely held and not released to the public, there have been several test results that have been released. LoVetri, *et al.* [29] describe both FDTD calculations and measurements aimed at analysing the penetration and coupling of electromagnetic energy into a typical personal computer (PC) cabinet. Various configurations were investigated: exposed motherboard; case-cover off, and case-cover on. The purpose of these investigations is to better understand the coupling mechanisms associated with the HPEM environment.

The interesting experimental results, which were reported in this reference, are as follows:

a) disruption of the computer occurred only at specific repeatable frequencies;

b) this same disruption occurred only for specific polarisations of the incoming electro-magnetic plane-wave; and

c) disruption always occurred in the form of a "hard" fault, *i.e.* the computer had to be rebooted in order to regain operation.

The polarisation and frequency dependencies of the coupling phenomenon were also studied by LoVetri, using a finite difference time-domain (FDTD) model.

The experiments of HPEM coupling to PCs were done in an anechoic chamber, where the PC was illuminated by a horn antenna from a distance of 1 m at an approximate level of 100 V/m. Three different PCs were tested at varying frequencies, field strengths and modulation of the carrier. The experimental results are shown in Table 1.

Table 1 – Description of PCs tested, the environment and effects (after LoVetri [29])

PC type	Carrier frequency GHz	E- field V/m	Modulation	Observed effects
133 MHz Pentium	2,713	30	CW	Loss of data
	2,770	50	AM	Loss of data
	1,133	50	AM, Pulse	Reset
	2,675	50,75	AM, Pulse	Loss of access
	2,887	75	AM	Loss of access
233 MHz	1,070	100	Pulse	Disk write error
Pentium II	1,460	100	CW, AM, Pulse	Power down
	1,480	100	CW	Power down
300 MHz	1,040	45	Pulse	Power down
Pentium II	1,400	100	CW	Power down
		100	AM	Power down
		100	AM	Reset
		75	Pulse	Power down
		75	Pulse	Power down
		50	Pulse	Power down
		85	Pulse	Power down
AM: amplitude modulation.				

In the measurements of Table 1, it is seen that the type of modulation (CW, AM 80 % 1 kHz, pulse with a repetition frequency of 217 Hz and 50 % duty cycle) is also a crucial parameter in terms of observed effects. All three modulations produced adverse effects on the PC. The observed effects range from loss of data, reset (where the PC reboots itself), and disc write error (message from the disk operating system, where manual power down is required to restore the system) to power down, which requires unplugging and plugging of the power cord. The smallest electric field that produced an adverse effect is seen to be 30 V/m. Such effects data is very useful in understanding the EM coupling phenomena in electronic systems.

It is important to note in passing, that newer equipment appears to be better designed, and as a consequence, typical upset levels for HPEM environments are on the order of 10's to 100's of V/m. This may be due to the higher processor speeds found in newer equipment and the need for these devices to adhere to various EMC requirements for radiated emissions lead to better shielding of the equipment.

In a second example relating to HPEM susceptibility testing of automobiles PCs and unshielded military equipment using radar pulses (typically one or a few microsecond pulse length and pulse repetition frequencies around 1 kHz) at 1 GHz – 3 GHz, Bäckström [30] reported upset (requiring a reboot or restart of a car) occurred at field strengths of a few 100 V/m (RMS peak field strength), while permanent damage required 20 – 30 dB higher levels.

From his results, it was concluded that upset could be caused in unprotected electronic systems from a maximum distance of around 500 m for a HPM source that can be located in a van. For a source of a smaller size, such that it can be located in a suitcase, the estimated distance decreases to 50 m. The maximum distance for causing permanent physical damage was estimated to be around 15 m for the HPM van, while the suitcase had to be placed very close to, or even in direct contact with the system. Table 2 summarises the results from this testing.

Table 2 – HPEM effects on an automobile as a function of range and source power (Based on measured data from Bäckström [30])

Source	Distance m		
	15	**50**	**500**
HPM Van *P* = 10 MW	Permanent damage	Upset [b]	Upset**)
HPM Suitcase [a] *P* = 100 kW	Upset**)	Upset [b]	No effect
HPM Van *SE* = 30 dB	Upset**)	No effect	No effect
HPM *Suitcase* SE = 30 dB	No effect	No effect	No effect

[a] May cause permanent damage very close to the victim (e.g. at a few metres).

[b] Upset generally refers to a temporary loss of function, however, in some cases it is possible that there will also be permanent damage.

