EMC for LARGE Installations

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THALES

EURAMET

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Introduction

Definition of EMC

“The ability of the System to Operate according to its Specifications in its Intended Electromagnetic Environment” [IMMUNITY]

“Without generating Unacceptable Electromagnetic Disturbances into that Environment” [EMISSION]

Three Criteria for EMC

1. No (intolerable) emissions into the environment

2. Operate satisfactorily in its EM environment

3. Not cause interference with itself
**Systems Perspective: Performance Criteria**

What happens when immunity threshold levels are approached?

**A** System continues to work according to specification
Degradation not acceptable
Generally applies to all interference with a continuous nature

**B** Temporary degradation acceptable, auto recovery.
Usually applies to sporadic interference
to a non-critical function.

**C** Degradation acceptable. Recovery after manual RESET.
e.g. at mains interruptions. Only for non-critical functions.

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**The necessary elements for an interference situation**

EMI, ElectroMagnetic Interference model: source – victim and coupling path

**Source**
**Victim**

Coupling path: always electrical interconnections

Effects appear at any scale
(relative to wavelength)

Very large....
EMC characteristics of LARGE installations

- SMPS, variable speed drives (frequency converters, servo drives)
- Switched applications (electrical motors, pneumatics, hydraulics)
- Measurement and control
- Datacommunication (fieldbus, ethernet)
EMC as per the requirements

Disturbance level
- voltage (LF)
- field (HF)

susceptibility (immunity)

EMC margin

Generic standards
- industrial immunity
  EN-IEC 61000-6-2
- residential immunity
  EN-IEC 61000-6-1
- industrial emission
  EN-IEC 61000-6-4
- residential emission
  EN-IEC 61000-6-3

Lack of EMC: EMI = EM Interference

Disturbance level
- voltage (LF)
- field (HF)

susceptibility

immunity (as per the standard)

emission limit (as per the standard)

emission

frequency
Necessity of EMC margin

- Large number of apparatus
- Deviations in EM levels, gaps in technical standards
- Different environments
- Different installation practices

**Warning**
This product complies with the requirements in accordance with product standard IEC 61800-3. In a domestic environment, this product may cause radio interference, in which case supplementary mitigation measures may be required.

- Very high EMC margin →

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Understanding the Physics of Electromagnetic Effects

Passive components and their (ideal) behavior in the time domain

- **Resistor**
  - Voltage: $V_R = IR \cdot R$
  - Described by Ohm's Law

- **Capacitor**
  - Current: $I_C = C \cdot \frac{dV_C}{dt}$

- **Inductor**
  - Voltage: $V_L = L \cdot \frac{di_L}{dt}$

---
Ideal Components do not Exist

all components have, so called, “parasitics”

Any current needs a magnetic field!

field of the return conductor is identical but opposite (if geometry is identical)

Biot Savart’s Law:

\[ H \approx \frac{I}{2\pi \cdot r} \]
Current carrying conductor always exhibits H-field

minimize fields by aligning conductors (not possible for twin wires)

Special Cable Geometries

COAX produces less fields than twin wires (under conditions)

ONLY if shield current uniformly distributed over 360°

Special care when mounting connectors or glands!
Special Cable Geometries

Make sure, current over shield can be uniformly distributed over 360°.

EMC gland with provision for 360° contact


“Pig-tails” Destroy Good Coax Properties

Effect of geometry changes: fields outside interconnections; CM currents

“Coax is better than twin wires”

F...
Induction in a Single Wire

Current in a conductor is only possible when a magnetic field exists.

1. Waveform for fast edge

- Signal integrity = no distortion on the signal line

1a. Waveform for fast edge @ reduced loop area

- Reduce loop area: less time and energy needed to build H-field
Induction in a Single Wire

Current in a conductor is only possible when a magnetic field exists.

2. Waveform for slow edge

Simulation of Wire Inductance Demonstration

in LTSpice IV
**All Currents Run in Loops**

Kirchhoff's Current Law: basic for the design of component networks

Kirchhoff's electrical current law

\[ I_3 = I_1 + I_2 \]

As a Designer, ask yourself:
Where does my Return Current Flow?

Every current must have a return path!

**Common-mode currents dominate the EMC arena**

currents, generated by cables’ “desired currents” into CM or ground-loop

Source

Load

\[ I_{dm} \]

“Differential-mode” current

\[ I_{cm} \]

“Common-mode” current

“Ground”

CM: 99% of all EMI problems!

Common-mode current is that part of the return current which follows a different path than the designers intended route

CM-currents can be created "elsewhere"
Demonstration of the Common Mode Current

using the three demonstration cables of slide 1

source (50Ω) → Any Cable → "ground" litz wire → Current clamp

amplitude depends on cable quality

50 Ω

“Common-Resistance” Crosstalk

resistance in the common return path of two loops (SPICE model)

\[ V_{\text{noise}} = I_{\text{source}} \cdot R_1 \]

PULSE(0 10 1e-6 100e-9 100e-9 5e-6 10e-6 5) .tran 0 25e-6 0 1e-8
Resistive Crosstalk Waveform

linear operation: noise signal shape is identical to source waveform

Kirchhoff Electrical Voltage Law

assumes all fields are inside the circuits components

Kirchhoff’s Voltage Law

\[ U_S + U_{R1} + U_{R2} = 0 \]

Faraday’s Law:

\[ \text{Voltage} = -\frac{\text{flux change}}{\text{transition time}} = -\frac{\partial \Phi}{\partial t} = -j\omega \Phi \]
Mutual induction: coupling of circuits (loops)

Field loop 1 induces voltage in loop 2 ("Crosstalk"- or: transformer)

\[ L_1 = \frac{\Phi_1}{I_1} \]

\[ M_{12} = \frac{\Phi_{\text{loop } 2}}{I_{\text{loop } 1}} \]

\[ \Phi_{\text{loop } 2} = M_{12} \cdot I_{\text{loop } 1} \]

\[ V_{\text{noise}} = -\frac{d\Phi_{\text{loop } 2}}{dt} = -j\omega\Phi_{\text{loop } 2} \]

or

\[ V_{\text{noise}} = -\frac{dM_{12} \cdot I_{\text{loop } 1}}{dt} = -j\omega M_{12} \cdot I_{\text{loop } 1} \]

Substitute source model for inductive crosstalk

Faraday’s Law expressed in the time and frequency domain

\[ L_1 = \frac{\Phi_1}{I_1} \]

\[ M_{12} = \frac{\Phi_{\text{loop } 2}}{I_{\text{loop } 1}} \]

\[ \Phi_{\text{loop } 2} = M_{12} \cdot I_{\text{loop } 1} \]

Note: capacitive model yields current source
Substitute source model for inductive probes

Faraday’s Law for a Loop Probe

Medium Permeability = $\mu_0 \cdot \mu_r$

External Magnetic Field H

Flux Density $= B = \mu_0 \cdot \mu_r \cdot H$

$\mu_r, \text{air} = 1 \quad \mu_0 = 4\pi \cdot 10^{-7} \left[ \frac{H}{m} \right]$

Flux $= \Phi_{\text{loop}} = B \cdot A_{\text{loop}}$

Faraday’s Law:

$$V_{\text{loop}} = -\frac{d\Phi_{\text{loop}}}{dt} = -j\omega\Phi_{\text{loop}}$$

or

$$V_{\text{loop}} = -\frac{d\mu \cdot H \cdot A_{\text{loop}}}{dt} = -j\omega \mu \cdot H \cdot A_{\text{loop}}$$

Inductive probe for Magnetic Fields: the Model

derivation using a substitute voltage source

Area: $A$

Magnetic Field: $H$

Principle of Operation: Mutual Induction

air gap in shielding

semi-rigid coax

chip resistor 50 $\Omega$

(instrument) 50 $\Omega$

(sometimes left out)

$\text{Flux Density } = B = \mu \cdot H$

$\text{Coupled Flux } = \Phi = B \cdot A$
**Alternative Shape: Current Clamps/Probes**

Current clamps use ferrite cores to guide magnetic field through coil.

