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Electromagnetic compatibility (EMC) —

Part 1-3: General — The effects of high-altitude EMP (HEMP) on civil equipment and systems

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British Standards

National foreword

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Cross-references

The British Standards which implement international publications referred to in this document may be found in the *BSI Catalogue* under the section entitled "International Standards Correspondence Index", or by using the "Search" facility of the *BSI Electronic Catalogue* or of British Standards Online.

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Electromagnetic compatibility (EMC) –

Part 1-3: General – The effects of high-altitude EMP (HEMP) on civil equipment and systems

Compatibilité électromagnétique (CEM) –

Partie 1-3: Généralités – Effets des impulsions électromagnétiques à haute altitude (IEM-HA) sur les matériels et systèmes civils

Reference number
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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 1-3: General – The effects of high-altitude EMP (HEMP) on civil equipment and systems

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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Technical reports do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful by the maintenance team.

IEC 61000-1-3, which is a technical report, has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility. It has the status of a basic EMC publication in accordance with IEC Guide 107.

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

Enquiry draft	Report on voting
77C/109/CDV	77C/121/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 3.

This document, which is purely informative, is not to be regarded as an International Standard.

The committee has decided that the contents of this publication will remain unchanged until 2007. 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 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 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: IEC 61000-6-1).

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 1-3: General – The effects of high-altitude EMP (HEMP) on civil equipment and systems

1 Scope

The purpose of this part of IEC 61000 is to describe the effects that have occurred during actual and simulated electromagnetic pulse testing throughout the world. These effects include those observed during the high-altitude nuclear tests conducted by the United States and the Soviet Union in 1962, and the HEMP simulator tests conducted by many countries during the years after atmospheric testing ended. In addition to direct effects, this technical report also contains information on HEMP coupling to "long lines" as it is important to verify that particular levels of currents and voltages can be induced by HEMP on these lines; this provides a basis for direct injection testing of electronic equipment. It should be noted that, in most cases, the electrical equipment tested or exposed did not contain the sensitive electronics in use today. Also it should be emphasized that all tests and exposures did not produce failure of the equipment; factors such as the geometry of the HEMP interaction and the electromagnetic shielding of the equipment are variables that can produce differing results. The description of these effects is intended to illustrate the seriousness of the possible effects of HEMP on modern electronic systems.

2 Reference documents

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.

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

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

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

IEC 61000-4-32: *Electromagnetic compatibility (EMC) – Part 4-32: Testing and measurement techniques – HEMP simulator compendium.* Basic EMC publication[1]

3 Definitions

For the purposes of this part of IEC 61000, the following definitions, together with those in IEC 60050(161) apply.

3.1
attenuation
reduction in magnitude (as a result of absorption and scattering) of an electric or magnetic field or a current or voltage; usually expressed in decibels

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[1] To be published.

3.2
aperture point-of-entry
aperture port-of-entry
aperture points-of-entry including intentional or inadvertent holes, cracks, openings or other discontinuities in a shield surface

NOTE Intentional aperture points of entry are provided for personnel and/or equipment entry and egress and for ventilation through an electromagnetic barrier.

3.3
common mode voltage
mean of the phasor voltages appearing between each conductor and a specified reference, usually earth or frame

[IEV 161-04-09]

3.4
conductive point-of-entry
conductive port-of-entry
penetrating conductor, electrical wire, cable or other conductive object, such as a metal rod, which passes through an electromagnetic barrier

3.5
electromagnetic compatibility
EMC (abbreviation)
ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment

[IEV 161-01-07]

3.6
electromagnetic disturbance
any electromagnetic phenomenon which may degrade the performance of a device, equipment or system

[IEV 161-01-05, modified]

3.7
electromagnetic interference
EMI (abbreviation)
degradation of the performance of a device, transmission channel or system caused by an electromagnetic disturbance

[IEV 161-01-06, modified]

NOTE Disturbance and interference are respectively cause and effect.

3.8
(electromagnetic) shield
electrically continuous housing for a facility, area, or component used to attenuate incident electric and magnetic fields by both absorption and reflection

3.9
(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]

3.10
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.

3.11
medium voltage (MV) power line
power line with a nominal a.c. voltage above 1 kV and not exceeding 35 kV

3.12
point-of-entry (PoE)
port-of-entry (PoE)
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

3.13
power lines
lines originating from the power supply (alternating or direct voltage)

3.14
transient
pertaining to or designating a phenomenon or a quantity which varies between two consecutive steady states during a time interval short compared with the time-scale of interest

[IEV 161-02-01]

NOTE A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity.

3.15
voltage surge
transient voltage wave propagating along a line or a circuit and characterized by a rapid increase followed by a slower decrease of the voltage

[IEV 161-08-11]NOTE The time parameters of a voltage surge are defined as follows:
• the rise time between 10 % and 90 % of the peak value (10 %/90 % rise time) according to IEV 161-02-05; and
• the duration at 50 % of the peak value between increase and decrease of the wave (50 %/50 % duration).

4 General considerations

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

early-time HEMP (t < 1 µs)	(fast);
intermediate-time HEMP (1 µs < t < 1 s)	(medium);
late-time HEMP (t > 1 s)	(slow).

Historically most interest has been focused on the early-time HEMP that was previously referred to as simply "HEMP". Here we will use the term high-altitude EMP or HEMP to include all three types of waveforms. The term NEMP[2] covers many categories of nuclear EMPs including those produced by surface bursts (SREMP)[3] or created on space systems (SGEMP)[4].

2 NEMP: Nuclear Electromagnetic Pulse

3 SREMP: Source Region EMP

4 SGEMP: System Generated EMP

5 Overview of effects experience

5.1 Atmospheric testing introduction

During the era of nuclear device testing in the atmosphere, there have been documented cases where unusual electrical effects have been noted by those involved in the test programmes. In particular, Enrico Fermi has been credited with being the first person to mention the presence of electrical effects at large distances where the direct effects of blast and shock were not effective. While it is noted that different types of electromagnetic pulse (EMP) are created depending on the height of the burst, the effects of high-altitude EMP (HEMP) are of the greatest interest due to the substantial distances over which effects may occur. High-altitude EMP occurs when the nuclear detonation is higher than an approximate altitude of 30 km above the earth's surface.

While the number of high-altitude tests performed by the United States and the Soviet Union was not large (in the order of 10), most of the effects noted were from the U.S. Starfish event above Johnston Island in the Pacific Ocean and the three Soviet Union tests over Kazakhstan in 1962. In all of the reported cases, the effects that occurred were not the result of planned experiments but were mainly effects (malfunction and damage) on civil electronics equipment that were reported and later analysed to confirm that the effects were related to the particular nuclear test.

In the following clauses, several effects will be reviewed from the US high-altitude test series in 1962. In particular, problems were noted in the input circuits of radio receivers, surge arresters triggered unexpectedly on an aircraft with a trailing wire antenna, and 30 strings of streetlights reportedly failed simultaneously during the Starfish experiment [1].[5] The streetlight case is the best documented and analysed, and this will be discussed in 6.1.

Regarding the experience of the Soviet Union in the fall of 1962, failures of several long-line systems, including power and telecommunications, were reported [2]. The failures of the protection devices on a 500-km-long telecom line are also well documented and are discussed in 6.2.

5.2 Simulator testing introduction

Beginning in the late 1960s and continuing through the present time, HEMP simulators have been built by over 10 countries throughout the world. These early-time HEMP simulators are designed to produce a bounded or radiating transient electromagnetic (EM) field in a defined test (or “working”) volume (IEC 61000-4-32). The objective of most of these simulator tests was to evaluate the immunity or susceptibility of equipment and systems to HEMP disturbances. While the HEMP waveforms that are produced in the various simulators have some variation in their waveform characteristics, the standardized electric field waveform today is described as a 2,5/25 ns waveform with an amplitude of 50 kV/m (IEC 61000-2-9).

While the HEMP simulators produce reasonable representations of the incident electric and magnetic field transient pulses in a limited volume, the actual HEMP is a plane wave field with no significant variation over tens of kilometres in extent. In HEMP simulators, the fields experience losses as they propagate from the pulser, and the test volumes where the fields exhibit the correct behaviour typically vary from a few to tens of meters. Because of this fact, and the fact that no simulator produces the full range of field polarizations and angles of incidence at the earth's surface, field simulator immunity tests do not provide complete results. This is especially true in the case of cables, which are attached to systems under test. It is very difficult to test a system cable PoE properly during a HEMP simulator field test. For this reason, *conducted* environment tests, which are applied to conductive PoEs, should be performed (see IEC 61000-2-10, for example), and results of these types of tests are also described in this technical report.

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5 Figures in square brackets refer to the bibliography.

As is well known, most of the system and equipment testing in HEMP field simulators involves military equipment, which is not the subject of this technical report. On the other hand, civil electronic and power-line equipment have occasionally been tested, and the results of five well-documented sets of experiments are reported in 7.1, 7.2, 7.3, 7.4, and 7.5.

As indicated above, this technical report will also consider the reported experience of conducted testing. A review of some recent information concerning high-voltage power-line equipment testing is discussed in clause 8.

6 Atmospheric nuclear testing experience

6.1 United States atmospheric test experience – Starfish test

The Starfish nuclear device, with a yield of approximately 1 MT, was detonated about 400 km above Johnston Atoll during the night of 8 July 1962 at approximately 11:00 p.m. Hawaiian local time (0900 GMT, 9 July 1962). The line-of-sight distance from the event detonation to the Hawaiian Island of Oahu was approximately 1 400 km. See figure 1 for a more detailed description of the geometry of the burst.

Figure 2 presents the headline on the front page of the New York Tribune, European Edition -- "U.S. Fires Atomic Blast 200 Miles Over Pacific" [3] The test was described as "probably the most grandiose military-scientific experiment in history", and it "triggered spectacular space fireworks over thousands of miles for six minutes....". In Hawaii the "dazzling white burst was followed by surges of most of the colours of the rainbow, from greens and brilliant yellows through orange and glowing blood reds." Aurora lights were observed in Somoa, 2 000 miles south of the test site and in New Zealand, 4 000 miles away. It was thought that these coloured lights were due to the "dumping of space radiation particles normally held in the Van Allen belts around the earth". The article also mentions that the Atomic Energy Commission in the United States reported that two satellites were in orbit to record the effects of the blast.

In terms of the electromagnetic effects that were reported, the New York Tribune article mentions the following items:

- Radio communications were blacked out for times up to 30 min due to ionospheric disruptions.
- The geomagnetic field measured by the Geodetic Survey in Honolulu showed a very sharp departure at the time of detonation followed by five or six minutes of activity with a gradual return to normal within about 30 min. The sudden impulse was much greater than expected by the local scientist.
- In Hawaii, burglar alarms and air-raid sirens went off at the time of the test shot. Some streetlights were extinguished while others came on. "There was no immediate explanation for the electrical malfunctions."

After the test there were also reports in the local Honolulu newspapers that streetlights in different parts of Oahu had gone out at the time of the test. The Honolulu Star-Bulletin on 9 July 1962 reported on their front page that "the City-County Street Lighting Department said today shock waves from the Johnston Island nuclear blast blew out fuses in several areas of the Island last night". Some reports indicated that 30 strings of lights had failed [4]. The results described below are from a technical report written by Dr Charles Vittitoe in 1989 in which he studied one of the specific circuits that failed [5].

A summary of the Vittitoe findings is that the estimated 5,6 kV/m incident peak HEMP electric field produced sufficient current flow in the lighting circuit (see figure 3) to damage a disk cut-out in the secondary of an isolation transformer. This transformer is believed to have a rating of 4 kV with a disk cutout failure level of up to 1 200 V (at 60 Hz). For a HEMP-induced voltage waveform, the failure level was estimated by Vittitoe to be five times higher. In terms of current, the operating current was 6,6 A and the failure level was expected to begin at 14 A, while the calculated HEMP-induced common mode current was 140 A. Vittitoe concluded that the HEMP fields and induced currents were consistent with the failures observed. It is also clear that due to the polarization of the incident HEMP fields and the many different orientations of lighting circuits, there would be a great variation in the induced currents in different circuits, thus explaining the fact that only some of the Hawaiian lighting circuits failed during the Starfish test.