A third example of HPEM coupling is that of a CW illumination of many electronic devices, at the microwave oven frequency of 2,4 GHz, as reported by Giri and Kaelin [8]. In this test, a standard pyramidal horn was used to radiate energy produced by a commercial microwave oven and to illuminate a number of test articles. The test articles were located at a distance of 6 m from the source, and the incident E-field was on the order of 350 V/m. Such a test demonstrates what could be accomplished using readily available commercial equipment.

The objects that were exposed to these fields included:

- AM, FM radios;
- plastic-cased wrist watches;
- small electro-explosive devices;
- hand held calculators;
- absorbing material;
- fluorescent lamps.

The observed effects were

a) radio showed thermal damage;
b) plastic watch was totally damaged;
c) EED exploded when the leads were made into a half-wave dipole;
d) calculator damaged, LCD display burnt;
e) absorber material, temperature rise;
f) fluorescent lamp lit.

It is seen from these examples, that the coupling of EM energy into electronic systems is a strong function of several parameters of the incident environment as well as the specific features of the electronic system itself.

6.3 Component/subsystem burnout and permanent damage

The HPEM effects described in 6.2 can be seen to result in either burnout (permanent damage) in the equipment, or a disruption of device functioning due to logic upset. Typically, device burnout is the easiest effect to quantify, using various waveform norms to characterise the excitation to a device or component, and correlate these norms to device failure (See IEC 61000-5-3). For example, typical norms include the peak amplitude of an applied signal to a component, the total energy delivered to the component, etc.

Since 1970, a significant effort has been made to understand and quantify the failure and upset levels of components due to HEMP excitation. A large amount of data relating to component damage due to HEMP exists [1], and results of extensive testing on communications systems, power systems and components are available [31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, and 42].

Recently, several experiments have been performed to evaluate the upset and damage of individual components, subsystems (e.g., PCs connected to power and telecom lines), and to examine the propagation capability of potentially damaging transients on the power cables from the outside to the inside of a building. These results are discussed in the following sub-clauses.

6.3.1 Component damage

As noted earlier, radiated HPEM environments are different from the radiated HEMP fields, and consequently, not all of the HEMP component failure data are directly applicable for HPEM studies. A recent investigation into HPEM effects on components by Göransson [43] has concluded that with regard to HPM susceptibility on digital circuitry, there can be large differences in susceptibility between different digital circuit technologies. He observed small differences between different samples of the same type from the same manufacturer; however, differences of up to 16 dB in component susceptibility levels were noted for different manufacturers. Göransson also noted a very strong frequency dependence in the component susceptibilities, with the susceptibility threshold level increasing rapidly with increasing frequency. Such an effect in a TTL circuit component is illustrated in Figure 8.

