BRITISH STANDARD

BS EN
61000-2-10:1999
IEC
61000-2-10:1998

Electromagnetic compatibility (EMC) —

Part 2-10: Environment — Description of HEMP environment — Conducted disturbance

The European Standard EN 61000-2-10:1999 has the status of a British Standard

ICS 33.100.10

National foreword

This British Standard is the English language version of EN 61000-2-10:1999. It is identical with IEC 61000-2-10:1998.

The UK participation in its preparation was entrusted to Technical Committee GEL/210, Electromagnetic compatibility, which has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this committee can be obtained on request to its secretary.

Cross-references

Attention is drawn to the fact that CEN and CENELEC Standards normally include an annex which lists normative references to international publications with their corresponding European publications. The British Standards which implement these international or European publications may be found in the BSI Standards Catalogue under the section entitled "International Standards Correspondence Index", or by using the "Find" facility of the BSI Standards Electronic Catalogue.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, the EN title page, pages 2 to 44, an inside back cover and a back cover.

This British Standard, having been prepared under the direction of the Electrotechnical Sector Committee, was published under the authority of the Standards Committee and comes into effect on 15 May 1999

ISBN 0 580 32560 1

Amendments issued since publication

Amd. No.	Date	Text affected

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 61000-2-10

February 1999

ICS 33.100.01

Descriptors: Electromagnetic compatibility, environments, pulses, electromagnetism, nuclear radiation, explosions, altitude, electromagnetic waves, radio disturbances

English version

Electromagnetic compatibility (EMC)
Part 2-10: Environment - Description of HEMP environment
Conducted disturbance
(IEC 61000-2-10:1998)

Compatibilité électromagnétique (CEM)
Partie 2-10: Environnement
Description de l'environnement
IEMN-HA - Perturbations conduites
(CEI 61000-2-10:1998)

Elektromagnetische Verträglichkeit (EMV)
Teil 2-10: Umgebungsbedingungen
Beschreibung der HEMP-Umgebung
Leitungsgeführte Störgrößen
(IEC 61000-2-10:1998)

This European Standard was approved by CENELEC on 1999-01-01. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the Central Secretariat has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.

CENELEC
European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung
Central Secretariat: rue de Stassart 35, B - 1050 Brussels

Ref. No. EN 61000-2-10:1999 E

Foreword

The text of document 77C/61/FDIS, future edition 1 of IEC 61000-2-10, prepared by SC 77C, Immunity to high altitude nuclear electromagnetic pulse (HEMP), of IEC TC 77, Electromagnetic compatibility, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61000-2-10 on 1999-01-01.

The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	1999-10-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2001-10-01

Annexes designated "normative" are part of the body of the standard.
Annexes designated "informative" are given for information only.
In this standard, annex ZA is normative and annexes A, B, C and D are informative.
Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 61000-2-10:1998 was approved by CENELEC as a European Standard without any modification.

CONTENTS

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 (insofar as these limits do not fall under the responsibilty 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, published either as International Standards 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.

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 2-10: Environment – Description of HEMP environment – Conducted disturbance

1 Scope

This International Standard defines the high-altitude electromagnetic pulse (HEMP) conducted environment that is one of the consequences of a high-altitude nuclear explosion.

Those dealing with this subject consider two cases:

- high-altitude nuclear explosions;
- low-altitude nuclear explosions.

For civil systems the most important case is the high-altitude nuclear explosion. In this case, the other effects of the nuclear explosion: blast, ground shock, thermal and nuclear ionizing radiation are not present at the ground level.

However, the electromagnetic pulse associated with the explosion may cause disruption of, and damage to, communication, electronic and electric power systems thereby upsetting the stability of modern society.

The object of this standard is to establish a common reference for the conducted HEMP environment in order to select realistic stresses to apply to victim equipment for evaluating their performance.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 61000. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this part of IEC 61000 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050(161):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 161: Electromagnetic Compatibility*

IEC 61000-2-9:1996, *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 1: Description of HEMP environment – Radiated disturbance* – Basic EMC publication

IEC 61000-4-24:1997, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 24: Test methods for protective devices for HEMP conducted disturbance* – Basic EMC publication

3 General

A high-altitude (above 30 km) nuclear burst produces three types of electromagnetic pulses which are observed on the earth's surface:

- early-time HEMP (fast);
- intermediate-time HEMP (medium);
- late-time HEMP (slow).

Historically most interest has been focused on the early-time HEMP which was previously referred to as simply HEMP. Here we will use the term high-altitude EMP or HEMP to include all three types. The term NEMP [1] covers many categories of nuclear EMPs including those produced by surface bursts (SREMP) [2] or created on space systems (SGEMP) [3].

Because the HEMP is produced by a high-altitude detonation, we do not observe other nuclear weapon environments such as gamma rays, heat and shock waves at the earth's surface. HEMP was reported from high-altitude nuclear tests in the South Pacific by the US and over the USSR during the early 1960s, producing effects on electronic equipment far from the burst location.

This standard presents the conducted HEMP environment induced on metallic lines, such as cables or power lines, external and internal to installations, and external antennas.

---

[1] NEMP: Nuclear electromagnetic pulse.

[2] SREMP: Source region EMP.

[3] SGEMP: System generated EMP.

4 Definitions

For the purpose of this International Standard, the definitions given in IEC 60050(161) apply, as well as the following definitions:

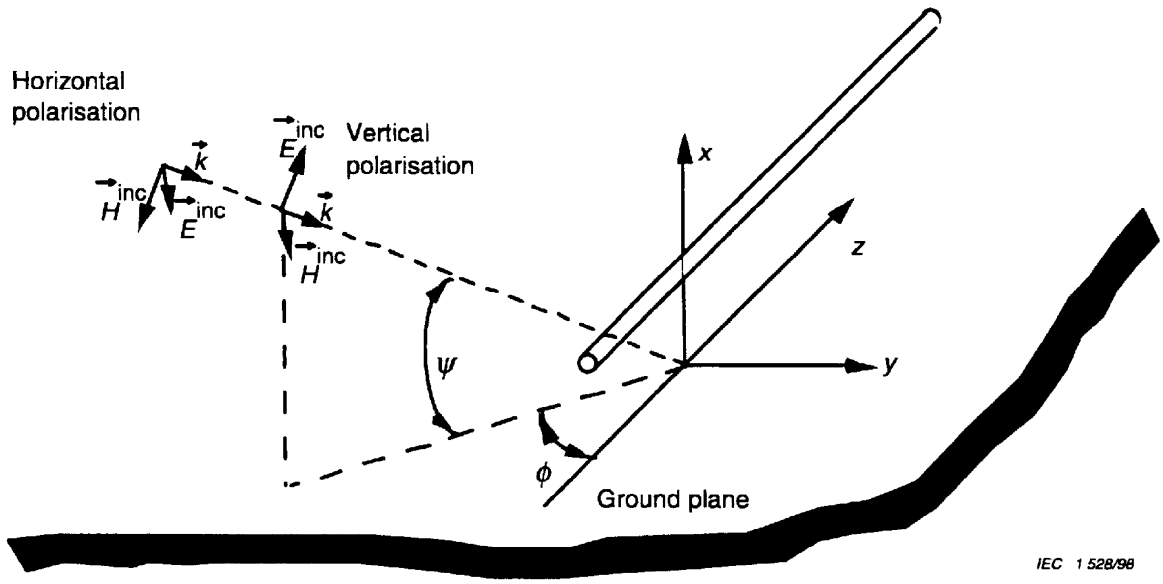


Figure 1 – Geometry for the definition of polarization and of the angles of elevation ψ and azimuth ϕ

4.1

angle of elevation in the vertical plane, ψ

angle ψ measured in the vertical plane between a flat horizontal surface such as the ground and the propagation vector (see figure 1)

4.2

azimuth angle, ϕ

angle between the projection of the propagation vector on the ground plane and the principal axis of the victim object (z axis for the transmission line of figure 1)

4.3

composite waveform

waveform which maximizes the important features of a waveform

4.4

coupling

interaction of the HEMP field with a system to produce currents and voltages on system surfaces and cables. Voltages result from the induced charges and are only defined at low frequencies with wavelengths larger than the surface or gap dimensions

4.5
direction of propagation of the electromagnetic wave

direction of the propagation vector $\vec{k}$, perpendicular to the plane containing the vectors of the electric and the magnetic fields (see figure 2)

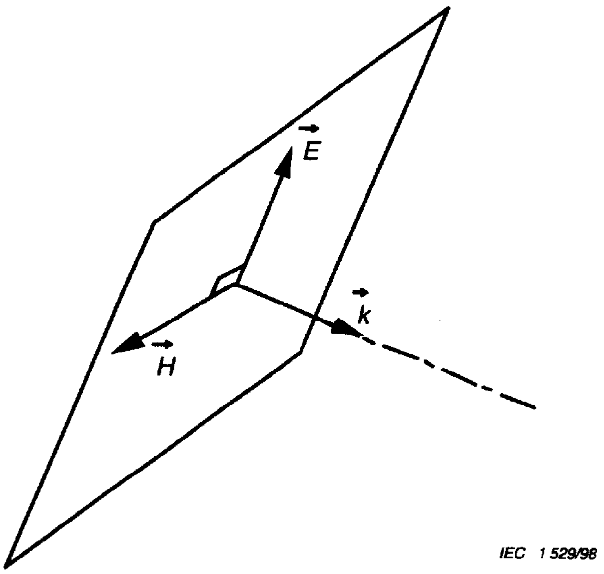


Figure 2 – Geometry for the definition of the plane wave

4.6
E1, E2, E3
terminology for the early, intermediate and late-time HEMP electric fields

4.7
EMP
any electromagnetic pulse, general description

4.8
geomagnetic dip angle, θ_{dip}

dip angle of the geomagnetic flux density vector $\vec{B}_e$, measured from the local horizontal in the magnetic north-south plane. θ_{dip} = 90° at the magnetic north pole, –90° at the magnetic south pole, (see figure 3)

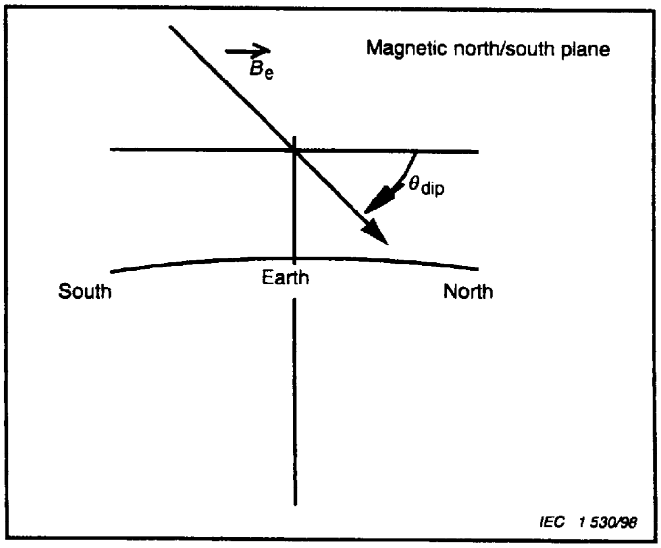


Figure 3 – Geomagnetic dip angle

4.9
HEMP
high-altitude nuclear EMP

4.10
high-altitude (nuclear explosion)
height of burst above 30 km altitude

4.11
horizontal polarization
an electromagnetic wave is horizontally polarized if the magnetic field vector is in the incidence plane and the electric field vector is perpendicular to the incidence plane and thus parallel to the ground plane (see figure 1). (This type of polarization is also called perpendicular or transverse electric (TE).)

4.12
incidence plane
plane formed by the propagation vector and the normal to the ground plane

4.13
low-altitude (nuclear explosion)
height of burst below 1 km altitude

4.14
NEMP
nuclear EMP; all types of EMP produced by a nuclear explosion

4.15
point-of-entry (PoE)
the physical location (point) on an electromagnetic barrier, where EM energy may enter or exit a topological volume, unless an adequate PoE protective device is provided. A PoE is not limited to a geometrical point. PoEs are classified as aperture PoEs or conductive PoEs according to the type of penetration. They are also classified as architectural, mechanical, structural or electrical PoEs, according to the functions they serve

4.16
pulse width
the time interval between the points on the leading and trailing edges of a pulse at which the instantaneous value is 50 % of the peak pulse amplitude, unless otherwise stated

4.17
rectified impulse (RI)
the integral of the absolute value of a time waveform's amplitude over a specified time interval

4.18
rise time (pulse)
the time interval between the instants in which the instantaneous amplitude of a pulse first reaches specified lower and upper limits, namely 10 % and 90 % of the peak pulse amplitude, unless otherwise stated

4.19
short-circuit current
the value of current that flows when the output terminals of a circuit are shorted. This current is normally of interest when checking the performance of surge protection devices

4.20
source impedance
the impedance presented by a source of energy to the input terminals of a device or network

4.21
vertical polarization

an electromagnetic wave is vertically polarized if the electric field vector is in the incidence plane, and the magnetic field vector is perpendicular to the incidence plane and thus parallel to the ground plane (see figure 1). (This type of polarization is also called parallel or transverse magnetic (TM).)

