IEC/TS 61000-5-8

Edition 1.0 2009-08

TECHNICAL SPECIFICATION

colour
inside

BASIC EMC PUBLICATION

Electromagnetic compatibility (EMC) – Part 5-8: Installation and mitigation guidelines – HEMP protection methods for the distributed infrastructure

IEC/TS 61000-5-8:2009(E)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE U

ICS 33.100.20

ISBN 2-8318-1060-3

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 5-8: Installation and mitigation guidelines – HEMP protection methods for the distributed infrastructure

FOREWORD

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The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a technical specification when

- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC/TS 61000-5-8, which is a technical specification, has been prepared by subcommittee 77C: High power transient phenomena, of IEC technical committee 77: Electromagnetic compatibility.

This Technical Specification forms Part 5-8 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107 [1][1].

This document is being issued in the Technical Specification series of publications (according to the ISO/IEC Directives, Part 1, 3.1.1.1) as a “prospective standard for provisional application” in the field of protection of the infrastructure against HEMP because there is an urgent need for guidance on how standards in this field should be used to meet an identified need.

This document is not to be regarded as an “International Standard”. It is proposed for provisional application so that information and experience of its use in practice may be gathered. Comments on the content of this document should be sent to the IEC Central Office.

A review of this Technical Specification will be carried out not later than 3 years after its publication with the options of: extension for another 3 years; conversion into an International Standard; or withdrawal.

The text of this standard is based on the following documents:

Enquiry draft	Report on voting
77C/192/DTS	77C/196/RVC

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

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

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

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

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

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this publication using a colour printer.

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[1] Figures in square brackets refer to the Bibliography.

INTRODUCTION

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

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

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

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

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

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 5-8: Installation and mitigation guidelines – HEMP protection methods for the distributed infrastructure

1 Scope

The aim of this part of IEC 61000 is to provide guidance on how to protect the distributed infrastructure (power, telecommunications, transportation and pipeline networks, etc.) from the threat of a high altitude electromagnetic pulse (HEMP). In order to accomplish this goal, it is necessary to describe the special aspects of the HEMP threat to electrical/electronic systems that are connected and distributed in nature. In particular a nuclear burst at a typical altitude of 100 km will illuminate the Earth to a ground radius from the point directly under the burst to a range of 1 100 km. This means that any distributed and connected infrastructure such as power or telecommunications will observe disturbances simultaneously over a wide area. This type of situation is not normally considered in the EMC or HEMP protection of facilities that are part of a distributed network as the impact of a local disturbance is usually evaluated only locally.

This publication provides general information concerning the disturbance levels and protection methods for all types of distributed infrastructures. Due to its importance to all other parts of the infrastructure, the distributed electric power system (power substations, generation plants and control centres) and its protection are described in more detail. While the telecommunication system is also critical to most of the other distributed infrastructures, the protection of the telecommunication network from HEMP and other electromagnetic threats is covered by the work done by ITU-T.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

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

IEC 61000-2-11, *Electromagnetic compatibility (EMC) – Part 2-11: Environment – Classification of HEMP environments*

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

IEC 61000-4-5, *Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test*

IEC 61000-4-23, *Electromagnetic compatibility (EMC) – Part 4-23: Testing and measurement techniques – Test methods for protective devices for HEMP and other radiated disturbances*

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

IEC 61000-4-25, *Electromagnetic compatibility (EMC) – Part 4-25: Testing and measurement techniques – HEMP immunity test methods for equipment and systems*

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

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

IEC/TS 61000-5-9, *Electromagnetic compatibility (EMC) – Part 5-9: Installation and mitigation guidelines – System-level susceptibility assessments for HEMP and HPEM*

IEC 61000-6-6, *Electromagnetic compatibility (EMC) – Part 6-6: Generic standards – HEMP immunity for indoor equipment*

IEC 61850 (all parts), *Communication networks and systems in substations*

3 Terms and definitions

For the purposes of this document, the definitions contained in IEC 60050(161) as well as the following apply.

3.1
distributed infrastructure
the portions of the infrastructure of a society that are connected either physically or through real-time communications over distances of hundreds of kilometres, and include electrical and electronic controls to operate that infrastructure

NOTE This normally includes the electric power system, the telecommunications system, pipeline networks, and the transportation system.

3.2
E1, E2, E3
terminology for the early, intermediate and late-time HEMP electric fields. E1 is for times less than 1 microsecond, E2 for times between 1 microsecond and 1 second and E3 is for times greater than 1 second.

NOTE See IEC 61000-2-9 for additional information.

3.3
equipment
this term is not limited and includes modules, devices, apparatuses, subsystems, complete systems and installations

[IEV 151-11-25, modified]

3.4
HEMP
high-altitude electromagnetic pulse

3.5
HEMP 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

3.6
installation
combination of apparatuses, components and systems assembled and/or erected (individually) in a given area; for physical reasons (e.g. long distances between individual items) it is in many cases not possible to test an installation as a unit

[IEV 151-11-26, modified]

3.7
point-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

NOTE 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.

3.8
pulse width
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

3.9
rectified impulse
RI
integral of the absolute value of a time waveform’s amplitude over a specified time interval

3.10
rise time (of a pulse)
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

[IEV 161-02-05, modified]

3.11
severity
the probability that a level of HEMP environment will be less than the stated value

NOTE For example a 90 % severity level of current induced on an elevated, randomly oriented conductor is 1,5 kA. This means that only 10 % of currents would exceed this value.

3.12
short-circuit current
the value of current that flows when the output terminals of a circuit are shorted

NOTE This current is normally of interest when checking the performance of surge protection devices.

[IEV 441-11-07, modified and IEV 603-02-26, modified]

3.13
source impedance
impedance presented by a source of energy to the input terminals of a device or network

3.14
system
combination of apparatuses and/or active components constituting a single functional unit and intended to be installed and operated to perform (a) specific task(s)

4 General

The publications developed to protect civil systems from the threat of high-altitude electromagnetic pulse (HEMP) in the past have mainly covered the methods to protect important equipment, systems and installations against the threat of a severe electromagnetic pulse environment at the location of the system of interest. IEC 61000-2-9 recommends that an early-time (E1) HEMP with a peak value of 50 kV/m be used to design protection and to perform radiated tests, if the system of interest is fully exposed to the environment. It is well known that the HEMP field will vary across the Earth, however, since the location of a burst is not known in advance, system specifications have usually considered the maximum field level likely to be found anywhere at the Earth's surface.

In the same manner IEC 61000-2-10 indicates that the full HEMP field will illuminate and couple to all conductors, including cables and wires, creating a conducted HEMP environment, which may flow into connected equipment. For the early-time (E1) HEMP environment, the levels of currents induced will vary due to the polarization and angle of incidence of the HEMP field and the orientation of the conductor to the HEMP propagation. This means that large variations of currents are possible for randomly oriented above-ground conductors ranging from a 50 % severity value of 500 A to a 99 % severity value of 4 kA (based on a cumulative probability density function).