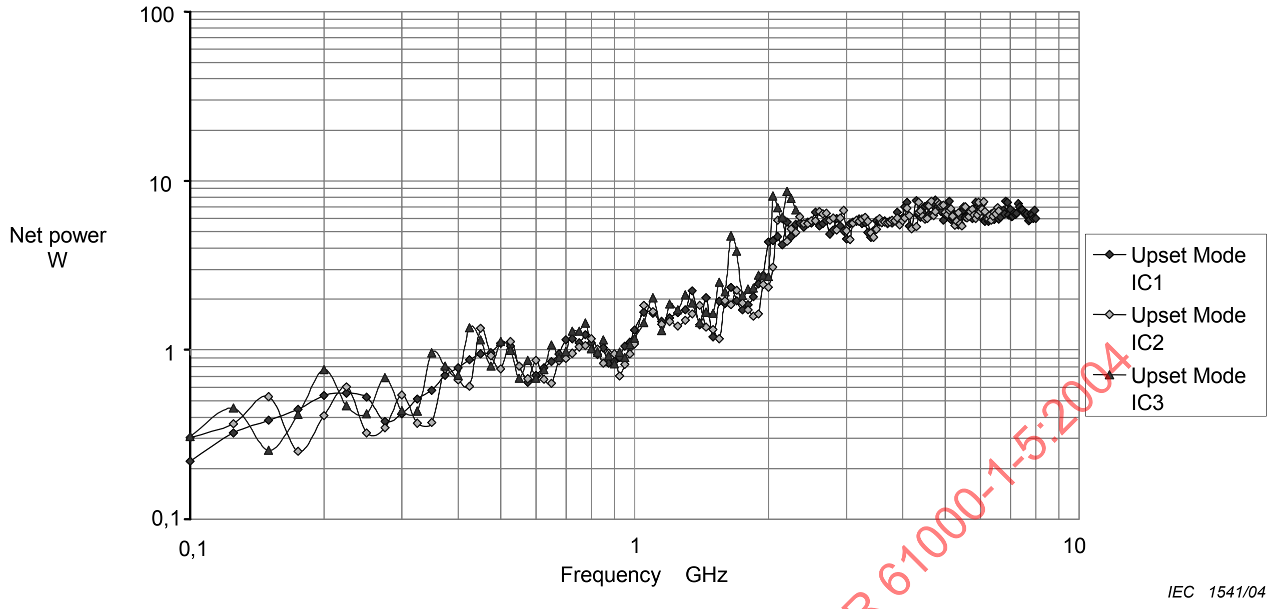


Figure 8 – Example of measured susceptibility thresholds in a DM74LS00N [TTL] quad 2-input NAND gate as a function of frequency, illustrating increased susceptibility thresholds at higher frequencies [43]

Note that the system susceptibility may be different from the individual component susceptibilities. For analogue systems, the HPM susceptibility level was seen by Göransson to be dependent on the application. However, it is usually possible to obtain an application-independent measure of the HPM effect. The susceptibility level for different applications then can be calculated.

6.3.2 Conducted transient effects on PCs

For this investigation, Radasky, *et al.* [44] decided to use well-calibrated and repeatable transient test generators. For this reason the generators employed were those defined by the International Electrotechnical Commission (IEC) for testing equipment to the transients produced by lightning and electrical fast transients. While these transients often begin on power lines outside of a building, there is cross coupling to the telecommunications wiring both outside and inside the building.

For the experiments summarised here, two specific generators were used. One produced either a "combination pulse" (1,2/50 μs rise/fall) or "telecom pulse" (10/700 μs) for the open circuit voltage waveform. These waveforms are referred to as the CWG (combination wave generator) waveform and the Telecom waveform, respectively, and their generators are specified in IEC 61000-4-5 [45]. The second generator produced an electrical fast transient (EFT) (5/50 ns) voltage waveform into a 50 Ω load. This waveform and generator are specified in IEC 61000-4-4 [46].

6.3.2.1 Equipment tested

For the tests performed four old personal computers were used. One was a Macintosh SE, and the other three were PCs (#1 – Pentium 66 MHz, #2–486, #3–Pentium 120 MHz). For all four computers the power cords were tested for the EFT waveform, while two of the PCs were tested for the Telecom pulse. In addition, the EFT waveforms were applied to the mouse cords, keyboard cords, and to modem input wiring.

In a second set of experiments, network ports were tested to the EFT, CWG and the Telecom waveforms. Two types of Ethernet ports were examined on the PCs: the 10Base-2 (RG-58 coaxial cable) and the 10Base-T (Category 5 twisted pair cable). An AppleTalk port on the Macintosh was also tested to EFT.

6.3.2.2 Test results – CWG and telecom pulses

The first set of results to be described cover the use of the energetic telecom pulse and the CWG lightning pulse. Transient waveforms with pulse widths greater than 200 µs were injected on the power cords of computers and on the Ethernet wiring connected to computers through internal Ethernet cards. Table 3 summarises the results of the testing.

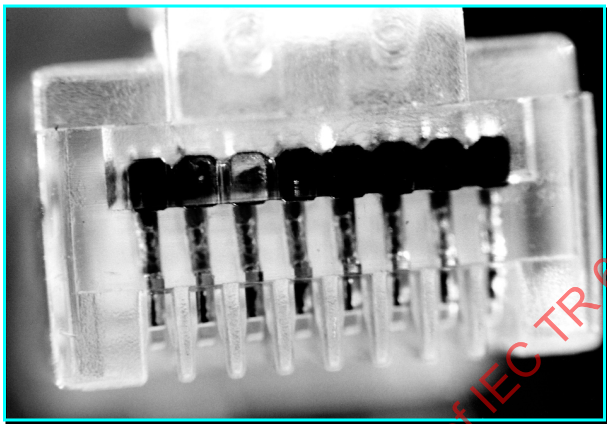
In the case of the power cords, there were no reproducible effects noted up to the maximum generator output of 4,5 kV open circuit. Note that the voltage delivered to the test objects was only 1,2 kV for 4 µs followed by ~300 V for 300 µs. While the sound of arcing was apparent during the testing, there were no effects exhibited by the computers after the tests were performed.

