EMC Design Issues for Power Electronics Converters

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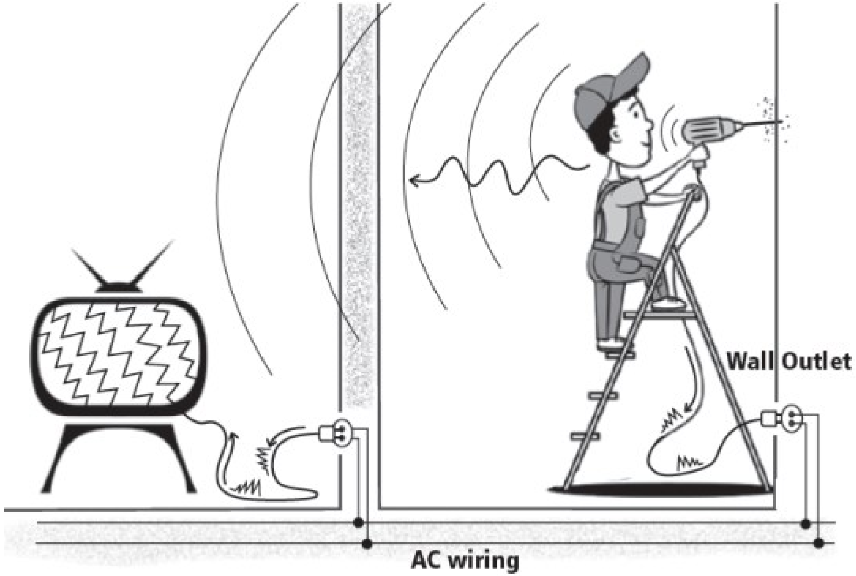
Maschinenfabrik Reinhausen

OUTLINE

- Introduction
- Overview on Electromagnetic Basics
- Coupling Mechanisms
- Design Process
- Standards and Regulations
- Summary

$$\boxed{E \propto I.f^2.A.\frac{1}{r}}$$

r = distance
I = current
A = loop area
f = frequency



INTRODUCTION

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Importance of EMC

♦ Practical impact can be minor annoyance to lethal *…and everything in between;*

- Loss of life, property or system
- Injury, damage to system, loss of operation
- Annoyance, nuisance, temporary loss of performance
- Product may be blocked from the market

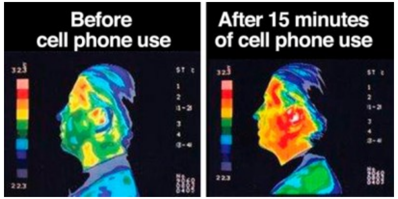
Problems with Non-Compliance

Annoyance, Delays	Lost Revenue, Minor Property Loss	Significant Property Loss	Death or Serious Injury
Minor			Major

- AM/FM/XM/TV Interference
- Cell Phone Interference

- Critical communications Interference/Interruption
- Automated Monetary Transactions

- RADAR, Landing System Interruption
- Erroneous Ordnance Firing
- Improper Deployment of Airbags



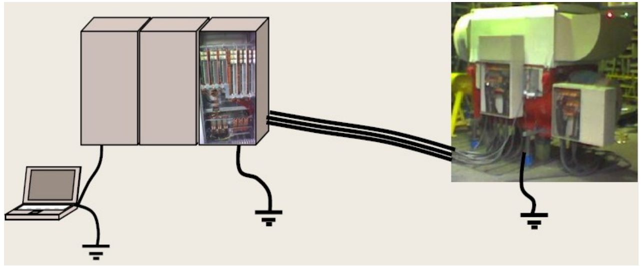
EMC Problems

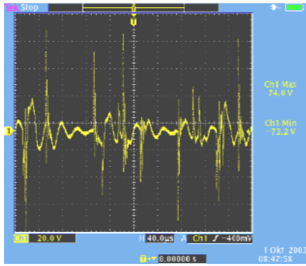
Failing to meet requirements, most common cause is radiated emission.

Ex. 1. Start up of a wind turbine inverter.

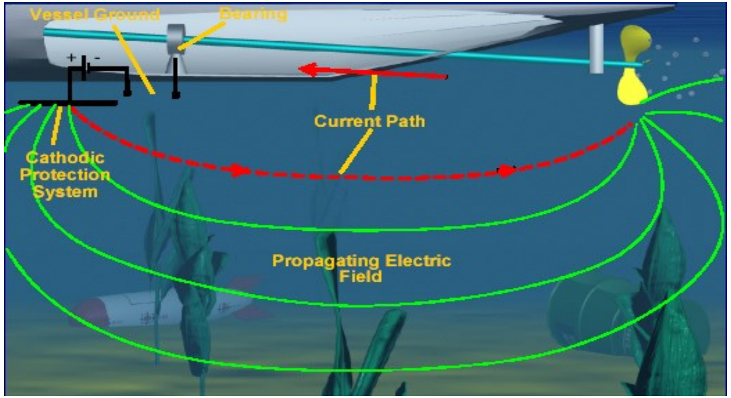
The power supply of the converter blew up.

Grounding potential of inverter bounces.
Current via the shield exceed the limits of the computer





Ex. 2. The magnetic field of the ships trigs the torpedo and cause explosion



A Cell Phone and Static Electricity

Electromagnetic Interference by 2-Way Radios vs CRT Monitor

EMC Problems

Ex. 3. Brazil rocket explosion (2003) - Alcantara launch center

21 people killed

20 more injured

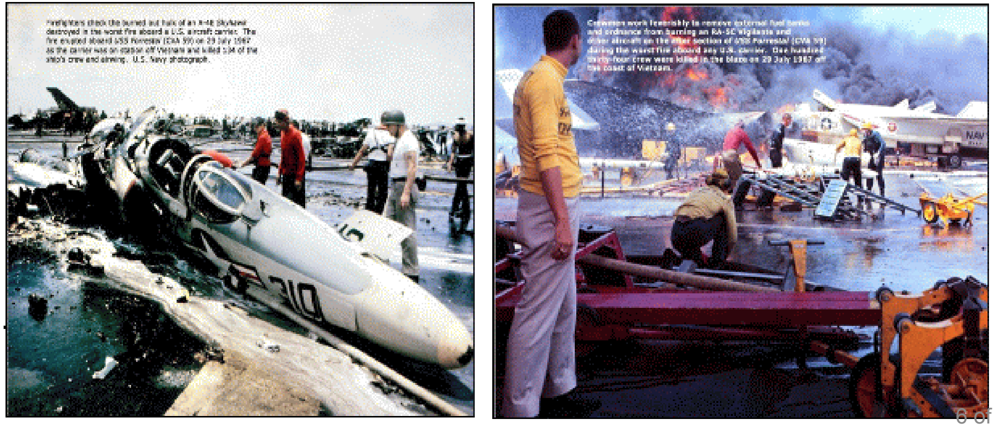
Reason: EMI triggered one of the rocket's four solid fuel boosters