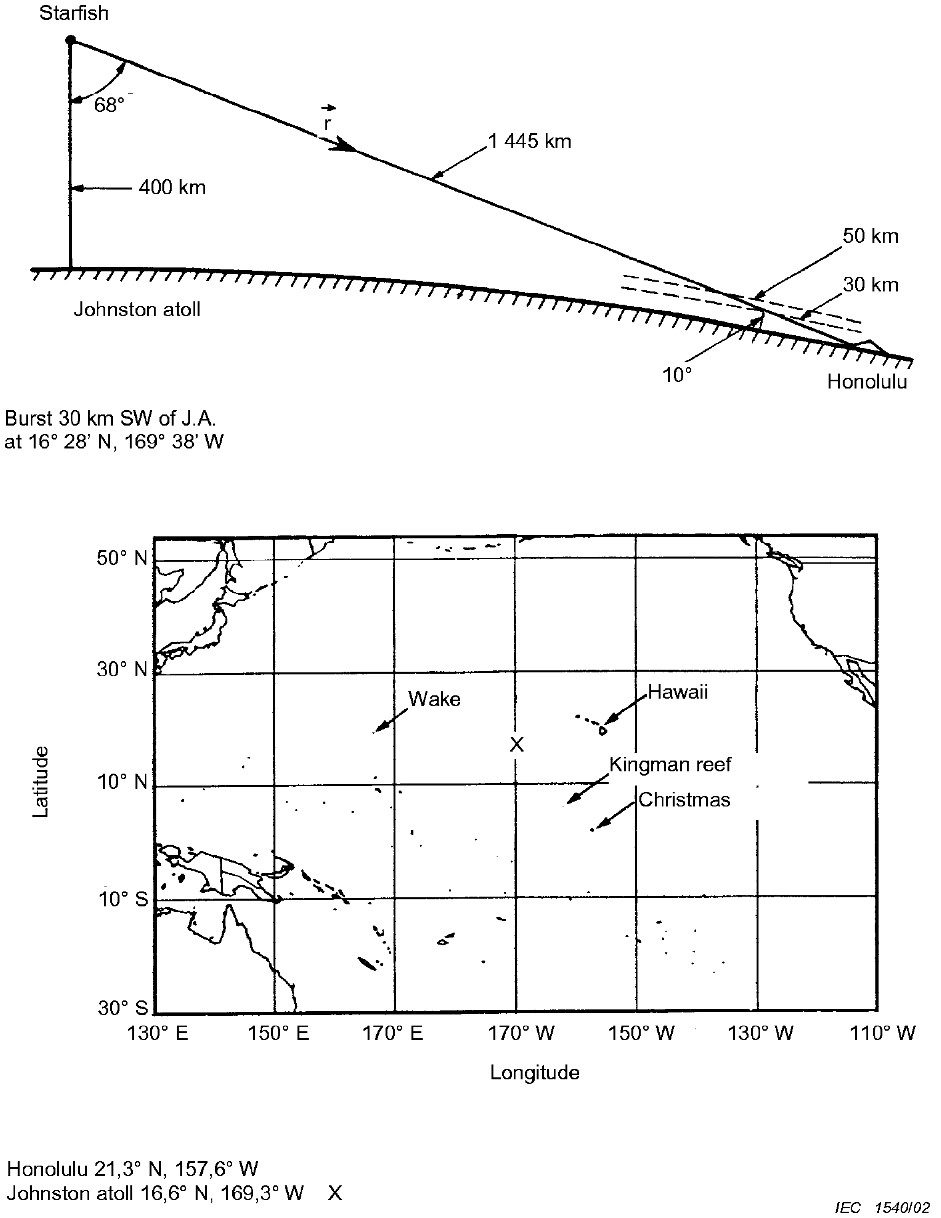


Figure 1 – Starfish-Honolulu burst geometry, with the X indicating the location of Johnston Atoll

YORK Tribune

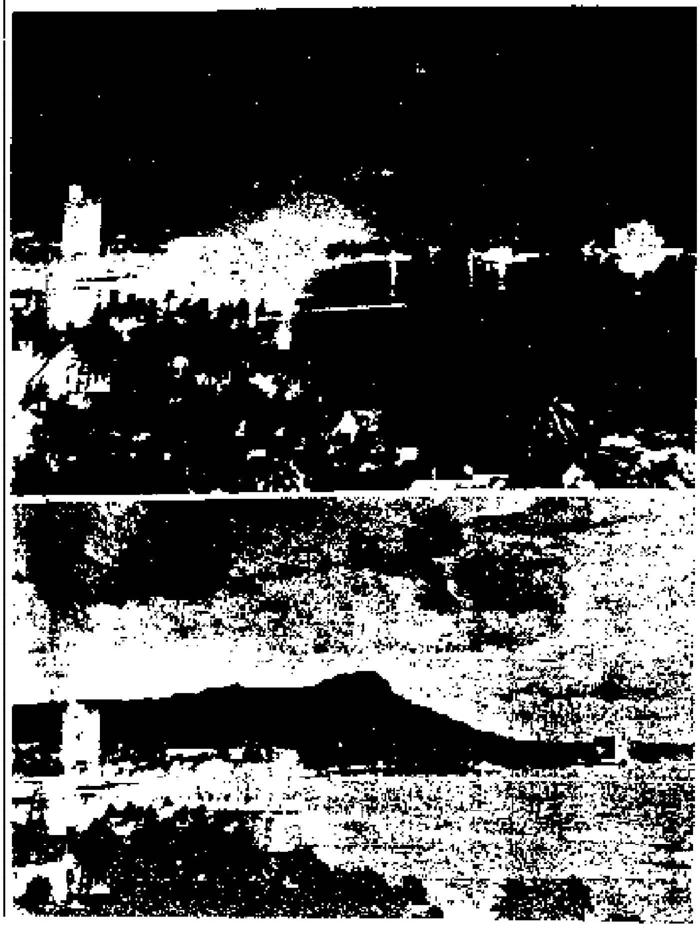
ean Edition

Price Per Copy:

JULY 10, 1962

Largest circulation of any American newspaper published abroad

U.S. Fires Atomic Blast 200 Miles Over Pacific



Light Seen In Hawaii And Samoa

2 Satellites Up To Check on Shot

By Robert C. Toth

From t e Herald Tri une Bureau
WASHINGTON, July 9 - The Unit d States, in probably the most grandi se mi ary-scienifi t experimen i the story, t dayoset off a hydrogen exp osi h 200 mi es over Johnst n Island in the mi -Pacific.

Its energy grea er than that from 1 il on tons of TNT, triggered spect cul ar space fireworks over thousands of mi es for 6 minu es start g at 11 00 p m. l. st night, i Hawai an i t me i (0900 GMT Monday).

Two Satel es In Orbit t i

At Hawai, 750 mil s nort west of Johnston a ,dazzl ng whi e burst was f o lowed by surges of most of het colors of the rai bow, from greens and bril an lyel ows t rough orange and glowing bl od red.

Curt ns of aurora li hts were report d at Samoa, 2000 mil s south f t o the si e. t

In New Zealand, 4000 mi es away, a red glow began on the northern horizon and spread throughout the sky, bathi g the sea in rich co or. l Th s phenomenon may have been caused by the dump ng of space rad at on part cl s normal y held in the Van Al en belts around t e Eart . h

IEC 1541/02

Figure 2 – Front page of *New York Tribune*, European Edition, 10 July 1962

The pictures are of poor quality, but the upper night-time photo of Diamond Head and Waikiki in Honolulu was taken minutes before the test shot, while the lower picture was taken just afterwards, showing a bright sky and ocean reflection.

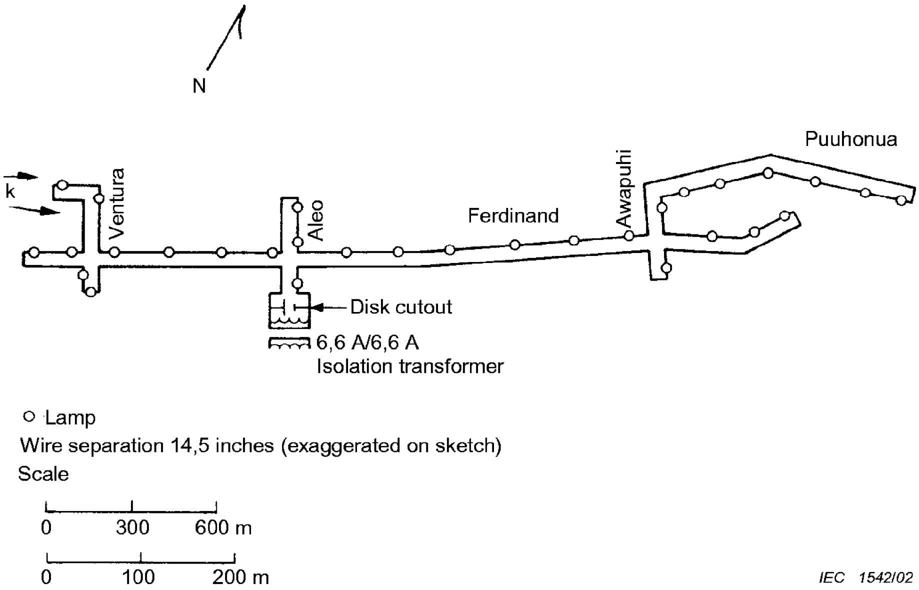


Figure 3 – Ferdinand Street (Honolulu, Hawaii) series lighting system in 1962

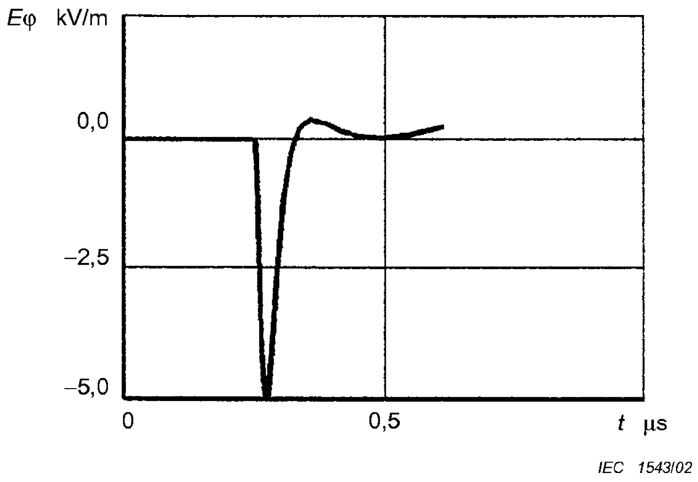
6.2 Soviet Union atmospheric test experience

In 1962 the Soviet Union conducted a series of high-altitude nuclear tests over Kazakhstan. During a presentation at the EUROEM Conference in 1994, Prof. Vladimir Loborev, the Director of the Central Institute of Physics and Technology, reviewed the HEMP effects observed during a large yield, 300 km height of burst test through the use of several examples [2]:

- a long, radially oriented, above-ground communications line failed;
- a buried communications line more than 600 km away from ground zero failed;
- a power line insulator was damaged, resulting in a short circuit on the electrical line;
- diesel generators failed;
- antenna systems were affected.

Using data obtained during the test series, one particular telecom circuit was analysed in detail to examine the failure of the line's protective devices during the tests [6]. The above-ground telecom line extended for a distance of approximately 500 km, beginning at a ground range of 180 km at an azimuth of 90° and ending at a ground range of 650 km at an azimuth of approximately 50°. At each repeater element on the line, which was spaced at some tens of kilometres, there were gas-filled surge arresters and fuses. It was ascertained after the test that all of the surge arresters fired and all of the fuses were damaged, requiring that the line be repaired.

In the analysis in [6], the HEMP early-time electric fields were computed and are shown in figures 4 and 5 where the phi component is the transverse horizontal field and the theta component is the transverse, vertical field. Note that the total transverse electric field does not vary much over the length of the line. Figure 6 presents the computed late-time (MHD EMP) magnetic field for ground ranges of 433 km and 574 km. Note that magnetic field variations of 400 nT are typical of geomagnetic storms although the rise time shown in figure 6 is much more rapid, inducing a more significant late-time electric field. In fact, the maximum derivative of the incident magnetic field is approximately 1 800 nT/min, which is more than four times as high as the geomagnetic storm derivative which caused the collapse of the Hydro-Quebec power system in March 1989.



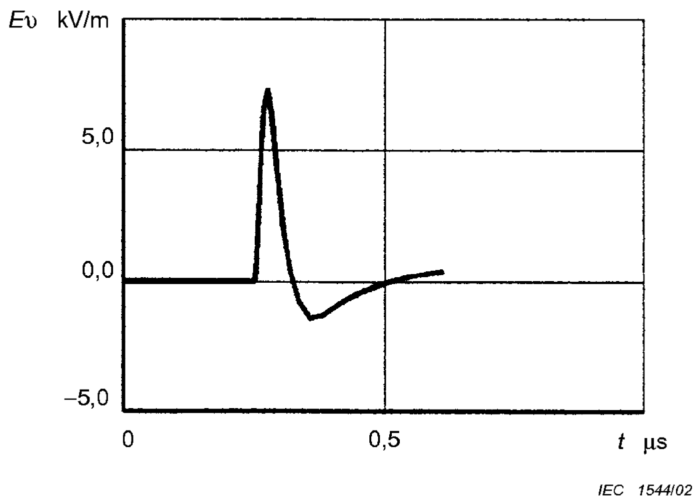
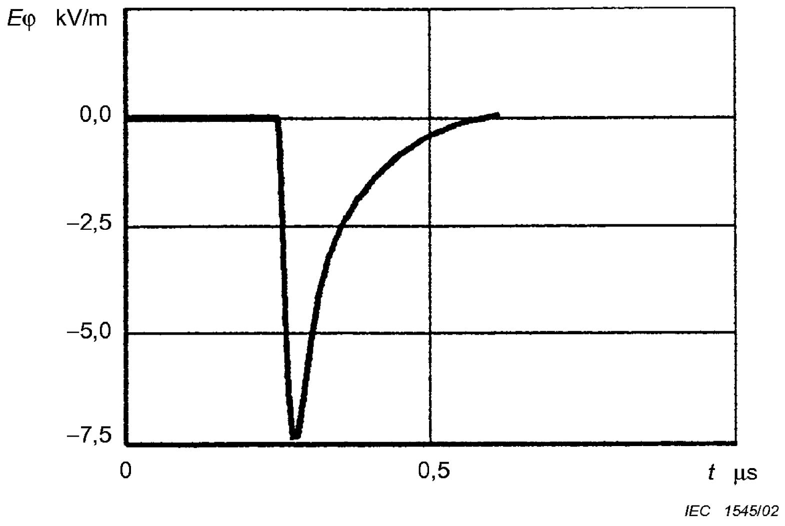


Figure 4 – The amplitudes of the computed early-time HEMP E-field components versus time for the near end of the 500-km telecom line