Table 3 – Summary of results of testing power and data ports with the telecom and CWG pulse generators

Telecom / CWG Pulse Test Summary
• Power cord (Telecom pulse test only): o No reproducible damage or computer upsets up to max voltage capability. o Arcs heard from power supply area. o Typical maximum stresses at load (4,5 kV generator open circuit voltage): ▪ 1,2 kV peak voltage spike (4 µs wide) followed by 200 V – 300 V slow decay (300 µs width). ▪ 300 A peak current (limited by generator).
• 10Base-2 Ethernet (coax) o Port destroyed by both CWG and Telecom pulses. ▪ 500 V pulse (minimum generator voltage). ▪ 50 V DC (100 V/s –200 V/s ramp). o No damage to computer beyond Ethernet card.
• 10Base-T Ethernet (twisted pair) o Damage occurred at 4 kV for Telecom pulse. ▪ About 4 J required for damage. ▪ Arcs began at 3 kV for both CWG and Telecom pulses. o No damage to computer beyond Ethernet card.

For the Ethernet cables, the results were more interesting. In the case of the 10 Base-2 coax cable, the Ethernet card was damaged at the lowest test level of 500 V for both the CWG and the Telecom pulses. It is noted that a 50 V d.c. test level also damaged the Ethernet card. Upon inspection it was found that the RG-58 cable ground was left floating at the card by design, thereby allowing the common mode voltage to be converted to a differential signal. It should be emphasised that while the Ethernet card and the communication capability was lost after this experiment, the computer that held the Ethernet card was itself not damaged.

In the case of the 10Base-T twisted pair cable, the results were similar although the damage that occurred happened at a much higher level. The damage that resulted during testing was at the 4 kV level (differential mode) for the Telecom pulse. During the experiments arcing was heard at 3 kV for both the CWG and the Telecom pulse, but the only damage occurred for the Telecom pulse. Figure 9 illustrates one case where the RJ-45 plug was damaged by significant arcing in the connector during the Telecom pulse testing. The energy delivered for damage was estimated at 4 J, and as in the case of the 10Base-2, no damage to the computer was found. It is clear that the 10Base-T is much less sensitive to damage given that the damage levels were much higher and the testing was performed in a differential mode.



IEC 1542/04

Figure 9 – Example of damage caused by the telecom pulse generator due to a single shot of 4,5 kV

6.3.2.3 Test results-EFT

A series of EFT tests were performed on the power cords of all four computers using the standard IEC 61000-4-4 capacitive cable drive set-up. While some effects were noted, including computer "beeps" and mouse pointer movements, these effects did not always require computer power resets. In some cases with the Pentium computers, single EFT pulses between 2 kV and 2,5 kV did force the computer to hang up forcing a power reset (cold boot). The results were felt to be due to "bit pollution" which is probably caused by EM radiation within the cabinet changing memory bit states. In most cases it appeared that voltages higher than 4,5 kV for the EFT generator are needed to cause repeatable reset problems.

For testing data lines, the EFT generator was directly connected to the computers (the voltage delivered to the test object is the same as the generator output voltage); the resultant computer upsets were found to be very repeatable for different computers and types of interface cabling. In Table 4 for the AppleTalk cabling connected to a Mac SE, there appears to be a trend between voltage level and the number of injected pulses. If one examines the bottom row for a single shot, it is only at 4,5 kV that any effect is noted, and this is for 1 time out of 10 tests. As the test pulses are repeated, for example to 20 pulses at 1 kHz, the effects begin at 2 kV and occur during every test at 4 kV. This trend continues as upsets are found at 1;5 kV for all repetition rates at and above 10 kHz.

Table 4 – Results of injecting EFT pulses on an AppleTalk cable with the number of upsets/number of test sequences indicated (x denotes case not tested)

Voltage level → Spike freq. (pulses) ↓	1 000 V	1 500 V	2 000 V	3 000 V	4 000 V	4 500 V
1 000 kHz (20 000)	0/3	4/4	3/3	3/3	3/3	2/2
100 kHz (2 000)	0/5	4/4	3/3	3/3	x	3/3
10 kHz (200)	0/4	4/4	3/3	3/3	x	3/3
1 kHz (20)	0/6	0/5	3/5	4/6	4/4	3/3
Single shot	0/2	x	0/2	0/2	0/3	1/10

No failures	
Some failures	
All fail	

In Table 5 similar trends are presented although some upsets are found as low as 1 kV and there is an indication of an additional repetition frequency dependence. Note that at 2 000 V and below, the upset probability at 1 MHz is lower than at 100 kHz. There is also a lower probability of effect at 1 kHz than at 10 kHz or 100 kHz.