- **C-shaped Core**
  - Current in Wire “to be measured”
  - Both cores are clamped together around the current conductor to be measured

- **Conductor/Current to be measured**
  - Must be led through toroid

- **Coil:**
  - 90 turns of 0.5 [mm] wire

- **Principle of Operation:**
  - Mutual Induction

**Small Magnetic Sniffer Probe**

5-turn loop probe using ferrite to concentrate flux lines.

- **Small C-shaped Core**
  - Conductor under test (or external field)
  - Usable for lower frequencies:
    - More sensitive than single loop probe
    - Ferrite concentrates magnetic field lines

**Note for Loop and Sniffer Probe**

The probe output voltage is proportional to $\frac{\partial B}{\partial t}$ or $\dot{B}$

Hence, the MIL-STD-461 calls it a "B-dot" probe.
Operation of the current probe

derivation using a substitute voltage source

Measurement setup:

Equivalent circuit diagram:

\[ V_{out} = j\omega \cdot M \cdot I \]

\[ V_{out} \approx \frac{R}{L_{probe}} \]

\[ \omega \ll \frac{R}{L_{probe}} \]

\[ V_{out} = j\omega \cdot M \cdot I \]

\[ \omega \gg \frac{R}{L_{probe}} \]

\[ V_{out} = \frac{R}{L_{probe}} \cdot M \cdot I \]

---

Operation of the current probe

graphical representation of results

low frequency cut-off of probe

Calibration level: \[ \frac{R \cdot M \cdot I}{L_{probe}} \]

Note

Current probe: \( \Phi = M \cdot I \)
Loop probe: \( \Phi = B \cdot A \)

\[ \omega_c = \frac{R}{L_{probe}} \]

\[ R = 50 \ \Omega \]
Measure \( L_{probe} \)
Calculate \( \omega_c \)

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SPICE Simulation of an Inductive Probe

With LTSpice IV

Calibrating the Current Probe

use the following setup

\[ I_{\text{Probe}} = \frac{V_{\text{Channel A}}}{50\Omega} \]
\[ V_{\text{OutProbe}} = V_{\text{Channel B}} \]

Make table for frequencies:
0.1, 0.2, 0.5, 1, 2, 5, 10 kHz etc.
Simulate Current Probe in LTSpice

model the frequency dependent source using a transformer

The source I1 is the “current to be measured”, set as 1 Amp (no DC)
A transformer is used to model the “frequency dependent source”
Coupling Factor $K_1 = 1$


Examples of “home made” magnetic field probes

useful if professional equipment is unavailable
Mutual induction in practice

two circuits with a common return ("ground") conductor

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Mutual induction in practice

crosstalk created by mutual induction between two loops

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Mutual induction in practice

“common return” = common impedance, largely inductive

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Note that a slower rise time produces less or no crosstalk at all!
Mutual induction in practice

thin line: two adjacent loops: high mutual inductance!

Mutual inductance also known as "Common-Impedance"

solution 1: reduce loop area of source

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Mutual induction in practice

Solution 1a: also reduce area of victim loop

Ground Plane

Wide ground plane is preferred return path for current!

Solution 2: wide return conductor (ground plane)
**Mutual induction in practice**

proximity effect: return current concentrates under “red” wire

Separation of “loops” becomes much easier!

**Proximity effect**

current concentrates under conductor, minimizing loop inductance

Current concentrates under conductor (proximity effect)

Field distribution can be measured with small sniffer probe
Return Current Distribution Magnitude in Ground Plane

lowering the wire reduces volume “filled with flux”

\[
\frac{J_D}{J_0} = \frac{\Phi_D}{\Phi_0} \approx \frac{1}{1 + \left(\frac{D}{H}\right)^2}
\]

Source: Johnson, H
“High-Speed Digital Design” 1993

Wire /cable (!) distance is important

once a metal plane is used for separation

Current distribution of \(I_{cm}\) in cable guide is measure of flux density, \(\Phi\), coupling into cable: at source \(\sim L\), at victim \(\sim M\)!

\[
M_{source} \approx \frac{\Phi_{victim}}{I_{cm}}
\]

\[
L_{source} \approx \frac{\Phi_{source}}{I_{cm}}
\]

proximity effect

Source: Johnson, H
“High-Speed Digital Design” 1993

COUPLING FACTOR: \(k\)

\[
k = \frac{M}{L_{source}} = \frac{1}{1 + \left(\frac{D}{H}\right)^2}
\]
Wide metal also features: the Skin Effect

Lenz’ Law and the basis for shielding effects

\[ J_0 \cdot e^{-\frac{d}{\delta}} \]

\[ \delta = \frac{1}{\sqrt{\pi f \sigma \mu}} \]

- Induced Eddy currents oppose direction of external current (Lenz’ Law)

Any Voltage needs an Electric Field!

Two conductors in an interconnection each have an individual field pattern

(Electric Force lines)
Combined Electric Field Pattern

Concentric circles model the actual E-field pattern of two conductors.

Capacitive Probe for Electric Fields, the Model

Derivation using a substitute current source.

External E-field

\[ D = \varepsilon_0 \cdot E \]

E [V/m]

\[ C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A_e}{d} \]

Dielectric height = d

Medium Permittivity = \( \varepsilon_0 \cdot \varepsilon_r \)

\[ \varepsilon_0 = 8.85 \cdot 10^{-12} \left( \frac{F}{m} \right) \]

Relative dielectric constant = \( \varepsilon_r \)

Capacitance to "ground"
Substitute source for capacitive probe

a current source, based on Gauss' Theorem

\[ Q = A_e \cdot \varepsilon_0 \cdot E \]  
\[ I = \frac{\partial Q}{\partial t} \]  
\[ I = j\omega Q \]  
\[ I = j\omega \cdot A_e \cdot \varepsilon_0 \cdot E \]

Note:
\[ \varepsilon_0 \cdot E = D \]  
(Dielectric Displacement)
\[ I = \frac{\partial Q}{\partial t} = A_e \cdot \frac{\partial D}{\partial t} \]  
or
\[ A_e \cdot \frac{\partial D}{\partial t} \]

The MIL-STD-461 hence calls this device a "D-dot probe"

Equations for the measurement circuit

when loaded with a resistor

Equivalent Circuit Model:

\[ I = j\omega \cdot A_e \cdot \varepsilon_0 \cdot E \]

\[ C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A_e}{d} \]

\[ R=50\Omega \]
Using a Capacitive Probe for Voltage Measurements
replace \( E \) by \( V \) (Voltage) divided by \( h \) (distance)

\[
I = j\omega \cdot A_e \cdot \varepsilon_r \cdot \frac{V}{h}
\]