5 Description of HEMP environment, conducted parameters

5.1 Introductory remarks

The electromagnetic field generated by a high-altitude nuclear explosion described in IEC 61000-2-9 can induce currents and voltages in all metallic structures. These currents and voltages propagating in conductors represent the conducted environment. This means that the conducted environment is a secondary phenomenon, a consequence of the radiated field alone.

All metallic structures (i.e. wires, conductors, pipes, ducts, etc.) will be affected by the HEMP. The conducted environment is important because it can direct the HEMP energy to sensitive electronics through signal, power, and grounding connections. It should be noted that there are two distinct categories of conductors: external and internal conductors (with regard to a building or any other enclosure). While this may seem simplistic, this separation is critical in terms of the information to be provided in this standard.

The difference between these two types of conductors is explained by electromagnetic topology. In general, external conductors are those which are located outside of a building and are completely exposed to the full HEMP environment. This category includes power, metallic communication lines, antenna cables, and water and gas pipes (if metallic). For the purposes of this standard the conductors can be elevated above the ground or buried in the earth. Internal conductors are those which are located in a partially or completely shielded building where the HEMP fields have been reduced by the building. This is a much more complex situation, because the HEMP field waveforms will be significantly altered by the building shield, and the coupling to internal wires and cables is consequently very difficult to calculate, although some measured data are available from simulated HEMP tests.

In this standard the external conducted common mode environments are calculated using simplified conductor geometries and the specified HEMP environments for the early, intermediate, and late-time waveforms. These conducted external environments are intended to be used to evaluate the performance of protection devices outside of a building, and because of variations in telecom and power systems, the effects of transformers and telephone splice boxes are not considered here. This process results in approximate, but well-defined waveforms that are needed to test protective elements on external conductors in a standardized manner. For the internal conductors, a procedure is defined to estimate the conducted environments appropriate for equipment testing. For unshielded multiconductor wires, it is assumed that the line-to-ground currents are equal to the common-mode current.

5.2 Early-time HEMP external conducted environment

For the early-time HEMP, the high-amplitude electric field couples efficiently to antennas and to any exposed lines such as power and telephone lines. The antenna coupling mechanism is extremely variable and dependent on the details of the antenna design. In many cases, it is advisable to perform continuous wave (CW) testing of an antenna and to "combine" the response function of the antenna with the incident HEMP environment using a convolution technique. We have, however, provided simple equations to compute the response of thin antennas (see 5.5). For long lines, it is possible to perform a comprehensive set of common mode calculations that are reliable and depend only upon a few parameters. These parameters include conductor length, exposure situation (above ground or buried), and the surface ground conductivity (for depths between 0 m and 5 m). In addition, because the HEMP coupling is dependent on angle of elevation and polarization (see figure 1), it is possible to statistically examine the probability of producing particular levels of current.

Table 1 below describes the calculated, coupled, common-mode short-circuit currents and the Thévenin equivalent source impedances (used to determine the open-circuit voltages) as functions of severity level, length of conductor, and ground conductivity. These results are appropriate for the common-mode currents flowing on bare wires, overhead insulated wires, and the shields of shielded cables or coaxial transmission lines. For shielded cables one should use measured or specified cable transfer impedances to determine internal wire currents and voltages. Although some waveform variation occurs for different exposure geometries, a single time waveform is specified for elevated lines. The waveform is defined in terms of the rise time (10 % to 90 %) and the pulse width (at half maximum); when the pulse characteristics of rise time and pulse width are described together, the usual description is $\Delta t_r/\Delta t_{pw}$.

In table 1 a severity level of 99 % indicates that 99 % of the currents produced will be less than this value. The buried line currents calculated vary much less with angle of incidence and indicate a very broad probability distribution (small differences between 10 % and 90 % severity) and therefore are not described in terms of severity levels; variations are shown for ground conductivity. In terms of applicability for table 1, the elevated conductor currents are accurate for heights above 5 m while the buried currents can be used for conductors slightly (h < 30 cm) above the surface and below the surface. For conductor heights below 5 m, the values in table 1 may be linearly interpolated (between 0,3 m and 5 m). For cases where the lines from an elevated geometry enter the ground in an insulated manner, the currents will initially resemble waveform 1, decreasing as a function of burial distance until waveform 2 is reached (requires approximately 20 m). Consult annex A for further information regarding the derivation of these waveforms.

Table 1 – Early-time HEMP conducted common-mode short-circuit currents including the time history and peak value I_{pk} as a function of severity level, length L in metres and ground conductivity σ_g

Table 1a – Elevated conductor

	I_{pk} A		
Severity (%)[1)]	**L > 200 m**	**100 ≤ L ≤ 200 m**	**L < 100 m**
50	500	500	5,0 × L
90	1 500	7,5 × L	7,5 × L
99	4 000	20 × L	20 × L

1) Percentage of currents smaller than the indicated value.
Waveform 1: 10/100 ns.
Source impedance: Z_s = 400 Ω.

Table 1b – Buried conductor

	I_{pk} A
σ_g S/m	**All lengths > 10 m**
10^{-2}	200
10^{-3}	300
10^{-4}	400

Waveform 2: 25/500 ns.
Source impedance: Z_s = 50 Ω.

5.3 Intermediate-time HEMP external conducted environment

The intermediate-time HEMP environment only couples efficiently to long conductors in excess of 1 km. It is therefore of interest primarily for external conductors such as power and communication lines. Because the pulse width of this environment is much wider than that of the early-time environment, the coupling varies less as a function of angle of elevation. This means that the statistical variation is less important than in the case of the early-time coupling. On the other hand, the ground conductivity is more important here affecting the coupling to elevated lines in addition to buried lines. See annex B for a more detailed discussion.

Table 2 describes the conducted external environment as a function of line length and ground conductivity (to depths of 1 km).

Table 2 – Intermediate-time HEMP conducted common-mode short-circuit currents including the time history and peak value I_{pk} as a function of length L in metres and ground conductivity σ_g

Table 2a – Elevated conductor

	I_{pk} A			
σ_g S/m	L > 10 000 m	1 000 ≤ L ≤ 10 000 m	100 ≤ L ≤ 1 000 m	L < 100 m
10^{-2}	150	75	0,05 × L	0
10^{-3}	350	200	0,15 × L	0
10^{-4}	800	600	0,45 × L	0
Waveform 3: 25/1 500 µs. Source impedance: Z_s = 400 Ω.				

Table 2b – Buried conductor

	I_{pk} A		
σ_g S/m	L > 1 000 m	100 ≤ L ≤ 1 000 m	L < 100 m
10^{-2}	50	0,05 × L	0
10^{-3}	150	0,15 × L	0
10^{-4}	450	0,45 × L	0
Waveform 3: 25/1 500 µs. Source impedance: Z_s = 50 Ω.			

5.4 Late-time HEMP external conducted environment

The late-time HEMP environment is only important for coupling to long external conductors such as power and communication lines. In this case, however, the computation of short circuit currents for typical cases of interest is not easily accomplished. This is because the late-time HEMP environment is described as a voltage source that is produced in the earth which induces currents to flow only in conductors that are connected to the earth at two or more points. Since the current that flows is strongly dependent on the resistance present in the circuit, an analytical method is provided here to develop a standard conducted environment.

In order to describe the method to be used, an example case is provided. In figure 4a, a three-phase Y-delta power configuration is shown along with an equivalent circuit in figure 4b (where E_0 is the peak value of the late-time HEMP). Note that the problem can be described as a quasi-d.c. problem with the voltage source calculated directly from the late-time HEMP environment. Since the highest frequencies contained in the late-time HEMP environment are of the order of 1 Hz, this is clearly appropriate. It can therefore be assumed that the voltage source V_s has the same time dependence as E_0. Given that the resistances in figure 4b (the parallel Y winding resistances R_y and the "footing" or grounding resistances R_f) are not frequency dependent for f < 1 Hz, then the induced current I_{pk} will have the same time dependence as E_0.

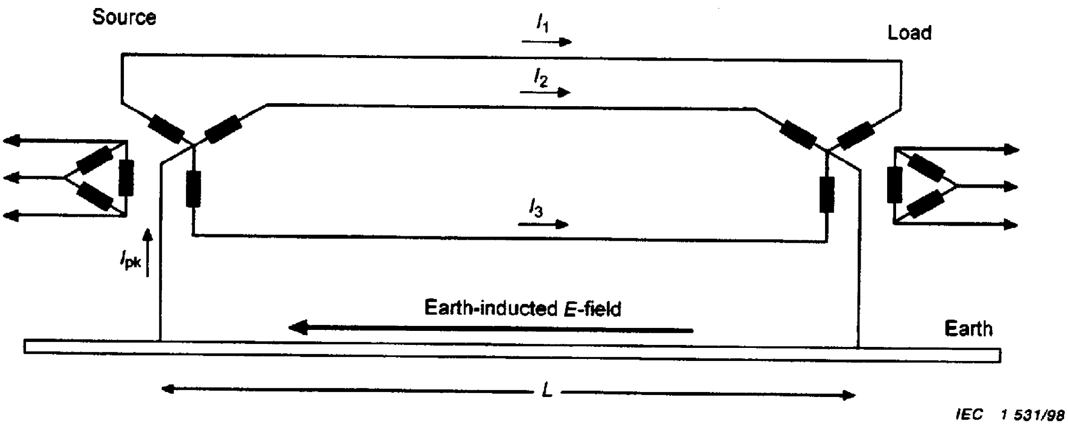


Figure 4a – Three-phase line and transformer configuration

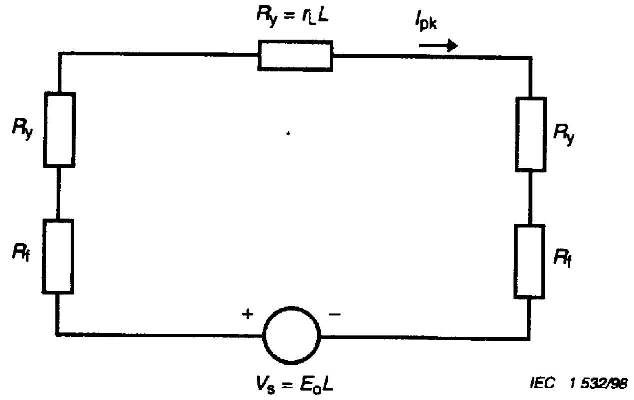


Figure 4b – Simple equivalent circuit where E_0 is the induced late-time HEMP electric field

Figure 4 – Three-phase line and equivalent circuit for computing late-time HEMP conducted current

Using the example provided, the peak current can be calculated as:

$$I_{pk} = \frac{E_0 L}{2(R_f + R_y) + r_L L} \tag{1}$$

where

r_L is the parallel wire resistance per unit length (Ω/m);

R_f is the ground resistance (Ω);

R_y is the parallel winding resistance in one transformer (Ω);

L is the line length (m).

For a long transmission line in North America, a 500 kV line would have a resistance per unit length of 8,3 × 10^{-6} Ω/m, a transformer winding resistance of 0,06 Ω and a grounding resistance of 0,75 Ω. For a 10^5 m length line, this provides a peak current of approximately 40 000 × E_0 (where E_0 is given as 0,04 V/m in IEC 61000-2-9 for a deep (d >> 10 km) ground conductivity of 10^{-4} S/m) or approximately 1 600 A. Given this peak value, the current time waveform can be approximated by a unipolar pulse with a rise time and pulse width of 1/50 s. To simulate the waveform for this example, one should use a voltage source of 4 kV with a source impedance of 2,45 Ω. It is important to recognize the necessity to ground transformers in order to use the circuit in figure 4. Some transformers are delta-delta and do not possess a direct path to ground.

Equation 1 above can easily be translated to cover cases other than power lines by computing the total resistance in the circuit, and dividing it into the total voltage induced over the length of the conductor. Equation 1 is provided for the case of long cables over land, and for deep undersea cables, the currents calculated may be reduced by up to a factor of 100. This reduction is due to the behaviour of the electric field E_0 which is inversely proportional to the square root of the deep ground conductivity (to depths of 10 km to 100 km). For freshwater lakes or shallow seas, the currents may not be reduced as much.

5.5 Antenna currents

Antennas come in many different sizes and shapes. At frequencies in the VLF and LF range (3 kHz to 300 kHz), such antennas are often in the form of very long wires which are sometimes buried in the earth. Antennas in the MF band (300 kHz to 3 000 kHz) are often in the form of a vertical tower which is fed against a buried counterpoise grid buried in the earth. In the HF and VHF bands (3 MHz to 30 MHz and 30 MHz to 300 MHz, respectively), the antennas typically appear as centre-fed dipoles, and at the higher frequencies (UHF, SHF, etc.) they become more like a distributed system, involving reflecting dishes and radiating apertures.

Usually, antennas are operated in a narrow band of frequencies located around a fundamental design frequency. In order to enhance their narrow-band performance, such antennas are often "tuned" by adding lumped impedance elements, by adding additional passive elements near the active antenna, or by locating the antenna in an array.