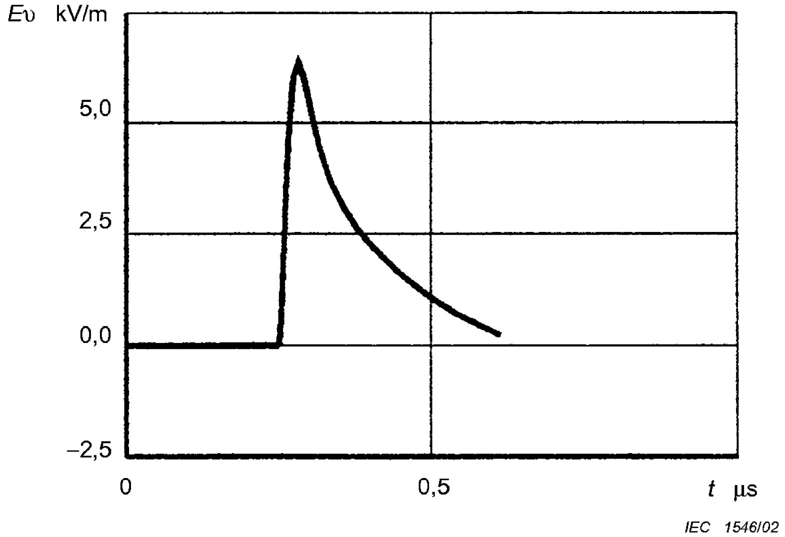
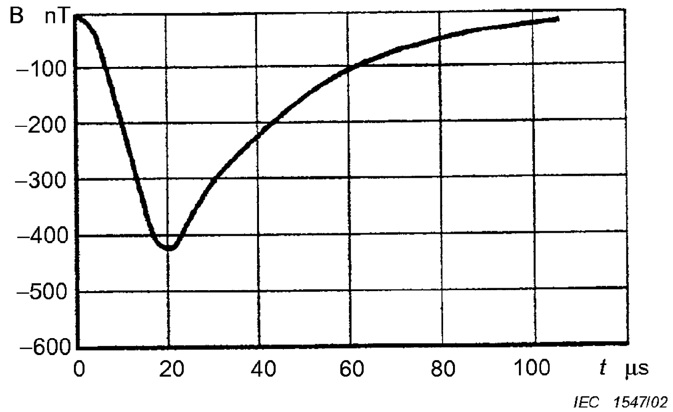
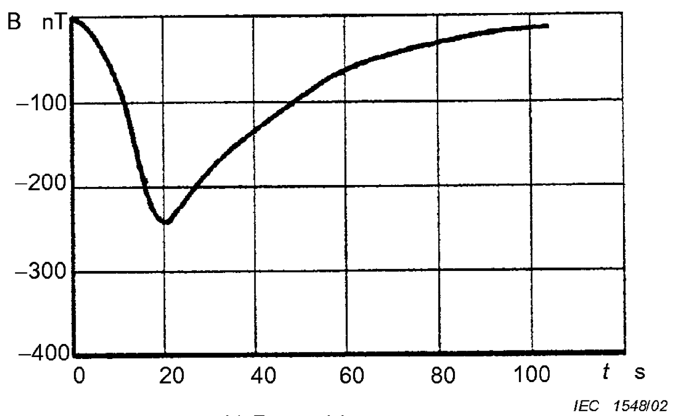


Figure 5 – The amplitudes of the computed early-time HEMP E-field components versus time for the far end of the 500-km telecom line



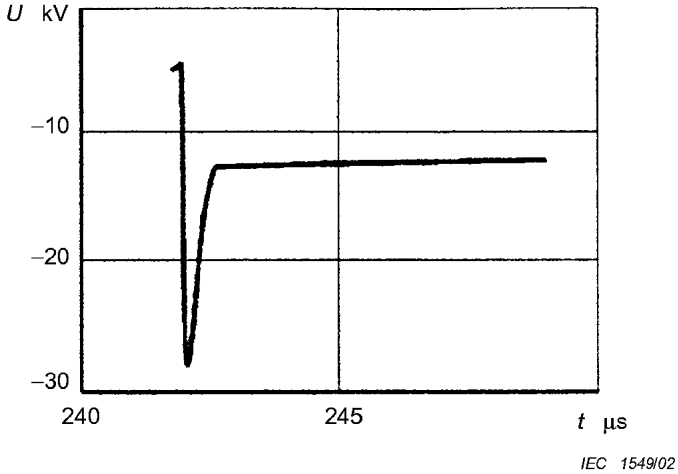
a) R = 433 km



b) R = 574 km

Figure 6 – Computed transverse late-time HEMP magnetic flux density at the earth's surface at ground ranges of 433 km and 574 km from the surface zero point

Using the early-time HEMP fields of approximately 8 kV/m, the common mode load voltages and short-circuit currents flowing on the telecom line were computed in [6] and are shown for subline 2 (an 80 km section of line at the far end of the 500 km telecom line) in figures 7 to 9. It is noted that the induced early-time HEMP voltage of nearly 30 kV is large enough to fire the surge arresters according to the data presented in table 1. However, the computed early-time currents are less than 100 A which are not large enough to induce damage according to table 2. Additionally, using the computed late-time electric fields of approximately 10 V/km (only peak values were computed), calculations of the peak-induced late-time voltage and current on the lines are approximately 400 V and 4 A, respectively, which are high enough to short the fuses as indicated in table 2. The authors in [6] concluded that the late-time HEMP fields were probably responsible for the failures documented on the above-ground communications line.



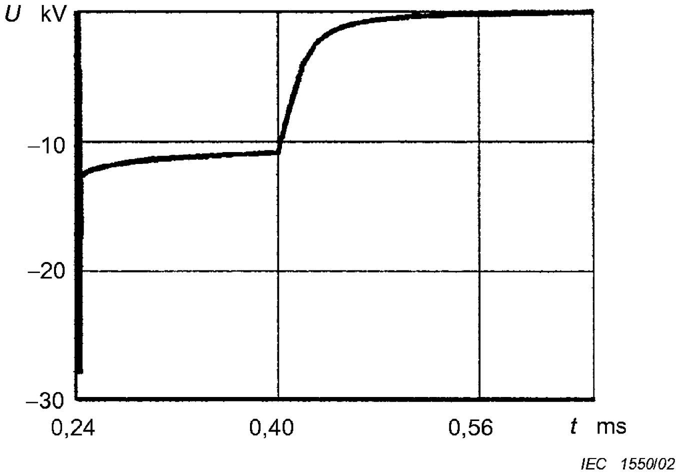
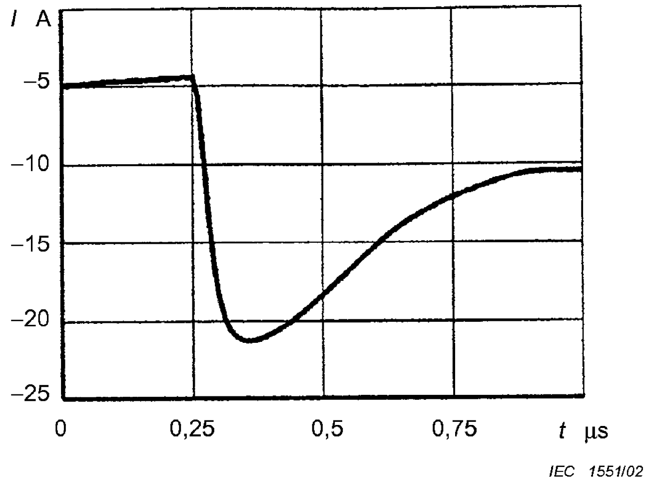


Figure 7 – Computed early-time HEMP load voltage versus time for the far end of the 80-km long subline 2 (the top figure shows the earliest time, while the bottom figure shows a later time view)



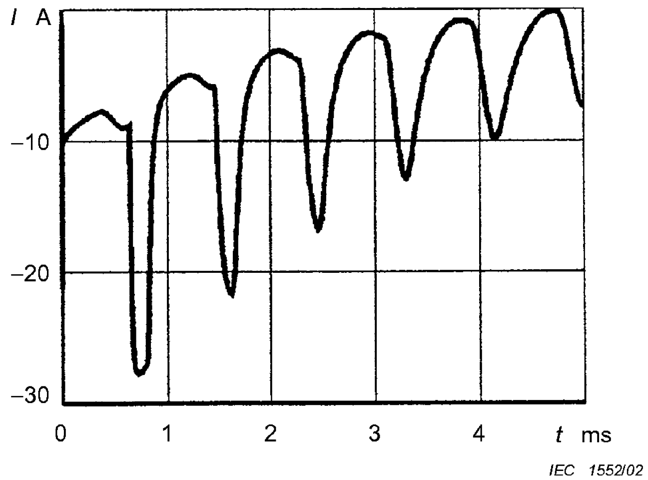
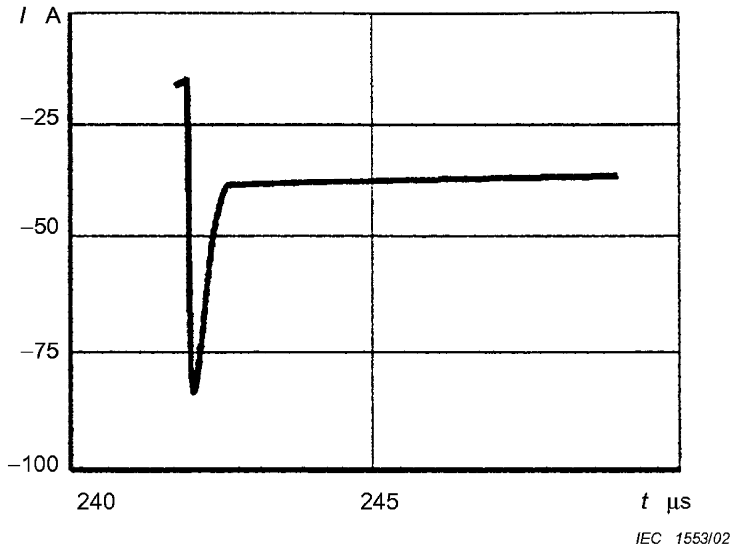


Figure 8 – Computed early-time HEMP short-circuit current versus time for the near end of the 80 km long subline 2 (the top figure shows the earliest time, while the bottom figure shows a later time view)



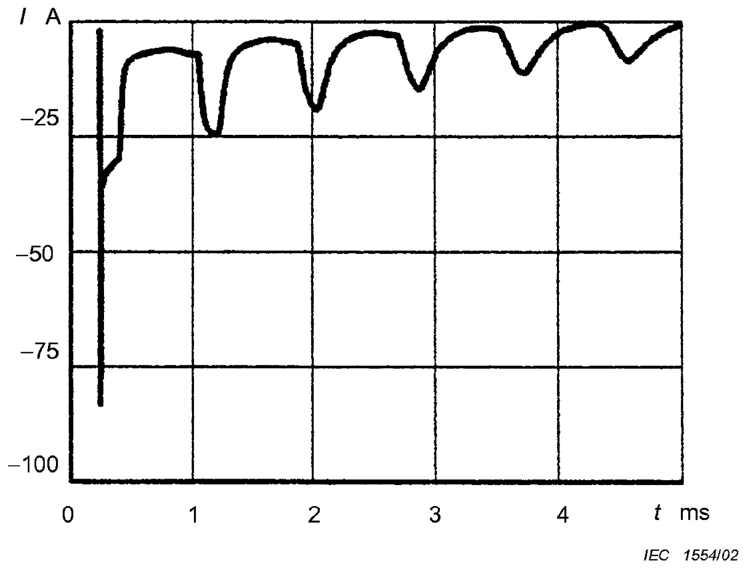


Figure 9 – Computed early-time HEMP short-circuit current versus time for the far end of the 80 km long subline 2 (the top figure shows the earliest time, while the bottom figure shows a later time view)

Table 1 – Data on the arrester firing voltage as a function of the voltage waveform characteristics (from [6])

	Applied voltage characteristics	Arrester firing voltage V
1	Direct	350 ± 40
2	Alternating voltage (f = 50 Hz)	350 ± 40
3	Surge voltage for various pulse rise times (µs)	
	a) τ = 100	450
	b) τ = 50	480
	c) τ = 25	500
	d) τ = 20	520
	e) τ = 16	550
	f) τ = 14	580
	g) τ = 12	600
	h) τ = 10	620
	i) τ = 8	650
	j) τ = 6	670
	k) τ = 4	700
	l) τ = 2	750

Table 2 – The peak pulse currents in kA damaging the fuse SN-1 (from [6])

Number of pulses	Time pulse characteristics τ/tf (rise/fall in µs)				
	5/10	15/40	20/40	20/60	25/70
1	3,6	1,4	1,35	1,07	0,92
2	2,0	0,80	0,75	0,60	0,52
3	1,5	0,56	0,54	0,40	0,30
10	0,40	0,12	0,11	0,088	0,075

7 HEMP simulator testing with radiated transients

In this clause, five sets of simulator experiments using radiated fields are reviewed. Several of these experiments provide direct effects data for commercial equipment while others provide validations of coupling codes that are needed to verify the correct levels of conducted environments produced under actual HEMP conditions. These validated coupling codes are then used to compute the levels required for conducted transient testing using HEMP direct-injection simulators (see clause 8).

7.1 Consumer electronics

In the late 1980s, 91 different examples of consumer electronics were tested with the FEMPS HEMP simulator to obtain information concerning the potential effects of consumer electronics operating near fast-rise HEMP simulators [7]. Three HEMP peak field levels were used including low (6,7 kV/m), medium (12,4 kV/m) and high (16,6 kV/m). The results are described in table 3, and it is clear that even for incident fields of 6,7 kV/m, many critical upsets are observed with damage occurring at the higher level of 16,6 kV/m.