Gauss rewritten:
\[
Q = C_{\text{total}} \cdot V
\]

assumption: \( d << h \)

\[
C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A_e}{d}
\]

Equations for the measurement circuit
when loaded with a resistor

\[
\frac{V_o}{V} = \frac{R}{j\omega RC + 1}
\]

\[
I = j\omega \cdot A_e \cdot \varepsilon_r \cdot E
\]

\[
V_o = j\omega \cdot \frac{d \cdot E}{\varepsilon_r} \cdot \frac{1}{j\omega + \frac{1}{RC}}
\]

**LF:** \( \omega \leq \frac{1}{RC} \)

\[
V_o = j\omega R \cdot A_e \cdot \varepsilon_r \cdot E
\]

**HF:** \( \omega > \frac{1}{RC} \)

\[
V_o = \frac{d \cdot E}{\varepsilon_r}
\]
Operation of the capacitive probe

graphical representation of results

\[ \omega = \frac{1}{RC} \]

low frequency cut-off of probe

“Calibration” level:

\[ \frac{d \cdot E}{\varepsilon_r} \]

dielectric height = d

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SPICE Simulation of a Capacitive Probe

Using LTSpice IV

LTSpice IV (free on the Internet):

http://www.linear.com/designtools/software/
Example of some electric field probes

useful if professional equipment is unavailable

Commercial Capacitive Clamp

Insulate!

Can sense E-fields and generate them!

Combination of capacitive and inductive crosstalk

depending on load of source line, capacitive or inductive effects dominate

Construction details

sizes in mm, line impedances 130 Ω

Aluminium groundplane

Brass conductors

50 Ω instrument or termination

passive line

active line

50 Ω instrument or termination

Termination select switch

Electrical Diagram

Source: J.J. Goedbloed “EMC”, Kluwer 1993

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Flow of currents determines crosstalk behaviour
always look for the current paths, inductive and capacitive

**Capacitive situation**
Crosstalk “in phase”

**Inductive situation**
Crosstalk “in anti-phase”

Balancing capacitive and inductive crosstalk
terminating the source line with its characteristic impedance

**Z₀ terminated situation**
Crosstalk far end “balanced”
Capacitive or Inductive Sniffer Probe shows Field

magnetic field (shorted source line) or electric field (open source line)

Use probe near source line

Note
Terminated Line:
Both Field Types

Crosstalk between two circuits (loops)

interference between line 1 and 2; mutual induction, substitute source model

\[ V_2 = j\omega \cdot M_{12} \cdot I_1 \]
Addition of a cable screen

crosstalk not only between line 1 and 2 but also between line 1 and screen!

Line 2 and screen S together act as a transformer

The effect of a cable screen

how does screening actually work for cables?

First step:
\[ M_{1S} \approx M_{12} \]

Remains to be proven:
\[ V_C = -V_2 \]
Inside metal tube there is no field

if current is distributed evenly over 360° circumference of this tube

- Evenly distributed current density over 360° circumference
- No flux inside tube!
- Presence of inner conductor: no change!

\[
L_S = \frac{\Phi_S}{I_S}
\]

if all flux is "outside"

\[
M_{S2} = \frac{\Phi_S}{I_S}
\]

hence,

\[
M_{S2} = L_S
\]


---

To find the remaining noise voltage after screening

fill out the equation for \((V_2 - V_C)\)

\[
I_S = \frac{V_S}{R_S + j\omega L_S}
\]

\[
V_C = j\omega L_S \cdot I_S
\]

\[
V_S = j\omega M_{12} \cdot I_1
\]

\[
V_2 = j\omega M_{12} \cdot I_1
\]

Remaining noise voltage on line 2 (fill out equations):

\[
V_2 - V_C = j\omega M_{12} \cdot I_1 - j\omega L_S \cdot I_S
\]

Improvement and replace \(I_S\):

\[
V_2 - V_C = j\omega M_{12} \cdot I_1 \left(1 - \frac{j\omega}{j\omega + R_S/L_S}\right)
\]

original crosstalk without screening!
Graphic representation of screening effect
in relation to the crosstalk in the unscreened situation

\[ \omega_{SC} = \frac{R_S}{L_S} \]  
(screen cut-off frequency)

Message: Audio (low frequency) screening is difficult!

Improvement

with (ideal) screen

without screen

Crosstalk at higher frequencies
transmission line effects when wire or cable length reaches \( \lambda/4 \)

Crosstalk does not increase with frequency forever!

asymptote

Wire-length = \( \lambda/4 \)

logarithmic frequency scale

linear frequency scale

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The Common-mode Coil

appearances: from factory installed to self made

- Clip-on version
- Open
- Closed
- UTP cable wound on ferrite ring

factory installed
Common-mode coils

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The Common-mode Coil

improve, essentially, the low frequency behaviour of a cable

ferrite increases \( L_s \) (\( R_s \) unaffected)
Loop-area responsible for \( L_s \) and \( M_{s2} \)

\[
\omega_{SC} = \frac{R_s}{L_s}
\]

\( V_{noise} \)

\( \omega_{SC} = \frac{R_s}{L_s} \)

\( L_s \) increased

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The Common-mode Coil

drawback: does not work at very high frequencies (fields travel around it)

Input and output “see” each other (for high frequencies)

Incomplete screening

What if the screen does not completely cover the inner wire?

Ideal Screening

Workable Compromise (Pig-Tail)

\[ M_{S2} \neq L_S \]

e.g. \( M_{S2} = 0.95 \cdot L_S \)
Incomplete screening

in relation to the crosstalk in the complete- and un-screened situation

\[ \omega_{SC} = \frac{R_S}{L_S} \]

\[ \omega_{HF} = \frac{1}{1 - 0.95} \frac{R_S}{L_S} \]

Pig-Tails

to some extent, pig-tails are unavoidable
Measures to Improve Low Frequency Performance

Balancing measures e.g. using Unshielded Twisted Pairs (UTP)

Two identical substitute sources are introduced.

Balanced Receiver common mode noise is cancelled!
Advanced Topic: STP and Triax cables

inside the screen: now we have two wires or a coax

differential driver receiver pair
(receiver with high cm-rejection)

outer braid shields high frequencies

grounds connected at only one position

termination resistor

screen floating!

outer braid shields high frequencies

Advanced Topic: STP and Triax cables

the remaining low-frequency noise is removed by balancing & cm-rejection

Major threat: \( I_{cm} \times R_s \) noise
(Very Low Frequencies e.g. lightning)

\( I \times R \) noise removed by insulation

\( V_z = j \omega M_{12} I_1 \)
reduced by balancing & cm-rejection
Properties of cables: Transfer Impedance $Z_T$

cable may produce or pick up common mode currents

1. Coupling into external noise

$$Z_T = \frac{U_{noise}}{I_{noise} \cdot D}$$

[Ohm per meter]

2. Generation of noise in other conductors (e.g. "ground")

Signal and Return Circuit have Mutual Induction

COAX example: screen and centre wire form a transformer
Mechanism of the transfer impedance
common-mode current flows in return impedance

\[ U = j\omega \cdot M_{S1} \cdot I_{cm} \]

\[ U_{in} = I_{cm} \left( R_S + j\alpha (L_m - M_{S1}) \right) \]

Transfer Inductance (L_T)  
(Don White)

Examples of Transfer Impedance
addition of the skin effect as important aspect of screening