Given such a large variation in antenna configurations, it is difficult to provide an accurate response specification (current and voltage waveforms) for every type of antenna. As an approximate model, however, it is possible to consider the simple thin-wire vertical dipole antenna shown in figure 5, and to use its response as an indication of what would be the responses for other more complex antennas. Of course, this model is applicable only to antennas of the electric dipole class: loop (i.e. magnetic) antennas and aperture antennas are not adequately modelled by this simple structure. For more complex antennas, it is recommended that CW illumination or high level pulse testing be performed to evaluate antenna responses.

These types of test methods are described in IEC 61000-4-23*.

The antenna in figure 5 is assumed to be loaded by a nominal 50 Ω resistance, which is typical of a realistic in-band load on the antenna. The antenna has an end-to-end length of ℓ and a radius of *a*; these parameters are used to compute the form parameter $\Omega = 2 \ln (\ell / a)$. The resonance bandwidth factor *Q* of the load current of this antenna may be approximated by $Q = \Omega/3{,}6$. For non-ideal antennas, the *Q* parameter should be derived from antenna response measurements.

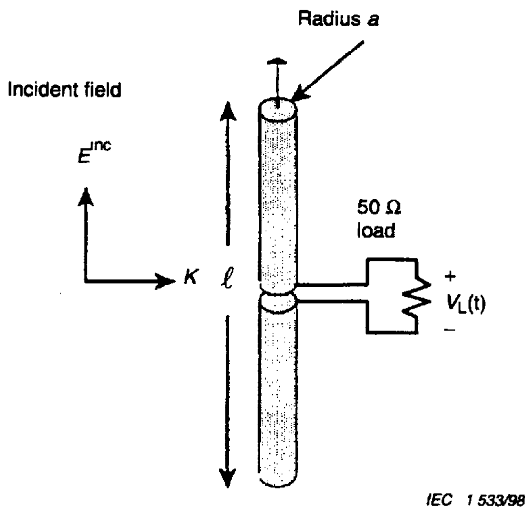


Figure 5 – A centre-loaded dipole antenna of length ℓ and radius *a*, excited by an incident early-time HEMP field

Usually the antenna of figure 5 is located in the vicinity of other conducting bodies that modify the incident field and, consequently, change the response from that obtained for the isolated antenna. For example, the antenna can be located on or near the ground where an earth-reflected field can provide an additional antenna excitation. Equally the dipole might be mounted on a long mast where the scattered field from the mast and support wires will modify the excitation.

As with the variations in the antenna geometry, it is difficult to take into account all of these possibilities in developing a standard response waveform. The problem is made a bit easier, however, by the fact that in many cases, the reflected field arrives at the antenna after the incident field has excited the antenna, suggesting that the incident field response can still provide an adequate specification of the response. For this simplified specification process, the influence of any scattered field excitation is neglected.

* IEC 61000-4-23: *Electromagnetic compatibility (EMC) – Part 4-23: Testing and measurement techniques – Test methods for protective devices for HEMP and other radiated disturbance.* Basic EMC publication (in preparation).

To calculate the response of the antenna, the fundamental resonance frequency is given by

$$f_c = \frac{c}{2\ell} \qquad (2)$$

where

c is the speed of light, and

ℓ is the total length of a dipole or twice the height of a monopole over a ground plane.

The response of the antenna is then given as a load current into 50 Ω:

$$I_L(t) = kI_p e^{\frac{-\pi \ f_c \ t}{Q}} \sin(2\pi f_c t) \qquad \text{for } t \geq 0 \qquad (3)$$

with I_p defined below in table 3. The normalizing factor k is defined to allow I_L to peak at a value of I_p, and it depends on the values of Q and f_c. In table 3, I_p is defined as the product $\ell \hat{I}$, where $\hat{I}$ is the peak incident HEMP magnetic field. Below 10 MHz the peak antenna current is assumed constant.

Table 3 – Maximum peak electric dipole antenna load current versus frequency for antenna principal frequencies

f_c MHz	ℓ m	$\hat{I}$ A/m	$\ell \hat{I}$ A	I_p A
<1	>150	–	–	2 000*
1 – 10	15 – 150	–	–	2 000*
10	15	130	1 950	1 950
100	1,5	130	195	195
200	0,75	130	97,5	97,5
>200	$150/f_c$	130	$19\ 500/f_c$	$19\ 500/f_c$

* Maximum allowed value.

While the previous approach provides near-worst case coupling results for a thin-wire vertical dipole antenna (but without earth reflections), it is possible to provide probabilistic coupling information using a technique similar to that employed earlier in table 1. Using an approach which considers the variation of the angle of elevation with area coverage from a 100 km burst height, annex C provides detailed coupling results for two thin wire antennas. These include a vertical monopole antenna of length ℓ_m (including HEMP earth reflections) and a horizontal dipole antenna of length ℓ_h (without earth reflections), both with 50 Ω loads. These results are summarized in tables 4 to 6 for the vertical monopole antenna and tables 7 to 9 for the horizontal dipole.

Table 4 – HEMP response levels for V_{oc} for the vertical monopole antenna

Values are in kV

Length ℓ m	1 m			3 m			10 m			100 m		
Severity	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %
Dip angle												
0°	13,6	28,4	33,6	46,5	91,7	104,6	125,7	232,0	249,0	383,2	470,7	477,1
15°	13,1	27,0	32,4	45,1	88,5	101,1	125,3	226,2	240,5	365,5	454,0	461,0
30°	11,8	24,3	29,0	40,5	80,3	90,4	107,2	200,2	215,5	326,9	406,9	413,1
45°	9,5	19,5	23,7	32,7	64,9	73,8	89,0	164,3	175,9	273,6	332,3	337,3
60°	6,6	14,1	16,5	23,3	45,6	52,1	63,9	116,4	124,4	190,1	234,8	238,4
75°	3,5	7,2	8,6	12,0	23,9	26,9	33,2	60,1	64,3	98,8	121,6	123,3
90°	0	0	0	0	0	0	0	0	0	0	0	0

Table 5 – HEMP response levels for I_{sc} for the vertical monopole antenna

Values are in kA

Length ℓ m	1 m			3 m			10 m			100 m		
Severity	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %
Dip angle												
0°	0,08	0,19	0,22	0,33	0,66	0,70	1,12	1,74	1,91	3,13	3,68	4,37
15°	0,08	0,18	0,21	0,32	0,64	0,68	1,13	1,68	1,85	3,02	3,55	4,31
30°	0,07	0,16	0,19	0,28	0,57	0,61	0,96	1,50	1,65	2,71	3,25	4,13
45°	0,06	0,13	0,16	0,23	0,47	0,50	0,79	1,23	1,35	2,23	2,72	3,67
60°	0,04	0,10	0,11	0,16	0,33	0,35	0,57	0,87	0,95	1,57	1,94	2,73
75°	0,02	0,05	0,06	0,08	0,17	0,18	0,30	0,45	0,49	0,81	1,01	1,38
90°	0	0	0	0	0	0	0	0	0	0	0	0

Table 6 – HEMP response levels for I_L for the loaded vertical monopole antenna*

Values are in kA

Length ℓ m	1 m			3 m			10 m			100 m		
Severity	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %
Dip angle												
0°	0,06	0,15	0,17	0,23	0,49	0,55	0,76	1,31	1,33	2,37	2,71	3,53
15°	0,06	0,14	0,16	0,23	0,48	0,53	0,76	1,26	1,29	2,28	2,59	3,34
30°	0,05	0,13	0,15	0,20	0,43	0,47	0,65	1,13	1,15	2,03	2,32	3,00
45°	0,04	0,10	0,12	0,16	0,35	0,39	0,54	0,92	0,94	1,69	1,91	2,51
60°	0,03	0,07	0,08	0,12	0,25	0,27	0,39	0,65	0,67	1,17	1,35	1,79
75°	0,02	0,04	0,04	0,06	0,13	0,14	0,20	0,34	0,34	0,61	0,70	0,91
90°	0	0	0	0	0	0	0	0	0	0	0	0

* For the corresponding load voltage values, multiply these values by 50 Ω.

Table 7 – HEMP response levels for V_{oc} for the horizontal dipole antenna

Values are in kV

Length ℓ_h	1 m			3 m			10 m			100 m		
Severity	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %
Dip angle												
0°	0,8	4,0	11,5	2,8	13,5	44,0	7,9	37,9	110,4	19,0	99,8	289,1
15°	4,9	7,0	13,1	17,1	25,1	45,8	44,3	68,2	113,3	115,3	162,2	309,1
30°	8,9	12,5	15,4	31,0	45,6	53,9	81,3	128,1	154,6	211,9	291,0	367,3
45°	12,5	17,6	18,6	43,1	64,1	67,3	112,7	179,7	188,2	293,9	407,4	434,7
60°	15,1	21,4	21,9	52,5	78,2	79,8	136,2	218,6	224,0	355,4	495,9	508,0
75°	16,8	23,9	24,2	58,3	87,0	88,4	152,2	243,9	248,6	395,1	552,1	563,6
90°	18,0	24,6	25,1	60,0	89,9	91,5	159,4	251,7	257,2	404,8	573,1	583,3

Table 8 – HEMP response levels for I_{sc} for the horizontal dipole antenna

Values are in kA

Length ℓ_h	1 m			3 m			10 m			100 m		
Severity	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %
Dip angle												
0°	0,003	0,01	0,04	0,01	0,05	0,15	0,03	0,16	0,47	0,10	0,53	1,66
15°	0,02	0,02	0,04	0,06	0,09	0,17	0,19	0,27	0,48	0,55	0,81	1,71
30°	0,03	0,04	0,05	0,11	0,17	0,20	0,35	0,49	0,62	1,04	1,36	1,99
45°	0,04	0,06	0,06	0,15	0,24	0,25	0,49	0,69	0,73	1,47	1,87	2,27
60°	0,05	0,07	0,07	0,18	0,29	0,30	0,59	0,84	0,86	1,79	2,27	2,52
75°	0,05	0,08	0,08	0,20	0,32	0,33	0,65	0,94	0,96	2,00	2,52	2,65
90°	0,05	0,08	0,08	0,21	0,34	0,34	0,67	0,97	0,99	2,06	2,61	2,69

Table 9 – HEMP response levels for I_L for the loaded horizontal dipole antenna*

Values are in kA

Length ℓ_h	1 m			3 m			10 m			100 m		
Severity	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %	50 %	90 %	99 %
Dip angle												
0°	0,002	0,012	0,032	0,008	0,040	0,13	0,028	0,14	0,39	0,078	0,42	1,26
15°	0,014	0,020	0,036	0,050	0,078	0,14	0,16	0,23	0,40	0,45	0,65	1,33
30°	0,024	0,036	0,044	0,092	0,15	0,17	0,29	0,44	0,54	0,84	1,10	1,58
45°	0,034	0,050	0,054	0,13	0,20	0,22	0,41	0,61	0,64	1,17	1,51	1,83
60°	0,042	0,062	0,062	0,16	0,25	0,26	0,50	0,74	0,76	1,44	1,83	2,05
75°	0,046	0,068	0,070	0,17	0,28	0,29	0,55	0,83	0,85	1,60	2,04	2,18
90°	0,048	0,070	0,072	0,17	0,28	0,30	0,57	0,86	0,88	1,66	2,10	2,22

* For the corresponding load voltage values, multiply these values by 50 Ω.

5.6 HEMP internal conducted environments

As discussed previously, the internal conducted environments (inside of a building or installation) are more difficult to determine than the external conducted environments. The internal conducted signals are produced by external conducted signals which penetrate through a shield (with or without attenuation due to PoE hardening), and by any HEMP fields which are able to penetrate the building and couple to exposed wiring. Because there is a large variety of electromagnetic shield materials for buildings which range from wood construction to high-quality welded steel shield rooms, it is difficult to calculate the coupling to cables and other conductors inside a facility. It is, however, possible to define a simple procedure which will allow one to estimate the internal conducted transients.

The first step in the internal conductor problem is to recognize that the leakage of external conducted transients is a major consideration. One should take the conducted environments specified above and determine the type of protection present at the entry point into the facility. Using either analyses or test data, one can estimate the current waveform that penetrates the facility. It should be noted that if a non-linear device is present, it will probably be necessary to perform a test using IEC 61000-4-24, unless the amount of suppression is expected to be very high.

The second step is to estimate the amount of electromagnetic attenuation that will occur for the early-time HEMP radiated environment. (It is not necessary to evaluate the intermediate or late-time field attenuation because those low frequency fields will not couple well to the compact cable geometries present inside most facilities.) Defining A_t as the plane wave attenuation factor (for $f > 1$ MHz), D as the internal cable length of interest in metres, and B as an amplitude factor based on the severity factors introduced in table 1, one may estimate the peak internal common mode cable current I_{pk} as

$$I_{pk} = BDA_t \text{ for } D < 100 \text{ m} \qquad (4)$$

The amplitude parameter B in units of A/m has been developed so the product BD is consistent with the last column in table 1, elevated conductor; B is defined as 5,0 A/m, 7,5 A/m and 20 A/m for severity levels of 50 %, 90 % and 99 %, respectively. Therefore for a severity level of 50 %, a building attenuation factor of 0,01 (–40 dB) and a conductor length of 10 m, the peak coupled current is 0,5 A. As indicated in annex D, the current waveforms produced are expected to resemble damped sinusoids. Equations (2) and (3) should be employed assuming $\ell = D$ and $Q \geq 60$.