While the two examples above refer to the early-time HEMP environment, the intermediate-time (E2) and late-time (E3) HEMP waveforms are also a concern to very long conductors, such as exposed power lines and telephone wires. As indicated in IEC 61000-2-10, the peak currents that are induced may be determined from the peak electric field, the length of the conductor and the resistance of the conductor over the exposed coupling length.

For high voltage power transmission lines, the late-time (E3) HEMP induces currents on the order of hundreds of amperes for tens of seconds; these currents are likely to create half-cycle saturation in high voltage transformers and will also produce severe harmonics that can disrupt the voltage regulation of the network [2].[2]

For telecommunication lines the late-time (E3) HEMP environment has the ability to induce currents of up to tens of amperes for tens of seconds that are high enough to trip safety protection systems and to shut down each exposed line [3]. The currents induced are lower in telecommunication lines as the resistance per unit length of these lines is much higher than for power transmission cables.

Given these threats to important infrastructures, this publication provides methods to determine the appropriate levels of electromagnetic radiated and conducted disturbances for particular types of distributed infrastructures. In addition, these disturbances are compared to other natural EM environments that have well defined protection and test methods. This publication concludes with recommended protection strategies and methods that vary due to the cost versus effectiveness considerations involved, especially given a low probability event such as HEMP.

5 Description of the distributed infrastructure

Each critical infrastructure is dependent upon other infrastructures as shown in Figure 1. This figure is an example that describes in a simplified way the many interdependencies between them (not all connections are shown). The interdependence of critical infrastructures is likely to create difficulties in the ability to recover from the widespread disruption and damage that could be caused by an HEMP attack due to the large area impacted within a short time.

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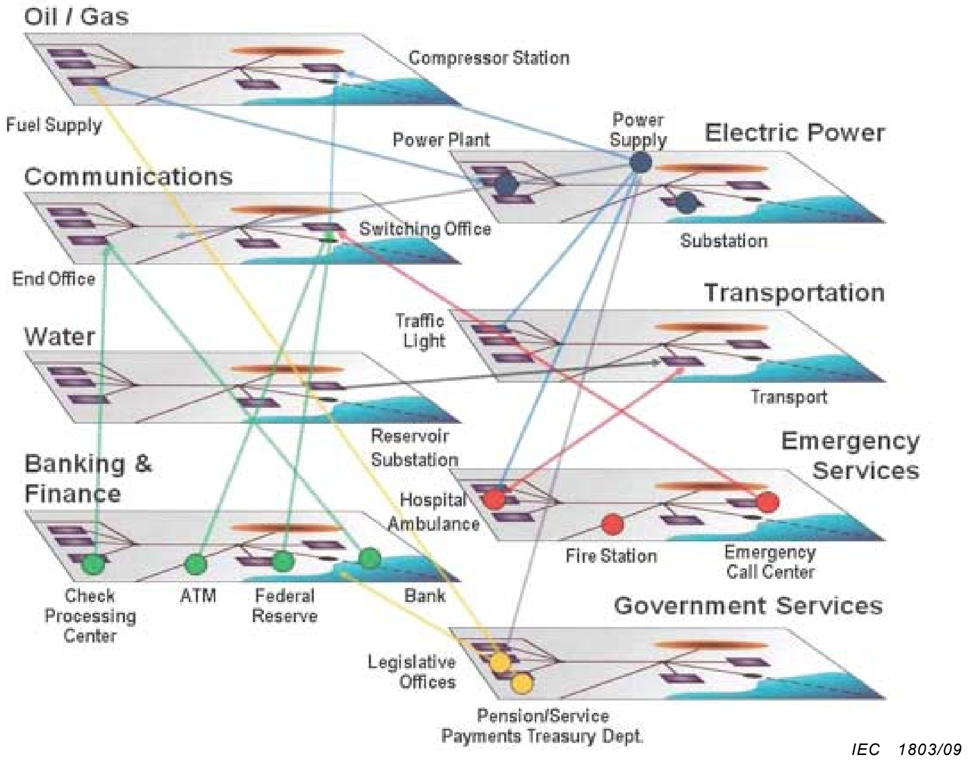
[2] Figures in square brackets refer to the Bibliography.



IEC 1803/09

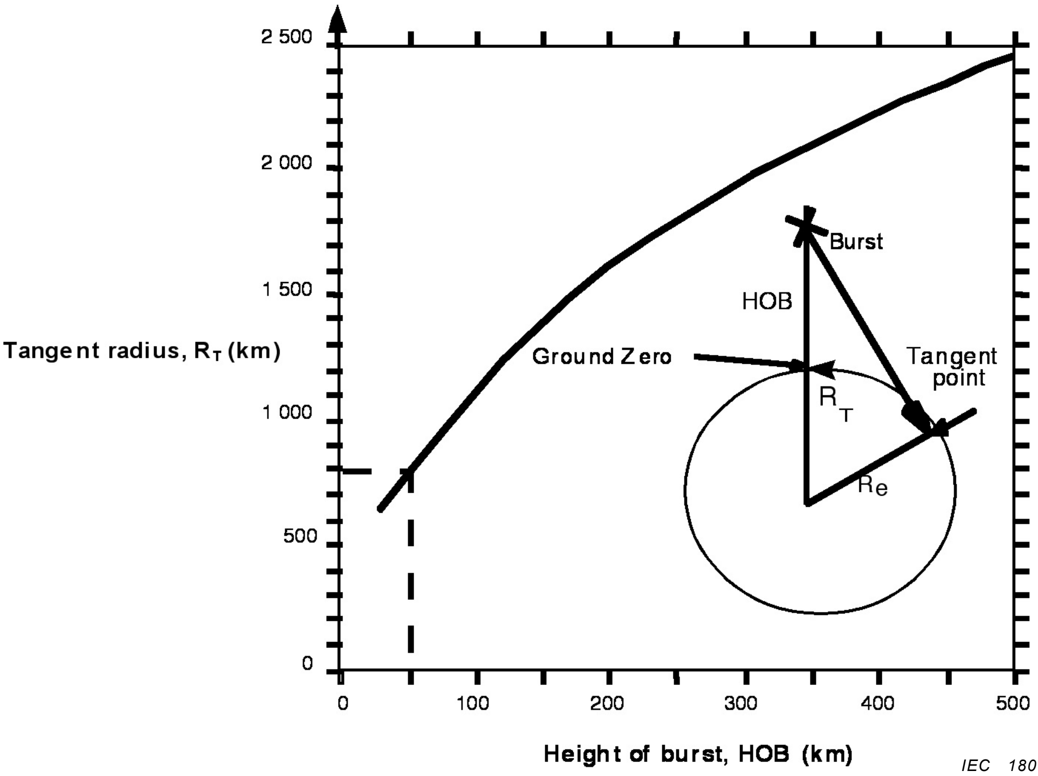
Figure 1 – Simplified depiction of the interdependency of critical infrastructures [4]

All of the critical functions of infrastructures, such as electric power, telecommunications, energy, financial, transportation, emergency services, water, food, etc., have electronic devices embedded in most aspects of their systems. Electric power is clearly the primary service underlying society and all of its other critical infrastructures. Any large-area blackout created by a HEMP event will be difficult to alleviate quickly due to the loss of communications and the difficulties in maintaining transportation networks to repair damage and to re-energize the grid.