Source: Green, M. "Optimized and Superscreened Cables" (Raychem)
In addition come the “Pig-tails”

- Effect of geometry changes: fields outside interconnections; CM currents

- "Coax is better than twin wires"

- Pig-tail destroys cable symmetry

- Fields are generated

- Z_T goes up

Transfer-Impedance

- Every cable leaks to some extent... Here, twin-wires driving a motor with a PWM signal

- 50 Ω Load

- Unscreened wire
Transfer impedance of PWM driven DC motor

Switching moments visible as $2 \ V_{pp}$ transients

Transfer Impedance Crosstalk in practice

Looks remarkably similar to inductive crosstalk between wires!
EMC demo installation

- EM sources: variable speed drive, circuit breaker, RF transmitter
- EM victims (analog measurement/control, protection relay)
- Coupling paths
- Cable shielding

EMC specification + installation requirement

2.3. (EMC) electromagnetic compatibility

Complies with EMC Directive 2004/108/EC

Immunity to interference in acc. with EN 61000-6-2
- Electrostatic discharge (ESD)
  - Criterion B: 8 kV discharge in air
  - EN 61000-4-2
- Electromagnetic IP field
  - EN 61000-4-3
  - Criterion A: 10 V/m
- Radiated immunity
  - EN 61000-4-4
  - Criterion B: 20 Handbook
  - CME 1 kHz
- Surge voltage capacities
  - EN 61000-4-6
  - Criterion B: 20 Handbook
  - CME 1 kHz
- Conducted disturbance
  - EN 61000-4-6
  - Criterion A: 10 V

Noise emission in acc. with EN 61000-6-4

EN 61000 corresponds to IEC 1090
EN 61801 corresponds to CISPR1
a) I = input / O = Output / G = Supply

Criterion A: Normal operating behavior within the defined limits.
Criterion B: Temporaty impairment or operational behavior that the device corrects itself.
Criterion C: Areas of application: industry, without special installation measures.
Frequently experienced EM sources

- **Power electronics** (variable speed drives/VSD, thyristor controllers, softstarters, UPS, HF lighting)
- **Switched devices** (relays, circuit breakers, contactors, vacuum/GIS, pneumatic- and hydraulic valves/solenoids)
- **Lightning and induction effects**
- **HF transmitters** (portable transmitters, mobile telephones, fixed transmitters for communication en navigation)
- **ESD** (moving materials, machines with non-conductive elements, conveyor belt, oil tanks, etc.)

Continuous and transient sources

**Continuous**
- VSD
- Servo drive
- UPS
- Switched mode power supply (SMPS)

**Transient**
- Relay, circuit breaker/contactor
- Valve (solenoid)
- ESD
- Lightning, short circuit
Power electronics (UPS and VSD)

UPS = Uninterruptible Power Supply

VSD = Variable Speed Drive

FC = Frequency Converter

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Basic EMC concepts of VSD

- Capacitance of motor winding(s) and motor cables causes capacitive current due to high dV/dt: \( I = (C_M + C_C) \cdot \frac{dV}{dt} \)
- Output filter required to mitigate dV/dt
- Motor cable shield provides preferred return current path
- Internal return path capacitors required in VSD (in DC bus and/or in power supply filter)

![Diagram of VSD and EMC concepts]

Frequency spectrum of VSD emissions

**TIME DOMAIN**

- \( I(t) \)
- \( t_h \), \( t_f \), \( T \)

**FREQUENCY DOMAIN**

- \( I(f) = \frac{2A t_h}{T} \sin \left( \frac{X_b}{X_h} \right) \sin \left( \frac{X_r}{X_h} \right) \)
- \( f_s = \frac{1}{T} \)
- \( X_b = n \pi f_s t_h \)
- \( X_r = n \pi f_s t_r \)

**FOURIER**

**Typical IGBT switching rate:** 5kV/\( \mu \)s (high efficiency)
**Example:**
- \( f_{inv} = 4 \text{kHz} \rightarrow T = 250 \mu \text{s} \)
- \( t_h = 50 \mu \text{s} \rightarrow 1/\pi t_h = 6.4 \text{kHz} \)
- \( t_r = 100 \text{ns} \rightarrow 1/\pi t_r = 3.2 \text{MHz} \)
In the field
1. Coupling via process piping, vessels and instruments
2. Coupling via parallel cables

In the control room
3. Coupling via local control ports
4. Coupling via LV power distribution system

Installation aspects of VSD/servo drive
1. Type of motor (isolation class, eddy current losses)
2. Motor cable length (cable capacitance, $I_{CM}$, transient peak voltage at motor winding)
3. Shielding quality of motor cable (transfer impedance)
4. Low impedance terminations of cable shields (drive, motor, safety switch etc.), control cables
5. In- and output filters: reduction of $dV/dt$, noise voltage reduction on power supply
6. Segregation of power supplies
7. Segregation with other cables
Conducted emission via power supply

- Emission level as per the product standard IEC 61800-3
- EMC plan required for category C4

IEC 61800-3 categories and emission limits:

- C1: Equivalent to generic emission level for residential environment (IEC 61000-6-3)
- C2: Equivalent to generic emission level for industrial environment (IEC 61000-6-4)
- C3: Iph ≤ 100A. No reference to generic standard. Severe industrial emission level (EM level 4+)
- C4: Iph > 100A. Very severe industrial emission level (EM level 4+)

Overview of VSD per power range

<table>
<thead>
<tr>
<th>VARIABLE SPEED MOTOR DRIVES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power range</strong></td>
</tr>
<tr>
<td>Typical power supply arrangement</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Cond. emission IEC 61000-3</strong></td>
</tr>
<tr>
<td>EMI level</td>
</tr>
<tr>
<td>LV motor</td>
</tr>
<tr>
<td>HV motor</td>
</tr>
<tr>
<td>No limit, EMC plan required</td>
</tr>
</tbody>
</table>

Category C3/C4
EMI voltage in time domain
The Three Dimensions of EMC

systems EMC requirements are set by the environment it is intended for

Environments

Industry

At Sea

Domestic

[Tests to cover]

Phenomena

Standards address different EM Phenomena

tests are defined to check each relevant aspect
Front Door / Back Door EMI

Front Door: Intended Coupling Path; Back Door: Unintended Coupling Path

- **Front Door**
  - Intended Coupling Path
  - 100 MHz in-band interference
- **Back Door**
  - Unintended Coupling Path
  - 9 MHz out-of-band interference
  - Receiver 87 - 108 MHz
  - Mains Cord I/O interface
  - ICM

Performance Criteria Determine Urgency of Measures

depending on criticality of failure, a criterion is selected (usually in test standard)

**A**
- System continues to work according to specification
- Degradation not acceptable
- Generally applies to all interference with a continuous nature

**B**
- Temporary degradation acceptable, auto recovery.
- Usually applies to sporadic interference to a non-critical function.