This process is not precise because the attenuation of an incident electromagnetic field is not uniform with frequency, especially if apertures are present. In addition, once the internal field is established, there are often many cables present that make accurate coupling calculations difficult. Finally, the size and shape of a facility will produce cavity modes that will impact the waveshape of the coupled currents. In spite of these difficulties, this procedure can provide a rough estimate of the internal conducted currents.

A second alternate procedure for estimating internal conducted currents I_{pk} due to HEMP includes the direct use of data collected in the past for three classes of building construction. As provided in annex D, the 50 %, 90 %, and 99 % severity currents are given for concrete block, riveted metal and poured concrete construction. 50 % peak-to-peak currents are 10 A, 10 A and 3 A for the three construction methods, while the 99 % values are 25 A, 25 A and 7 A, respectively. These internal currents are due only to external HEMP field coupling and do not include the contribution of currents which enter through penetrating conductors. The time waveforms of the currents are found using equations (2) and (3), with $f_c = 7$ MHz and $Q \geq 60$.

A third (and most accurate) procedure for deriving the internal conductor currents is through experimental measurements. The procedure usually involves the use of a continuous wave simulator over the range of 100 kHz to 500 MHz. The building is exposed at several positions for different angles of elevation and field polarizations while measuring the internal cable currents. The transfer functions are then convolved with the incident early-time HEMP waveform to compute internal cable current waveforms. It is usually necessary to evaluate the variation of the current waveform peak values and pulse shapes to develop composite waveforms for equipment testing purposes.

It is important to recognize that the three procedures indicated here provide only the internal currents due to direct HEMP field coupling. It is necessary to estimate (or measure) the leakage of external currents through the facility walls (including surge protection) to determine the contribution of the external currents to the total internal currents.

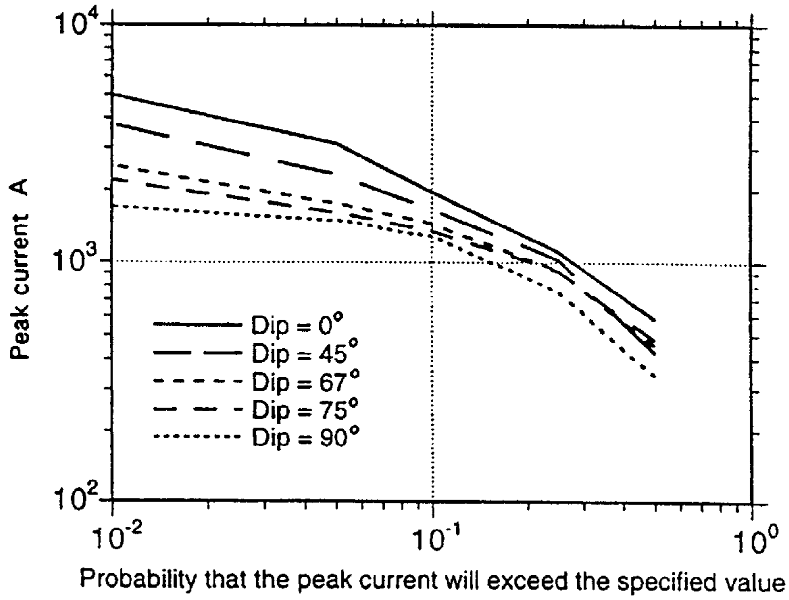
Annex A
(informative)

Discussion of early-time HEMP coupling for long lines

A.1 Elevated lines

The results presented earlier in table 1 were produced from a series of probabilistic coupling calculations from Ianoz et al [A.1]*. In these calculations, the authors used the IEC early-time HEMP electric field pulse as defined in IEC 61000-2-9 to compute the coupling (short-circuit current) to a 10 m high, 1 km long line over a ground with a 10^{-2} S/m conductivity. The calculations were performed separately for both 100 % horizontal and 100 % vertical polarization. For each polarization, angles of elevation ψ and azimuth ϕ between the incident field propagation vector and the line were varied over a 2,5° mesh. These results were saved and recombined for any burst height and earth location (by the geomagnetic latitude) of interest.

Figure A.1 presents a summary of the calculations for a 100 km burst for five magnetic dip angles (0°, 45°, 67°, 75° and 90°). For the coupling results, the 0° degree results were not used here because the coupling calculations did not consider the reduction of the HEMP electric field due to the lower value of earth's magnetic field at the magnetic equator. This would result in a reduction of the incident field and the coupled currents by 30 % to 40 %. From the results shown (θ_{dip} > 45°) in figure A.1, the selection of 4 000 A for 1,0 % of the cases, 1 500 A for 10 %, and 500 A for 50 % is indicated (within 10 % accuracy). The 1 %, 10 %, and 50 % probabilities discussed in this annex are equivalent to the 99 %, 90 % and 50 % severity levels discussed in clause 5.



IEC 1 534/98

Figure A.1 – Variation of peak coupled cable current versus local geomagnetic dip angle

* The figure in square brackets refers to the reference document in clause A.3.

For the time waveform current characteristics presented in this standard, the study performed in [A.1] also considered several waveform characteristics including the waveform rise time (10 % – 90 %) and the rectified impulse which is the pulse area for a monopolar pulse. The rectified impulse values for the vertical polarizations are given in table A.1 along with the computation of the effective pulse width, Δt_{pw} r.m.s. (rectified impulse divided by peak), using the specified peak currents.

Table A.1 – Rectified impulse (*RI*) and computed effective pulse widths for vertical polarization of the early-time HEMP for an elevated conductor (*h* = 10 m)

Probability %	*RI* > A × s	Peak *I* > A	Δt_{pw} r.m.s. ns
50	$3,7 \times 10^{-5}$	500	74
10	$1,9 \times 10^{-4}$	1 500	127
1	$3,0 \times 10^{-4}$	4 000	75

For this evaluation a maximum effective pulse width of 127 ns is selected and is translated into a pulse width at half maximum of 88 ns by assuming an exponentially decaying waveform. This is approximated as 100 ns in table 1.

The evaluation of the rise time characteristics was more difficult for this coupling study. The 10 % – 90 % rise time was tabulated in [A.1] for both horizontal and vertical HEMP polarization. The results indicated minimum rise times of 2,3 ns and 5,1 ns for horizontal and vertical field polarization. After careful examination it was found that these rise times did not occur when the peak currents were the largest. Since the derivative itself was not tabulated in that study, additional calculations were required.

For complete vertical polarization of the IEC electric field pulse, a maximum current derivative of $2,7 \times 10^{11}$ A/s was calculated at an elevation angle of 5° for the same coupling geometry used in [A.1]. This maximum value was found from a series of calculations, and the peak value of the coupled current was maximized at the same angle. For the specified 1 % probability case, the computed 10 % – 90 % rise time is:

$$(0,8) \times (4\,000 \text{ A})/(2,7 \times 10^{11} \text{ A/s}) = 1,2 \times 10^{-8} \text{ s}$$

For the purposes of this document, a rise time of 10 ns was selected. Although it appeared likely that slower rise times would be appropriate for the more probable cases, calculations showed that the 50 % case indicated a rise time of 14,4 ns. Therefore given the relatively small difference, the same pulse rise time is used for all cases in table 1.

A.2 Buried line coupling

For buried communications or power lines, the coupled HEMP signal does not vary substantially with field polarization or angle, although the near-surface ground conductivity is of some importance. HEMP calculations using the IEC pulse were performed for a line buried at a depth of 1,0 m in three ground conductivities: 10^{-2} S/m, 10^{-3} S/m and 10^{-4} S/m. The results of 42 calculations which considered variations in angles of elevations and field polarization are summarized below in table A.2.

Table A.2 – Coupled early-time HEMP currents for a buried conductor (z = –1 m)

σ_g S/m	Polarization	Max I_{sc} A	ψ degrees
10^{-2}	V	152	60
10^{-2}	H	148	90
10^{-3}	V	332	45
10^{-3}	H	267	90
10^{-4}	V	437	30
10^{-4}	H	418	90

For the two lower conductivities, these values are rounded to the nearest 100 A in table 1 (10^{-3} – 300 A, 10^{-4} – 400 A) which creates in both cases a 10 % reduction. For the higher conducting ground entries shown in table A.2, the current is adjusted upward to 200 A to account for the higher field levels nearer to the earth's surface (appropriate for shallower burial depths).

In terms of the waveshapes to be used, the range of 10 % – 90 % rise times and pulse widths at half maximum are given in table A.3 below.

Table A.3 – Waveform parameters for early-time HEMP buried conductor coupling (z = –1 m)

σ_g S/m	Polarization	Δt_r (10 % – 90 %) ns	Δt_{pw} (50 % – 50 %) ns
10^{-2}	V	26,7 – 34,7	185 – 355
10^{-2}	H	17,6 – 19,5	263 – 282
10^{-3}	V	25,0 – 29,2	198 – 398
10^{-3}	H	19,3 – 26,5	236 – 267
10^{-4}	V	27,0 – 29,8	309 – 583
10^{-4}	H	27,4 – 29,3	361 – 458

Averaging the variations provided in table A.3 for each ground conductivity, table A.4 indicates the results.

Table A.4 – Average waveform parameters for early-time HEMP buried conductor currents

σ_g S/m	Δt_r (10 % – 90 %) ns	Δt_{pw} (50 % – 50 %) ns
10^{-2}	24,6	271
10^{-3}	25,0	275
10^{-4}	28,4	428

Given this information, it is recommended that a rise time of 25 ns be used. For the pulse width, the variations are stronger with ground conductivity, and a value of 500 ns is recommended (rather than 400 ns) to cover the larger pulse widths computed (see table A.3) for low ground conductivity. These values are applied in table 1.

A.3 Reference document

[A.1] Ianoz, M., Nicoara, B. and Radasky, W.A., *Modelling of an EMP Conducted Environment,* IEEE/EMC Transactions on EMC, Vol. 38, No. 3, p. 400-413, August 1996

Annex B
(informative)

Discussion of intermediate-time HEMP coupling for long lines

The short-circuit results presented in table 2 were produced from a series of 70 HEMP coupling calculations for an elevated (h = 10 m) and buried (h = –1 m) conductor. The study considered variations in line length (1 km – 100 km), angle of elevation (0° – 85°) and ground conductivity (10^{-2} S/m, 10^{-3} S/m and 10^{-4} S/m). A time-dependent transmission line code was employed for the calculations, and the IEC incident intermediate-time waveform was used assuming vertical polarization.

B.1 Elevated lines

For lines greater than 10 km in length, the maximum peak short-circuit currents and waveform characteristics are shown in table B.1.

Table B.1 – Coupled HEMP intermediate-time short-circuit currents for an elevated conductor (h = 10 m)

Ground conductivity S/m	I_{pk} A	Δt_r (10 % – 90 %) µs	Δt_{pw} r.m.s. µs
10^{-2}	138	60 – 120	700 – 2 100
10^{-3}	342	25 – 65	850 – 2 100
10^{-4}	849	30 – 65	1 000 – 2 100

For shorter lines, the peak currents are reduced but the pulse characteristics are similar. Recommended values for the peak currents are approximated as 150 A, 350 A and 850 A in table 2. The pulse characteristics can be approximated to provide a rise time of 25 µs and an effective pulse width of 2 100 µs; this effective pulse width is converted to a pulse width at half maximum of 1 500 µs.

B.2 Buried lines

For buried lines longer than 1 km, the peak currents calculated are nearly constant, varying only with the ground conductivity. For line lengths shorter than 1 km, length scaling is appropriate. Angle of incidence variations for elevation angles from 0° to 85° indicate a variation of less than 10 %. Table B.2 presents the summary of the HEMP calculations.

Table B.2 – Coupled HEMP intermediate-time short-circuit currents for a buried conductor (h = –1 m)

Ground conductivity S/m	I_{pk} A	Δt_r (10 % – 90 %) µs	Δt_{pw} r.m.s. µs
10^{-2}	46	38 – 57	1 800 – 2 000
10^{-3}	147	40 – 61	1 900 – 2 100
10^{-4}	431	46 – 78	1 900 – 2 100

The results shown above can be approximated for peak values of 50 A, 150 A and 450 A by a single pulse waveform with a rise time (10 % – 90 %) of 40 µs and an effective pulse width of 2 100 µs. Converting the effective pulse width to a half width (assuming an exponential decay) yields a value of 1 455 µs or 1 500 µs. Because the waveform characteristics are similar for both elevated and buried lines, only a single waveform is required in table 2, and the values of 25 µs and 1 500 µs are used.

Annex C
(informative)

Responses of simple linear antennas to the IEC early-time HEMP environment

C.1 Introduction

For the understanding of the protection requirements of civilian systems against the effects of a high-altitude electromagnetic pulse (HEMP), it is useful to have an indication of the possible responses of various types of antennas. The analysis of antennas is a mature discipline, with many different calculational models available for use in determining typical responses [C.1]*. However, the analysis of antennas is frequently conducted only in the in-band (i.e. the operational) frequency range, and this is not particularly useful for obtaining the transient response of an antenna, in which a very wide-band analysis is required.