Ex. 4. Aircraft carrier explosion (1967) - Vietnam

134 sailors killed

161 injured

Reason: Due to EMI a rocket on the flight deck was discharged



OVERVIEW ON ELECTROMAGNETIC BASICS

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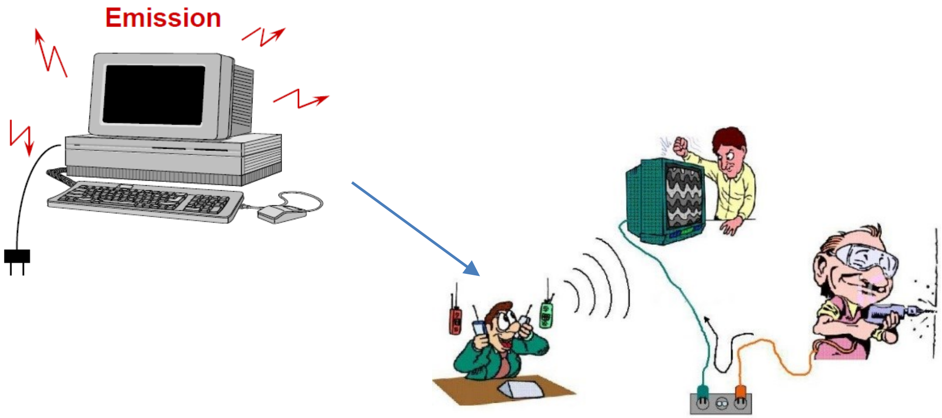
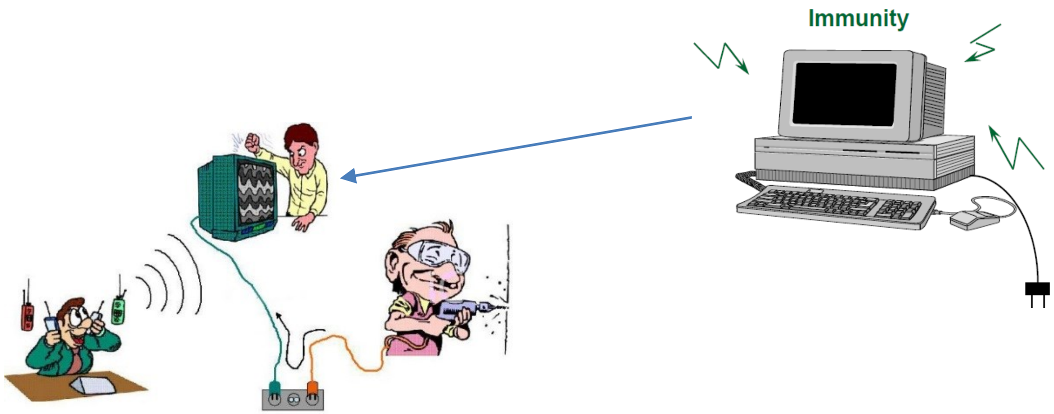
Emission

- The manufacturers are obliged to ensure that the electrical devices produce very little electromagnetic disturbances (within the limits) to their surroundings.



Immunity

- Electrical device manufacturers are obliged to protect their devices from electromagnetic disturbances.

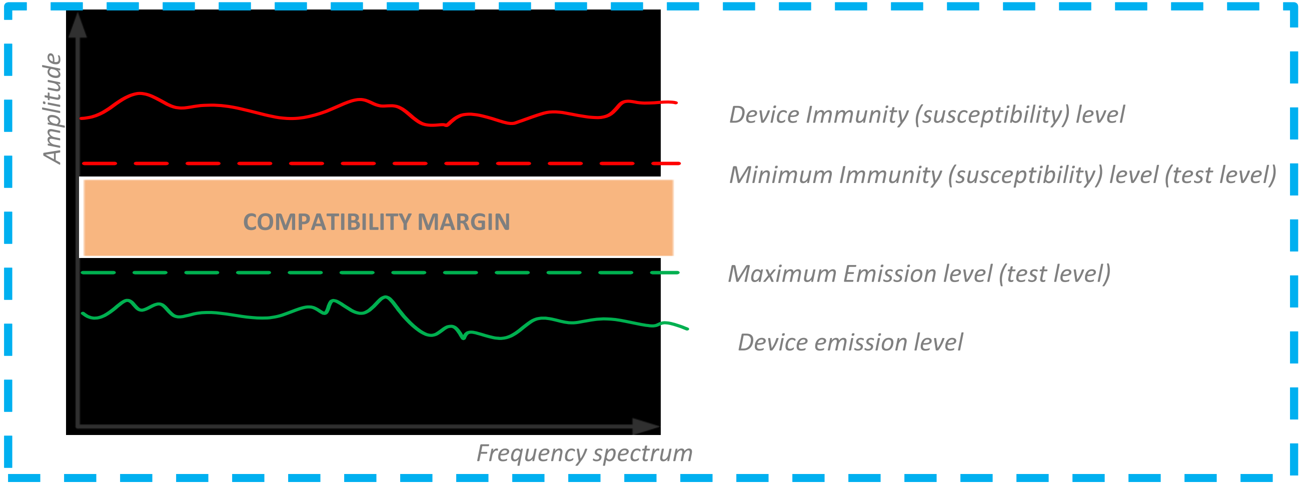


EMC

- Does NOT cause interferences with itself and other systems
- Is NOT susceptible to emissions from other systems