**C**
- Degradation acceptable. Recovery after manual RESET.
  - e.g. at mains interruptions. Only for non-critical functions.
System Boundary is EM-Environment Boundary

within the system boundary, compatibility levels can, in theory, be set as desired

External Environment
example: Naval Military

System Internal Environment
example: Industrial

System

Boundary

is

EM

Environment Boundary

within

the

system

boundary,

compatibility

levels
can,
in
theory,
be
set
as
desired

Measures to be taken by Designer at all interfaces

Conducted and Radiated Emission / Susceptibility

type determines the approach to EMC measures

Conducted

Radiated

Emission

CE

RE

Susceptibility

CS

RS
(Continuous) Immunity Aspects

“interference” from “others” through EM-fields

from “elsewhere” through cabling (conducted interference)

Minimize Dissipation with Fast V/I Transitions
In High Field Environments Equipment May Fail

booster transmitters and antennas are often installed for communication

Car remote controls were disturbed…

Search party for the hidden source

Non-linear Effects

out of band interference

- Prevent HF signals from reaching semiconductors
- Do not amplify HF signals that did get in
Non-Linearity Disaster Pictures

ElectroStatic Discharge

charges built on persons or equipment cause electric sparks (and currents)
Electric charging by induction

direct contact not necessary!

1. Charging of an insulator

Source:
IEEE EMC Education Manual
Page 13-15: “ESD”
Tony Nasuta
Westinghouse Electric Corp.

2. Insulated PCB on charged surface

3. Touch or Ground PCB:
   negative charge disappears (spark)
   (PCB possibly damaged)

\[ V_{PCB} = \frac{Q_{PCB}}{C_{PCB}} \]

(C_{PCB} decreases)

4. Lift PCB: voltage increases! Sparks fly!
the ESD Threat

ESD pulse from IEC 61000-4-2 immunity standard

The ESD contact discharge current waveform (IEC 61000-4-2)

Time to frequency domain conversion

two characteristic frequencies appear related to pulse duration and rise time
ESD pulse can be decomposed into two trapezoids

Building blocks contact discharge pulse

- Fast pulse: $\tau_1=0.7$ ns; $\tau_2=10$ ns
- Slow pulse: $\tau_1=10$ ns; $\tau_2=60$ ns

To convert the ESD pulse to frequencies, it can be split into two trapezoids

Short and long pulse added in the time domain

Spectra of slow and fast pulse can be added

The resulting spectrum is used for shielding analyses
**Inductive load switching**

Relays, Valves, and PWM motor control systems

Basic model

\[
\text{Energy} = \frac{1}{2} L \cdot I^2
\]

\[
\text{Energy} = \frac{1}{2} C \cdot V^2
\]

Analysis:

- \(L = 0.1 \, \text{H}\)
- \(C = 100 \, \text{pF}\)
- \(I_0 = 1 \, \text{A}\)

\[
\frac{1}{2} L \cdot I^2 = \frac{1}{2} C \cdot V^2
\]

\(V = 32 \, \text{kV} (!)\)

Source: Jasper J. Goedbloed, "EMC"
Prentice Hall/Kluwer 1992

---

**High Voltage in Switch Arcs and Creates Spikes**

reason for Electrical Fast Transients (EFT) tests on equipment

5/50 ns pulses

Figure 2 – General graph of a fast transient/burst
from EN 61000-4-4

---
Lightning Electromagnetic Pulse (LEMP)

Time domain representation of Lightning First Stroke

Severe Lightning Strike, defined in terms of lightning current

\[ LEMP(t) = I_0 \cdot k \cdot (e^{-qt} - e^{-rt}) \]

- \( I_0 = 200 \, [kA] \)
- \( k = 1.09 \)
- \( q = 11354 \)
- \( r = 647265 \)

Note: the LEMP is a powerful Low Impedance Effect

Rates of change @ 10 [m]

\[ \frac{\partial E}{\partial t} = 6.8 \cdot 10^{11} \, [V/m/s] \]
\[ \frac{\partial H}{\partial t} = 2.2 \cdot 10^9 \, [A/m/s] \]
Frequency Domain graph of Lightning First Stroke

It is clear that most of the lightning energy is in the low frequency area.

Calculate the Effect of an Indirect Lightning Stroke using Faraday’s Law

- Flux in Loop: $\Phi = B \cdot A$ where $B = \mu \cdot H$
- Induced Voltage: $V = -\frac{d}{dt} \Phi$
- Surface: $A$ [m$^2$]
- $R =$ distance to stroke
- $H = \frac{I}{2\pi R}$
- Induced Voltage in frequency domain: $V(\omega) = -j\omega \cdot B \cdot A$
- $I$, $B$ or $\Phi$ is multiplied by frequency!
Normalized Frequency Domain Graph of Lightning

shows frequencies of maximum impact (voltage induced in small loop)

multiply every amplitude in the graph by its frequency: “Normalization”

Distribution of Lightning over the World and the Year

NASA movie clip

Source: YouTube
High Altitude Nuclear Explosion Initiates E-field Pulse

The Compton Effect converts Gamma Ray Energy into Electric Field

The Compton Effect

Extra-Atmospheric Nuclear EMP Blast is Far-Field

in the far field there is a fixed ratio of Electric and Magnetic Field (Impedance)

\[
\frac{E}{H} = 120 \cdot \pi = 377 \, \Omega = Z_0
\]

Impedance of Vacuum or Air

- This means that if you know one (E or H)
- You can calculate the other!
- EMP is usually specified in terms of E (!)
- If you need H, calculate it.
HEMP Impulse Illuminates Large Areas

Ground Coverage for High-Altitude Bursts at 100, 300 and 500 km

The HEMP Phenomenon (movie clip)
Characteristics of the HEMP

time domain representation

\[ HEMP(t) = E_0 \cdot k \cdot \left( e^{-qt} - e^{-rt} \right) \]

- \( E_0 = 50000 \, [V/m] \)
- \( k = 1.3 \)
- \( q = 4 \times 10^7 \)
- \( r = 6 \times 10^8 \)

Note: the HEMP is a relatively High Impedance Effect (377 \( \Omega \))

Characteristics of the HEMP

frequency domain representation

HEMP in the frequency domain
Normalizing to find Frequency of Maximum Impact

effective induced voltage in a small loop as function of frequency

![Induced voltage spectrum for HEMP](image)

Estimation of the Effects

![EMR Detonation](image)
Power Quality: influence of power-users

EMI related; Compatibility required

"Voltage Quality" or "Quality of Supply"

Various Power disturbances -> Conducted Susceptibility

Power Supply - Mains Generator

Power Line

Power User

Conducted Emissions

User Load Fluctuations

Other users

"Current Quality" or "Quality of Consumption"


Non-Sinusoidal Currents and Ohm’s Law

the root cause of most power-quality related problems

Original Mains Voltage

User Load Current

User Mains Voltage

\[ \Delta V = \Delta I \times R_{\text{LINE}} \]
Mains Voltage and Current as Users Like to See It

clean sine wave voltage and resistive load

History: Reactive Loads

result: phase shift, \( \cos(\phi) \)
Today: Non-Linear Loads

most prominent: diodes charging bulk capacitors

Legend

- Mains Voltage
- Mains Current

Modern Compact Fluorescent Lamp (CFL)

electronic circuit with diode bridge and bulk capacitor

Problem with Diode Rectifiers: Synchronicity

all conduct simultaneously on mains voltage! distortion adds up

Same Fluorescent Lamp in Large Office Building with distorted Voltage

Small Users <75 W Have No PF Requirements

e.g. all LED’s, CFL’s and many laptops are exempt

Effect….

Heavily Distorted Voltage Waveform

This effect is called: Harmonic Distortion

Wave-Shape in Large Office Building: Multiple Zero Crossings!
Mapping of EMC on Power Quality (User Aspects)

users on the grid are sources and victims, the grid is the coupling path!