Furthermore, when a transient response of an antenna is conducted, the results are often presented in the form of a transient waveform for a limited number of angles of incidence of the excitation. Thus, a global understanding of the behaviour of the antenna and its typical responses usually is not available.

One way of remedying this situation is to perform a large number of individual transient antenna calculations for different angles of incidence of the HEMP and then to present the results of the antenna response (e.g., the peak value of the open-circuit voltage of the antenna) in the form of a cumulative probability distribution (CPD) which provides an indication of the probability of a response of the antenna exceeding a specified value. In this standard, the responses of two different antennas are determined for the IEC early-time HEMP environment. The antennas are a vertical monopole antenna which is assumed to be fed against the earth, and a horizontal dipole antenna which is located above the earth. In each of these cases, the observables considered are the peak values of the open-circuit voltage (V_{oc}), the short-circuit current (I_{sc}), the peak voltage across a 50 Ω load connected to the input of the antenna (V_L), and the corresponding peak current flowing through the 50 Ω load (I_L).

C.2 The IEC early-time HEMP environment

As described in IEC 61000-2-9, the HEMP is represented by an incident plane wave shown in figure C.1 which is incident on a system on or near the ground with a vertical angle of elevation ψ and an azimuthal angle of incidence ϕ, which is measured with respect to some convenient reference direction (the x-axis).

Because of the spherical earth geometry, only a limited area on the earth's surface is directly illuminated by the HEMP fields. As shown in figure C.2, the illuminated region on the earth is defined by the tangent radius R_t, which is given by the expression

$$R_t = R_e \arccos\left(\frac{R_e}{R_e + HOB}\right) \tag{C.1}$$

where HOB is the height of the burst, and R_e is the earth radius (6 371,2 km). For HOB < 500 km, this expression is approximated by

$$R_t \approx 110\sqrt{HOB} \quad \text{units in km} \tag{C.2}$$

* References in square brackets refer to the reference documents in C.6.

For the present study, we assume that the burst is located at a height of 100 km. This implies that the tangent radius is $R_t \approx 1\ 100$ km.

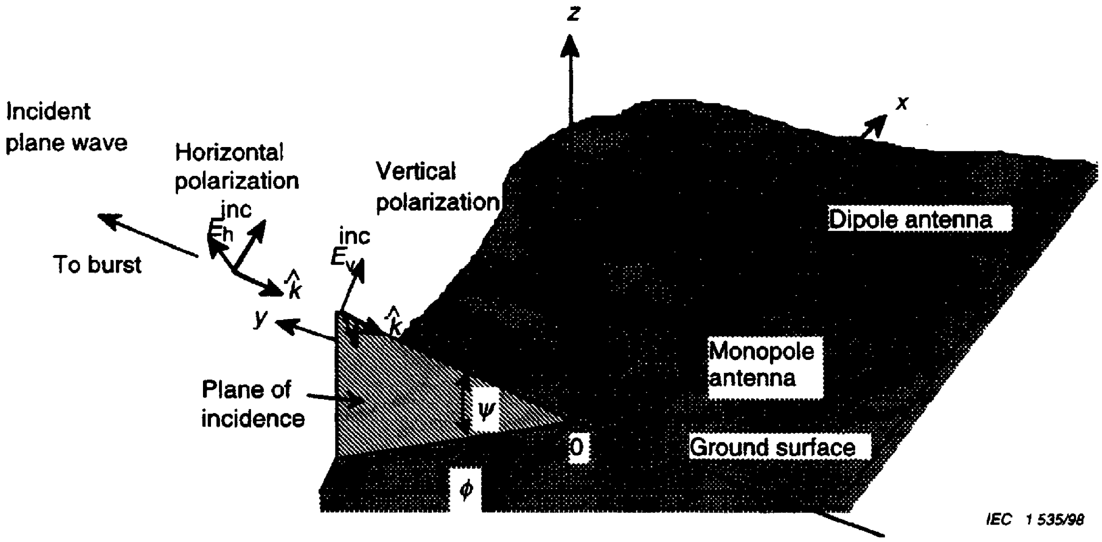


Figure C.1 – Illustration of the incident HEMP field

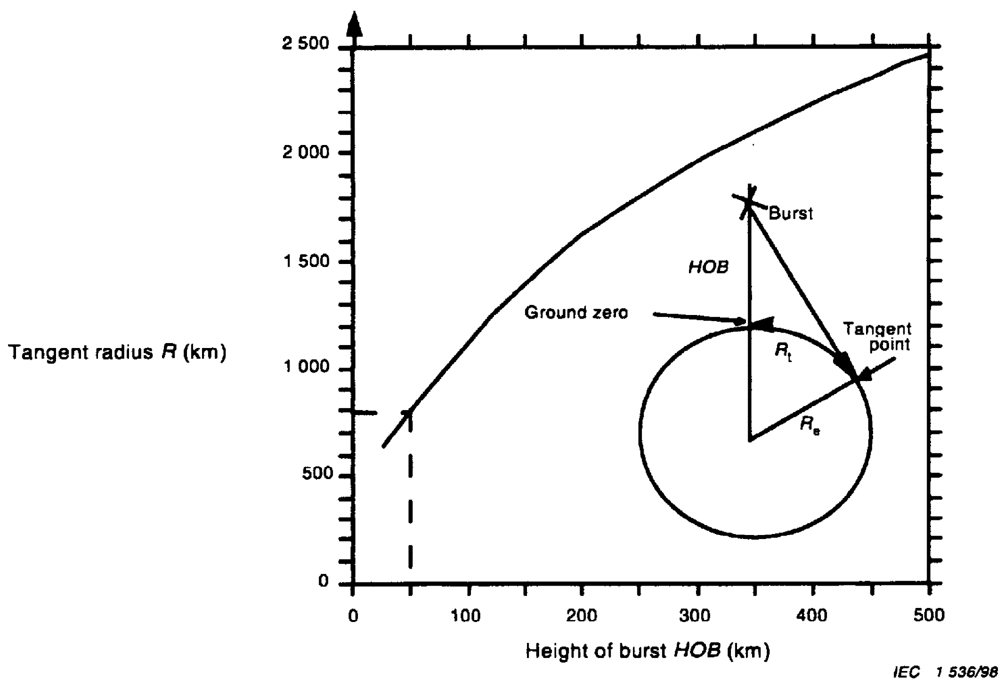


Figure C.2 – The HEMP tangent radius R_t defining the illuminated region, shown as a function of burst height (*HOB*)

Outside the illuminated region, the HEMP fields are taken to be zero. Within this region, the incident field is assumed to have a time history given by a double exponential waveform of the form

$$E^{inc}(t) = 65\,000\left(e^{-4\times 10^{7}t} - e^{-6\times 10^{8}t}\right) t > 0 \text{ (V/m)} \tag{C.3}$$

and is decomposed into vertically and horizontally polarized components, as indicated in figure C.1.

As discussed in IEC 61000-2-9, the division of the incident HEMP field into vertical and horizontal components depends on the dip angle of the geomagnetic field θ_{dip}. This parameter varies with the locations of the burst and observer, and hence, it is treated as an independent variable in this study: responses for different values of θ_{dip} are calculated. The vertical and horizontal components of the incident field are denoted by E_v^{inc} and E_h^{inc} and are given in terms of the polarization fractions f_v and f_h, as $E_v^{inc} = f_v E^{inc}$ and $E_h^{inc} = f_h E^{inc}$. For this study we have approximated the polarization fractions at their maximum values, $f_v = \cos\theta_{dip}$ and $f_h = \sin\theta_{dip}$.

As shown in figure C.1, the two antennas considered are a vertical monopole antenna mounted on the earth, and a horizontal dipole antenna extended parallel to the earth. To compute the induced current in these antennas, it is necessary to know the tangential excitation E-field along the antennas. This field consists of the incident HEMP field, plus the ground-reflected field. For the vertical monopole, the excitation field is z-component of the E-field, which at any height z, is given as [C.2].

$$E_z = E^{inc}\cos\theta_{dip}\cos\psi\left(1 - R_v e^{-jk2z\sin\psi}\right) \tag{C.4}$$

where R_v is the Fresnel reflection coefficient for a vertically polarized field, given by [C.3]:

$$R_v = \frac{\varepsilon_r\left(1+\frac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right)\sin\psi - \left[\varepsilon_r\left(1+\frac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right) - \cos^2\psi\right]^{1/2}}{\varepsilon_r\left(1+\frac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right)\sin\psi + \left[\varepsilon_r\left(1+\frac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right) - \cos^2\psi\right]^{1/2}} \tag{C.5}$$

where σ_g is the electrical conductivity of the ground, ε_r is the relative permittivity of the ground and ε_o is the free-space permittivity. Notice that for this vertical field, only the vertically polarized component of the incident HEMP field contributes to the response.

For the horizontal antenna, which is assumed to be parallel to the x-axis, the E_x field component at a height h over the ground is required as the excitation. This field is expressed in terms of both the vertically polarized and horizontally polarized waveform components as [C.2]:

$$E_x = E^{inc} e^{-jkx\cos\psi\cos\phi}\left[\cos\theta_{dip}\sin\psi\cos\phi\left(1 - R_v e^{-jk2h\sin\psi}\right) + \sin\theta_{dip}\sin\phi\left(1 + R_h e^{-jk2h\sin\psi}\right)\right] \tag{C.6}$$

where the Fresnel reflection for the horizontal field, R_h, has been introduced. This is also given in [C.3] as

$$R_h = \frac{\sin\psi - \left[\varepsilon_r\left(1+\frac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right) - \cos^2\psi\right]^{1/2}}{\sin\psi + \left[\varepsilon_r\left(1+\frac{\sigma_g}{j\omega\varepsilon_r\varepsilon_o}\right) - \cos^2\psi\right]^{1/2}} \tag{C.7}$$

C.3 Evaluation of the antenna responses

Given the tangential excitation fields of equations (C.4) and (C.6), together with a specification of the antenna length, radius and load impedance, the induced currents on a given antenna and in the loads can be computed by using the method of moments [C.4]. This is a numerical procedure which solves the frequency-dependent integral equation for the current. Once the frequency domain spectrum of the response is computed, the transient response is computed using the fast Fourier transform (FFT). Details of such calculations are presented in references [C.5] and [C.6].

C.3.1 The monopole antenna

Figure C.3 illustrates the geometry of the vertical monopole used in this study. As noted in equation (C.4), the excitation field is independent of the azimuthal angle ϕ. Consequently, only the vertical angle of elevation ψ enters into the calculation. The monopole has a length L, a radius a, and has a 50 Ω load at the base of the antenna connected to the ground. For such antennas, it is common to specify the length to radius ratio through a parameter Ω_0, defined as

$$\Omega_0 = 2 \ln \left(\frac{2L}{a} \right) \qquad \text{(C.8)}$$

For the present calculation, the parameter $\Omega_0 = 8$, which corresponds to an L/a ratio of 27,3, represents a reasonably thick antenna.

In these calculations, the earth is taken to have a conductivity σ_g = 0,01 S/m and a relative permittivity ε_r = 10, which are typical values according to [C.3].

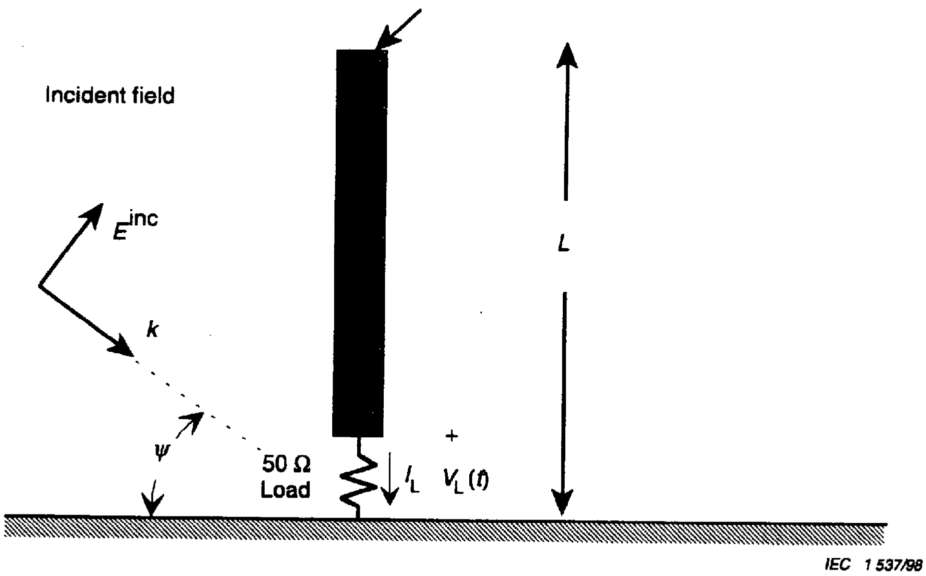


Figure C.3 – Geometry of the monopole antenna.