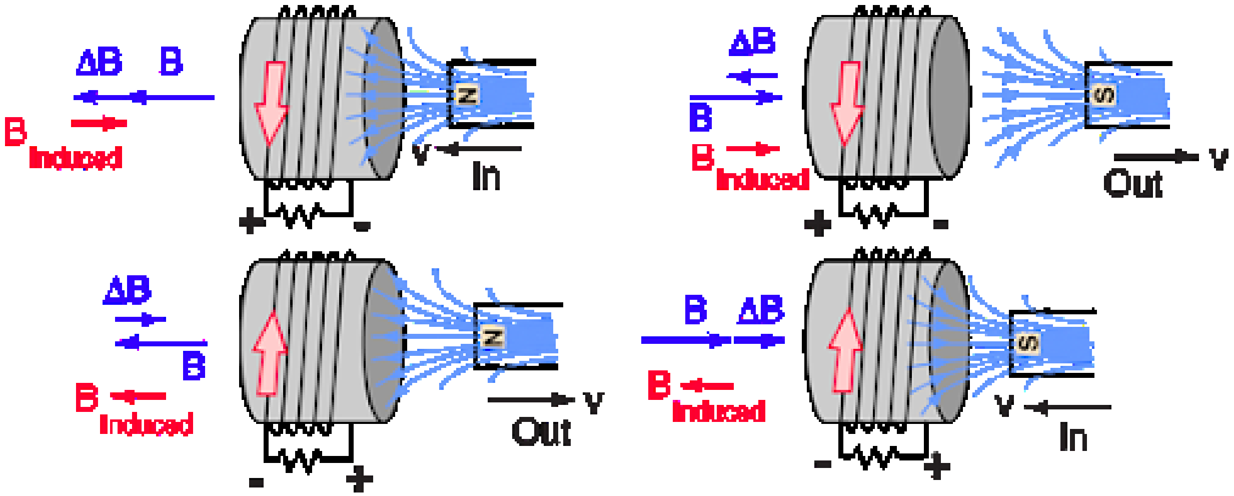
EMI
Electromagnetic Interference

EMS
Electromagnetic Susceptibility



Electromagnetic Wave Basics

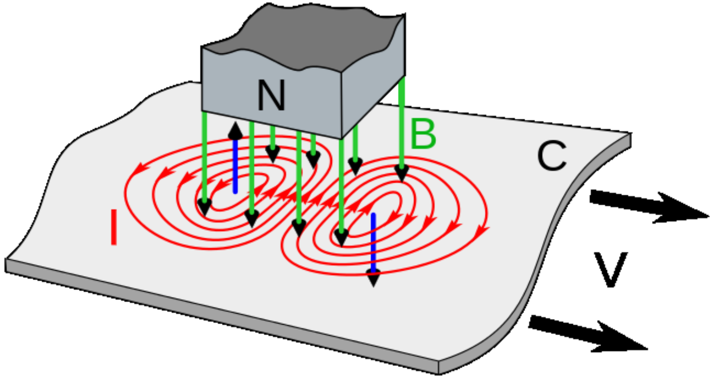
A changing magnetic field induces an emf and therefore an electric field.



$$\oint \vec{E}.d\vec{l} = -\frac{d\Phi_B}{dt}$$

Electromagnetic Wave Basics

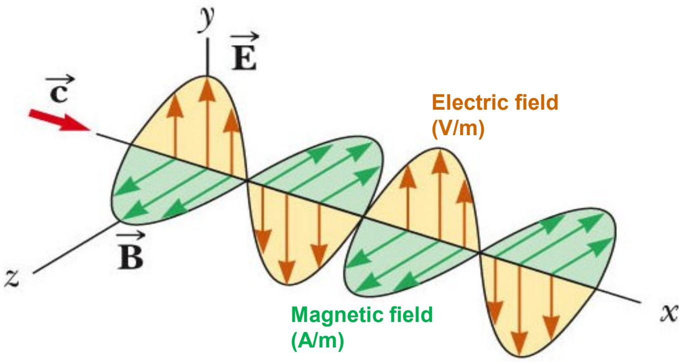
A changing electric field produces magnetic field.



$$\boxed{\oint \vec{B} \cdot d\vec{l} = \mu_0 I + \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}}$$

Electromagnetic Wave Basics

An electromagnetic wave consists of combination of a transverse electric field and a transverse magnetic field perpendicular to each other.

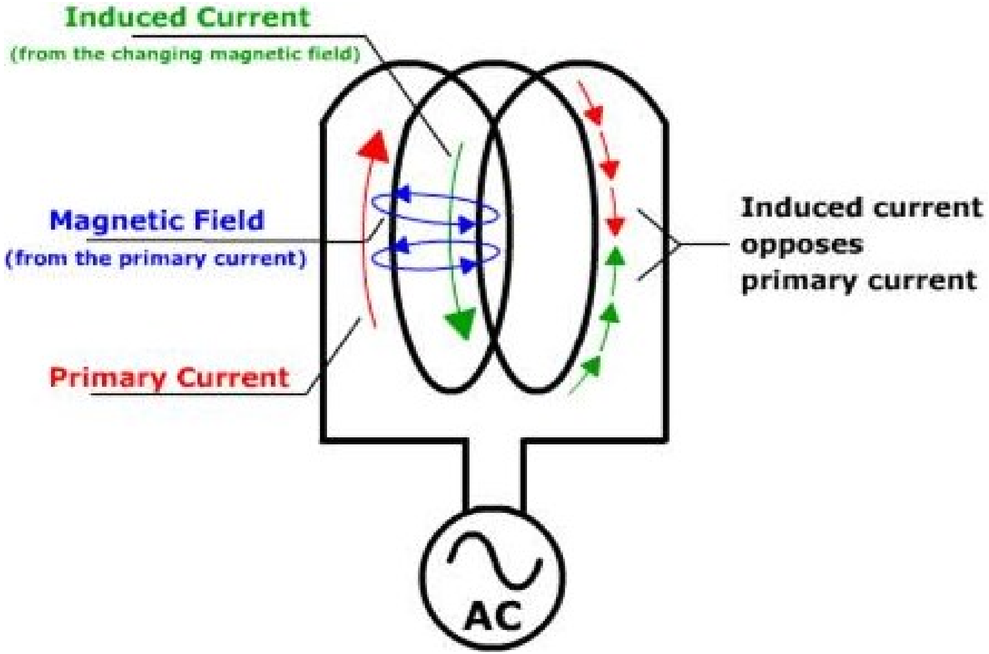


Direction of electromagnetic waves

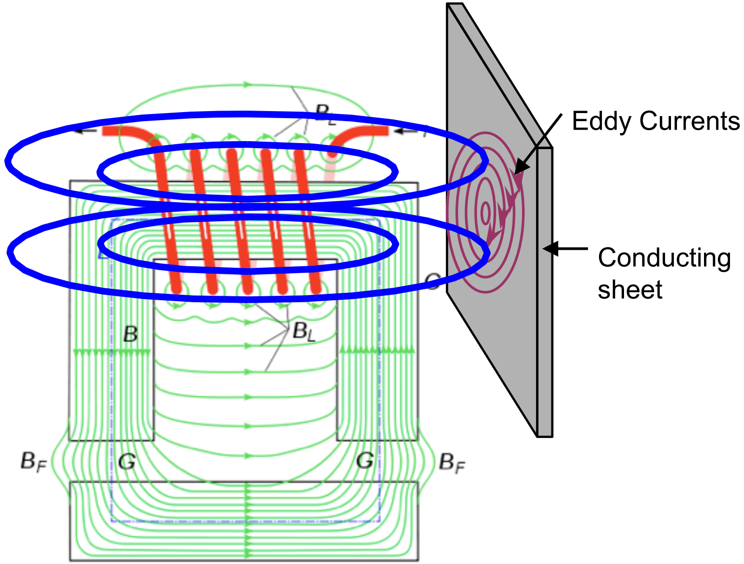
Electric field (V/m)