Table 3 – Summary of operational observations at FEMPS [7]

Test item type	Test item	Effects at various levels of testing		
		Low level	Medium level	High level
Television	Emerson 13 in.	Critical upset	Critical upset	Failure
	Portland 13 in.	Noncritical upset	Critical upset	Critical upset
	Zenith 19 in., SD1911W	—	Critical upset	Critical upset
	JC Penney 13 in.	—	Noncritical upset	Noncritical upset
	Montgomery Ward 25 in.	—	Critical upset	Critical upset
	Sony 13 in.	—	Critical upset	—
	Sharp 25 in.	—	—	Critical upset
VCR	Akai VS515U	Critical upset	Critical upset	Critical upset
	Sharp	Critical upset	Critical upset	Critical upset
	Sears	Critical upset	Critical upset	Critical upset
	Symphonic	Critical upset	Failure	Failure
	Goldstar	Noncritical upset	Noncritical upset	Noncritical upset
	Mitsubishi HS348UR	—	Critical upset	—
	Toshiba M4220	—	—	Noncritical upset
	Magnavox VR9525AT	—	—	Noncritical upset
Stereo receiver	Kenwood	Critical upset	Critical upset	Critical upset
	Onkyo	Noncritical upset	Noncritical upset	Noncritical upset
	JVC	—	Critical upset	Critical upset
	Pioneer	—	—	Failure
Mobile radio	Johnson 7171 uhf	—	Noncritical upset	Noncritical upset
	Johnson SDL6085, 16 channel	—	—	Noncritical upset
	GE PSX vhf	—	—	Noncritical upset
Computer	Leading Edge model D	Critical upset	Critical upset	Failure
	IBM PC AT	Critical upset	Critical upset	—
	Hayes 1200-baud modem	—	—	Critical upset
CD player	Sharp	Noncritical upset	Critical upset	Critical upset
	Sony	—	—	Critical upset
Cellular phone	GE	Critical upset	—	Critical upset
	NEC	—	—	Critical upset
Telephone	Realistic cordless	Critical upset	Critical upset	Critical upset
	Panasonic	—	—	Failure
Answering machine	Phone mate	Critical upset	Critical upset	Critical upset
Garage door opener	Genie	—	Critical upset	Critical upset
Medical equipment	Kangaroo feeder pump	Critical upset	Critical upset	Critical upset
	Infant monitor	—	Critical upset	Failure
Automobile radio	Craig AM/FM cassette	Noncritical upset	Noncritical upset	Noncritical upset
Satellite dish	Realistic 8,5 ft.	Failure (not verified)	—	—

— Indicates no abnormal observation or the unit was not tested at that level because of a previous failure.

After the testing was completed at the FEMPS (fast-rise EMP) simulator, some of the equipment was re-tested at the Woodbridge Research Facility (WRF) for a 4 kV/m pulse with a slower rise time (approximately 5 ns). Measurements of the induced current on many of the cables attached to the equipment were made to examine their levels and time behaviours (see figures 10 to 14). These figures give some indication of the magnitude of currents entering the equipment. Note that the maximum currents are approximately 10 A for the electric field value of 4 kV/m, and all waveforms show a damped sine behaviour. If the response is linear, these currents would be expected to peak at about 130 A for a 50 kV/m HEMP pulse; it should be noted, however, that arcing could occur in connectors thereby reducing the coupled voltages and currents. It is always best to test at the expected threat level when possible to determine immunity levels.

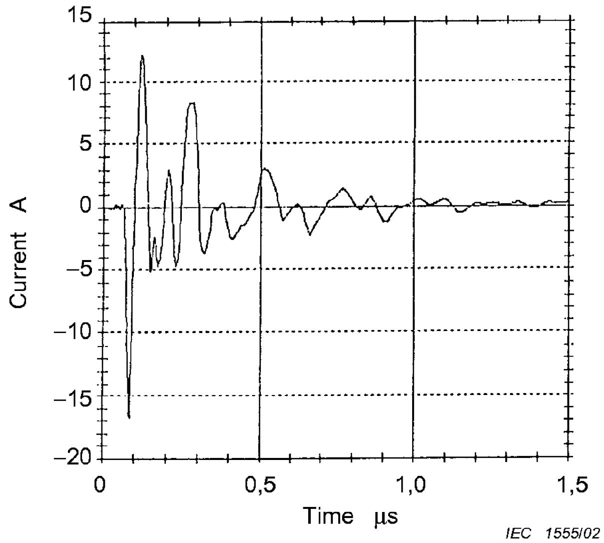


Figure 10 – Time response for a typical antenna cable coupled current measured at WRF

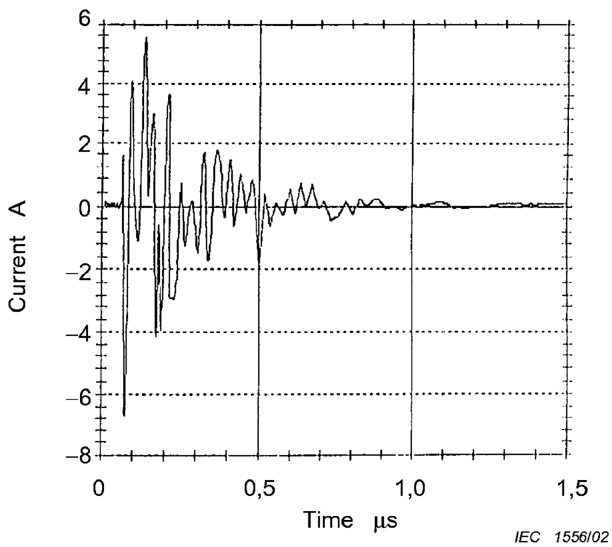


Figure 11 – Time response for a typical telephone cable coupled current measured at WRF

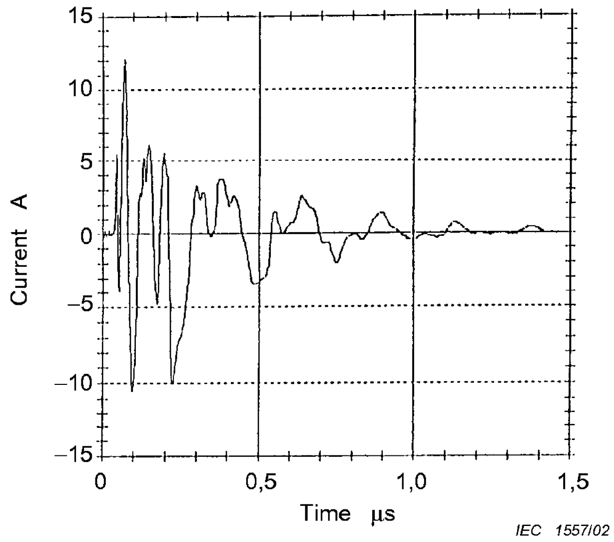


Figure 12 – Time response for a typical power cable coupled current measured at WRF

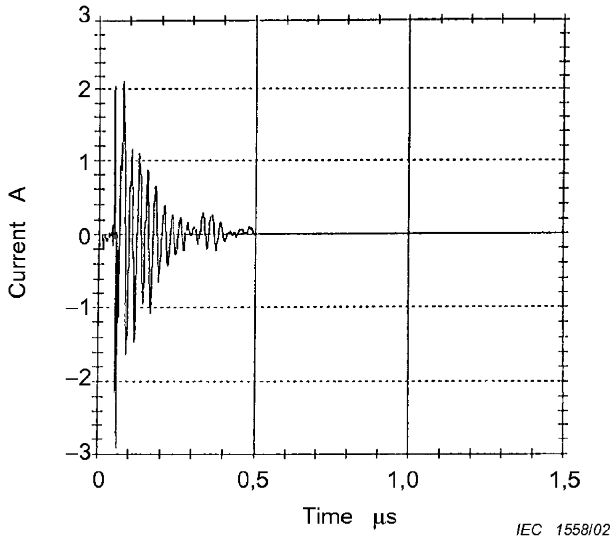


Figure 13 – Time response for a typical speaker wire coupled current measured at WRF

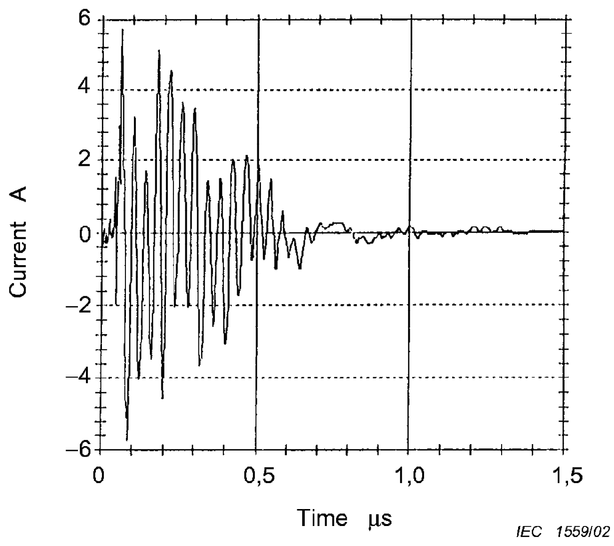


Figure 14 – Time response for a typical computer keyboard coupled current measured at WRF

7.2 Communication radios

One of the earliest studies of the performance of commercial electronics was published by Oak Ridge National Laboratory by Barnes in 1974 [8]. In this study, the ALECS HEMP simulator at Kirtland AFB in New Mexico was used. Radio equipment and antennas used in land mobile, amateur, citizens' and commercial broadcast band radio systems were tested. The HEMP field-pulse rise time varied between 4 ns and 10 ns with a pulse decay of approximately 500 ns. Peak field levels between 5 kV/m and 200 kV/m were applied during the testing. It should be noted that the mobile units were not connected to commercial power lines during testing, and it is likely that the threshold levels measured would have been lower if they had been connected to power leads.

Table 4 below presents the results of the test series. The thresholds of failures (or susceptibility levels) are shown as a range of field levels since the testing was done at discrete settings. For example, the failure of test object 2, the citizens' band "walkie talkie", is shown in column 5 to fail between 5 kV/m and 10 kV/m. This means that the test at 5 kV/m caused no problems, while the next test at 10 kV/m produced a failure of the RF transistor. It is possible that the threshold for failure is lower than the 10 kV/m level, so the range of values (5 kV/m to 10 kV/m) is shown in the table.

Upon a close review of the table, it is interesting to note that 10 of the 13 test objects did not fail at levels below 50 kV/m which is the IEC standard level for the early-time HEMP as given in IEC 61000-2-9. While this is a positive outcome, none of the radios used the low-voltage integrated circuits that are commonly used today. Unfortunately, there are no publicly available data on the performance of modern cellular phones to HEMP transient fields.

Table 4 – Summary of information on radios tested [8]

No.	Class and type	Frequency band	Manufacturer and model	Receiver type	Threshold failure level *Ef* (kV/m)	Obvious malfunctions	Damaged components
1	Amateur base receiver	20 m	Hallicrafters Co. Model S-40B	Tube	100 < *Ef*	None	Not checked
2	Citizens' band walkie talkie	11 m	Courier Model CWT-30		Transistor 5 < *Ef* ≤ 10	No reception	RF transistor
3	Citizens' band walkie talkie	11 m	Courier Model CWT-30		Transistor 10 < *Ef* ≤ 20	No reception	RF transistor
4	Land mobile Public safety Portable unit	VHF Low band	Motorola HT 21-16	Hybrid tube and transistor	30 < *Ef* ≤ 100	No transmission	tuning coils, RF transistor, and power supply diodes
5	Land mobile Public safety Mobile unit	VHF Low band	Motorola T41GGV	Tube	50 < *Ef* ≤ 100	Non-operational*	Antenna matching circuits, tuning coils, and wiring
6	Land mobile Public safety walkie talkie	VHF High band	Motorola HT 220	Transistor, and	100 < *Ef* ≤ 200 integrated circuit	No reception	RF transistor
7	Land mobile Public safety Portable unit	VHF High band	Motorola HT Radiophone	Transistor and an integrated circuit	70 < *Ef* ≤ 100	No transmission	audio-integrated circuit
8	Land mobile Public safety Mobile unit	VHF High band	Motorola Motrac HHT Series	Transistor and integrated circuit	100 < *Ef*	None	No damage
9	Land mobile Public safety Base station unit	VHF High band	General Electric ET 35A, ET 35B	Tube	100 < *Ef* 9 dB gain antenna	None	No damage
10	Land mobile Industrial service walkie talkie	UHF	Motorola H 24	Transistor	100 < *Ef*	None	No damage

Table 4 – Summary of information on radios tested (concluded)

No.	Class and type	Frequency band	Manufacturer and model	Receiver type	Threshold failure level *Ef* (kV/m)	Obvious malfunctions	Damaged components
11	Land mobile Industrial service Mobile unit	UHF	Motorola Motrac MHT Series	Transistor	$100 < Ef$	None	No damage
12	Commercial radio	AM broadcast	Realtone 2424	Transistor	$400 < Ef \leq 500$	Weak reception	RF transistor
13	Commercial radio	FM broadcast	Realtone 2424	Transistor	$400 < Ef \leq 500$	Little or no reception	Oscillator transistor

* Observed non-operational during the post-test equipment check.

7.3 Commercial power lines

In 1998 an EMP coupling experiment was performed by Imposimato *et al*. to examine the interaction of HEMP fields produced at the Italian CISAM simulator with a realistic medium voltage (MV) power line, including transformers [9]. The HEMP simulator was a guided wave simulator in a wedge-shaped geometry and it produced a peak vertical electric field of 50 kV/m in the test volume.