For this antenna (as well as for the dipole to be discussed in C.3.2, four quantities have been calculated: the open-circuit voltage (V_{oc}) at the source "gap" located at the base of the antenna, the short-circuit current (I_{sc}) flowing at the base of the antenna, the loaded voltage (V_L) across the impedance at the input of the antenna, and the corresponding load current (I_L). All of these quantities are related by the integral equation for the antenna current as described by Harrington [C.4]. Because of the simple v-i relationship at the load impedance, the load voltage and load current are related trivially by $V_L = Z_L I_L$. Of special interest here is the peak value of the transient responses, and these are the quantities actually extracted and retained as the calculation progresses.

The determination of the CPDs for the above observables involves performing a large number of calculations of the antenna responses as an observation point is chosen at random in the illumination region. Typically, 3 000 distinct observation locations have been used and for each location, the solution of the integral equation is used to provide a knowledge of the observable values. This leads to a distribution of responses and ultimately to the CPD, which provides the probability of a particular response exceeding a specified value.

C.3.2 The dipole antenna

The geometry of the horizontal dipole antenna is shown in figure C.4. The excitation function for this antenna depends on both the ϕ and ψ angles of incidence, as well as on both polarization components of the incident field. For this antenna, the total length is denoted by L, the radius is a, and the load impedance is again chosen to be 50 Ω. The length to radius ratio for this case is defined as

$$\Omega_0 = 2 \ln \left(\frac{L}{a}\right)$$

where again the parameter $\Omega_0 = 8$ has been used. This corresponds to an L/a ratio of 54,6.

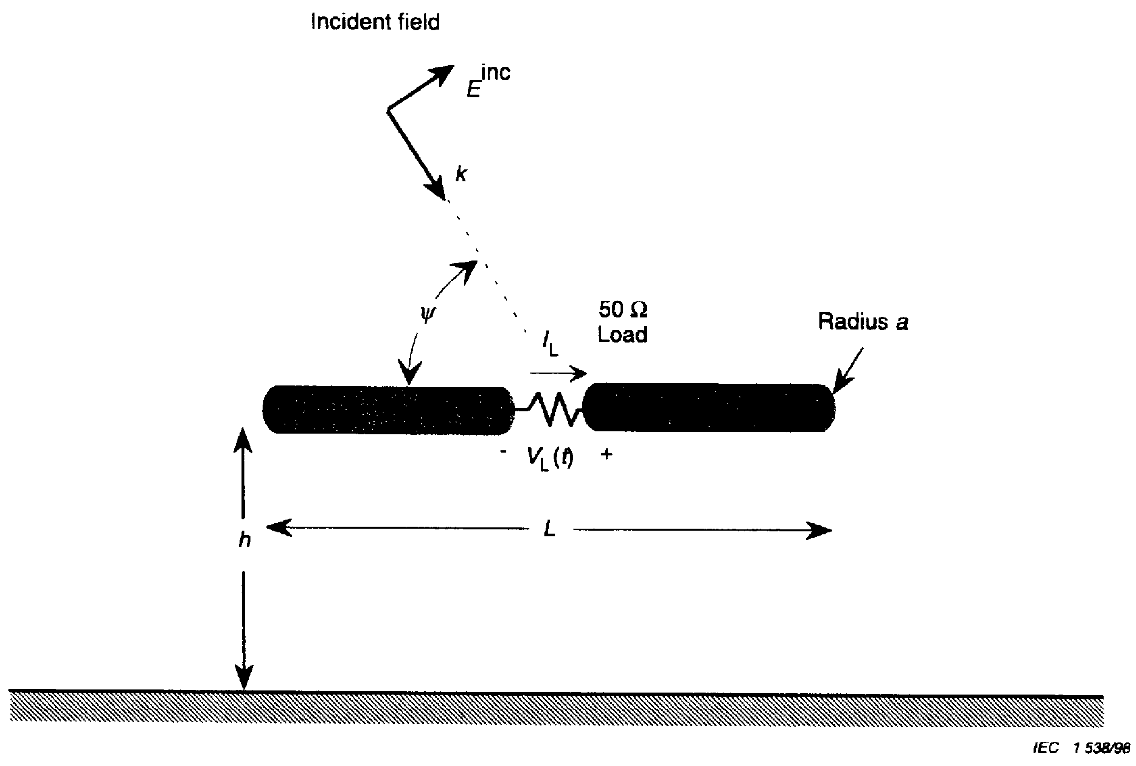


Figure C.4 – Geometry of the dipole antenna

The presence of the ground plane has caused another parameter to be needed in describing the geometry – namely the height of the antenna over the ground, h. As noted in equation (C.6), the excitation of the antenna arises from the incident field plus a ground-reflected contribution. Typically, the ground-reflected excitation tends to induce an antenna response that cancels the response induced by the incident field. However, this cancelling excitation contribution usually arrives at the antenna after the first peak in the response has occurred. Thus, the earth-reflected field often has no impact on the peak values of the response for antennas that are higher than $L/2$ over the ground. Therefore, a good estimate of the worst case response of the antenna is provided by neglecting the ground reflection completely, and treating the antenna as if it were in free-space. This is certainly reasonable, as these types of antennas are usually located far from the earth in order to optimize their in-band operational characteristics.

Calculations for the CPDs of the dipole antenna responses are carried out in the same way as for the monopole antenna, except that the variations of the angle ϕ shall also be taken into account. This is done by assuming that for a fixed antenna direction (along the x-axis), the angle ϕ can take any value between 0° and 360° with equal probability. For these calculations, a total of 3 000 antenna locations within the illuminated region were used, with a total of 500 values of ϕ being used for each antenna location. This required a total of 1,5 million coupling cases to be considered to generate the probability curves.

C.4 Calculated results

Using the previously discussed analysis procedure and numerical models, the CPDs for the four antenna responses to the IEC early-time HEMP environment have been calculated for both antenna types. For this study, four different values of length L have been used: L = 1 m, 3 m, 10 m and 100 m for both the monopole and the dipole antennas. These results are presented in this clause.

The computed CPDs for the vertical monopole antenna load currents and voltages are presented in figures C.5, C.6, C.7, and C.8, for the four different monopole lengths.

Similarly, the CPDs for the horizontal dipole antenna load currents and voltages are presented in figures C.9, C.10, C.11, and C.12, for the four different dipole lengths.

C.5 Summary of results

The probability curves of figures C.5 through C.12 provide significant detail as to the possible antenna behaviour subject to HEMP excitation. Frequently, however, only the responses for the 50 %, 10 % and 1 % cumulative probability levels are desired. These are referred to in this standard as the 50 %, 90 % and 99 % "severity levels", respectively, which indicates the percentage of antenna cases having a response less than the indicated response level. These values can be found in tables 3 to 9.

All of these results have been calculated for an antenna parameter $\Omega_0 = 8$, which corresponds to an L/a ratio of 27,3 for the monopole and an L/a ratio of 54,6 for the dipole. If a different aspect ratio for the antenna is desired, the antenna responses would change. Figure C.13 presents multiplicative correction factors, normalized to unity for $\Omega_0 = 8$, which may be applied to the data of this annex, and tables 4 to 9, to yield data for different antennas.

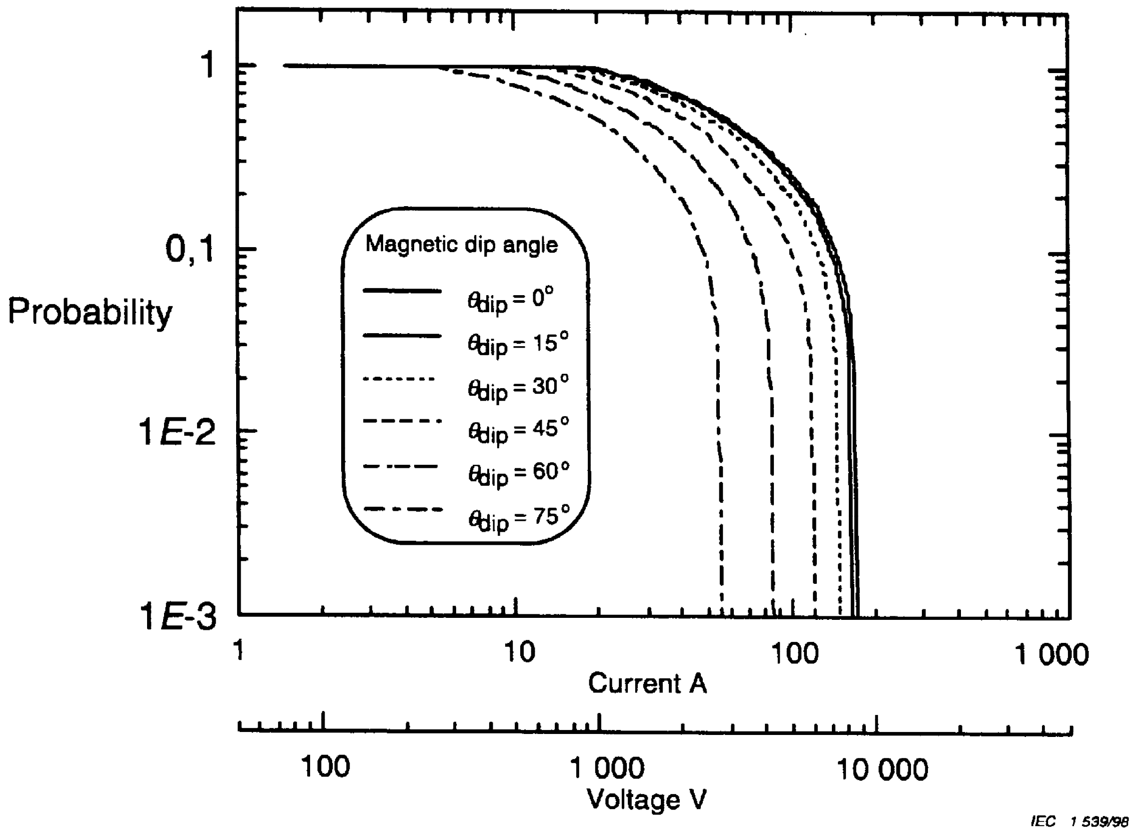


Figure C.5 – Cumulative probability distributions for the peak responses for the 1 m vertical monopole antenna load currents and voltages

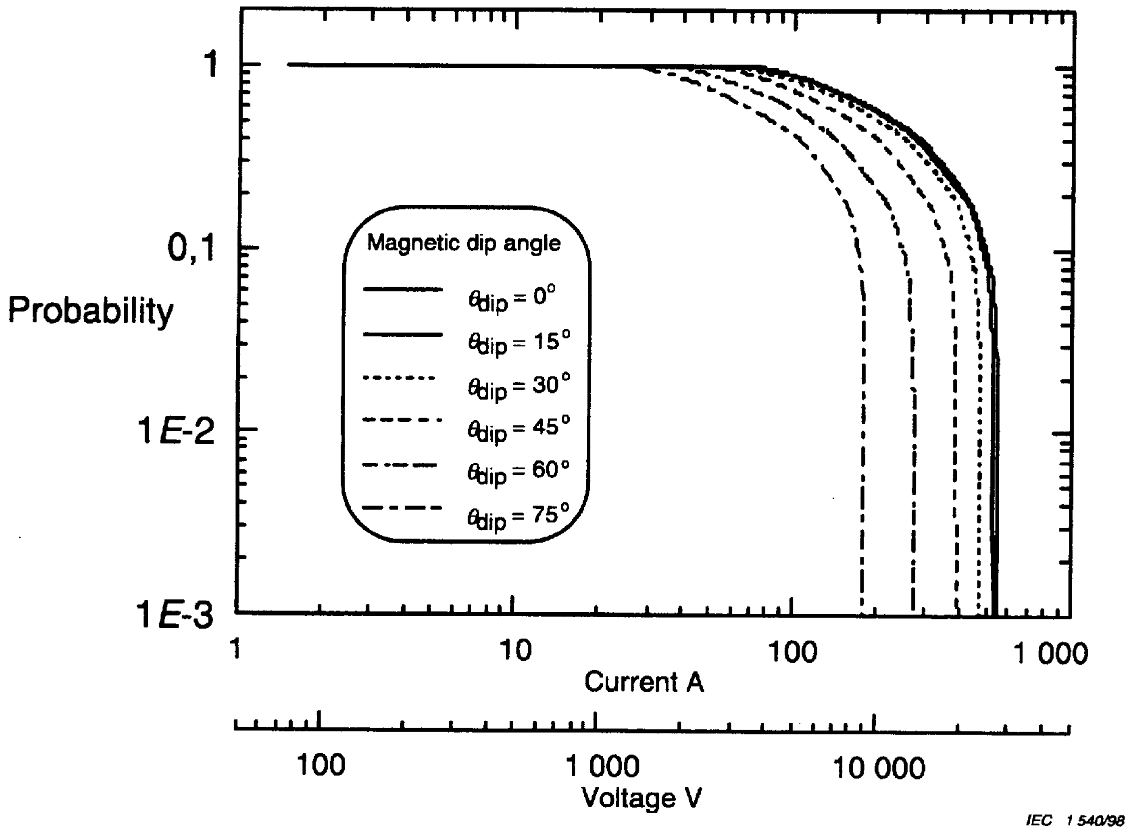


Figure C.6 – Cumulative probability distributions for the peak responses for the 3 m vertical monopole antenna load currents and voltages