Magnetic field (A/m)

$$E = cB$$

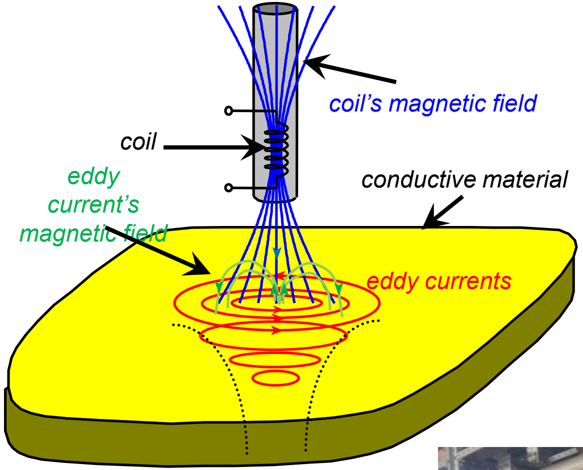


Eddy Currents



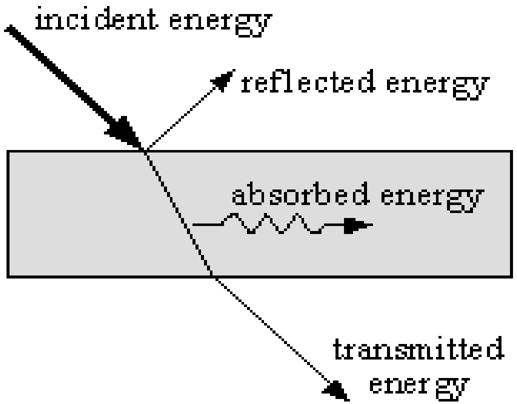
- Eddy currents are created through electromagnetic induction.
- They are induced electrical currents that flow in a circular path.

Eddy Currents



- Eddy currents flowing in the material will generate their own "secondary" magnetic field which will oppose the coil's "primary" magnetic field.
- Eddy currents are strongest at the surface of the material and decrease in strength below the surface.
- Thicker materials will support more eddy currents than thinner materials.
- The depth that the eddy currents are only 37% as strong as they are on the surface is known as the standard depth of penetration or skin depth. The depth changes with;
  - frequency
  - material conductivity
  - permeability.

Shielding



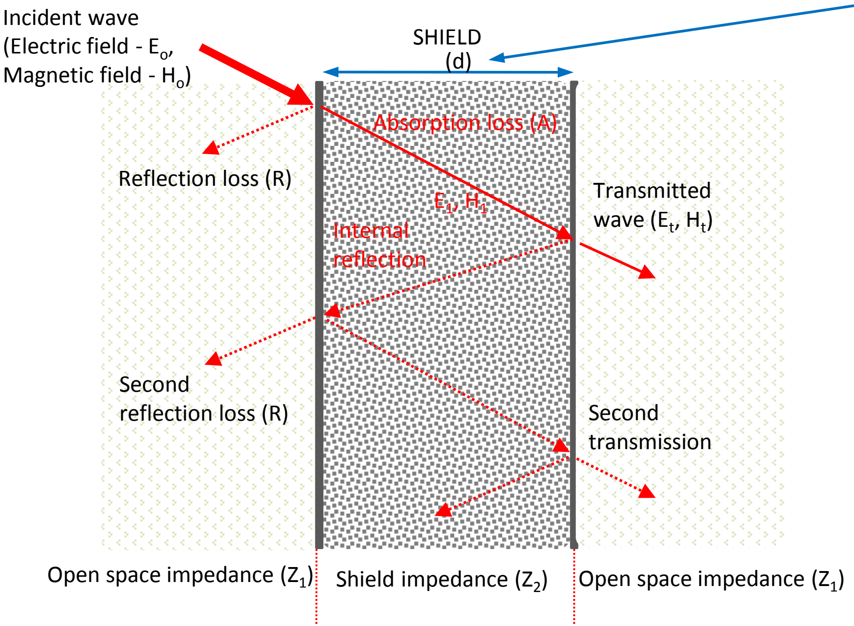
- When radiation strikes a surface, a portion of it is reflected, and the rest enters the surface.
- When radiation enters the surface, some are absorbed by the material, and the remaining radiation is transmitted through.
- The ratio of reflected energy to the incident energy is called reflectivity, ρ.
- Transmissivity (τ) is defined as the fraction of the incident energy that is transmitted through the object.

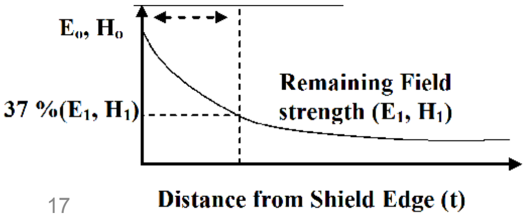
$$R + A + T = 1$$

Shielding effectiveness (SE) = R + A + B

R: Reflective losses
A: Absorption losses
B: Secondary reflective losses (ignore if A>8 dB)

Shielding





Required thickness for shielding magnetic field: $\boxed{d = \sqrt{\frac{2}{\omega K \mu}}}$

d = thickness of shield material
K = conductivity of shield material
μ = permeability of shield material

ex: at 150kHz, 0.1mm copper sheet will have a good shielding effect

Open shield impedance → $Z_1 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi = 377[\Omega]$

Shield instrinsic impedance → $Z_2 = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}[\Omega]$

Reflection losses → $R = 20.\log_{10}\left|\frac{(Z_1+Z_2)^2}{4.Z_1.Z_2}\right|$ [dB]

Internal electic field → $E_1 = \frac{2.Z_2}{Z_1+Z_2}.E_o$

Internal magnetic field → $H_1 = \frac{2.Z_1}{Z_1+Z_2}.H_o$

Transmitted electic field → $\boxed{E_t = \frac{2.Z_1}{Z_1+Z_2}.E_1}$

Transmitted magnetic field→ $\boxed{H_t = \frac{2.Z_2}{Z_1+Z_2}.H_1}$

Self Inductance of a Cable

- The self inductance of a solid round conductor: $L = K_u . l . \left[\log_e\left(\frac{2.l}{r}\right) - \frac{3}{4}\right]$

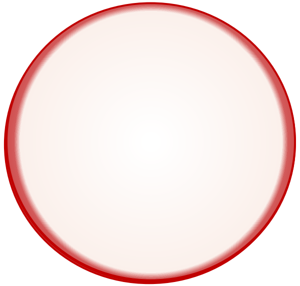
$$X_L = 2\pi f L$$

- A conductor is useless if L > $\frac{10}{f(MHz)}$ (ex: pigtail)

Skin Effect

Resistance of a cable with AC current: $R_{ac} = R_{dc} * (1 + Y_s + Y_p)$

due to skin effect



f = 50Hz

f = 3kHz

[illegible]

Single conductor carrying AC current

Skin Effect

Resistance of a cable with AC current: $R_{ac} = R_{dc} * (1 + \boxed{Y_s} + Y_p)$

due to skin effect

How to reduce skin effect:

- Segmenting the conductors
- Making hollow core conductors
- Metal coating for individual wire strands

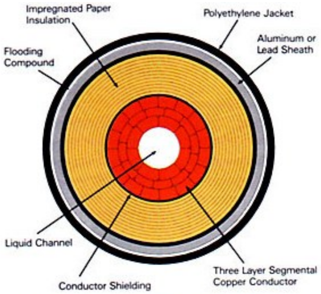
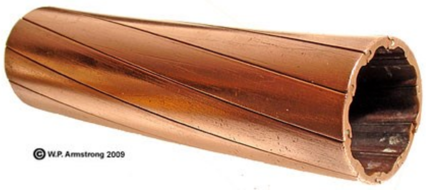