Although the experiment had several objectives, the most interesting aspect was the measurement of currents and voltages induced on the lines and at the transformers. The geometry of the exposure is shown in figure 15. Note that the three-wire power line runs transverse to the field propagation in the simulator and that the driving horizontal electric fields increase as the power line moves away from the simulator centreline. Note also that these fields are oriented in opposite directions. While this may not seem to be the best orientation to simulate the incident plane-wave HEMP field, it turns out that the incident horizontal electric fields reached a peak value of 20 kV/m under the edges of the simulator.

Through careful analysis and measurements, the HEMP field variations along the power line were categorized and modelled resulting in the comparison of the measured and calculated voltages as shown in figure 16 (~350 kV). The excellent comparison is important to the study of HEMP effects, as it is often necessary to use analysis to estimate the current levels flowing when an effect occurs. Another measurement is shown in figure 17, which shows that the coupled currents are as high as 600 A near the simulator edges and decrease to 200 A at location Q (4) due to ground losses and the lack of a driving HEMP field at this location.

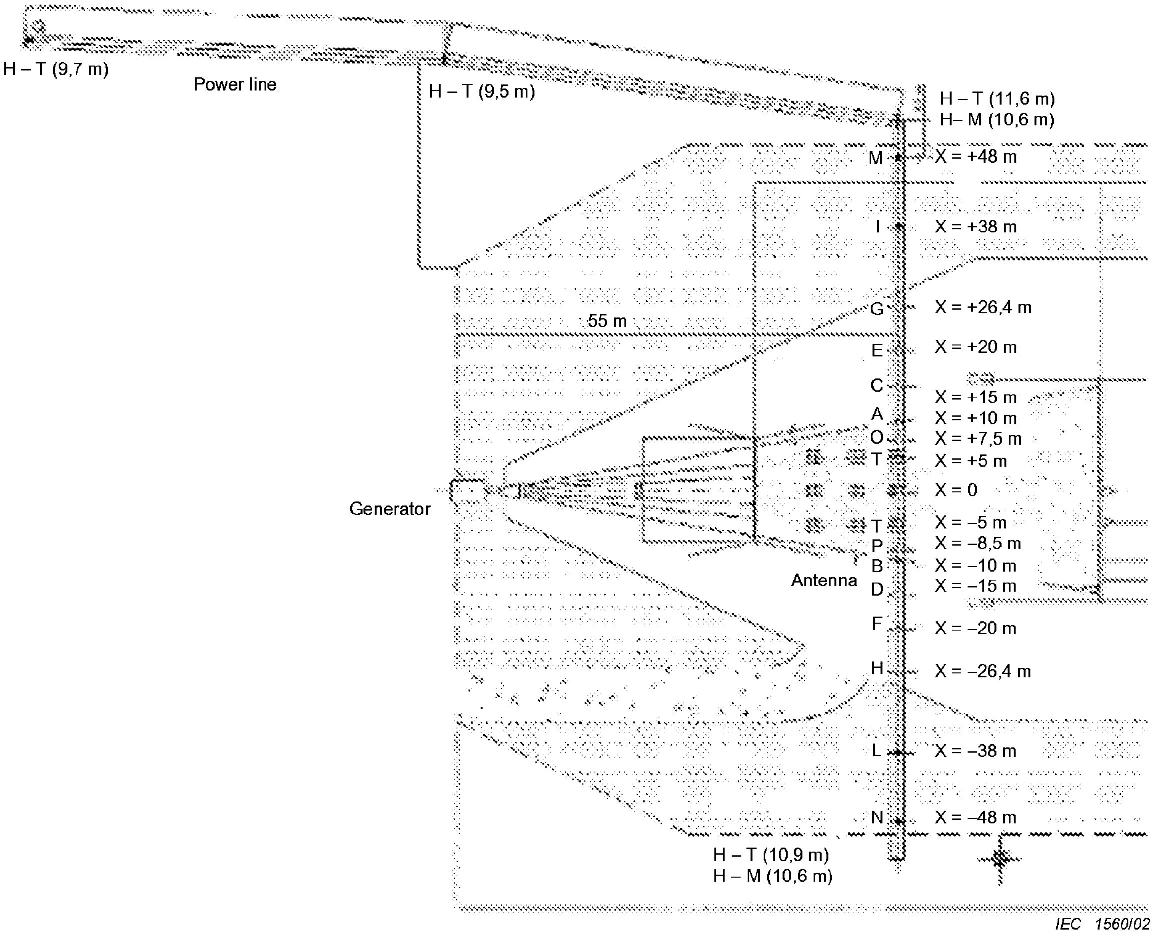
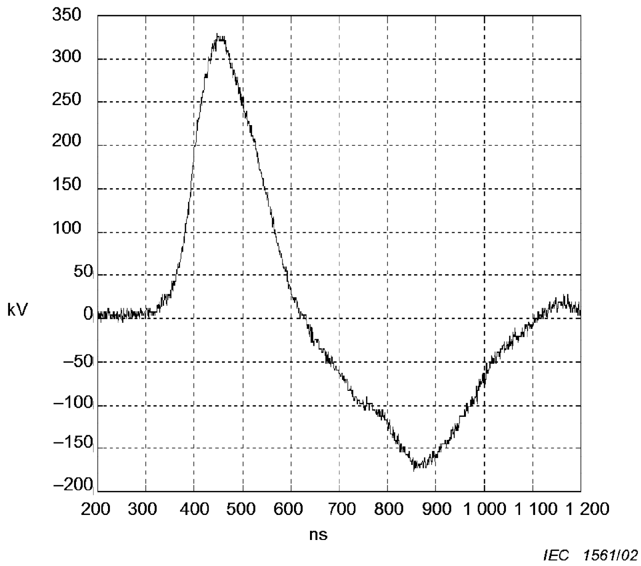


Figure 15 – Geometry of the medium voltage (MV) power lines with respect to the EMP simulator



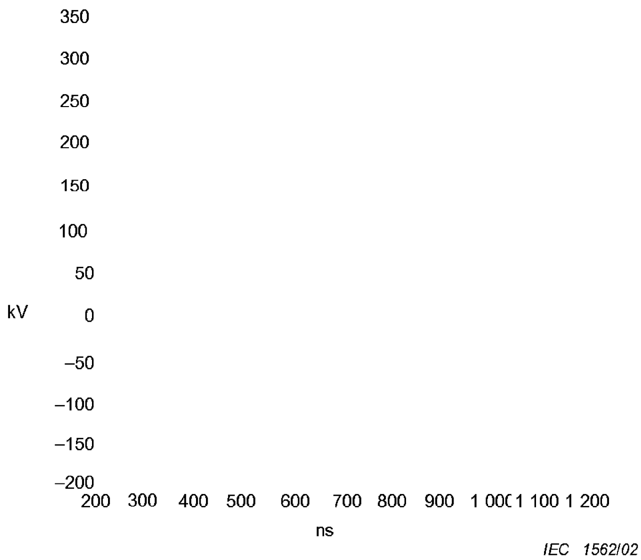


Figure 16 – Comparison of measured (left) and calculated (right) HEMP simulator-induced voltage (line to ground) at position M in figure 15, where the line turns 90°

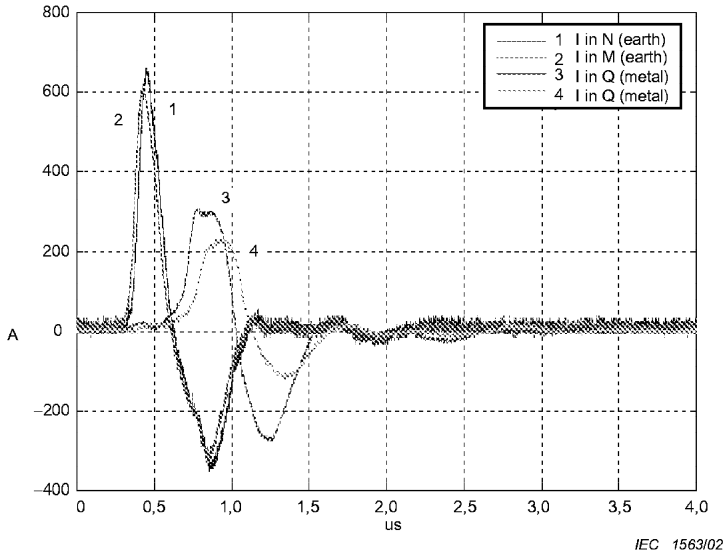


Figure 17 – Comparison of the measured currents in amperes at four different locations: 1 and 2 at 48 m on either side of the simulator centreline (points M and N in figure 15), and 3 and 4 near the far end of the line (near point Q in figure 15)

This experiment has shown that for a non-plane-wave HEMP field at 20 kV/m exciting a realistic three-wire power line, induced voltages of nearly 400 kV are possible, and currents as high as 600 A can be produced when the power line is loaded at both ends by its characteristic impedance. In addition, the accuracy of the long-line coupling model for this complex geometry is excellent, indicating that the basic model has enough accuracy to be used in the evaluation of HEMP effects.

7.4 Train power-line coupling experiment

A single line (simulating a power line) was placed directly over a set of rail lines and impedance-matched at both ends; a real locomotive was placed on the rails in the centre (see figure 18). A hybrid HEMP simulator was located 20 m away and produced a horizontally polarized electromagnetic field having roughly the characteristics of the old Bell Laboratory HEMP waveform [10] at the locomotive. The waveform characteristics were:

- rise time about 10 ns;
- fall-time to half-amplitude about 200 ns;
- electric field peak value about 50 kV/m;
- simulator length 60 m;
- line length 70 m;
- line height over the ground 5 m.

A perfect conducting ground was approximately represented by the rails of the locomotive; this assumption was used for the calculations done as part of the evaluations [11].

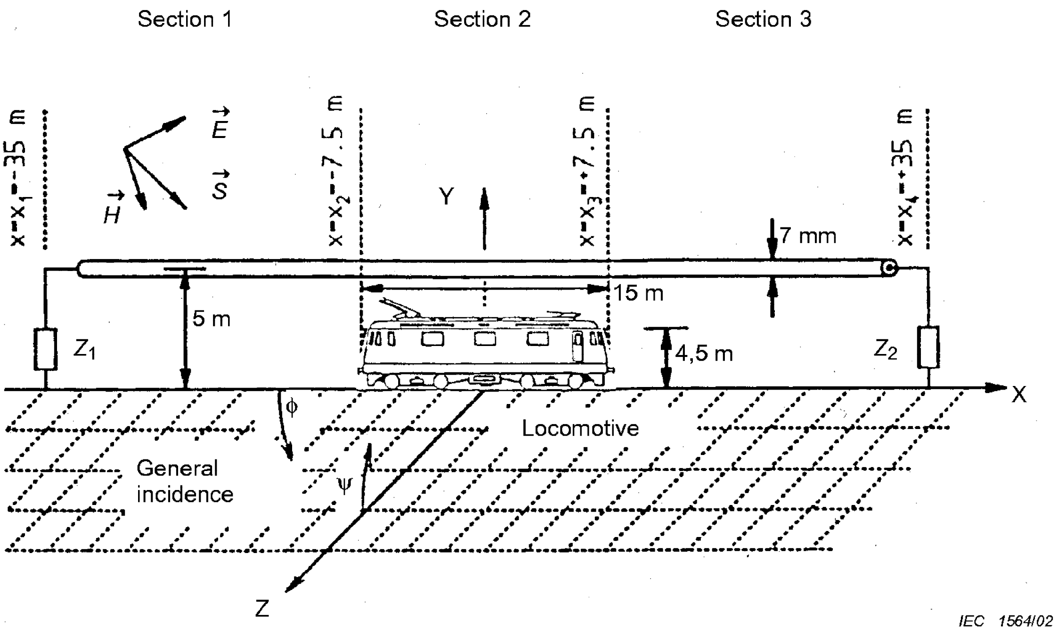
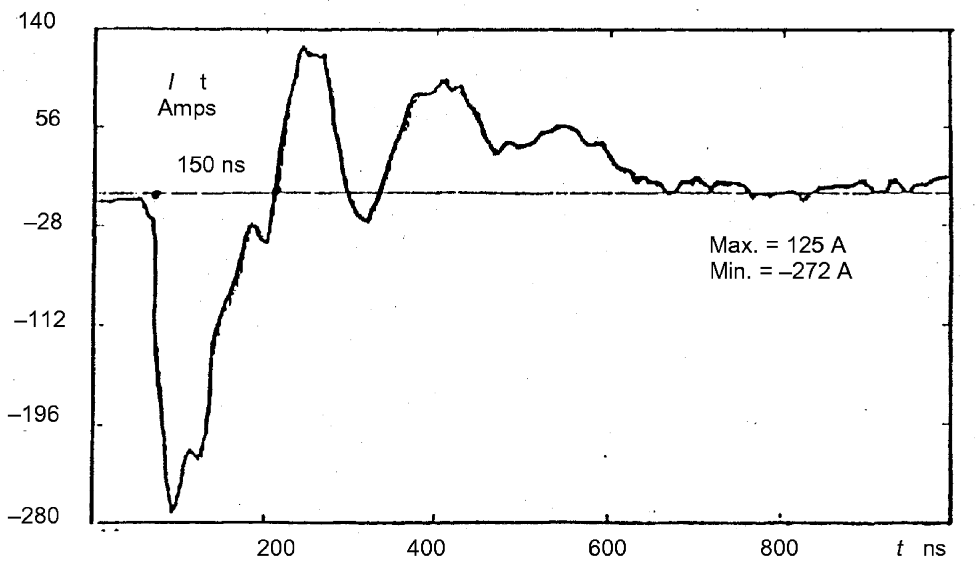


Figure 18 – Geometry for HEMP simulation test of locomotive with single power line

The current induced (see figure 19) in the overhead wire was measured at x = - 7 m, i.e. exactly over the left end of the locomotive as shown in figure 18. The coupled current with its amplitude of 272 A and a rise time of about 20 ns could be a concern to electrical and electronic systems associated with the train. Given this demonstrated level (which is not worst case due to geometry issues), it is possible to define a current injection procedure to test more easily equipment that is connected to the railway power system. It will be important to define methods to attenuate these HEMP-induced currents and voltages to avoid damage or malfunction of the train system. It is noted that during the radiated HEMP experiment there were problems experienced by the locomotive which required correction. In particular, the locomotive control electronics (TTL/CMOS) were confused by the HEMP-induced currents which caused the locomotive wheels to stop turning. This would have stopped a moving locomotive.