6 Spatial variation of HEMP environments

6.1 Early-time (E1) HEMP spatial variations

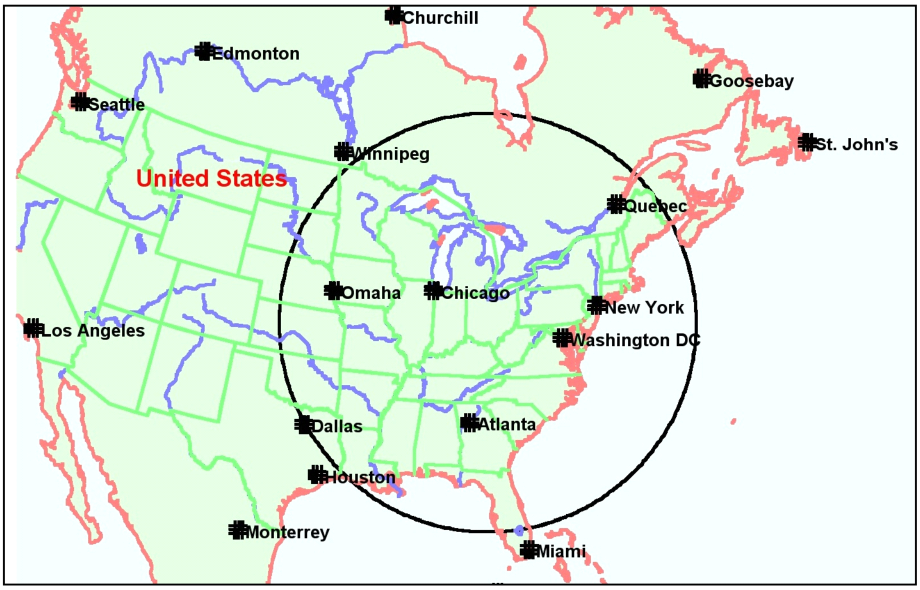
The early-time (E1) HEMP field has frequency content mainly above 1 MHz (with most of its energy in the tens of MHz); for this reason the field travels by line of sight. For typical burst altitudes above 100 km, the early-time HEMP field is actually generated only when the atmospheric density is high enough (between 20 km and 50 km altitude) to allow the prompt gamma rays to produce Compton currents (see IEC 61000-2-9). In spite of this fact, the early-time HEMP field appears to be radiated from the burst point of the detonation. For that reason it is straightforward to compute the radius of the Earth exposed to early-time HEMP by a given burst height (where the line of sight is tangent to the Earth's surface). Figure 2 indicates the tangent radius as a function of burst height. In addition, a simple formula may be used when the burst height is much smaller than the radius of the Earth, which is the usual case: R_T (km) ~ 110 square root [HOB (km)].



IEC 1804/09

Figure 2 – E1 HEMP tangent radius as a function of the height of burst

A more explicit example of the coverage of the early-time (E1) HEMP is shown in Figure 3, where a portion of the United States is shown covered by a 170 km burst over the state of Ohio. The early-time HEMP will illuminate the area inside the circle to electric field levels generally up to a maximum value of 50 kV/m. It is generally true that the maximum E1 HEMP fields are found near ground zero, and the fields decrease with ground range toward the tangent point. However, the impact of the Earth's geomagnetic field does affect this distribution near ground zero. For more details about the variation of the early-time (E1) HEMP field levels, see IEC 61000-2-9.



IEC 1805/09

Figure 3 – Example of the area covered by the early-time (E1) HEMP by a 170 km burst over the United States

An important issue concerning the early-time (E1) HEMP is the fact that it propagates at the speed of light from an apparent focal point at the burst. For the example and as shown in Figure 3 (burst height of 170 km), the time difference between the first and last arrival of the E1 HEMP at the Earth's surface is only 4,3 ms. This means that any disturbances created by the HEMP on a network, such as the power system, will create potential impacts over thousands of kilometres, but within one power cycle (20 ms/50 Hz; 16,7 ms/60 Hz). This provides a unique disturbance situation for a distributed infrastructure.

6.2 Intermediate-time (E2) HEMP spatial variations

For the intermediate-time (E2) HEMP environments, the E2 HEMP radiated field lasts between 1 µs and 1 s and has a peak field of 100 V/m (IEC 61000-2-9). The peak field of 100 V/m normally occurs within 100 km of surface zero and decreases to levels of a few V/m at the Earth's tangent. The frequency content contained in this pulse shape does not allow efficient coupling to equipment, systems or even small installations. In general the main effect is through the coupling to long (>100 m) conductors that lead to an installation and the equipment contained within.

6.3 Late-time (E3) HEMP spatial variations

The E3 HEMP radiated field is expected to be as high as 40 V/km (IEC 61000-2-9), with a rise time on the order of seconds and a pulse width on the order of 100 s. This level of peak field is somewhat dependent on the burst height and yield, however, in general the area of coverage for high levels of fields is within a radius of 250 km from surface zero. As in the case of E2, the even lower frequency content of this E3 field makes it suited only for coupling to very long cables (over 1 km in length).

7 Implications for HEMP coupling to extended conductors

7.1 General

Due to the fact that the HEMP conducted environments are only produced by coupling of the HEMP radiated environments, there are three distinct types of conducted environments: early-time (E1), intermediate-time (E2) and late-time (E3).

7.2 Early-time (E1) conducted environments

As described in IEC 61000-2-10 the early-time (E1) HEMP field couples efficiently to extended conductors (such as cables and wires) and can create large currents and voltages with rise times on the order of 10 ns. Depending on the polarization of the HEMP field, the angle of incidence to the Earth's surface and the relative orientation of an above-ground or buried conductor to the incident field, currents up to 4 kA may be induced. Table 1 from IEC 61000-2-10 presents several examples of probabilistic E1 HEMP currents that can be induced for the case of random conductor orientation over the entire area exposed by the HEMP. The upper portion of Table 1 indicates the results for above-ground conductors and the lower portion indicates similar results for buried conductors. The currents shown are for the flow on a conductor and are either shield currents or bulk currents for unshielded cables. The induced pulse shapes of the currents can be described by a (10/100) ns waveform (rise time/pulse width) for above-ground conductors and by a (25/500) ns waveform for buried conductors.