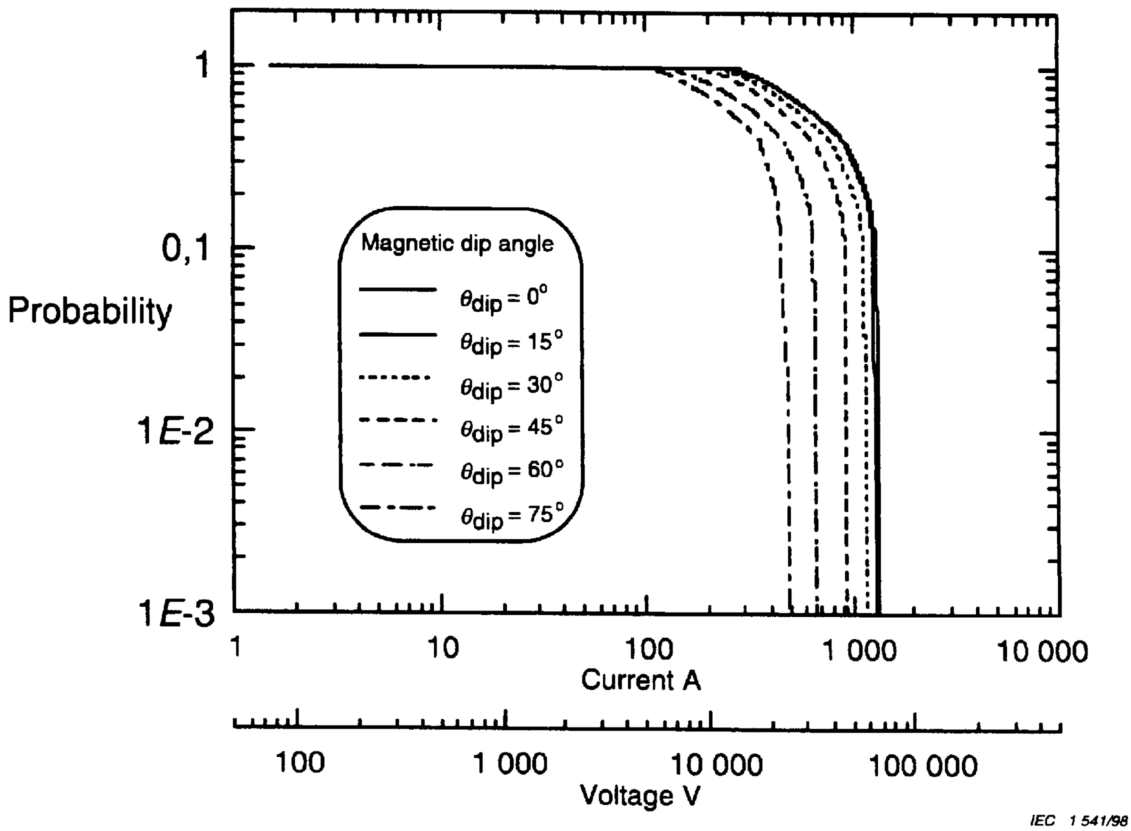


Figure C.7 – Cumulative probability distributions for the peak responses for the 10 m vertical monopole antenna load currents and voltages

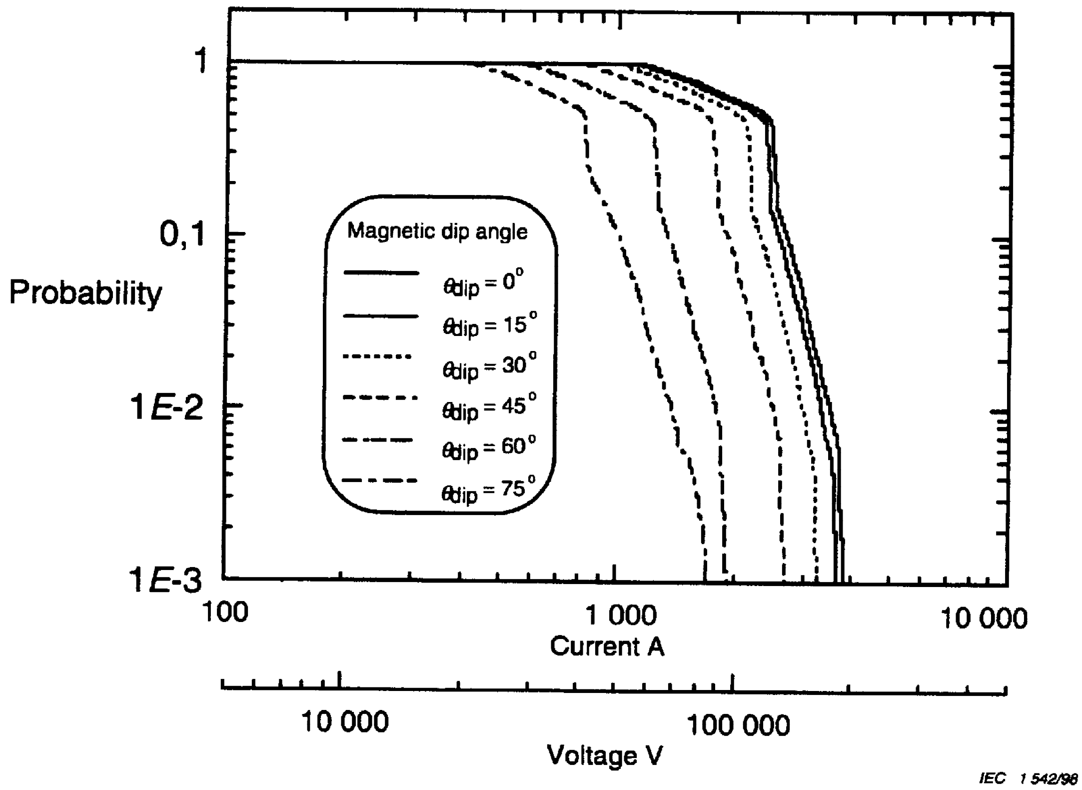


Figure C.8 – Cumulative probability distributions for the peak responses for the 100 m vertical monopole antenna load currents and voltages

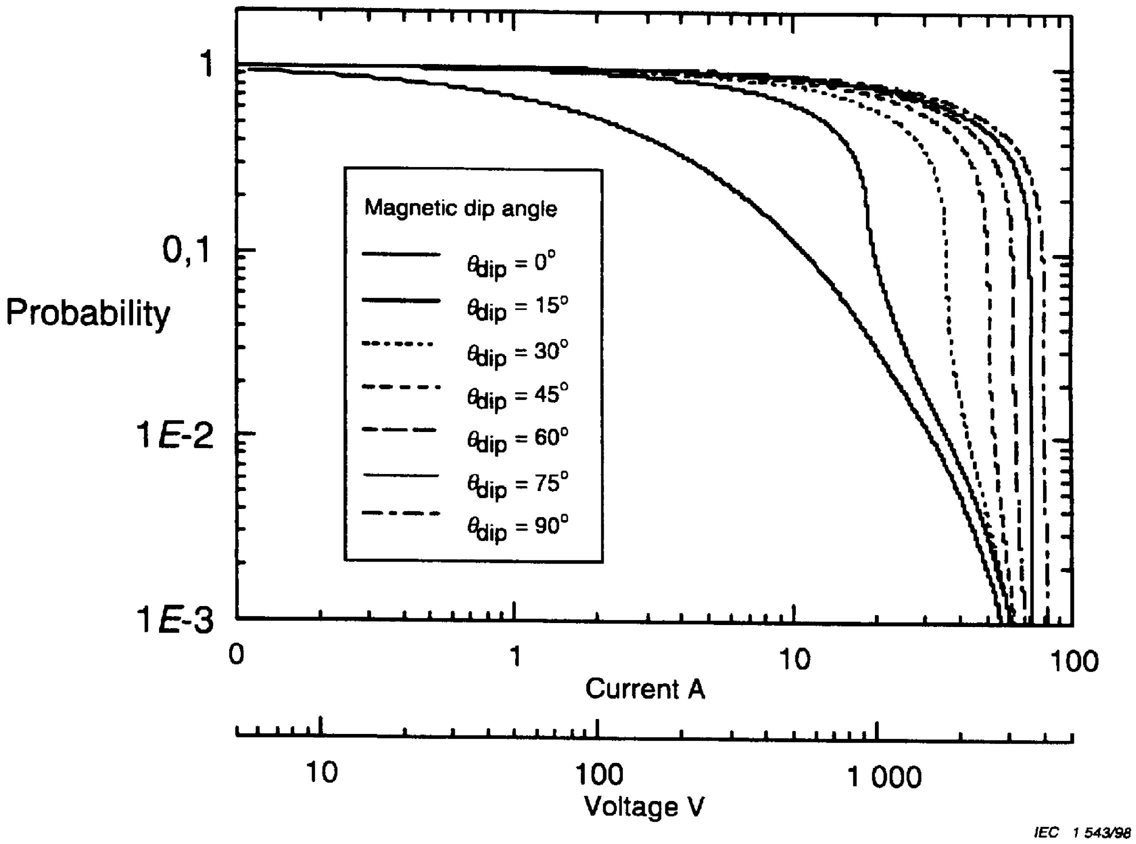


Figure C.9 – Cumulative probability distributions for the peak responses for the 1 m horizontal dipole antenna load currents and voltages

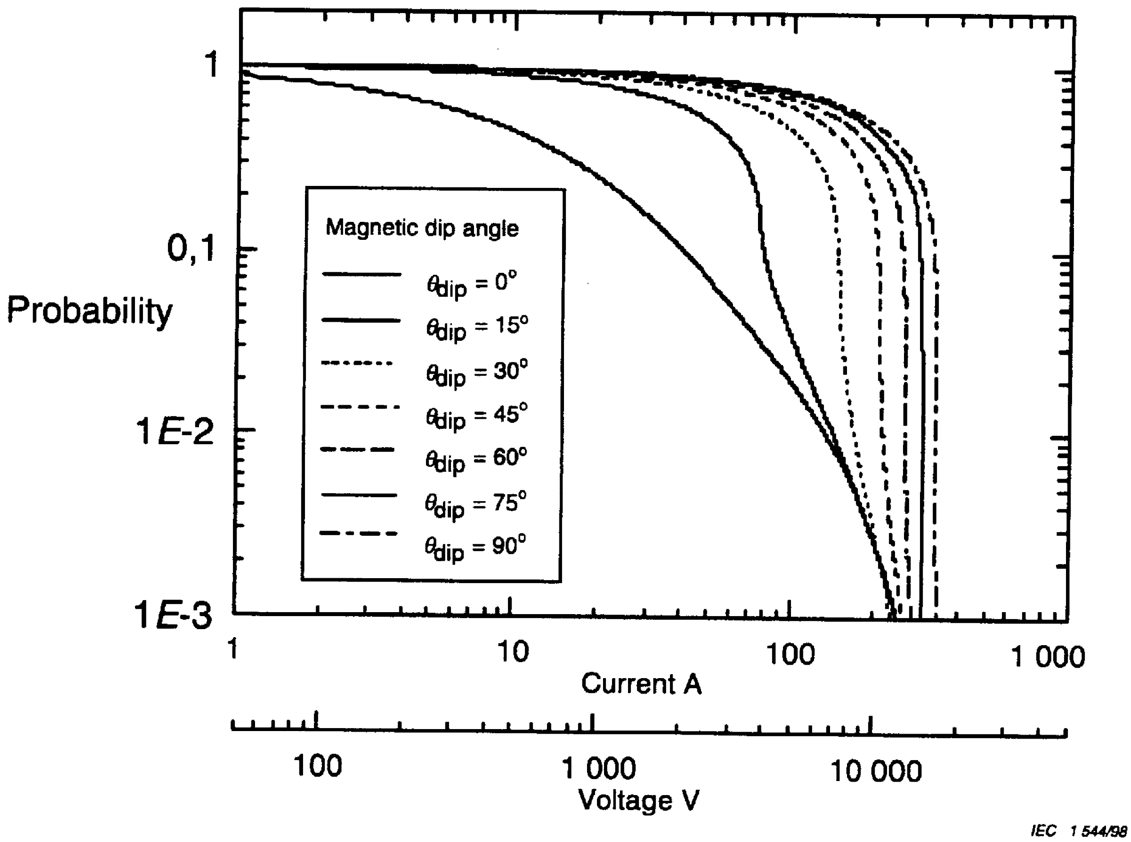


Figure C.10 – Cumulative probability distributions for the peak responses for the 3 m horizontal dipole antenna load currents and voltages