IEC 1565/02

Figure 19 – Measured HEMP-induced current on power line directly above left end of locomotive

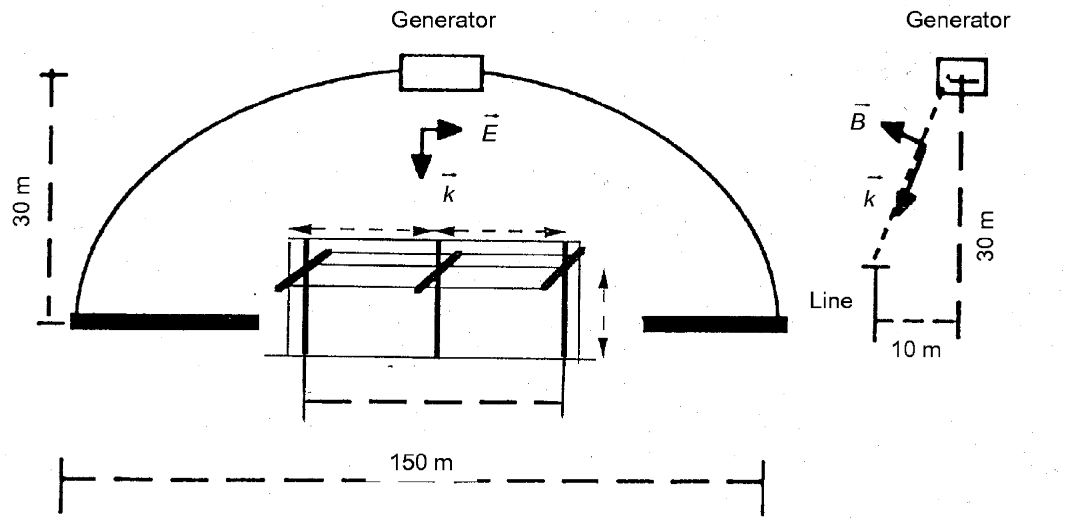
7.5 HEMP-induced currents on a three-phase line

A three-phase line is open-circuited at the two ends with a fourth grounding wire short-circuited to the ground at the two extremities. This line is installed in front of, and at 10 m distance from, a hybrid HEMP simulator (see [12]) as shown in figure 20. While this geometry may not be very realistic, the main purpose of the experiment was to perform a code/data validation.

The HEMP simulator produces a horizontally polarized electromagnetic field having the following characteristics:

- peak amplitude ~26 kV/m;
- rise time ~5 ns;
- pulse width ~25 ns;
- simulator length 150 m;
- line length 30 m;
- line height over the ground 3 m.

A perfectly conducting ground was approximately simulated by metallic plates, about 3 m wide, under the line.



(The elliptical line shown is the simulator conductor and the terminating resistors at the ground are not shown.)

Figure 20 – Geometry for three-phase line placed under a hybrid HEMP simulator

The measured induced current in the grounding wire (solid line) is compared to a calculation using Agrawal's transmission line model [13] as indicated in figure 21.

In figure 22 the current flowing in the centre of a single open-circuited phase wire is shown, with the grounding wire removed. Note that the peak current is nearly the same as the grounding wire current previously shown (240 A versus 275 A), but the damping of the waveform is much slower due to the open-circuit condition on the phase line as compared to the short-circuit condition for the ground wire.

As in previous cases, this experiment illustrates that the coupling of HEMP fields to long lines is well understood and can be predicted well with existing computer models. This supports conclusions derived from atmospheric nuclear test experiments where unexpected effects were observed, but where no measurements were performed. Therefore, for these cases, it has been necessary to compute the conducted transients that caused the reported system effects.

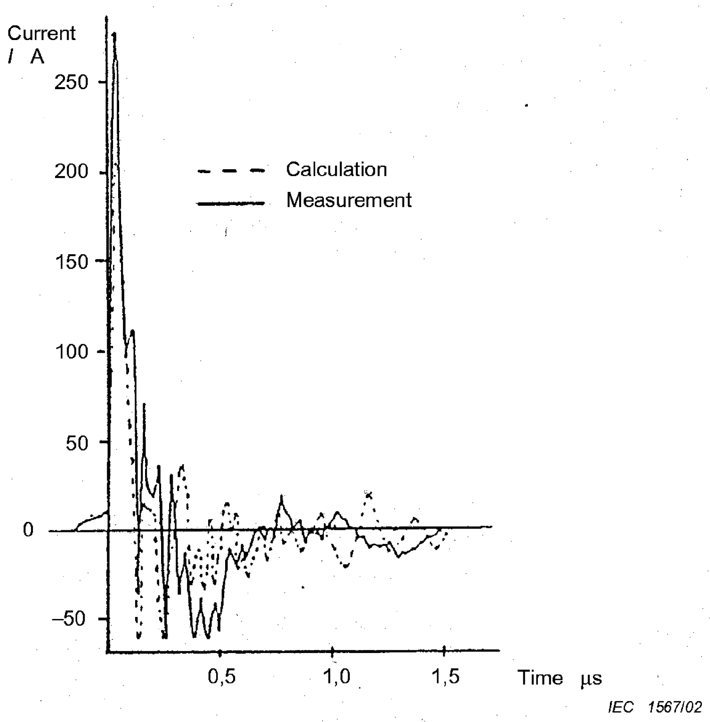


Figure 21 – Comparison of measured (solid line) and calculated (dashed line) currents flowing on the shielding wire

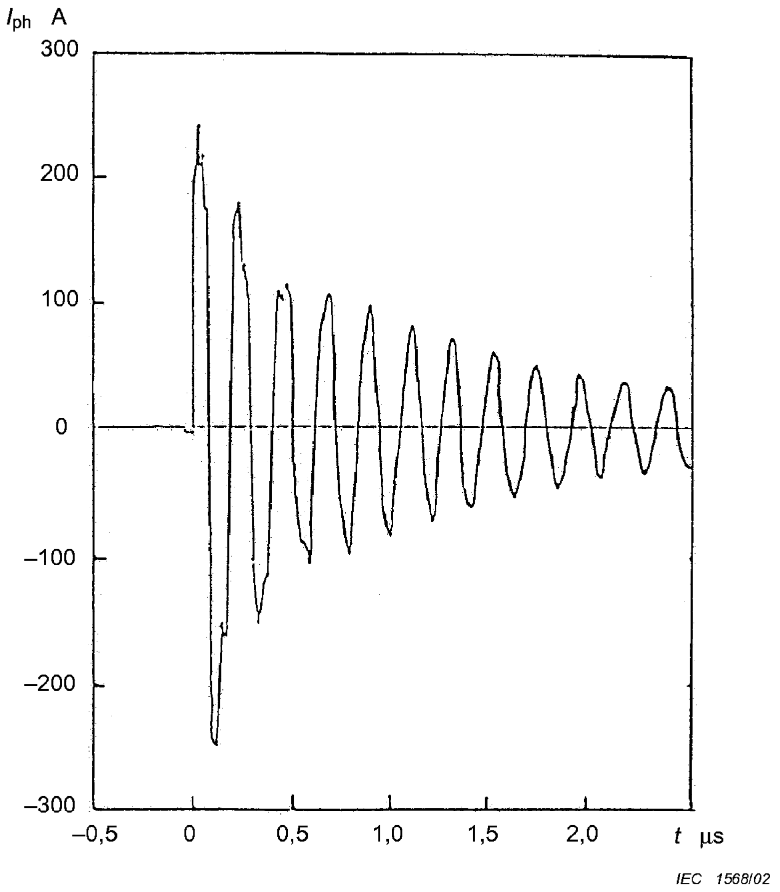


Figure 22 – HEMP current measured in the centre of one of the open-circuited phase wires when the grounding wire was removed

8 HEMP simulator testing with conducted transients

8.1 High-voltage power-line equipment

Over a period of many years, scientists in Russia performed HEMP tests on power lines to understand the effects that could accompany a high-altitude nuclear burst [14]. One of the early experiments on above-ground high-voltage lines found that insulators on 110 kV power lines could usually withstand HEMP open-circuit voltage pulses on the order of 400 kV (see figure 23a), although occasionally porcelain insulators were broken. It was found, however, that performing the same 400 kV test on an energized power line resulted in sparkover to flashover, 2 to 3 phase shorts and insulator failures at approximately 350 kV (see figures 23b and 24). It is noted that a peak HEMP-induced voltage of 400 kV on an above-ground power line is well below the worst-case HEMP threat of 1,6 MV as defined in IEC 61000-2-10.

Thus, it is important to perform these types of tests in the most realistic fashion possible (see figure 24). In addition to testing the line insulators, tests were performed on other high-voltage equipment such as valve and tube dischargers, shield gaps and non-linear resistors. In most cases, it was established that these protective means are not sufficiently fast-acting and cannot protect the equipment from the HEMP effects. Also it was found that breakdowns occurred in the low-voltage windings of high-voltage transformers at 400 kV (see figure 25). In addition to the public power system, experiments found that mobile diesel power stations were also vulnerable to the effects of HEMP when currents were induced in the supply power cables (see figure 26).

In the past, most of the attention concerning HEMP effects was related to military requirements, and military systems did not depend on the public power grid for critical operations, relying instead on locally generated power. In addition, there was not much evidence that power systems were vulnerable to HEMP. Therefore, telecom and radio systems were studied in the most detail. However, the newly documented Russian experience described here is that high-voltage power systems without special protection measures could be vulnerable. In addition, the power system can efficiently transfer the HEMP energy to the inside of buildings (see figure 27) where additional damage to connected equipment may occur. A sample test set-up for performing these types of tests is shown in figure 28.

8.2 Testing of distribution transformers to conducted HEMP transients

Nineteen standard commercial, 7,2 kV, 25 kVA distribution transformers were tested in [15] to determine the vulnerability of their insulation systems to a fast-rising conducted transient similar to HEMP. The waveform generator could produce peak open-circuit voltages of 400 kV, 500 kV, 800 kV and 1 000 kV, with a rise time of 60 ns and a pulse width of 2 000 ns. When injecting a voltage into a transformer, a 400-ohm series resistor was used to simulate the distribution-line surge impedance expected under realistic conditions.

Standard lightning impulse tests for this voltage class of distribution transformers were performed prior to the injection testing to verify insulation integrity, and these tests were repeated after the injection testing to determine whether insulation failure had occurred during the test. In addition, failed transformers were disassembled to evaluate failure modes. In all cases the injection testing was done without the transformers being energized.

The 19 transformers tested were all pole-mount single-phase distribution transformers with high-voltage windings rated at 12 470Y/7 200 V with a 95-kV basic insulation level (BIL). Most of the transformers had single bushings although some had double bushings. The low- voltage windings were all 120/240 V.

The transformers were tested in groups with the following characteristics. Six were single high-voltage bushing units with no surge arresters (ZS1-ZS6). Four were completely self-protected units with a single high-voltage bushing and an externally gapped silicon carbide surge arrester (ZV1-ZV4). Four were self-protected units with a single high-voltage bushing and a directly mounted and connected gapped silicon carbide surge arrester (ZW1-ZW4). Two units were equipped with double high-voltage bushings and no surge arresters (ZD1-ZD2). Two were completely self-protected units with double high-voltage bushings and directly mounted and connected gapped silicon carbide surge arresters (ZE1-ZE2).

While all of the transformers described above were provided by the same supplier, two additional transformers were manufactured by a different company. These two transformers were equipped with a single high-voltage bushing and a directly mounted and connected gapped silicon carbide surge arrester (XV1-XV2).

The results of the testing are shown in table 5. It is important to note that the non-self-protected units (ZS and XV) show a clear behaviour of failures in all cases where mounted surge arresters were not used. It is noted that the 400 kV open-circuit test level was the lowest level applied, and the lowest failure level is therefore unknown. The authors of reference 15 also indicate that they mounted the surge arresters directly on the transformer tanks during the testing, but found that arresters mounted 1,2 to 1,8 metres away were less effective in protecting the transformers.

The authors of [15] concluded that unprotected transformers failed between 250 kV and 300 kV. The failure mode was usually found to be an internal flashover/puncture between the first few turns of the outer layer of the high-voltage winding and the low-voltage winding. They also found cases were the failure occurred between the outer and inner layers of the high-voltage winding.

It is important to note that these results indicate that HEMP current levels of 625 A to 750 A are a threat to unprotected distribution transformers. Since this was the lowest level tested, it is possible that the levels for damage are even lower. In addition, if lightning protection is not mounted on the transformer tank, it may be ineffective against the much faster HEMP transients. Finally, this testing was done in a power-off mode, and as suggested in 8.1, power-on testing may result in lower failure levels.