It is noted that the currents carried on above-ground conductors can be much larger than those from buried conductors. In addition, there is little variation shown due to the effect of the ground reducing the efficiency of the phasing of the incident field and the propagation of the induced currents on the conductors. The ground conductivity itself is, however, a factor in terms of the peak induced currents. As the information provided in Table 1 has been with regard to shield or bulk currents, the characteristic impedance of the cables must be considered to determine the appropriate voltage levels. The common-mode characteristic impedance of the above-ground conductors has a value of 400 Ω versus only 50 Ω for the buried conductors. This means that the induced peak voltages average 200 kV for above-ground conductors and range between 10 kV and 20 kV for buried conductors.

Table 1 – Peak currents induced by the E1 HEMP on above-ground and buried conductors

Table 1a – Above-ground conductor

	I_{pk}		
Severity %[a]	$L > 200$ m	$100 \leq L \leq 200$ 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

[a] Percentage of currents smaller than the indicated value.

Waveform 1: (10/100) ns.

Source impedance, $Z_s = 400\ \Omega$

Table 1b – Buried conductor

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

Waveform 2: (25/500) ns.

Source impedance, $Z_s = 50\ \Omega$

NOTE Source impedances are used in Table 1 to inject the proper ratio of voltages and currents. They are the same as the common-mode characteristic impedances.

7.3 Intermediate-time (E2) conducted environments

For the intermediate-time or E2 HEMP field coupling to extended conductors, results from IEC 61000-2-10 are summarized here. Table 2 describes the currents induced in long conductors as a function of the ground conductivity, length of the conductors and whether the conductors are above ground or buried. Table 2 indicates that lower ground conductivities produce larger currents for both locations of conductors; however, the currents for the above-ground conductors are higher by factors of 2 to 3 and the characteristic impedance is higher. Note also that the currents do not increase further for above-ground conductors greater than 10 km long or for buried conductors greater than 1 km. In both cases, the induced current waveform can be expressed as a (25/1 500) µs waveform.

Table 2 – Peak currents induced by the E2 HEMP on above-ground and buried conductors

Table 2a – Above-ground conductor

	I_{pk} A			
Ground conductivity S/m	**L > 10 000 m**	**1 000 ≤ L ≤ 10 000 m**	**100 ≤ L < 1 000 m**	**L < 100 m**
10^{-2}	150	75	0,05L	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 – Buries conductor

	I_{pk} A		
Ground conductivity S/m	**L > 1 000 m**	**100 ≤ L ≤ 1 000 m**	**L < 100 m**
10^{-2}	50	0,05L	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			

NOTE 1 Source impedances are used in Table 2 to inject the proper ratio of voltages and currents. They are the same as the common-mode characteristic impedances.

NOTE 2 In Table 2a for values of L between 1 000 m and 10 000 m, the values provided are approximate values. This accounts for the discontinuity for values below 1 000 m. For L < 1 000 m, use the formula provided.

7.4 Late-time (E3) conducted environments

The late-time or E3 HEMP waveform rises in a time of seconds but cannot couple efficiently to anything other than conductors longer than 1 km. Since the maximum peak field is 40 V/km, this could induce a voltage over 1 km of 40 V. If the conductor and its grounding system have 10 Ω of resistance, then a current of 4 A will flow. While this is a very low current, it also has a pulse width of 100 s, thereby providing a threat to fuses and other similar protective devices. As described here and in IEC 61000-2-10, a simple DC approach may be taken to evaluating the currents induced by the E3 HEMP, where the field level and the length of a conductor are first used to determine the induced voltage. The next step is to evaluate the entire resistance in the ground loop, which is then divided into the voltage to determine the induced current. This current will have the same time dependence as the incident E3 electric field.

8 Relation of HEMP disturbances to natural EM environments

8.1 General

In terms of the radiated pulse field that is associated with the E1 HEMP, similar natural pulses are the EM transient fields produced by arcing events in power substations and the pulsed fields created by electrostatic discharge (ESD) events. In the case of the substation events, pulsed fields have been measured with rise times on the order of 10 ns and peak field levels of 10 kV/m. In the case of ESD, measurements have been made at a distance of 0,1 m from an arc produced by an ESD test gun and have indicated a peak field up to 10 kV/m with a rise time of 0,7 ns and a pulse width of 30 ns. The E1 HEMP waveform described in IEC 61000-2-9 is a (2,5/25) ns waveform with a peak field of 50 kV/m. In the case of ESD, tests have indicated that electronic equipment can be affected by these types of fields unless protection is provided. In the case of power substations, it is known that significant high-frequency currents and voltages can be induced on equipment cables in substations providing over-voltages that connected equipment must withstand. HEMP fields are often compared to nearby lightning fields, and measured lightning fields have peak fields of 10 kV/m or higher; however, the lightning field rise times are longer than 100 ns (often 1 μs) and therefore are not as similar to E1 HEMP as ESD or substation arcing events (IEC 61000-5-3).

With regard to the E2 HEMP radiated fields, the waveform is very similar to natural lightning, although the peak field value of 100 V/m is far less than nearby lightning electric fields. It does appear that because the E2 HEMP field propagates as a plane wave, it is more efficient in coupling to conductors and therefore creates levels of currents nearly as high as 1 kA. The E2 HEMP conducted environment, previously discussed, has a waveform that rises in 25 μs and has a pulse width of 500 μs. This is very similar to the ITU-T immunity test waveform that has a pulse shape of (10/700) μs (IEC 61000-4-5). A typical level of performance for the immunity of equipment to this EM pulse is 2 kV. As indicated above in Table 2, the HEMP E2 conducted environment may be as high as 300 kV on above-ground conductors longer than 10 km.

The E3 HEMP electric fields are very similar in their time dependence to the natural electric fields produced in the Earth due to geomagnetic storms created by enhanced solar activity. Direct measurements of the geomagnetic fields, the induced electric fields and the currents induced in high-voltage power networks have been made and published over many years. It is noted that recent measured electric fields have reached levels of 1 V/km, although it is possible that the fields may be as high as 5 V/km during severe storms where no direct electric field measurements were made.

8.2 Comparison of HEMP E1 to EFT and surge

The conducted E1 HEMP environment for an above-ground conductor is defined in IEC 61000-2-10 as a waveform that rises in 10 ns (10 % to 90 %) and has a pulse width (50 % – 50 %) of 100 ns (this is typically described as a (10/100) ns waveform). Of course the real HEMP conducted transients can vary due to the coupling angle of incidence and the conductivity of the Earth in the vicinity of a conductor. For a buried conductor the waveform is expected to be (25/500) ns for well-buried conductors. For surface conductors the HEMP waveforms are expected to have rise times and pulse widths that are between these two ranges.