Grid → POI → User

Quality of supply | Quality of consumption

SOURCE VICTIM

Coupling path: always electrical interconnections

Problem 1: Synchronous Peaks Add Up

initial power budget new office building exceeded almost twofold

- Estimated required power: 3 MW
- Initial installation: 4 MVA (4 x 1 MVA)
- Installation upgraded to: 7.2 MVA (+ 2 x 1.6 MVA)
- Question: are we or are we not saving cost and energy?
Problem 2: Switcher Frequencies Pollute Environment

low power fast switching requires short risetime IGBT’s and MOSFETs

Source: YouTube

Problem 3: Power Islands: Overproduction

mains voltage too high at high illumination levels

>253 VAC @ 45 KVA generation
Mechanism of Overvoltage at Sunny Days: Ohm’s Law

farm’s powercable cannot handle 45 KVA in the opposite direction

\[ \Delta V = I \times 2R \]

What if all Neighbours Install Solar Panels?

like the little lamp-currents, many small ones make one big one!
How to Solve these Conflicts?

supply and demand, storage, who is in control? the Smart Grid!

Traditional: One Way Traffic

Now: Everybody can Supply or Use

Coffee Break

Time for a Break!
The **Current Boundary**

- A provision to split loops (and shut out noise sources)

![Diagram showing current boundary](image)

- **Current boundary at natural interfaces**
  - Edge of PCB, cabinet wall, basement of a building; **one** boundary per unit!

**Install current boundaries at natural interfaces**

- **Right**
  - **Wrong**

<table>
<thead>
<tr>
<th>Drawbacks:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Current follows long path over equipment</td>
</tr>
<tr>
<td>- Loop area cannot easily be minimized</td>
</tr>
</tbody>
</table>

**Situation in practice**

- **Detector:** AM-radio

**Create one or more “inner-loops”**

- **Short circuit(s) reduce loop area**

**Unit 1**

- (Mains cord 1)

**Unit 2**

- (Mains cord 2)

- (I/O cable 1-2)

**“Ground 1”**

**“Ground 2”**

**I<sub>cm</sub> (noise current)**

**Loop closes through “ground”**

5/3/2016
Examples of current boundaries on equipment

Wide conductors and low-resistance transitions (be careful with paint)!

 Protect all units with a current boundary!
(and check any conductor that passes it)

Check DC resistance with a milli-Ω meter: < 1 mΩ!

Use Current Boundary to protect existing “pig-tail”

Pig-tails can be acceptable as long as CM currents are kept away from it

H-field lines
Wide metal plate
(Current Boundary)
EMC glands
If many Cables are Guided through Shielding Wall...

other options exist

Roxtec / Brattberg Glands
Special Gland System: Many Cables Through Wall

all make good electrical contact in wall (< 10 mΩ)

MIL-STD-1310H

Next: Separate Cables with Current Boundaries
classify cables into categories

Category
1. Noisy (E)
2. Sensitive (I)
3. Indifferent (N)

red = “source” = “Emission”
green = “sensitive” = “Immunity”
blue = “indifferent” = “Neutral”

Model
Model the Real System in CM loops

Both sensitive (analog, various busses) and (polluted) power lines

Process control system

- Power supply 10 kV/400 V
- Power electronics
- Relay’s circuit breakers
- Control equipment
- Control bus
- Control bus
- Control equipment PLC/PC/μC
- Machine structure
- Production process / machine
- Pneumatic/hydraulic valves
- Sensors
- I/O module
- Pumps, fans, drives

Industrial Environment

Source: C.J. Post “EMC of Large Systems” PATO 2007

Separating Cables with Current Boundaries

Use neutral conductor to reduce loop area; then insert current boundary

Steps:
1. Recognize loop
2. Reduce loop area
3. Add boundary
Separating Cables with Current Boundaries

neutral conductor in practical cases: never a “wire”, always a structure part

(CM-) Transfer impedance of combination of two relatively thin conductors is too high (radiates fields) (does not work for high frequencies)

Wide sheet metal ("cable guide") is far superior to the previous situation. The common-mode transfer impedance is much lower. Skin effect helps.

Separating Cables with Current Boundaries

wide metal reduces fields i.e. the transfer-impedance of the cm-current loop

 advantge: proximity & skin effects
Separating Cables (Alternative)

use structure metal parts to “guide” cables and insert current boundaries

Steps:
1. recognize loop
2. guide cables with metal strips or trays
3. connect current boundaries to strips

Separating Cables with Current Boundaries

use (Ground-) Plane to reduce loop area; then insert current boundaries

Note: we are actually reducing CM-loop areas here, using wide metal “short-circuits”

Steps:
1. recognize loop
2. cover loop with metal (ground-)plane
3. connect current boundaries to plane

5/3/2016
Separating Cables with Current Boundaries

instead of a metal plane a metal mesh could be used

“Plane” could be metal mesh

wavelength is key to mesh size: apertures should be very small with respect to \( \frac{1}{4} \) wavelength (\( \lambda/4 \))

Transfer Impedance improvement

mechanism identical to the single wire case

I\(_{\text{cm}}\) "squeezes" under cable

(proximity effect)
Use available metal to “short-out” CM-currents
e.g. a ship’s deck and walls can be used as groundplane(s)

Good contact (<1 mΩ)

Important: keep cables near metal over their full length!
(unless cables have sufficient shielding to go “unprotected”)

Cable distance is important
once a cable guide is used for protection

Current distribution of $I_{cm}$ in cable guide is measure of flux density, $\Phi$, coupling into cable: at source ~L, at victim ~M!

$M_{source \over victim} \approx \frac{\Phi_{victim}}{I_{cm}}$

$M \approx \frac{L_{source}}{1 + \left(\frac{D}{H}\right)^2}$

COUPLING FACTOR: $k$

$k = \frac{M}{L_{source}} = \frac{1}{1 + \left(\frac{D}{H}\right)^2}$

Source:
Johnson, H
"High-Speed Digital Design" 1993
Two Types of Current Boundaries

Short Circuit for Common-Mode “Sources”

Environment Region "0"

1. Connector Plate

Environment Region "1"

Enclosure / EMC Cabinet / Shielded Room

2. Cable Tray

Three Types of Current Boundaries

Short Circuit for Common-Mode “Sources”

Environment Region "0"

1. Connector Plate

Environment Region "1"

Enclosure / EMC Cabinet / Shielded Room

2. Cable Tray

3. Completely Shielded Enclosure
Motor demonstration

After the addition of a metal cable tray

Motor demonstration

after the addition of a metal cable tray
Either filter or shield entire cable when passing through shielding wall.

- **O.K.**
- **Not O.K.**

---

**Shielding Experiment**

Shielding a noisy interconnection using a metal tube (wave guide).

- Generator
- Battery DC cable
- Radio tuned to RF harmonic frequency
- Modulation Detected
- Wire carrying modulated RF signal

---

EMC Europe 2016, Wroclaw, Poland  
EMC for LARGE installations
Shielding Experiment

Entering a conductor into tube couples out the noise again

Wire carrying modulated RF signal

Radio tuned to RF harmonic frequency

Modulation Detected

Shielding Experiment

Insulating generator case: battery cable now reradiates noise (antenna)

Wire carrying modulated RF signal

Radio tuned to RF harmonic frequency

Modulation Detected

EMC Europe 2016, Wroclaw, Poland

EMC for LARGE installations
Shielding Experiment

Entering a screened conductor into tube also couples out the noise again.