Table 5 – Results of injecting EFT pulses on a 10Base-T cable with the number of upsets/number of test sequences indicated (x denotes case not tested)

Voltage level → Spike freq. (pulses) ↓	1 000 V	1 500 V	2 000 V	3 000 V	4 000 V	4 500 V
1 000 kHz (20 000)	0/7	2/5	1/5	3/3	3/3	x
100 kHz (2 000)	7/9	3/3	3/3	3/3	2/2	x
10 kHz (200)	6/8	1/3	3/3	3/3	2/2	x
1 kHz (20)	0/6	2/5	3/5	6/8	3/3	x
Single shot	0/2	x	0/3	1/3	0/3	4/4

No failures	
Some failures	
All fail	

In Table 6 the upsets for single shots on the 10Base-2 cable (the only data that were taken) indicate the highest level of sensitivity with single shot upsets being consistent at 2,5 kV as opposed to at 4,5 kV for the 10Base-T and above 4,5 kV for AppleTalk.

Table 6 – Results of injecting EFT pulses on a 10Base-2 cable with the number of upsets/number of test sequences indicated

Voltage level → Spike freq. (pulses) ↓	500 V	1 000 V	1 500 V	2 000 V	2 500 V	3 000 V	4 000 V	4 500 V
Single shot	1/6	3/6	3/6	4/6	3/3	3/3	6/6	4/4

No failures	
Some failures	(light grey)
All fail	(dark grey)

6.3.2.4 Conducted transient conclusions

These experiments, while limited in injection peak voltage, have indicated that energetic pulses such as the CWG and Telecom pulse are definite threats to Ethernet cable data systems in terms of creating damage to the connected computer Ethernet cards. It is also known that the lower frequency content of these test pulses (below 1 MHz) propagates very well along these types of cables. For the EFT pulses, it is also clear that they are a serious threat to creating computer upsets at very low levels (1 kV – 2 kV) injected on Ethernet cables. These pulses do decay with distance on the category 5 cable, but the attenuation is modest (30 % for 30 m).

For power cord injections, the pulser limitations did not allow clear results for any of the pulse waveforms, although some EFT upsets were noted as low as 2 kV. The high-energy pulses (Telecom, CWG) could not couple more than 1 kV to the load, and no damage or upsets were noted from these waveforms.

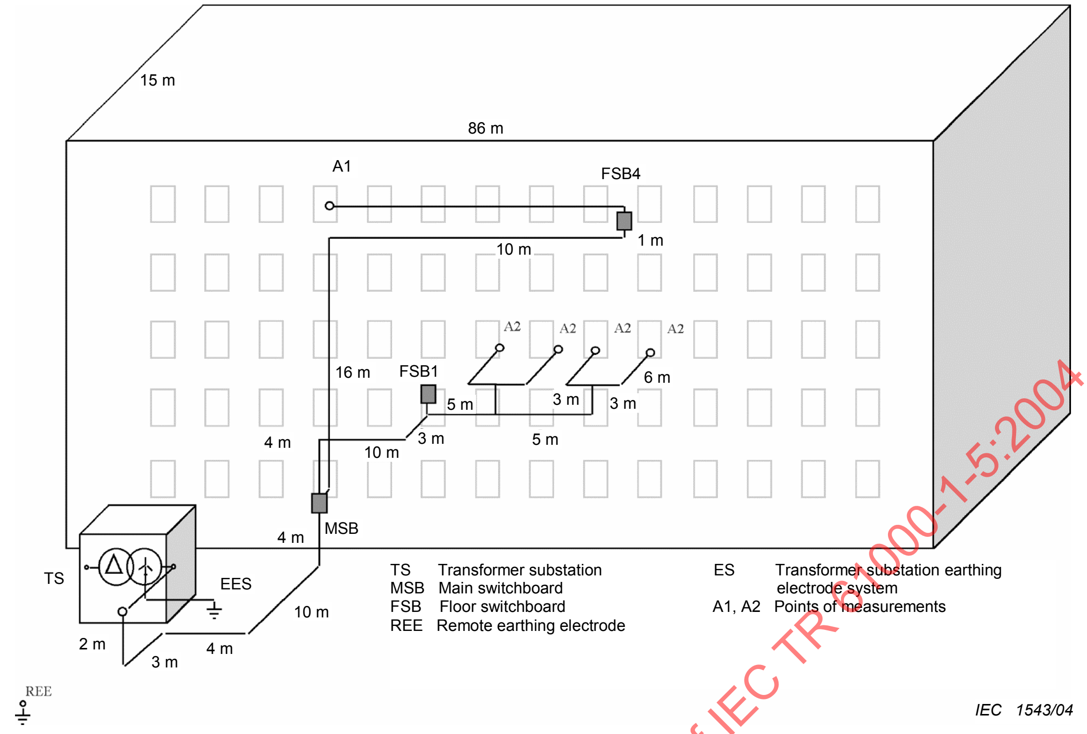
6.3.3 Conducted testing at the building level