The electrical fast transient (EFT) waveform is typically produced from arcing events in power substations and is a threat to electronic control equipment in the substations and to nearby factories. It is described in IEC 61000-4-4 as a (5/50) ns waveform. It occurs in bursts of pulses with a repetition rate between 5 kHz and 100 kHz. It is important to recognize that the test method defined by the IEC is widely used and most electronic systems are tested to this disturbance, although at lower peak voltages than those that can be produced by HEMP. Typically, the test levels for EFT range between 0,5 kV and 4 kV (open circuit voltage). For HEMP the levels can be 10 kV to 20 kV for equipment inside of buildings and much higher for fully exposed equipment.

It should be noted that the main differences between the E1 HEMP waveform and the EFT waveform is the fact that the rise time is slower for the HEMP waveform and the pulse width is longer for the HEMP waveform. This means that the derivative norm (d*V*/d*t*) for the HEMP waveform is one half that of the EFT for the same peak value. It also means that the rectified impulse of the HEMP waveform is twice as large as the EFT, again for the same peak value. Since charge transfer and energy are not normally the primary means for causing damage (damage is usually caused by the triggering of arcs on circuit boards that allow the equipment power supply to damage low voltage components), the derivative norm is the most important to consider. This means that for a given peak voltage level, the EFT test produces twice the derivative norm than does a HEMP. For this reason test level EC9 in IEC 61000-4-25 identifies the largest open circuit voltage test of 16 kV using the IEC 61000-4-4 test method, which produces the same maximum derivative as a 32 kV HEMP waveform.

The IEC also has defined a surge immunity test for most electronic systems that are likely to be exposed to lightning transients inside a building due to a nearby lightning stroke. This test is defined in IEC 61000-4-5 and can be described by an open circuit voltage waveform with a (1/50) µs pulse shape. This waveform is much slower in its rise (100 times) and longer in its pulse width (nearly 1000 times) than the E1 HEMP conducted transient waveform. For this reason there is no relationship between these waveforms, and tests using IEC 61000-4-5 cannot replace tests for the E1 HEMP waveform (in spite of more rectified impulse and energy delivered for the same peak value).

8.3 Comparison of HEMP E3 to currents induced by geomagnetic storms

The late-time (E3) HEMP electric field waveform is defined in IEC 61000-2-9 as (1/20) s waveform as illustrated below in Figure 4 (although with significant amplitude to times of several hundred seconds. This electric field is created by the interaction of the incident magnetic field with the conductivity of the Earth, and it couples to conductors such as high voltage power transmission lines that are grounded through the neutrals of their transformers [5 to 7]. The peak field shown is approximately 40 V/km, which will induce currents with the same time history in the phase wires with an amplitude that is determined from the length of the conductor and the resistance of the conductor. For an example of a 100 km power line and 5 Ω of wire resistance, an approximate total current flow of 800 A is possible. Quasi-d.c. currents will seriously impact the efficient operation of a large high-voltage transformer by producing harmonics from half-cycle saturation and creating a large inductive load due to transformer losses. As many transformers produce this inductive load rapidly and simultaneously over a large area of a power grid, this provides a serious threat to the stability of the network; this can cause a power blackout as in the case of the power system in Quebec, Canada on 13 March 1989 [8].

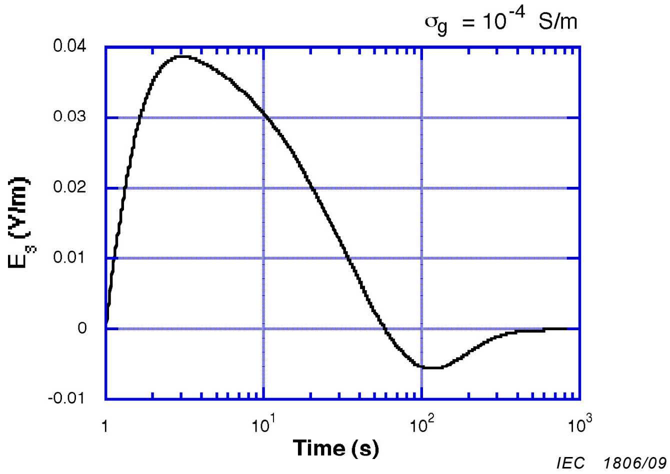


Figure 4 – Late-time (E3) electric field waveform from IEC 61000-2-9

In the case of geomagnetic storms, which are produced by enhancements of the solar wind coupling to the Earth magnetotail, these periodic storms can create electric field waveforms that are similar to the HEMP E3 waveform. Typically the induced geomagnetic storm electric fields are lower than the HEMP E3 fields (on the order of 1 V/km during a severe storm), but could reach levels of 5 V/km or more in extreme cases. For the case described above and for a 1 V/km geomagnetic storm electric field, the peak induced quasi-d.c. current would be 20 A. This is a level large enough to saturate a high voltage transformer, but the level is lower than the IEC E3 HEMP waveform induced current by a factor of 40 (the difference in the peak electric fields).

In terms of the time dependence, both waveforms have rise times as short as a few seconds and have pulse widths on the order of minutes. Of course each geomagnetic storm may display somewhat different characteristics, as may the late-time HEMP.

In terms of spatial coverage, it appears that significant levels of late-time (E3) HEMP will cover regions of 250 km in radius from ground zero, while geomagnetic storms appear to extend over much larger geographic areas with linear dimensions often greater than 1 000 km. This difference is understandable since the late-time HEMP begins with a point source of energy within the ionosphere, while geomagnetic storms are caused by a widely dispersed "curtain" of charged particles flowing from space downward into the ionosphere or by other large-scale magnetospheric disturbance processes.

In terms of system effects, the power blackout of 13 March 1989 in Quebec, Canada occurred due to an estimated induced electric field level on the order of 1 V/km [8]. For the late-time (E3) HEMP, the Soviet nuclear test experience is directly relevant as they performed high-altitude nuclear tests over land. Their analyses indicated that the failures of two telecommunication systems were due to HEMP-induced electric field levels on the order of 5 V/km [3]. Given the similarities of the late-time HEMP and geomagnetic storm environments, it is likely that the effects created would be similar for both types of disturbances.

9 Protection strategy

9.1 General

In general, the HEMP protection strategy for an infrastructure consists of four major components:

a) HEMP immunity standards for new electrical and electronic equipment,

b) selected retrofit protection including redundancy considerations,

c) emergency operational procedures, and

d) plans for restoration in the event of widespread failures.

In this international publication, items c) and d) should be combined into a comprehensive HEMP and widespread disaster plan.

An important consideration for civil systems is cost. A goal of this publication is to identify protection methods that provide a substantial level of protection at relatively low cost. Infrastructures that apply these protection strategies will benefit from a greater reliability from non-HEMP threats such as electrical and EM transients (including intentional electromagnetic interference), sabotage, widespread physical damage from hurricanes, earthquakes, etc. and geomagnetic storms. The protection strategies are listed in the order of importance and cost effectiveness.