Table 5 – Summary of distribution transformer tests [15]

XFMR	Shots #@kV	Peak voltage kV	Time to peak ns	Surge arrester	Notes	Result
ZS1						Pulser calibration
ZS2	1@400	264	618	No	(1)	T-T failure
ZS3	2@400	288	668	No	(2)	HV-LV failure
ZS4	2@400	280	600	No	(1)	L-L failure
ZS5	1@400	272	550	No	(2)	HV-LV failure
ZS6	2@400	290	643	No	(1)	No damage
ZV1	1@400	296	601	No	(1)	No damage
ZV2	1@400	304	592	No	(2)	HV-LV failure
ZV3	2@400	110	100	Yes	(3)	No damage
ZV4	2@500	110	100	Yes	(3)	No damage
ZV4	2@780	116	110	Yes	(3)	No damage
XV1	1@400	272	500	No	(2)	HV-LV failure
XV2	2@400	115	110	Yes	(3)	No damage
ZW1	2@400	292	552	No	(1)	No damage
ZW2	2@400	16	Oscillatory	No	(4)	No damage
ZW3	2@780	100	110	Yes	(3)	No damage
ZW4	2@1000	112	105	Yes	(3)	No damage
ZD1	2@400	120	550	No	(5)	No damage
ZD2	2@400	20	Oscillatory	No	(4)	No damage
ZE1	2@1000	95	100	Yes	(6)	No damage
ZE2	6@780	95	100	Yes	(6)	No damage

(1) External flashover on HV bushing: T-T failure denotes turn-to-turn failure; L-L failure denotes line-to-line failure

(2) No external flashover; HV-LV failure denotes a high-voltage winding flashover to the low-voltage winding

(3) Surge arrester operation and no external flashover

(4) Surge applied to the low-voltage bushings with no external flashover

(5) Surge applied common mode to both HV bushings with external flashover

(6) Surge applied common mode to both bushings, and both arresters operated

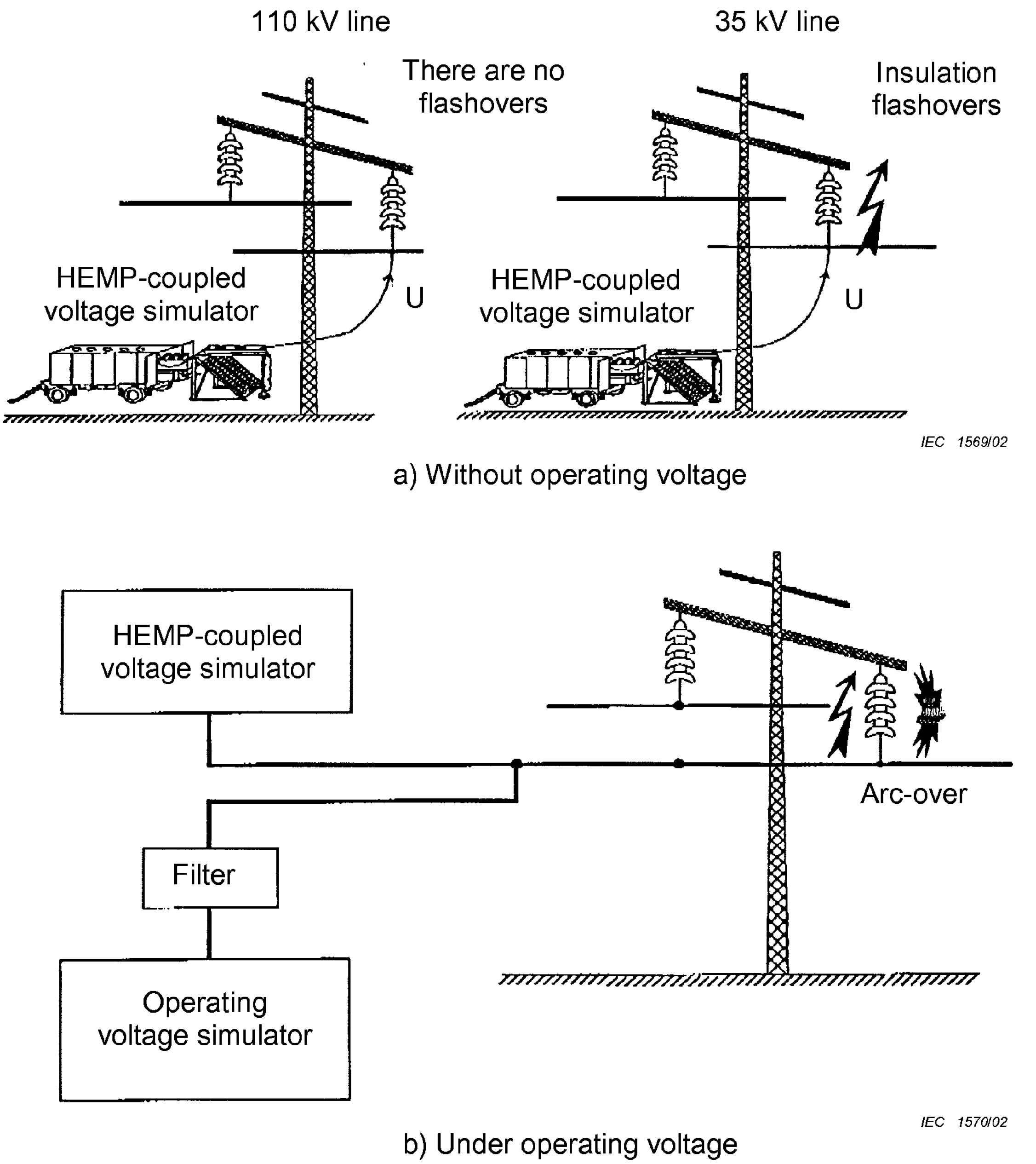


Figure 23 – Experimental HEMP investigation of high-voltage equipment showing the importance of testing power lines when they are energized. Note that the lower figure b) is for a 110-kV power line

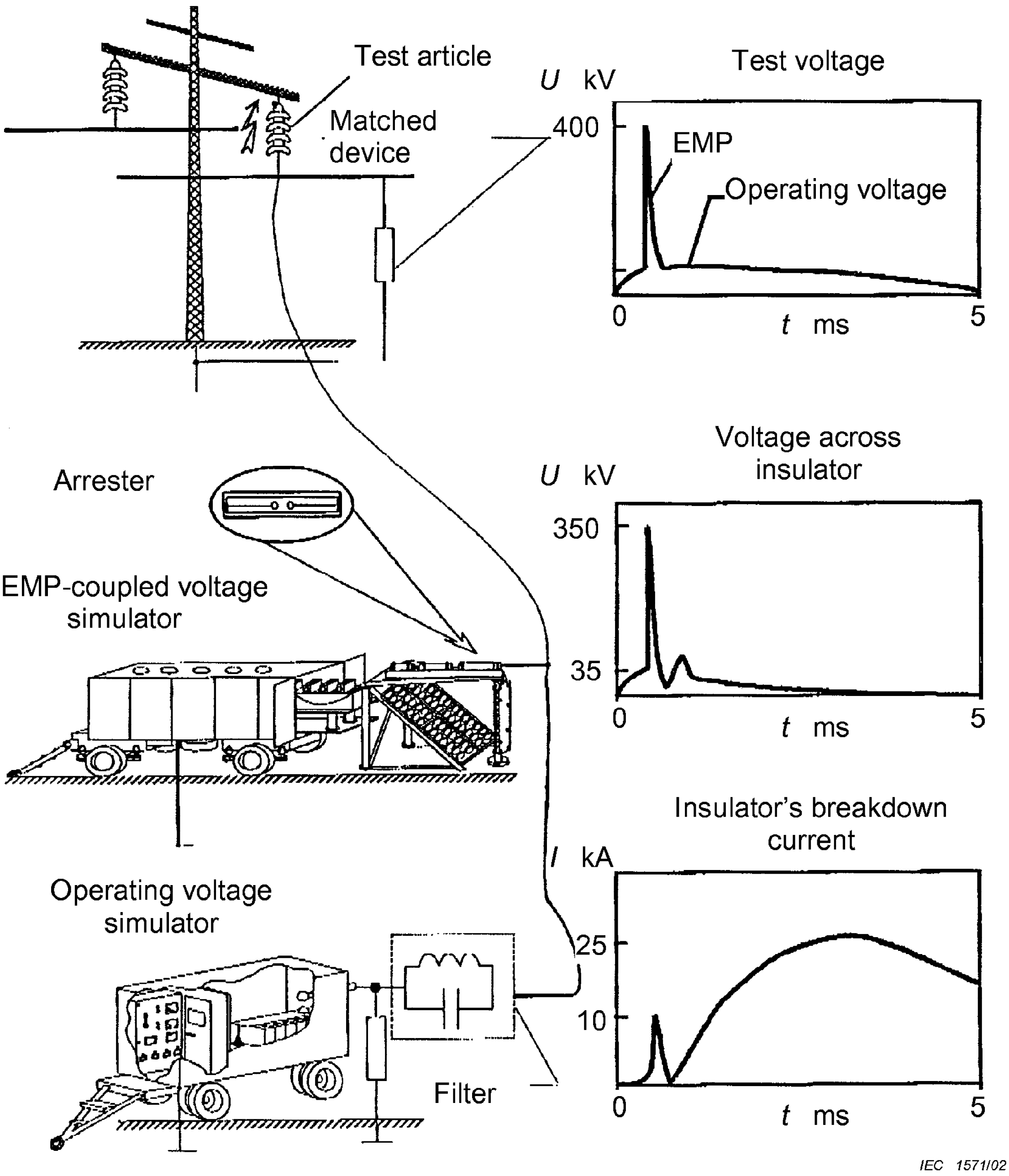


Figure 24 – Simulation of HEMP effects on a 110 kV power line under operating voltage