Concern has been raised in recent years about the ability of criminals or terrorists to intentionally use electromagnetic transients to disrupt the operation of businesses to operate in a normal fashion. While many of the postulated threats involve radiating high-frequency EM fields at a building from a hidden location, it is just as likely that conducted EM transients could be injected on the power or telecom wires entering a building when there is no limitation of access.

The following is a summary of unique work performed by Parfenov *et al.* [47, 48], where they injected different types of transient signals into the wiring of an operational building to investigate the propagation characteristics of those transients from the outside to wall plugs inside. In addition, the authors investigated the types of transients that could damage a computer power supply.

6.3.3.1 Test set-up

The building tested was supplied by a pad-mounted delta-wye 1 MW, 10 kV/380 V transformer as shown in Figure 10. The building has five floors, and measurements were performed on the 1st and 4th floors. Note that the main building switchboard and the floor switchboards were part of the experiment.



NOTE First level is labelled ground floor while the following is denoted first floor, the next second floor etc.

Figure 10 – Description of conducted disturbance injection experiment

In terms of the testing, pulsers were set up on the secondary side of the transformers, and the testing was performed in an un-energised mode. This was done for convenience only, and the authors note that it is not difficult to perform such injections while operating with full voltage input to the building. The authors injected in various ways including between:

- phase 1 and neutral;
- phase 2 and neutral;
- phase 1 and the remote earthing electrode;
- phase 2 and the remote earthing electrode;
- neutral and the remote earthing electrode.

In all cases the measurements were made in the building between phase 1 and the neutral at the various wall plugs.

The types of transients injected included both pulse and continuous waves (CW). The pulse characteristics were varied but generally included a rise time of 30 ns with pulse widths that varied between 30 ns and 10 µs. The pulses had a peak value at the injection point of 1,5 kV and were repetitively pulsed at 5 Hz. From an assessment of the insulation and from the results themselves, it was clear that the injected 1,5 kV pulses would not cause insulation damage in the wiring of the building. For the CW injections, frequencies between 500 Hz and 1 MHz were applied.

6.3.3.2 Building test results

It was no surprise that the least attenuation of signals from the outside of the building to the wall plugs inside occurred when the phase line measured inside was the same as the phase line injected outside. It was also found that the attenuation was lowest with the widest pulse (10 µs), with no discernible peak attenuation noted. For the same tests performed with CW sources, the attenuation increased with frequency with a maximum attenuation of 5 dB at f = 1 MHz. It appears that as higher frequencies are used, impedance mismatches and higher inductive losses increase the attenuation.

In terms of the efficiency of coupling from one phase line to another, it was found that driving phase 2 and measuring phase 1 resulted in a 30 – 50 dB loss in signal for frequencies between 0,1 MHz – 1 MHz, although strong resonances were found at 250 kHz and 900 kHz. Interestingly, injecting between the phases (or neutral) and the remote earthing electrode and measuring phase 1 to neutral voltages also found a 40 dB attenuation in this same frequency range.

6.3.3.3 Computer power supplies

The second portion of the work of [47, 48] involved the examination of the vulnerability of computer power supplies to pulsed transients entering through the power cord. As it was felt that the power supply filter circuits were most likely to fail, three different power supply filter circuits were analysed – a low-load filter (200 W rating), a medium-load filter (500 W – 800 W rating), and an industrial filter.