9.2 Electric power

9.2.1 Background

The electric power infrastructure is a highly interconnected and dynamic system that may consist of a single integrated utility or a combination of many public and private utilities. These utilities use a supervisory control and data acquisition (SCADA) system to automate the control of electric power generation, transmission and distribution within and among control areas. The overall objective of power infrastructure controls is to match the generation with the load. Load changes that occur on a millisecond to second time frame are accommodated by the stored energy in the generator magnetic flux and the rotating mass of the generator cores. Energy is also exchanged with the adjacent control areas via the interconnected transmission lines. If the load change is large enough, the generators will slow down for an increase in load or speed up for a decrease in load. The generator control systems will increase or decrease power to the turbines as appropriate to maintain the proper power frequency. Thus, second-to-second and even minute-to-minute changes (within limits) are handled automatically without the intervention of the control centre or the use of the SCADA system.

In most SCADA systems, the master terminal unit (MTU) communicates with remote terminal units (RTUs) located at substations and power stations to send control commands and receive data. A scan of all data parameters in the system will normally be completed within several seconds. The SCADA system can provide complete logs of the operation and status of the power system. Modern power infrastructure control normally makes use of control systems that are responsive to frequency variations, cost factors, transmission losses and load-generation miss-matches. Corrective control pulses are sent to the generation units by the automatic generation control (AGC) system. The AGC is normally a part of the SCADA system and is a great step forward over generator plant governor control only. These systems provide frequency control with transmission loss considerations, control of interconnected transmission lines to other utility systems and economic operation of generation. The MTU is usually produced from personal computer components and is likely to be vulnerable to both radiated and conducted HEMP environments without some additional protection [11].

A forecast of the load as a function of time is used to anticipate the generation needs to ensure that generation matches load. Historical data, date, time of day, weather forecasts and other data are used to predict the load profile. The generation mix that will provide the most economical match to the load is determined. This process is called economic dispatch or energy management and it provides the hour-to-hour control. An energy management system (EMS) is often part of the SCADA system. The EMS communicates to the power plants that they should be on-line at a certain time with a certain participation factor (fraction of full output). Since some generators take some time to bring on-line, a good forecast of the generation needs is an important function of power system control.

If a large mismatch in actual load and the on-line generation occurs, the control area has to rely on the interconnected transmission lines to cover the power demand until adjustments in generation can be made. Many control centres have real time load-flow and stability analyses based on data provided by the SCADA system. The control centre operator monitors the system for thermal or stability limits, schedules the most economical energy supply and switches lines out of service for scheduled maintenance. The control centre operator is also a power broker. If more economical power can be purchased, then the more uneconomical plants in the system will be shut down to save operating cost. However, a certain amount of spinning reserve must be maintained in the event of a major line loss or generator shutdown. Spinning reserves are extra generating capacity that is kept running to respond to unexpected increased demand or drop in generation on the power grid.

Power systems also need to be protected against overcurrents, overvoltages and undervoltages and instabilities. High-voltage transmission lines have breakers that can be opened in the event of a fault. Faults are detected and signals are sent to actuate breakers by the protective relay system. These protection systems are independent of the SCADA system, yet are one of the most important control assets to be protected from the early-time HEMP waveform.

The interconnectedness of the power infrastructure provides for high reliability and economic operation during normal operations, but it also provides a major vulnerability during multiple malfunctions and widespread disturbances. If there is a widespread loss of loads due to line flashovers or line switching caused by an HEMP event, then the system will collapse. If there is a widespread mismatch in the reactive loads and generation due to geomagnetic storms or a late-time HEMP event, massive power failures could result.

9.2.2 Emergency planning, operating procedures and restoration

In many cases, an approaching crisis such a hurricane or geomagnetic storm event will be forecast to occur within days. Even a HEMP event could be preceded by a period of international tensions. The power infrastructure could be made more robust to withstand the widespread disturbance caused by these events if the operational strategy where changed from the normal economic mode to an emergency secure mode. This is accomplished by attempting to match load and generation within each control area and the power network islands that would occur in the event of a system break-up. Also, the spinning reserve could be greatly increased to allow for unexpected generation shutdowns. The detailed operational planning for each utility and control area will have to be developed by experts within the power infrastructure industry. It will also be necessary to determine the organization or government agency that would issue the command to switch to the emergency secure operational mode.

A major problem for the electric power infrastructure during and after widespread damage and disturbances such as those caused by a hurricane is the lack of adequate communications. Communications will also be critical during and after an HEMP event. An independent HEMP-immune communications system should be established to meet emergency operation and restoration requirements. During restoration, communications between control centres, generation stations and field operations is critical. It should be noted that during the August 2003 blackout in the north-eastern U.S., cell phone communications failed after several hours in some locations due to the lack of sufficient battery power at many cell towers. It is clear that communications are needed to help restore power after an outage and communications may be dependent on the electric power after some time. These factors must be considered.

An emergency restoration plan that includes the unique attributes of HEMP-induced problems should be prepared and tested by practice drills. Because HEMP blackouts can be widespread, restoration procedures based on assistance from neighbouring utilities or control areas may be ineffective. Thus, the restoration plans should not rely on other areas for electrical start-up power and personnel. To the degree necessary for system protection and personnel safety, a select number of power plant instrument and controls, protective relays and SCADA system components may have to be checked for damage before restoration can proceed. DC power supplies are critical for restoration of the electric power infrastructure. Backup emergency generators to recharge substation batteries may be required for extended outage times. All of these aspects are required in order to achieve a black start capability.

9.2.3 HEMP immunity standards for new equipment

It is recognized that equipment located in power substations and generation plants must operate in a harsh environment of conducted and radiated transients. Thus, EMC immunity standards are available for these environments. For example, IEC 60255 for substation equipment defines a variety of type withstand tests designed to simulate EMI phenomena commonly encountered in the substation. These include fast transients, transients due to inductive load switching, lightning strikes, ESD, RF interference due to personnel using portable radio handsets, ground potential rise resulting from high current fault conditions within the substation and a variety of other EM disturbance phenomena commonly encountered in the substation.

Although IEC immunity standards for substations and generation stations will not assure HEMP immunity, these standards will decrease the probability of equipment failure over a portion of the power infrastructure within the area of coverage of the HEMP fields. These standards should be used as a minimum for all new equipment purchases including critical communications and control centre equipment. However, a HEMP standard for power substations, generation plants, control centres and communications should be used to achieve a substantial level of immunity.

A new trend in SCADA and relay protection in power infrastructures is a utility communications architecture that uses Ethernet network technology. The overall goal is interoperability between varieties of Intelligent Electronic Devices. With this system, RTUs are no longer necessary and may not be included. This system is described in IEC 61850. Utilities should ensure that the equipment used in an IEC 61850 system meets EMC and HEMP standards.