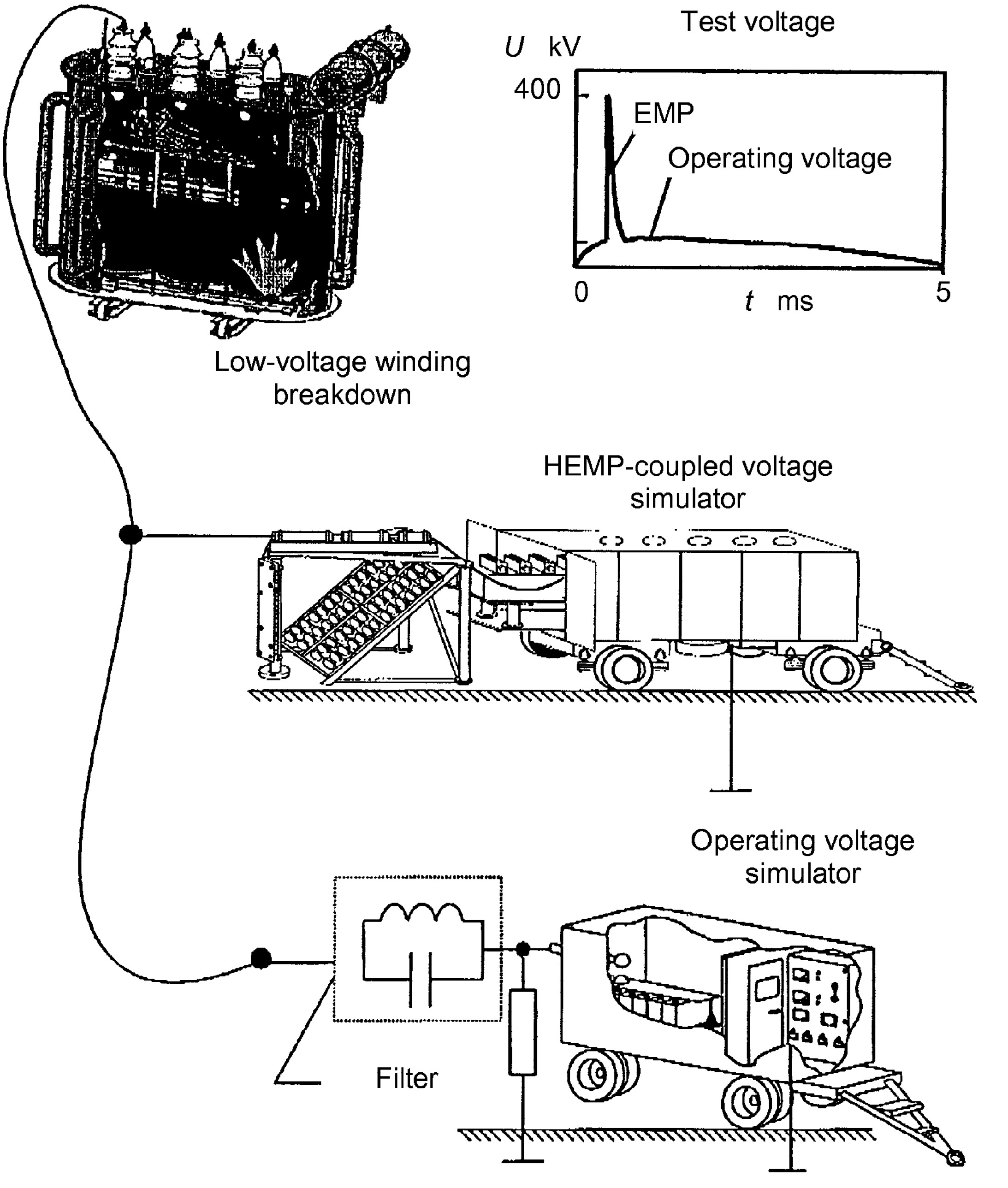


Figure 25 – Investigation of HEMP effects on high-voltage transformers

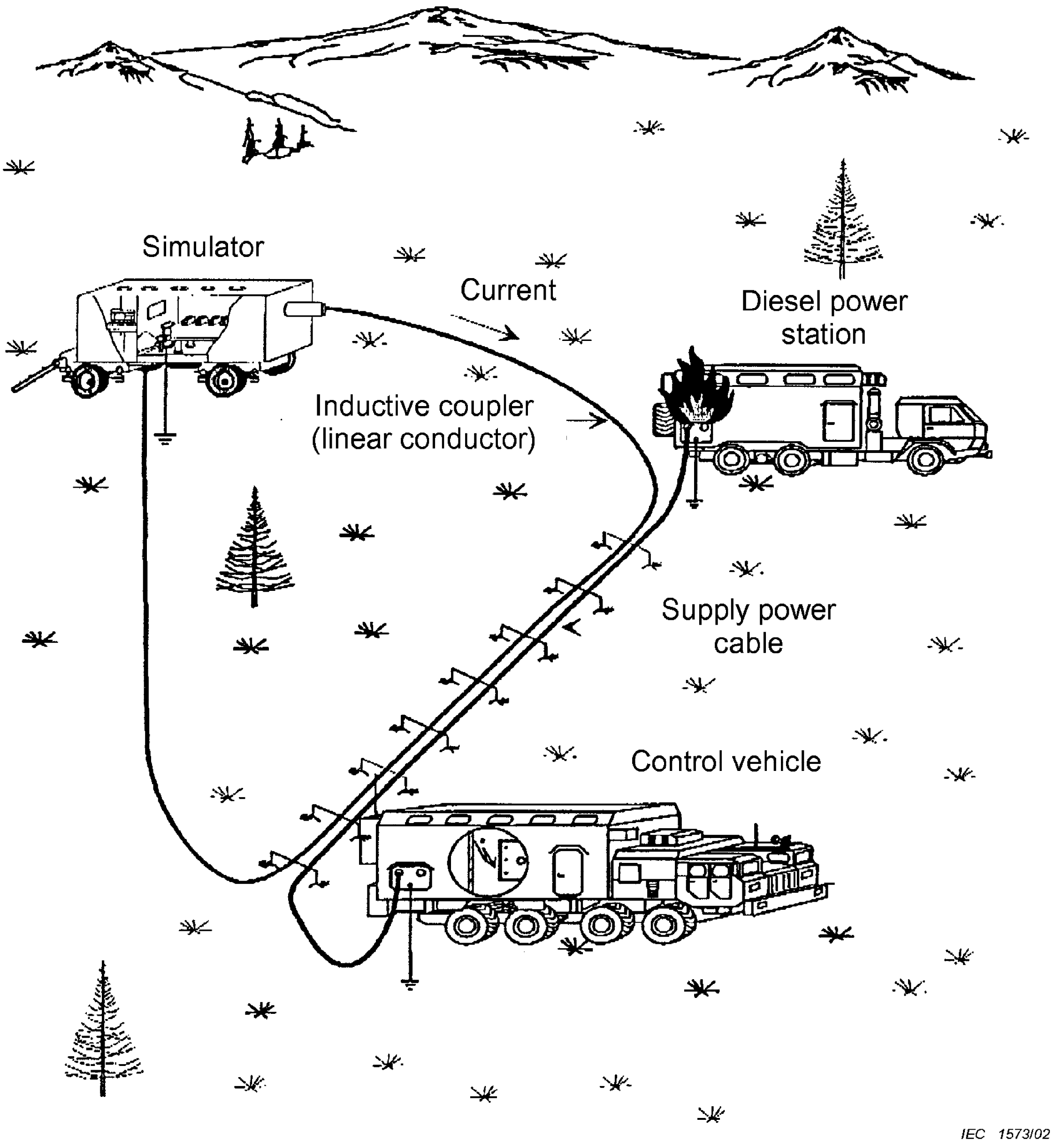


Figure 26 – Simulation of HEMP effects on a mobile diesel power station under operating voltage

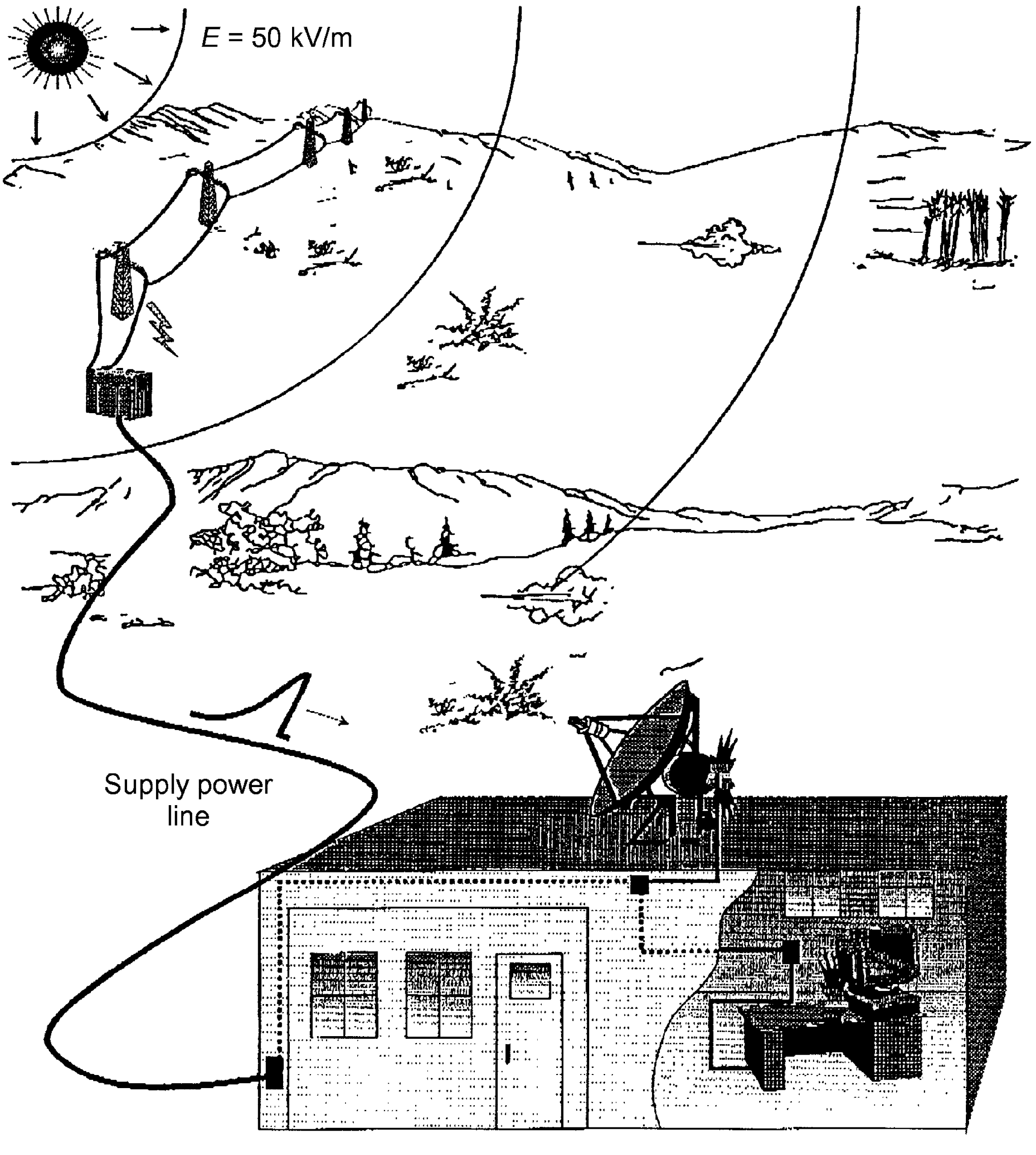


Figure 27 –Types of interference caused by HEMP penetration through the electric power supply system

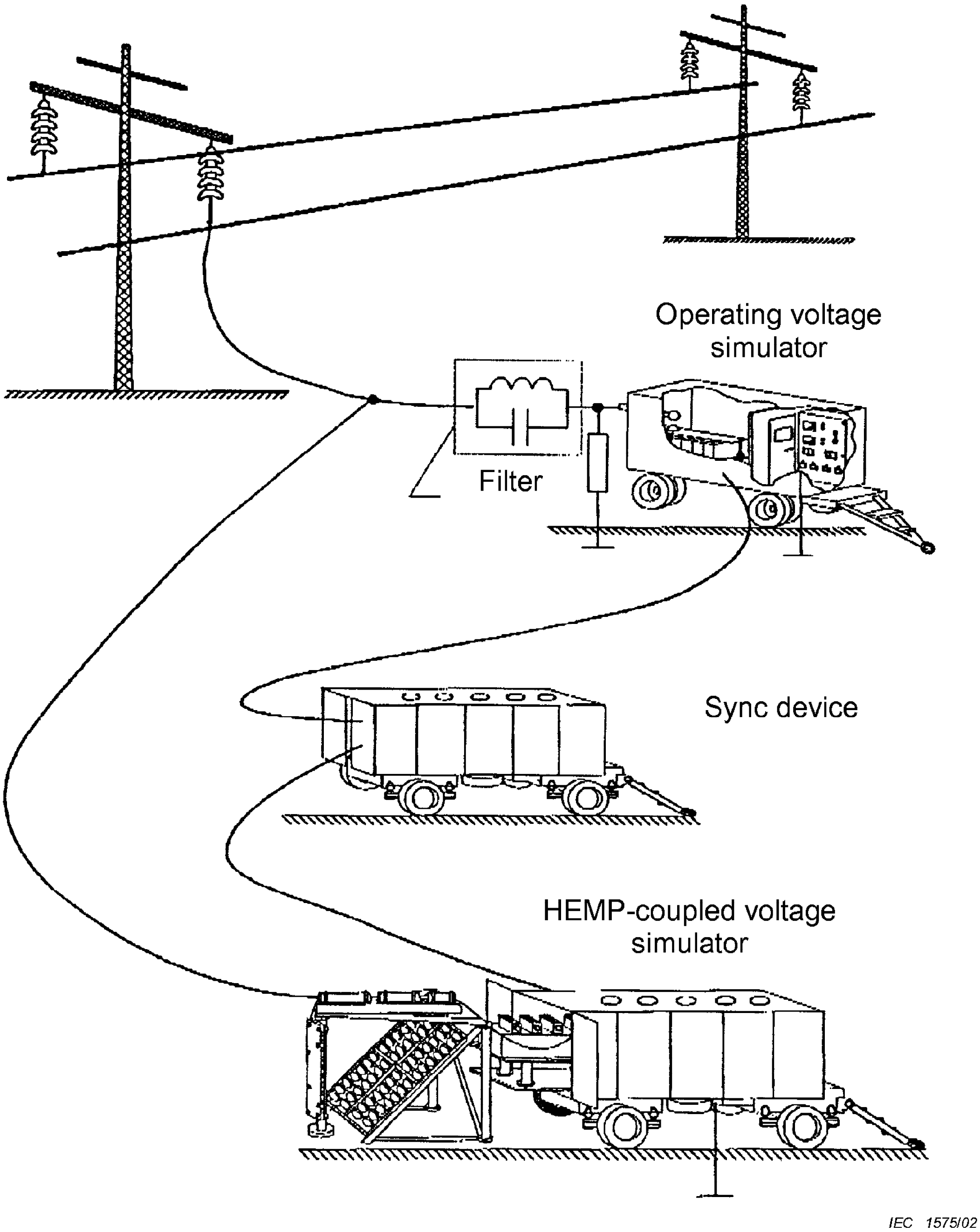


Figure 28 – HEMP test layout for power systems under operation

9 Summary

This report has reviewed several interesting sets of information on HEMP effects from nuclear atmospheric tests conducted by the United States and the Soviet Union in 1962, and electromagnetic simulator experiments performed in a variety of nations since that time.

In the case of the atmospheric testing presented in this report, the Starfish test produced noticeable effects including radio communication blackouts, geomagnetic field disturbances, burglar alarms and air raid sirens malfunctioning, and the extinguishing of streetlights. In the Soviet Union atmospheric testing, several communication lines failed at test time, a power line failed due to insulator damage, diesel generators failed to operate properly, and antenna systems were affected. It is interesting to note from the reports of problems that many of these failures were difficult to document in detail due to the lack of recognition that many of these problems were related to a nuclear detonation in space hundreds of miles away. It is also important to note that the level of electronics technology of the time (1962) was mostly tube and high power transistor, which is very different from the more susceptible integrated circuits of the 21st century.

In the 1970s and 1980s, large HEMP simulators were constructed throughout the world to simulate the expected incident electromagnetic pulse. These simulators were very reproducible and gave scientists the ability to investigate the response of equipment to the HEMP field. This report has clearly illustrated that a variety of consumer electronics and radios are vulnerable to the HEMP radiated field. In addition, it was noted during many tests that the currents induced on the attached power and data cables by the HEMP fields are often responsible for the malfunctions noted. In addition, HEMP field simulator tests were performed on a variety of power lines and electric train supply systems to show that large currents can be induced on these lines. These experiments have provided valuable data to verify the accuracy of HEMP coupling codes which can then be used to compute the realistic HEMP conducted environments that would be produced by a high-altitude nuclear burst.

In clause 8 HEMP coupling codes were used to derive realistic current- and voltage-conducted environments appropriate for testing electric power systems. The experience gained in Russia has shown that power system testing should be performed under full-voltage operating conditions in order to properly evaluate breakdown and damage effects.

While the cases examined in this report are not complete, they are representative of the types of problems that can be expected in the case of a high-altitude nuclear detonation. In addition, the amount of damage and malfunction expected will be related to the sensitivity of the equipment which has certainly changed since the early 1960s. It is for this reason that IEC SC 77C has developed a complete set of standards and reports to aid in the protection and testing of civil equipment and systems from the large-area effects of high-altitude EMP.

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