Grounding the shield with the wire does not solve the interference problem!
Shielding Experiment

Cable shield must be grounded directly to the metal shield to stop the noise

Bad “Grounding” habits

it is Inductance, not the milliOhms that count!
Shielding Experiment

A filter in the inserted wire does not help if only grounded with a wire.

Only when the wide metal filter plate touches, the shielding works.

Wire carrying modulated RF signal

Radio tuned to RF harmonic frequency

Generator

Battery

DC cable

Modulation Detected

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Filter = “Frequency Dependent” Current Boundaries

EMI filter is usually employed as frequency dependent current boundary

Conducted emission via power supply

- Example of intended segregation of power supply

- Alternative in case of shared power supply: power supply filter
Installation of filter

1) Earthing of filter and drive

2) Inductive coupling between in- and output of filter

OK

Filter demo

Source: Goedbloed
Examples of bad installation practice of filters

Inductive coupling between input and output wiring makes the filter ineffective → segregate input and output wiring

Vendor EMC installation requirements

Installation of mains RFI and output filters

Installation of shielded motor cable and cable termination details
Installations with switched loads (transients)

- Large number of switched applications (motors, valves etc.)
- No EMC requirements for single component
- Disturbing potential is determined by reactive properties of load, cable lengths, switching frequency and supply voltage
- Emission standard for switching transients (clicks) not up to date (based on radio interference (CISPR), whereas immunity of digital circuits, field buses etc. is the main issue.

Emission as per EN-IEC 61000-6-4

<table>
<thead>
<tr>
<th>Port</th>
<th>Frequency range</th>
<th>Limits</th>
<th>Basic standard</th>
<th>Applicability note</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>20 MHz - 230 MHz</td>
<td>40 dB(V/m) quasi-peak at 10 m</td>
<td>CISPR 16-2-2</td>
<td>See Note 1.</td>
<td>May be measured at 30 m distance using the limits decreased by 10 dB.</td>
</tr>
<tr>
<td></td>
<td>230 MHz - 1 GHz</td>
<td>41 dB(V/m) quasi-peak at 10 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2)</td>
<td>0.15 MHz - 0.5 MHz</td>
<td>79 dB(V) quasi-peak</td>
<td>CISPR 19-2-1: 7.4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>66 dB(V)average</td>
<td>CISPR 16-5-2: 4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5 MHz - 30 MHz</td>
<td>73 dB(V) quasi-peak</td>
<td></td>
<td>See Note 2.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>60 dB(V)average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3)</td>
<td>0.15 MHz - 0.5 MHz</td>
<td>97 dB(uV) quasi-peak</td>
<td>CISPR 22</td>
<td>See Notes 3, 4 and 5.</td>
<td>Continuous emissions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>94 dB(uV) quasi-peak</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>84 dB(uV) average</td>
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<tr>
<td></td>
<td></td>
<td>53 dB(uA) average</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>43 dB(uA) quasi-peak</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>40 dB(uA) + 20 dB(uA) average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.5 MHz - 30 MHz</td>
<td>87 dB(uV) quasi-peak</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>74 dB(uV) average</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>43 dB(uA) quasi-peak</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>35 dB(uA) average</td>
<td></td>
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</tr>
</tbody>
</table>

NOTE 1 If the internal emission source is operating at a frequency below 9 kHz then measurements need only be performed up to 230 MHz.

NOTE 2 Impulse noise (clicks) which occur less than five times per minute is not considered. For clicks appearing more often than 30 times per minute the limits apply. For clicks appearing between 5 and 30 times per minute, a reduction of the limits is allowed of 20 log 30/N dB (where N is the number of clicks per minute). Criterial for separated clicks may be found in CISPR 14-1.

NOTE 3 At transitional frequencies the lower limit applies.

NOTE 4 The limits decrease linearly with the logarithm of the frequency in the range 0.15 MHz to 0.5 MHz.

NOTE 5 The current and voltage disturbance limits are derived for use with an impedance stabilization network (ISN) which presents a common mode impedance of 150 Ohm to the telecommunication port under test (conversion factor 10 log150 / I = 44 dB).

EN-IEC 61000-6-4: generic emission standard for industrial environment
Ageing of switching contacts

Typical specification of relay:
- Maximum Operating Frequency (No-Load Operation): 3000 Operations / Hour
- Mechanical Durability: 10,000,000 Operations
- Electrical Durability: 1,000,000 Operations

Ageing of contacts due to repetitive sparking across contact material

Mitigation of switching disturbance

AC applications:
- **Solid state relay** (switching at zero-crossing, no stored energy)
### Mechanical switch versus solid state relay

- **Mechanical relay**
- **Solid state relay**

- Switching transients due to $dI/dt$
- No switching transients due to $dI/dt = 0$

---

### Electromagnetic environments

- **Residential or industrial**
- **But also:**
  - Medical/laboratory
  - Public space
  - Heavy industry
  - Shipping/offshore
  - Railways
  - etc.

Appropriate EMC specifications of equipment required to fit the EM level!
Electromagnetic zones in large installations

IEC:
1. very sensitive
2. sensitive, domestic / office
3. disturbing/noisy, industrial
4. very disturbing/noisy, heavy industry
5. exception disturbance

Interfaces between EM levels

→ Installation measures

EM zones

► Specify EM levels for equipment in various EM environments
► Specify interfaces between EM zones
► Similar to LPZ (Lightning Protection Zones) in EN-IEC-62305-3 and -4
Different look at civil engineering

Control building of plant

Building observed through spectacles

Cable entry of building
Demo cable entry

Current barrier at cable entry of Faraday Cage

\[ \lambda = \frac{c}{f} = 3 \times 10^8 / f \]
\[ \lambda [m] = \frac{300}{f[MHz]} \]

- f=100MHz (\(\lambda=3m\))
  - Mesh size: 1x1mm
- f=1MHz (\(\lambda=300m\))
  - Mesh size: 10x10cm

Planning of concrete reinforcement bonding

![Concrete reinforcement bonding images]
Cable entry inside (bonding of shield to cage)

Cable entry in equipment panel

Gland plate  Shielding clamps at panel entry
Cable entry at equipment enclosure

- Preferred: metallic enclosure with metallic connectors (cable shield terminated in connector)
- Additional current barrier in case of non-metalic connectors

Project approach for LARGE installations

- EPCC:
  - Engineering
  - Procurement
  - Construction
  - Commissioning
- Assign EMC focal point
- EMC management of sub-contractor
- Clarify typical EMC installation details in drawings for field installation
Separating Regions using Current Boundaries

enclosures with current boundaries form individual “environments”

Top level ("outside")
Region 0

Region N
Region N+1

Regions/Environments can be Nested

example: generator in waveguide demonstration
Only Limited Shielding can be achieved per Enclosure

20 - 40 [dB]; but it can be applied recursively!