To achieve a higher level of HEMP immunity, the power infrastructure industry should examine and improve the immunity of its equipment as defined in IEC 61000-4-25.

9.2.4 Selected retrofit protection

During the process of developing the emergency plan discussed in 9.2.2, critical links and systems that are necessary for the safe operation and restoration during and following a HEMP event should be identified. If the electronic boards and equipment used in these systems are not in compliance with recent IEC EMC standards for the power infrastructure, then retrofit hardening is required.

There are two major approaches defined for protecting equipment inside of a building or other facility. There is the building hardening approach, which is typically applied for the critical military systems [9]. This approach is not cost-effective for retrofit protection, but may be reasonable for new constructions. IEC 61000-5-6 describes approaches for using “layered” protection. This means that critical equipment can be protected with the addition of electromagnetic shielded racks or by small, shielded rooms. In addition to the shielding, it is necessary to properly bond any metallic wiring that connects the equipment to other equipment outside of the protected area. If fibre optic cables are used, they must penetrate any shielding with the use of waveguides below cut-off.

There are three other IEC publications that aid in the process of retrofit hardening. First IEC 61000-2-11 indicates how different levels of HEMP environments can be found in different types of facilities depending on their construction type. IEC 61000-5-3 describes how to protect equipment through the use of shielded racks and rooms, thereby reducing the HEMP environment on the equipment (see Table 3). IEC 61000-6-6 is a generic standard that provides detailed test requirements for equipment as a function of the protection concepts applied. This document uses a 90 % severity level for the HEMP conducted environment.

Table 3 – Minimum required attenuation of peak time domain external environments for the six principal protection concepts

Concept	**Minimum attenuation** dB		
	Electric field	**Magnetic field**	**Conducted current**
1A 1B	0 0	0 0	0 20
2A 2B	20 20	20 20	0 20
3	20	20	40
4	40	40	40
5	60	60	60
6	80	80	80
NOTE Frequency evaluation ranges for E and H fields are 100 kHz to 30 MHz for concepts 1 and 2, and 1 MHz to 200 MHz for concepts 3 to 6.			

In Table 3, Concept 1 describes an above-ground wooden or concrete (no steel reinforcement) building with large windows, Concept 2 describes and above-ground concrete building with steel reinforcement or a buried brick building (where B indicates the presence of lightning protection at the building level, which should provide a reduction in conducted transients at the equipment level). Concept 3 is a shielded enclosure with minimum RF shielding effectiveness (20 dB), and Concept 4 is a shielded enclosure with modest RF shielding effectiveness (40 dB). Concept 5 is a shielded enclosure with good RF shielding effectiveness (60 dB) and good PoE surge protection and filtering. Concept 6 is similar to Concept 5 except the shielding and PoE protection is of high quality (80 dB). Measurements should be made to confirm these levels through the use of IEC 61000-4-23 and IEC 61000-4-24. Assessments can also be made with IEC 61000-5-9, which is being developed to provide a methodology to assess the HEMP hardness of a facility.

9.2.5 Application to a high-voltage power substation

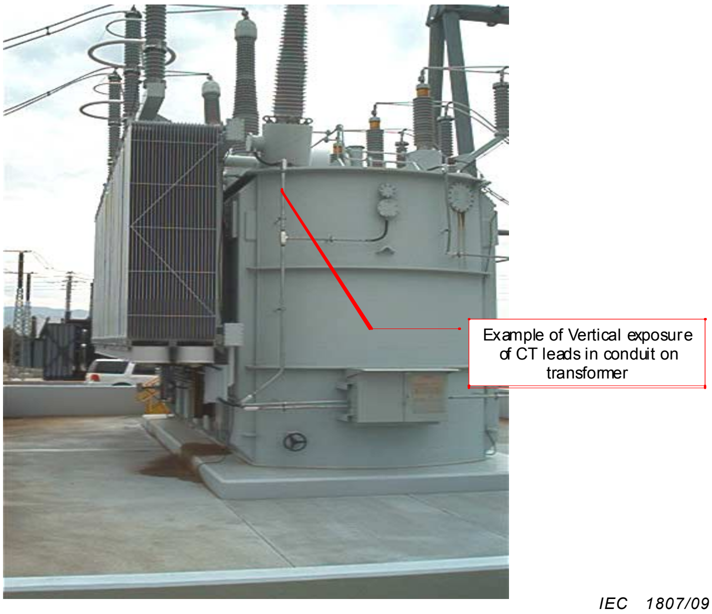
Supervisory control refers to equipment that allows for remote control of a substation's functions from a system control centre or other point of control. Supervisory control can be used to

- change the settings on circuit breakers,
- operate tap changers on power transformers,
- supervise the position and condition of equipment, and
- telemeter the quantity of energy in a circuit or in substation equipment.

The substation control house contains switchboard panels, batteries, battery chargers, supervisory control, power-line carrier, meters and relays. It should be noted that while relay settings can be changed in some cases using the SCADA system, their operation under disturbed conditions is autonomous from the control system itself due to the need to react quickly to over-current situations. The control house provides all weather protection and security for the control equipment. Control wires are installed connecting the control house control panels to all the equipment in the substation. A typical substation control house contains several hundred metres of conduit and miles of control wire.

The following figures indicate the scope of the E1 HEMP cable coupling and protection problem in a high-voltage substation from the cables connected to sensors, to the cable runs to the control house, to the cable connections inside and the cable runs to the control equipment. The exposure of the cables, the lack of shielding and the lack of high frequency grounding procedures are clearly shown.

Figure 5 illustrates the fact that cables and conduits will be directly exposed to the HEMP fields in a high-voltage substation. While a conduit is shown in this case, these conduits are not electromagnetically shielded for high frequencies, and therefore a portion of the coupled currents on the conduits will be transferred to the control cables at the point that the conduit ends.