Figure 1: Copper Segmental Conductor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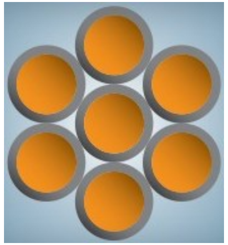


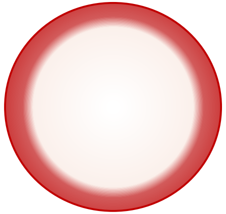
Proximity Effect

Resistance of a cable with AC current: $$R_{ac} = R_{dc} * (1 + Y_s + Y_p)$$

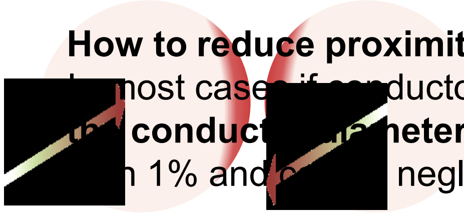
due to proximity effect

How to reduce proximity effect:

In most cases if conductor spacing exceeds **10 times** the **conductor [illegible]meter** p[illegible]ity effec[illegible] be less [illegible]n 1% and c[illegible] neglecte[illegible]

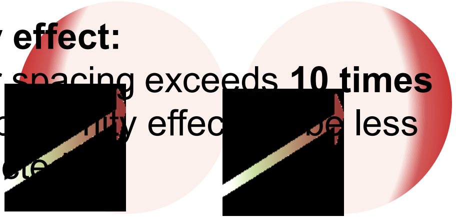


Single conductor carrying AC current



Proximity effect

Conductors carrying current in the opposite direction



Proximity effect

Conductors carrying current in the same direction

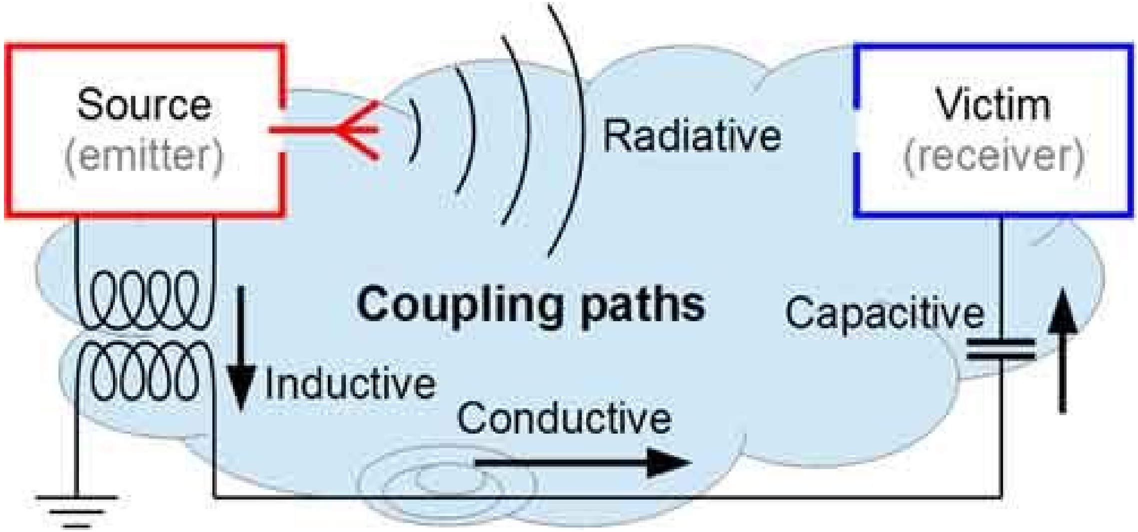
Magnetic Conduit & Length Effect

Resistance of a cable with AC current: $R_{ac} = R_{dc} * (1 + (Y_s + Y_p) * \underbrace{1.7)}_{\text{due to magnetic conduit effect}}$

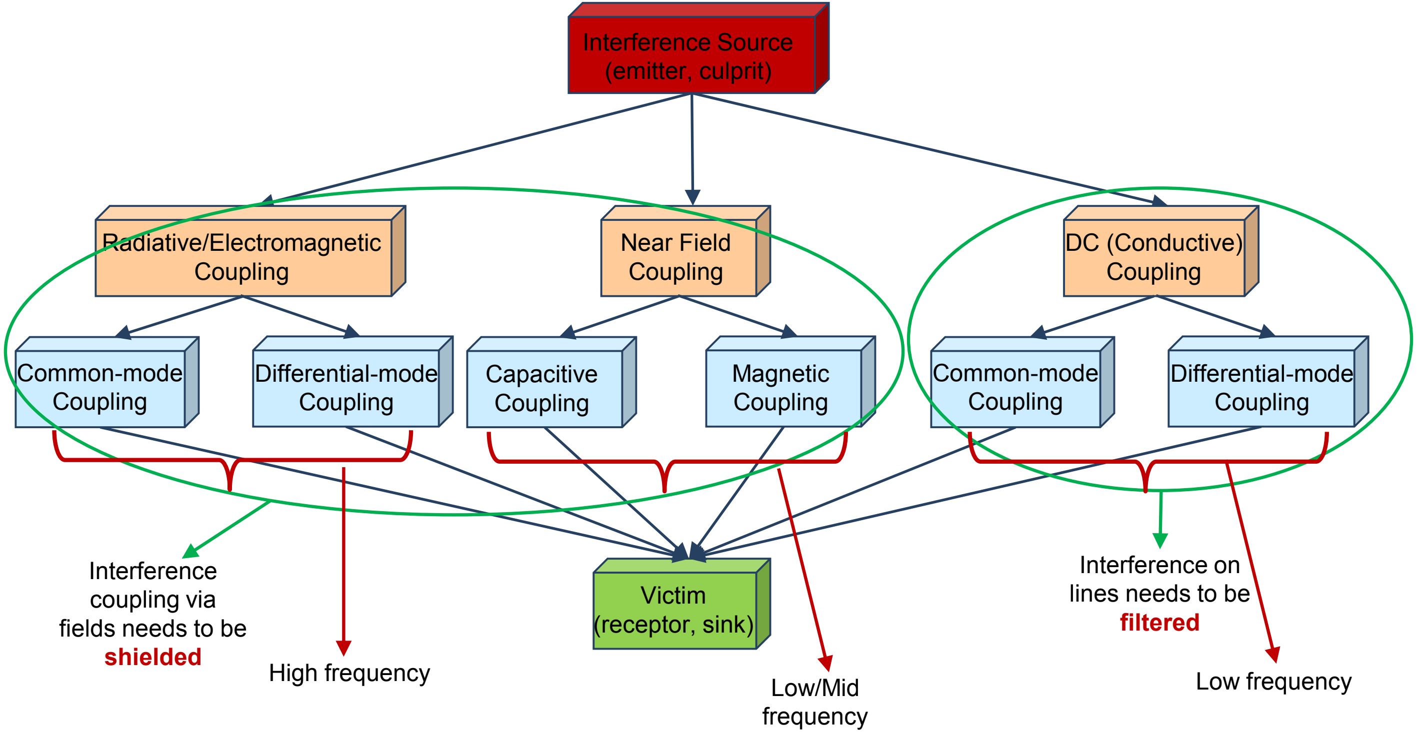
- Operation over long cables introduces distortion and noise which affect frequency response of the cable.
- For signals f < 10 kHz distortion generally is not a problem.
- If f > 10kHz, signal distortion may occur over cables longer than 30 meters.