In EMC terms, sometimes referred to as: Multipoint Grounding…

Regions are defined Electromagnetic Environments

(example) region 0: MIL-STD-464A, region 1: bridge, region 2: below deck

Aim: use commercial equipment in region 2 (susceptibility level 10 V/m)

Shielding between successive regions: 20 - 40 dB (factor 10 to 100)

- Define where EM zones will be
- Define the EM levels per region
- Use adequate current boundaries between regions
Multipoint Grounding

hierarchy of current boundaries

EMC Europe 2016, Wroclaw, Poland

EMC for LARGE installations

213

Multipoint Grounding

separating rooms in a ship is called Zoning (partitioning into EM-Regions)

EMC Europe 2016, Wroclaw, Poland

EMC for LARGE installations

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Voltage Dependent Current Boundaries

Varistors and tranzors are often used to absorb DM or CM spikes

Example from IEC 62305 part 4 (Annex C)

SPD1 SPD2 SPD3

Source: Jasper J. Goedbloed, “EMC” Prentice Hall/Kluwer 1992

Note: 1 [m] cable ≈ 1 µH

Try to stick to the “Low Frequency Approach”

Use current boundaries to restrain sizes to way below half-wavelength

Large Scale Low Frequencies

Small Scale High Frequencies
Conclusions, summary of EMC measures

- Take the EM level of the user’s environment, including EM zones, as basis of design for EMC specifications
- Design and procure equipment with corresponding emission and immunity levels (verify and avoid any pitfalls in product standards)
- Adhere to installation requirements mentioned in “user manuals”
  - Install de-coupling devices on inductive (switched) loads, use solid state relays for high switching frequencies
- Apply generic installation rules in terms of earthing, bonding at EM zone interfaces and cable segregation, e.g. IEC/TR 61000-5-2

EMC Basic Rules

- Do not use high frequency signals (voltages and currents)
  - If you do use them:
    - Do not transport them over large distances
      - If you do:
        - Provide adequate current boundaries
          - Reduce Loop Areas
          - Use Connector plates
          - EMC Glands
          - Metal cable guides
          - Properly terminate transmission lines
- Specify the EMC performance of your system
“Systems Designers Heaven”

independent building blocks with “abstract” behaviour

Object Oriented
- realise complex from simpler behaviour
- make assemblies independent
- solve “undesired” as low as possible

EMC Principal Laws
- No high frequencies
- Do not transport them
- Use adequate boundaries

EMC for LARGE installations

Two ways to achieve EMC: 1. The Crisis Approach

“Build the plane, push it off the cliff, let it crash and start all over again”
2. The “Systems Approach”

Consider EMC right from the start throughout the design.

Many Available Mitigation Options

Cost of Modification

- Requirements
- Measures
- Check bonding
- Repair/redesign
- Bankruptcy

Concept Design Manufacture Test Operational phase in the lifecycle

Four Key Elements of EMC implementation in large organizations

1. Awareness
2. Network
3. Rules & Guidelines
4. Program Support
Network – Connect with other Experts

Look for people interested in the subject, in-house or outside

Universities

Other industries

Professional societies

Research institutes

IEEE

IEEE – EMC chapters

Common Expert Team (CET, Thales)

Aware Employees

Division I

Division II

a way to implement EMC maturity
Build EMC assurance through the **Knowledge Cycle**

- Problem definition: "desired behavior"
- "Test"
- Validation/Verification
- Research/Analyses
- Validated models
- Behavioral Model
- Development Support
- Knowledge Transfer & Education

**EMC Rules and Guidelines**

A lot of information on EMC engineering can be found on the internet
a lot of good literature is available on the internet


Or try one of the EMC “Cahiers Technique” e.g. #149:


http://www.humerboard.at/ftkl/Design_Techniques_For_%20EMC.pdf

System Design for
Control of
Electrical Noise


or: buy a book!

Table 1: Activities and deliverables in system life cycle

<table>
<thead>
<tr>
<th>Activity</th>
<th>System specification</th>
<th>System design</th>
<th>Development</th>
<th>Production and deployment</th>
<th>Operational support</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Explicit, implicit and induced EMC requirements</td>
<td>Analysis of the system architecture</td>
<td>Tailor the EMC protections (shielding, filters, interfaces)</td>
<td>EMC performance assurance</td>
<td>Preventive and corrective actions</td>
</tr>
<tr>
<td></td>
<td>Critical function analysis</td>
<td>EMC topology</td>
<td>Technical choices</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>EMC margins</td>
<td>Risk analysis</td>
<td>EMC design approval</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>EMC radiation hazards</td>
<td>Compatibility with other constraints</td>
<td>Partial tests on risk elements</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Establish the EMC protection concept</td>
<td>EMC qualification/verification, subsystems, equipment</td>
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<tr>
<td></td>
<td></td>
<td>Derive the requirements</td>
<td>Follow up engineering changes</td>
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<td></td>
<td></td>
<td></td>
<td>EMC inspection during equipment integration</td>
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</tr>
<tr>
<td>Deliverable</td>
<td>EMC-MP</td>
<td>EMC requirements into system specification</td>
<td>EMC-AR</td>
<td>Update EMC-CP</td>
<td>Maintenance Documents</td>
</tr>
<tr>
<td></td>
<td>EMC requirements into system segment design document</td>
<td>EMC requirements into product definition</td>
<td>EMC Engineering Test Reports</td>
<td>Update EMC-CP</td>
<td></td>
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<tr>
<td></td>
<td>EMC-CP</td>
<td></td>
<td>EMC-TP</td>
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</tr>
</tbody>
</table>

F. Leferink, S. Lerose, M. Sauvageot, W. van Etten “The Four Key Elements of EMC Implementation in Large Organizations” EMCEurope, 2002, Sorrento Italy.

DEPARTMENT OF DEFENSE HANDBOOK

GUIDANCE FOR CONTROLLING ELECTROMAGNETIC ENVIRONMENTAL EFFECTS ON PLATFORMS, SYSTEMS, AND EQUIPMENT

### Product Development/Program Support

perform engineering & qualification tests

http://www.thales-ecc.nl/onze-expertise/emc/

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**Further questions?**
### Relation of MIL-STD-461F tests to Phenomena

<table>
<thead>
<tr>
<th>Test Identifier</th>
<th>Test Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CE102</td>
<td>Conducted Emissions, Power Leads, 10 kHz to 10 MHz</td>
</tr>
<tr>
<td>RE101</td>
<td>Radiated Emissions, Magnetic Field, 30 Hz to 100 kHz</td>
</tr>
<tr>
<td>RE102</td>
<td>Radiated Emissions, Electric Field, 10 kHz to 18 GHz</td>
</tr>
<tr>
<td>RE103</td>
<td>Radiated Emissions, Antenna Spurious and Harmonic Outputs, 10 kHz – 40 GHz</td>
</tr>
<tr>
<td>CS101</td>
<td>Conducted Susceptibility, Power Leads, 30 Hz to 150 kHz</td>
</tr>
<tr>
<td>CS114</td>
<td>Conducted Susceptibility, Bulk Cable Injection, 10 kHz to 200 MHz</td>
</tr>
<tr>
<td>CS116</td>
<td>Conducted Susceptibility, Damped Sinusoidal Transients, 10 kHz to 100 MHz</td>
</tr>
<tr>
<td>RS101</td>
<td>Radiated Susceptibility, Magnetic Field 30 Hz to 100 kHz</td>
</tr>
<tr>
<td>RS103</td>
<td>Radiated Susceptibility, Electric Field, 2 MHz to 40 GHz</td>
</tr>
<tr>
<td>RS105</td>
<td>Radiated Susceptibility, Transient Electromagnetic Field (NEMP)</td>
</tr>
</tbody>
</table>