IEC 1807/09

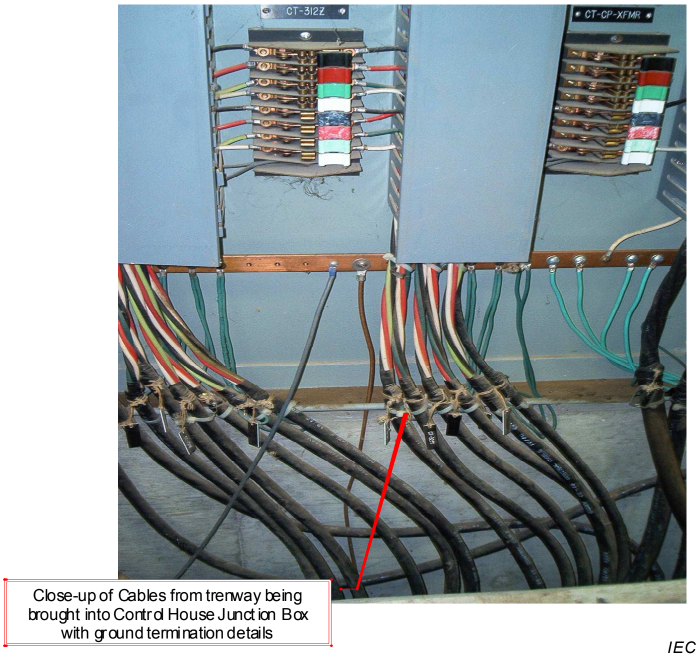
Figure 5 – Vertical conduit geometry for a current transformer (CT)

As the insulated cables enter the shallow below-ground trenches, they are no longer within metallic conduits. In addition, the cables do not have electromagnetic shields. In the case shown in Figure 6, the cables are grouped laid together in a concrete tray, which places the cables only slightly below the surface of the ground. While a shielded metallic conduit would add additional protection to the cables from E1 HEMP, there would still be transients flowing on the wiring from the exposed vertical cables that are required to measure the power flow in the substation.

IEC 1808/09

Figure 6 – Covered shallow trench for control cables

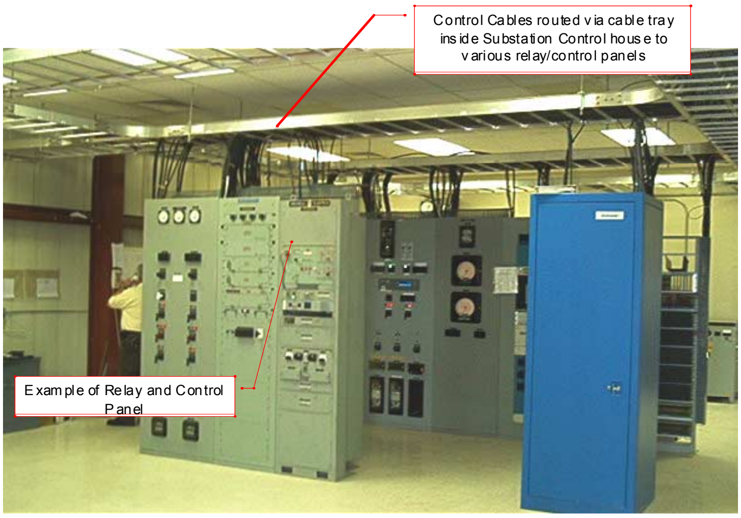
When the cables enter the control house, the ground wires and mechanical shields are grounded to a grounding bar as shown in Figure 7. However, the length of these high inductance grounds is very long and will not provide a low impedance ground for E1 HEMP conducted transients, which have tens of MHz content. Shorter ground wires (0,05 m to 0,1 m in length) would significantly reduce the HEMP transients flowing into the equipment.



IEC 1809/09

Figure 7 – Grounding of control cables at junction box

The control cables leave the junction box and in this case are distributed in the control house on elevated cable trays as shown in Figure 8. Another means of protection is to use shielded cables within the facility and to ground the cable shields to the racks before penetrating. Metallic cable trays will reduce the currents flowing to the equipment, although metal is heavier than fibre trays. Also shielded equipment racks or a small shielded room could be used to reduce the electromagnetic transients reaching the equipment.



IEC 1810/09

Figure 8 – Control cable access to equipment

The last approach to protect power system equipment from HEMP transients is to increase the immunity of the equipment used within the facility. In many ways this is most difficult and expensive unless one can buy new equipment that has higher immunity levels.

It should be noted that all of the protection concepts mentioned here are not usually necessary. A selection of protection approaches can be applied to reduce the HEMP transients reaching the equipment.

9.3 Telecommunication centres

In order to protect telecommunication centres and their equipment (switching, transmission, radio and power equipment) from HEMP, the main approach is to evaluate the shielding effectiveness of existing buildings and determine where to apply additional shielding and surge protection against the HEMP threat. At this time the International Telecommunication Union (ITU-T) is preparing a recommendation K.HEMP in TD 611 (GEN/5) to deal with this specific problem [10]. This ITU-T recommendation is applying the basic HEMP standards in the IEC 61000 series to their specific types of installations and equipment.

The approach is to first determine the protection concept being used in an existing telecommunication centre by analyzing the facility with regard to IEC 61000-5-3. Then a topological evaluation is performed to determine if global protection or distributed protection is recommended for the given centre (or both can be considered). In addition, an evaluation is made of the importance of various equipment relative to the threat of HEMP. For each piece of equipment, a determination of the performance criteria for HEMP immunity testing is also done. With this information a design flow chart is developed that indicates how the protection shall be accomplished.

Using this approach, the tables from IEC 61000-6-6 are used to determine the HEMP radiated and conducted immunity requirements for each piece of equipment for a given protection concept; IEC 61000-4-25 is then used to describe in detail the test methods to be applied.

After this process is completed, K.HEMP compares the various levels of HEMP immunity tests for equipment to those otherwise required under other ITU-T EMC recommendations. It becomes clear in the ITU–T document that those protection concepts, which provide little or no EM shielding for the internal electronics, have significantly higher equipment test levels for HEMP than for normal EMC purposes. For these cases shielded racks or rooms would be recommended along with surge arresters.

NOTE Since the ITU-T K.HEMP document is still under development, the summary provided in this clause will be considered sufficient at this time.

9.4 Other infrastructures

As indicated in Figure 1, there are a large number of critical infrastructures that can impact the ability of a modern society to operate. As in the case of the power and telecommunication systems, many of these infrastructures have some type of control centre and sensors to report on the status of the flow of water, transportation, natural gas, oil, etc. The data typically flows through a SCADA network to reach the control centre.

Each of the control centres will possess modern computers that are linked by wired and wireless networks that can be affected by the HEMP. Studies of modern personal computers indicate that without some protection these computers are highly vulnerable to both the radiated and conducted HEMP environments. While commercial computer centres may not possess the same vulnerability as personal computers, many of the same features are found in both sets of equipment. In addition, control centres can be affected more seriously by momentary outages, which typically occur at lower levels of HEMP environments.

In terms of the sensor and SCADA systems that are deployed in many infrastructures, these sensors and their controls are typically not shielded from the external electromagnetic environment. The controls usually consist of programmable logic controllers (PLCs), which are also not designed to withstand the HEMP radiated and conducted environments. Testing of PLCs for the EMP Commission [4] has clearly indicated their vulnerability to the early-time HEMP.

A special problem of the “other” infrastructures is their strong dependence on power and telecommunications. Those who wish to protect their infrastructures from HEMP should consider the high likelihood that no power or telecommunications will be available to operate for some time. This is a major consideration in addition to the direct protection of the considered infrastructure itself.

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