Coupling Mechanisms

Shielding or Filtering?



Coupling Mechanisms



Interference Source (emitter, culprit)

Radiative/Electromagnetic Coupling

Near Field Coupling

DC (Conductive) Coupling

Common-mode Coupling

Differential-mode Coupling

Capacitive Coupling

Magnetic Coupling

Common-mode Coupling

Differential-mode Coupling

Victim (receptor, sink)

Interference coupling via fields needs to be **shielded**

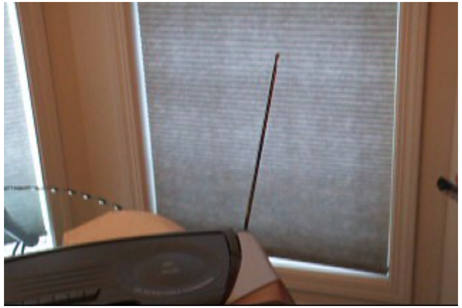
High frequency

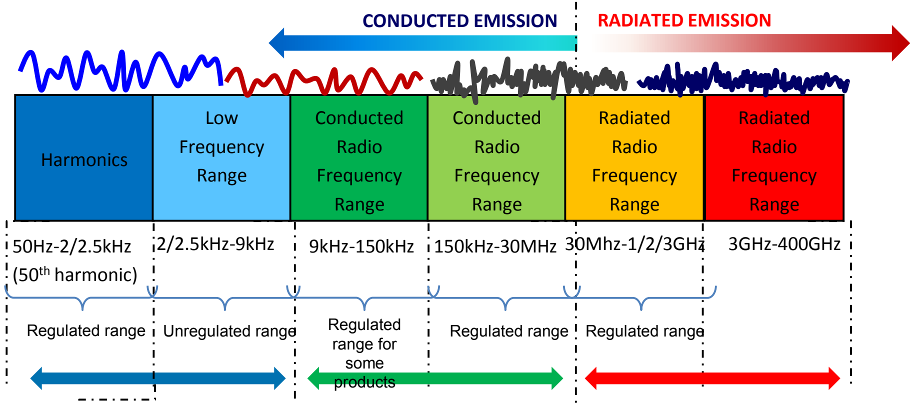
Low/Mid frequency

Interference on lines needs to be **filtered**

Low frequency

Electromagnetic Spectrum





CONDUCTED EMISSION

RADIATED EMISSION

Harmonics	Low Frequency Range	Conducted Radio Frequency Range	Conducted Radio Frequency Range	Radiated Radio Frequency Range	Radiated Radio Frequency Range
50Hz-2/2.5kHz (50th harmonic)	2/2.5kHz-9kHz	9kHz-150kHz	150kHz-30MHz	30Mhz-1/2/3GHz	3GHz-400GHz
Regulated range	Unregulated range	Regulated range for some products	Regulated range	Regulated range	

Conducted Low Frequency Phenomena:

-Harmonics, interharmonics
-Signalling voltages
-Voltage fluctuations
-Voltage dips and interruptions
-Voltage unbalance
-Power-frequency variations
-Induced low-frequency voltages
-DC in AC networks

Radiated Low Frequency Phenomena:

-Magnetic fields
-Electric fields

Conducted High Frequency Phenomena (RF):

-Induced continuous-wave voltages or currents
-Unidirectional transients
-Oscillatory transients

Radiated High Frequency Phenomena:

-Magnetic fields
-Electric fields
-Electromagnetic fields
    -continuous waves
    -transients

COUPLING MECHANISMS

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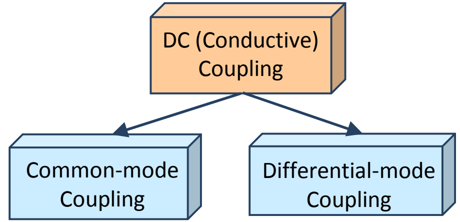
Direct Coupling

- Conductive coupling occurs when the coupling path is formed by direct electrical contact.

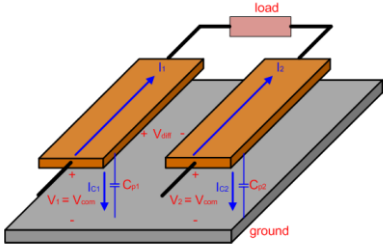


DC (Conductive) Coupling

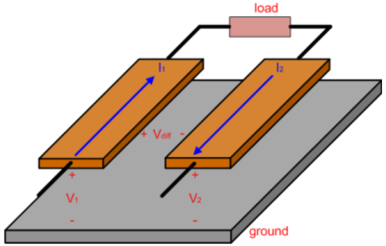
Common-mode Coupling

Differential-mode Coupling

Common Mode



Differential Mode



Disturbance flows via the phase/neutral line to the receiver and via ground back to the source.

$V_1 = V_{com1} \neq 0$
$V_2 = V_{com2} \neq 0$

Pure common mode occurs when;
$V_1 = V_2 = V_{com}$
$V_1 - V_2 = 0$

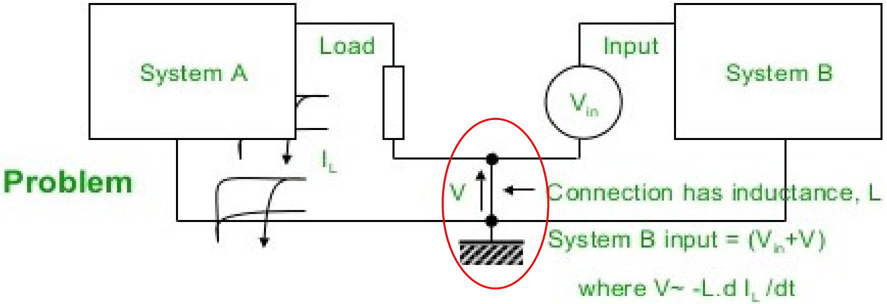
Disturbance flows via the phase line to the receiver and via the neutral line back to the source.