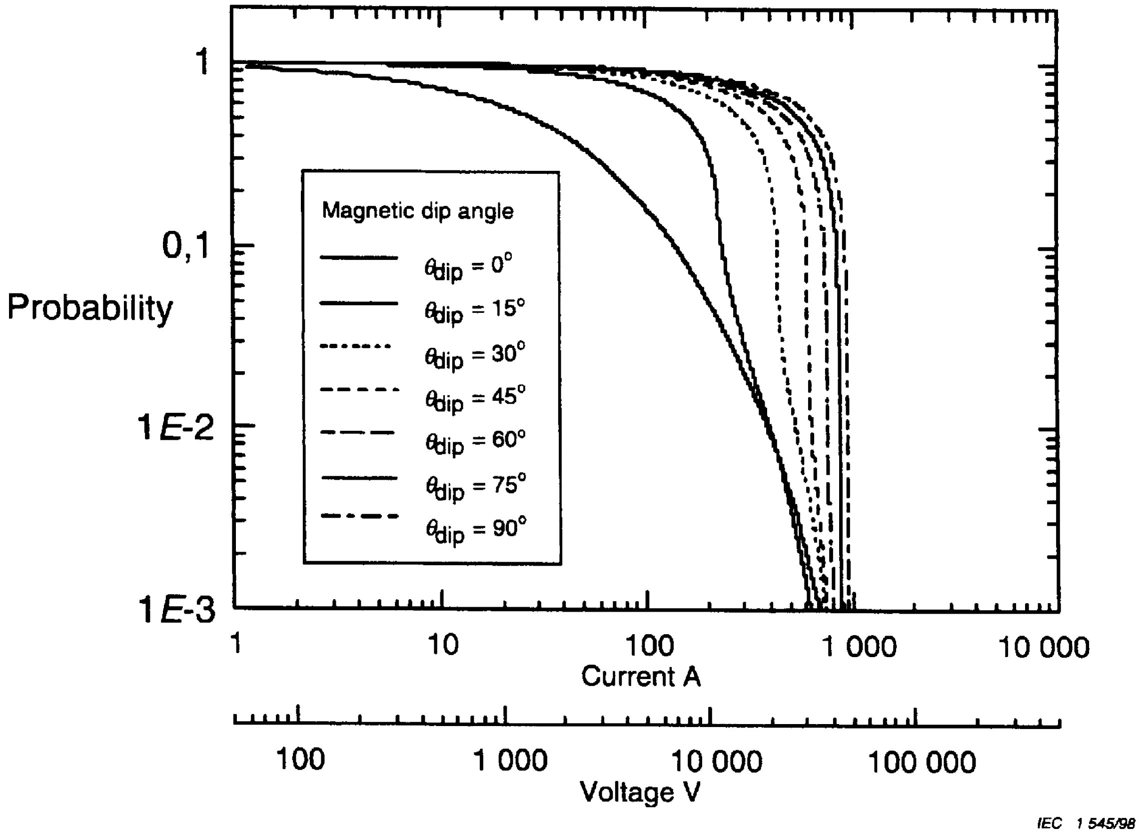


Figure C.11 – Cumulative probability distributions for the peak responses for the 10 m horizontal dipole antenna load currents and voltages

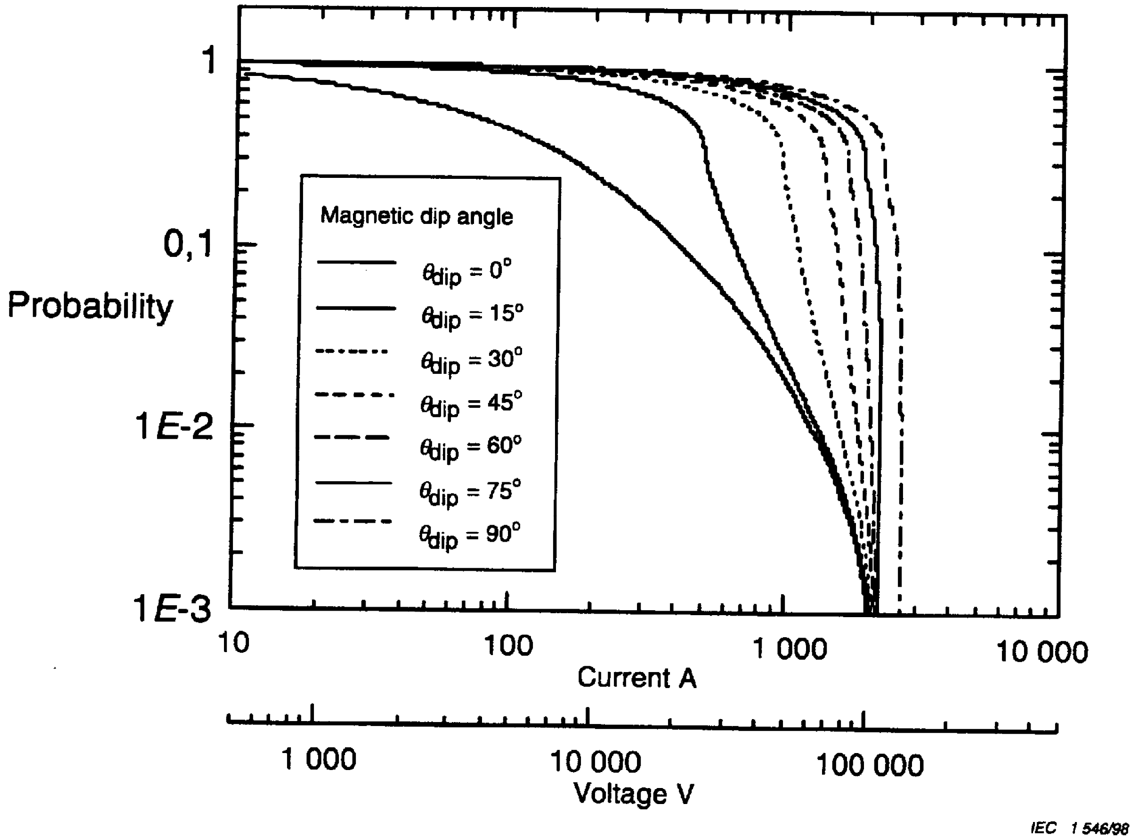


Figure C.12 – Cumulative probability distributions for the peak responses for the 100 m horizontal dipole antenna load current and voltages

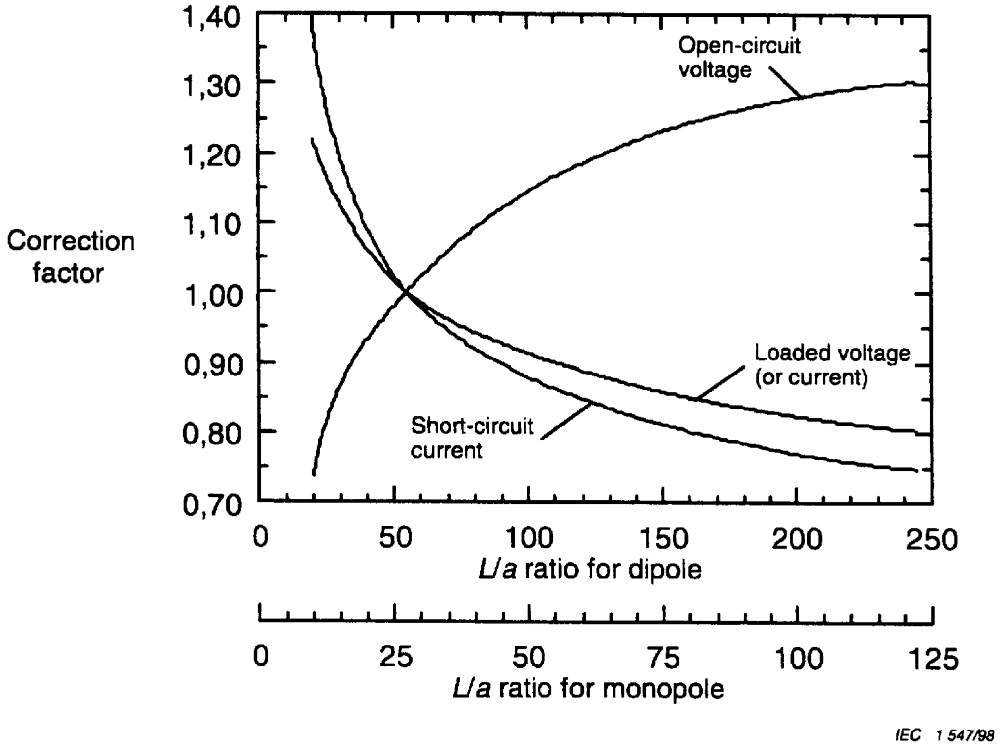


Figure C.13 – Plot of multiplicative correction factors for correcting the values of V_{OC}, I_{SC}, I_L and V_L for antennas having other L/a ratios

C.6 Reference documents

[C.1] *EMP Interaction: Principles, Techniques and Reference Data*, K.S.H. Lee, editor, Hemisphere Publishing Co. New York, 1989.

[C.2] Tesche, F.M. "Plane Wave Coupling to Cables," Chapter 4 in *Handbook of Electromagnetic Compatibility*, R. Perez, editor, Academic Press, 1995.

[C.3] Vance, E.F. *Coupling to Shielded Cables*, Krieger Publishing, 1987.

[C.4] Harrington, R.F. *Field Computation by Moment Methods*, Reprinted by the author, Syracuse University, Syracuse, NY, 1968.

[C.5] Balanis, C.A. *Advanced Engineering Electromagnetics*, John Wiley and Sons, New York, 1989.

[C.6] Tesche, F.M., Ianoz, M., Karlsson, T. *EMC Analysis Methods and Calculational Models*[1)]

1) To be published.

Annex D
(informative)

Measured cable currents inside telephone buildings

In the late 1960s and early 1970s, Bell Laboratories in the United States performed low-level continuous wave (CW) measurements of the coupling of incident HEMP fields to the wiring inside telephone switching buildings, which ranged in size from 22 m^3 to 8 700 m^3. They published distributions of currents for three types of building constructions (concrete block, riveted metal, and poured-in-place concrete with rebar). Although these measurements were derived with a different HEMP early-time waveform than used currently by the IEC, the frequency amplitudes of the two HEMP environments are nearly equal for frequencies between 6 MHz and 50 MHz. It is therefore expected that these currents can be used directly for IEC purposes. Table D.1 summarizes the Bell Laboratory results for peak-to-peak currents.

Table D.1 – Estimated internal peak-to-peak cable currents (I_{pp}) from direct HEMP illumination (from [D.1])

Type of building	50 %* current (I_{pp}) A	95 %* current (I_{pp}) A	99 %* current (I_{pp}) A
Concrete block	10	20	25
Riveted metal	10	20	25
Poured concrete	3	5	7
* Percentage of currents below the indicated value (severity).			

From the same set of measurements, the characteristics of the internal EMP current waveforms were summarized. The waveforms are well described by damped sine waves as shown in equation D.1 with the characteristics f_c and Q found in table D.2 and I_{pp} in table D.1.

$$I_c(t) = k(I_{pp}/2)e^{\frac{-\pi f_c t}{Q}} \sin(2\pi f_c t) \qquad \text{(D.1)}$$

The normalizing constant k is defined so that the maximum value of I_c will be equal to $I_{pp}/2$.

Table D.2 – Damped sinusoid waveform characteristics for internal cable currents (measured) (from [D.1])

		Damping parameter Q	
Case	Ringing frequency, f_c MHz	Average	Range
Minimum	1	20	15 – 25
Average	7	60	40 – 100
Maximum	16	150	100 – 200

Reference document:

[D.1] *EMP Engineering and Design Principles*, Bell Laboratories, 1975

Annex ZA (normative)

Normative references to international publications with their corresponding European publications

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

NOTE: When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050(161)	1990	International Electrotechnical Vocabulary (IEV) Chapter 161: Electromagnetic compatibility	-	-
IEC 61000-2-9	1996	Electromagnetic compatibility (EMC) Part 2: Environment Section 9: Description of HEMP environment - Radiated disturbance - Basic EMC publication	EN 61000-2-9	1996
IEC 61000-4-24	1997	Part 4: Testing and measurement techniques Section 24: Test methods for protective devices for HEMP conducted disturbance Basic EMC publication	EN 61000-4-24	1997

BSI — British Standards Institution

BSI is the independent national body responsible for preparing British Standards. It presents the UK view on standards in Europe and at the international level. It is incorporated by Royal Charter.

Revisions

British Standards are updated by amendment or revision. Users of British Standards should make sure that they possess the latest amendments or editions.

It is the constant aim of BSI to improve the quality of our products and services. We would be grateful if anyone finding an inaccuracy or ambiguity while using this British Standard would inform the Secretary of the technical committee responsible, the identity of which can be found on the inside front cover. Tel: 0181 996 9000. Fax: 0181 996 7400.

BSI offers members an individual updating service called PLUS which ensures that subscribers automatically receive the latest editions of standards.

Buying standards

Orders for all BSI, international and foreign standards publications should be addressed to Customer Services. Tel: 0181 996 9001. Fax: 0181 996 7001.

In response to orders for international standards, it is BSI policy to supply the BSI implementation of those that have been published as British Standards, unless otherwise requested.

Information on standards

BSI provides a wide range of information on national, European and international standards through its Library and its Technical Help to Exporters Service. Various BSI electronic information services are also available which give details on all its products and services. Contact the Information Centre. Tel: 0181 996 7111. Fax: 0181 996 7048.

Subscribing members of BSI are kept up to date with standards developments and receive substantial discounts on the purchase price of standards. For details of these and other benefits contact Membership Administration. Tel: 0181 996 7002. Fax: 0181 996 7001.

Copyright

BSI
389 Chiswick High Road
London
W4 4AL