Analyses were performed with a circuit code using different input pulse characteristics and a phase to neutral injection at the power plug. The modelling considered parasitic and non-linear elements of the power supply filters. The results of the study indicated that for an injected pulse with a width of 100 µs, that the following effects were expected:

- filter capacitor breakdown at 3 – 4 kV injected;
- rectifier diode breakdown at 5 – 6 kV injected;
- rectifier filter over voltage at 8 kV injected.

In order to test a portion of this analysis, the input section of a power supply was injected with the expected pulse characteristics beginning at 3 kV. The capacitor failure levels in the circuit were between 4,2 kV and 5,6 kV, which were slightly higher than predicted, but still consistent with the analysis.

To test the overall performance of a computer system with the industrial power filter, pulses were injected with a 50 µs pulse width. The test indicated a failure of the computer power supply at an injected voltage of 6 kV. The damage found in the power supply included: two rectifier diodes, a thermal compensation resistor, a filter input capacitor and a fuse. Further analyses examining the impact of pulse width revealed that for a pulse width of 1 ms, the failure level is expected to drop to 1 kV – 2 kV.

6.3.3.4 Summary of building study

The measurements performed by Parfenov, *et al.* Clearly indicate that voltages injected on external wiring can propagate fairly well through the wiring of a building even when considering multiple switchboards inside the building. It is clear from this work that frequencies less than 1 MHz propagate with low attenuation as do pulses with widths greater than 1 µs. Although this study did not address the issue of wiring insulation breakdown directly, it is felt that for the types of pulses considered, normal building wiring should be able to support peak voltages in the range of 10 kV.

In terms of the vulnerability of computers, both the analyses and limited testing revealed that computer power supplies, and in particular the input filters, appear to be vulnerable to levels of 6 kV for a 50 µs pulse. Analyses indicate that levels of 1 kV – 2 kV would create damage for a 1 ms-wide pulse.

By considering both aspects of this work, it appears possible to inject significant levels of voltage into the electrical wiring system of a building, and the injected voltage will propagate easily and can cause damage to computer power supplies.

6.4 Logic upset or service interruption

A more likely consequence of HPEM illumination of a system is upset (temporary malfunction) or latch-up (malfunction which causes a circuit to stop operation until the power is reset) of internal digital circuitry.

This type of system vulnerability is very difficult to predict, however, due to uncertainties in the following areas:

a) the system logic state and pending operations at the time of EM illumination,

b) the coupling of the EM energy into the system, due to the large number of important parameters, whose values are unknown or variable,

c) the unknown or time-varying orientation and distance of the system with respect to the EM source, and

d) target to target variations of the EM field vulnerability levels.

As a result of the difficulty of predicting these upset effects on systems, testing of the equipment is necessary to adequately understand the possible HPEM effects. It is possible, however, to examine the logic switching voltage levels within a particular device, and require that any HPEM signal be significantly lower than these normal system voltages. This conservative approach can lead to over protecting a system but is one technique that can be applied to the protection of highly critical systems.

7 HPEM protection concepts

As suggested in the previous clauses of this report, HPEM environments can cause the following effects on a system (in order of decreasing severity):

a) permanent physical damage;

b) permanent function failure;

c) temporary upset (with operator intervention);

d) performance reduction;

e) temporary upset (without operator intervention).

In some cases, it may be desirable to protect a system against HPEM fields. In this clause, various protection schemes are reviewed.

7.1 Strategy for selecting immunity levels

An important aspect of EM protection is to understand how robust the system should be. This is usually expressed as a probability of system failure, when subjected to a specified EM environment. To do this, statistical concepts must be used, due to uncertainties in EM field illumination on the system, as well as on the variations of the system parameters. Some systems may be deemed "performance critical" and have a very high survivability requirement; other non-performance-critical systems may be unprotected. Decisions about suitable survivability requirements are complex, involving attack scenarios, strategic planning, costs, etc.

To assess the possible need for HPEM protection, it is necessary to define the survivability requirement for the system in the larger context of its relation with other components within the infrastructure containing the system of concern. For example, if the system under study is a command and control communication unit within the civil defence infrastructure, its operation could be deemed crucial to the overall operation of the infrastructure. However, if the system is a non-critical electrical component (for heating coffee, for example) its survivability requirement may be minimal. Thus, a careful evaluation of the role played by the system must be made and its protection requirements assessed.