$V_{diff} = V_1 - V_2 \neq 0$

Pure differential mode occurs when;

$V_1 = - V_2$

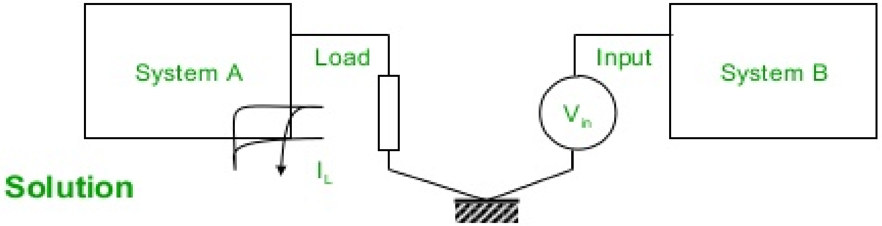
Direct Coupling



Connection has inductance, L

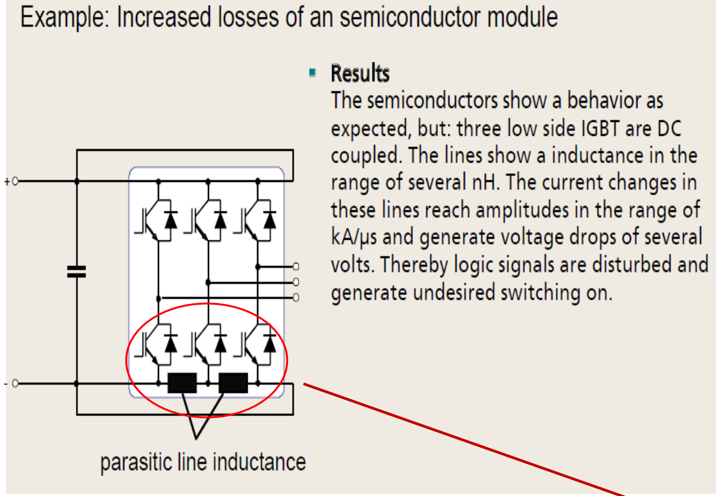
System B input = $(V_{in}+V)$

where $V \sim -L.d\,I_L/dt$



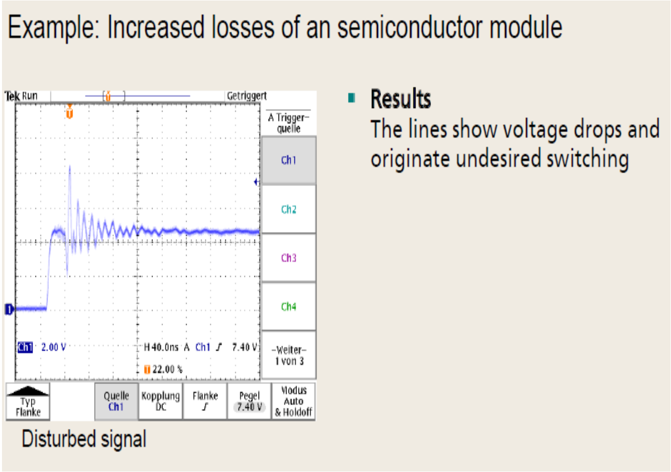
Common mode impedance coupling

Direct Coupling



Example: Increased losses of an semiconductor module

- **Results**
  The semiconductors show a behavior as expected, but: three low side IGBT are DC coupled. The lines show a inductance in the range of several nH. The current changes in these lines reach amplitudes in the range of kA/µs and generate voltage drops of several volts. Thereby logic signals are disturbed and generate undesired switching on.



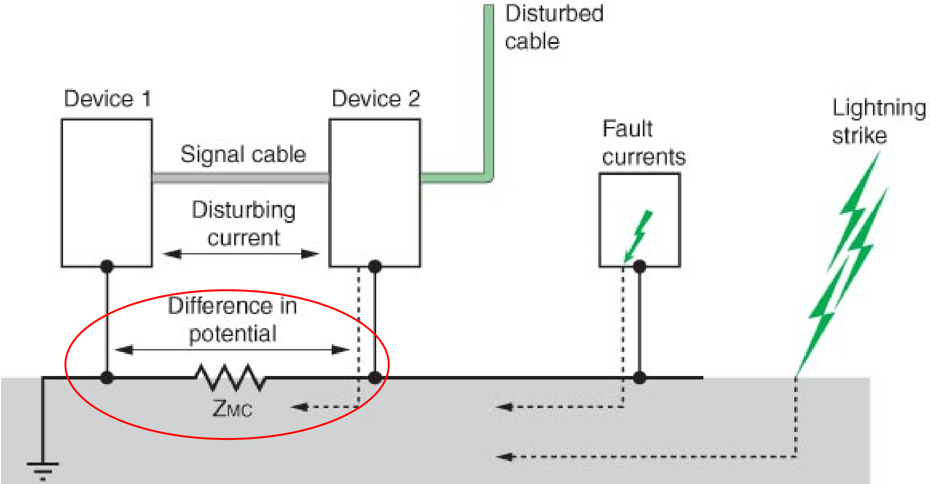
Example: Increased losses of an semiconductor module

- **Results**
  The lines show voltage drops and originate undesired switching

Disturbed signal

Direct Coupling

To reduce the effects of common-mode impedances:
- Mesh the common references,
- Use short cables or flat braids which, for equal sizes, have a lower impedance than round cables,
- Install functional equipotential bonding between devices.



•Reduce the level of the disturbing currents by adding common-mode filtering and differential-mode inductors

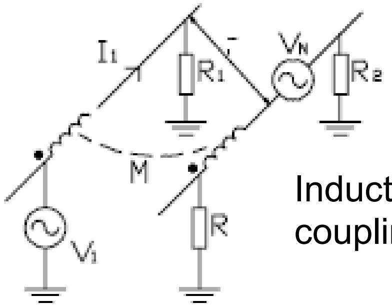
Reducing Inductive Coupling

- Reduce mutual inductance between circuits
  - Use twisted pairs signal cables **(A)**
  - Increase the distance between conductors **(r)**
  - Reduce the loop area by galvanic isolation **(A)**
  - Avoid parallel conductors and coils

- Reduce the switching frequency **(f)**

- Reduce current of the interfering circuit **(I)**

- Careful routing of wiring **(A)**



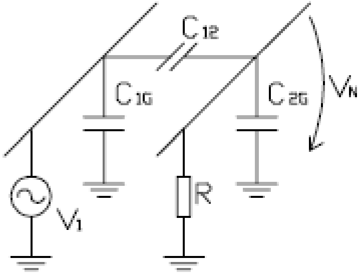
Inductive coupling

$$V_N = j2\pi f \times M_{12} \times I_1$$

$$M_{12} = \mu \times A\cos\theta / 2\pi r$$

Reducing Capacitive Coupling

- Reduce level of high dv/dt noise sources
- Use proper grounding schemes for cable shields
- Use grounded conductive faraday shields to protect against electric fields
- Reduce impedance level of the victim circuit
- Reduce stray capacitance
  - Keep traces short
  - Increase distance between conductors
  - Use metal cases, provide lower impedance discharge through metal planes
  - Use ground plane between conductors
  - Embed non-sensitive signal in between critical signal
  - Use shielded conductors
  - Reduce signal impedance so that only very high frequency noise is coupled



Capacitive coupling

$$V_N = j2\pi f \times V_1 \times C_{12} \times R$$

$$Z = \frac{1}{2\pi Cf}$$

DESIGN PROCESS

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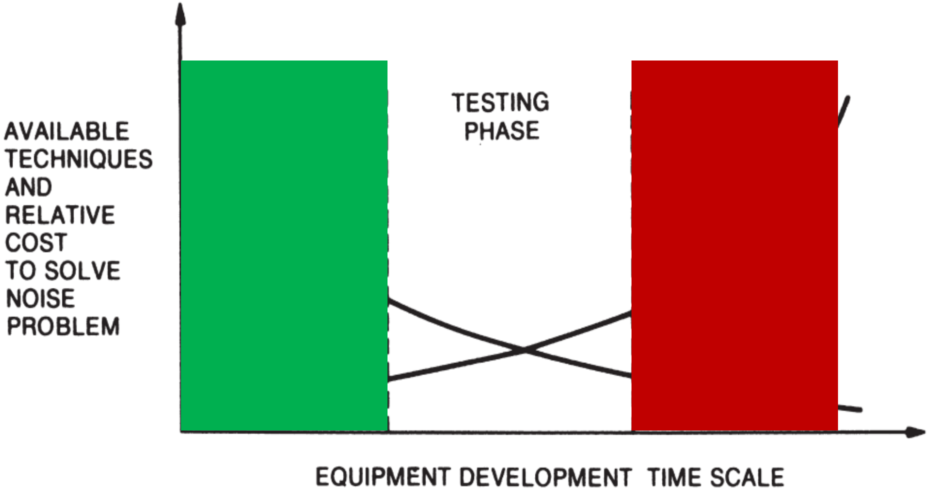
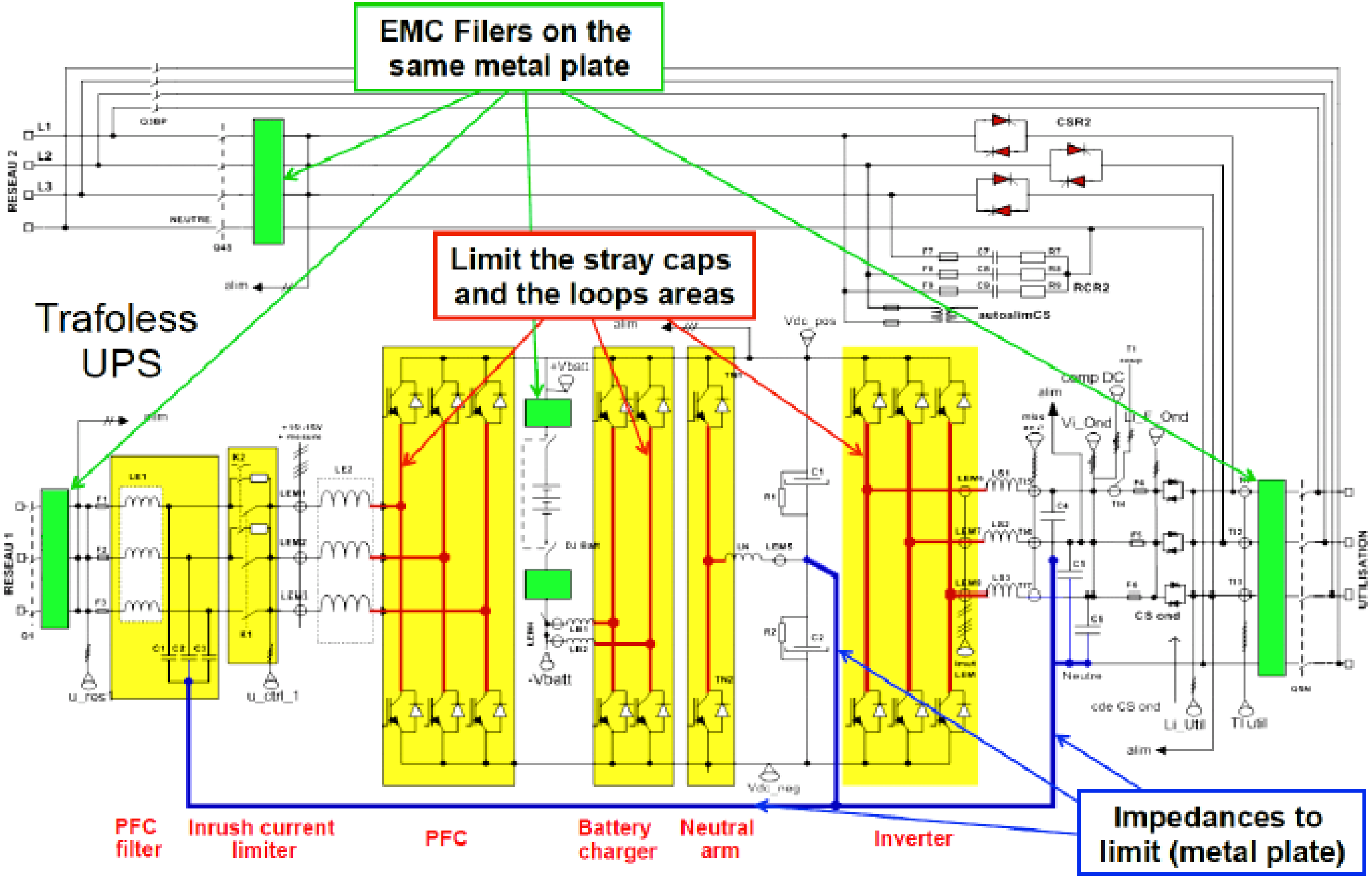
Design Process

EMC can be approached in two very different ways:

Crisis Management : Design your stuff with total disregard of EMC, see how it works, fix problems with add-ons if needed (and if possible!!!) ✓

System Design : Consider EMC right from the beginning. Then it will be designed into instead of added onto the product. ✓





EMC Filers on the same metal plate

Limit the stray caps and the loops areas

Trafoless UPS

PFC filter

Inrush current limiter

PFC

Battery charger

Neutral arm

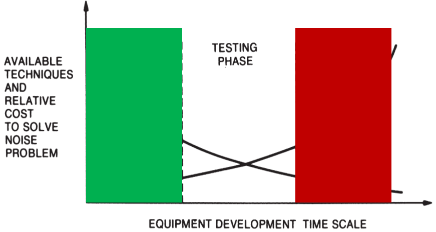
Inverter

Impedances to limit (metal plate)

Fig. 11: Example of UPS schematic diagram

Design Process

EMC Design Flow Diagram



- Identify system requirements & installation environment, etc.
- Describe EMC requirements, review contract & recommendations

Pre-study

- Develop an EMC control plan
  - Interference prediction (identify source/victims, use zone concept, make installation plan, equipotential bonding, collect best practices, etc.)
  - Design testing
  - Electrical and mechanical design reviews
  - Amend the EMC control plan, as necessary

Design

- Liaison with manufacturing
- In-process inspection during manufacturing

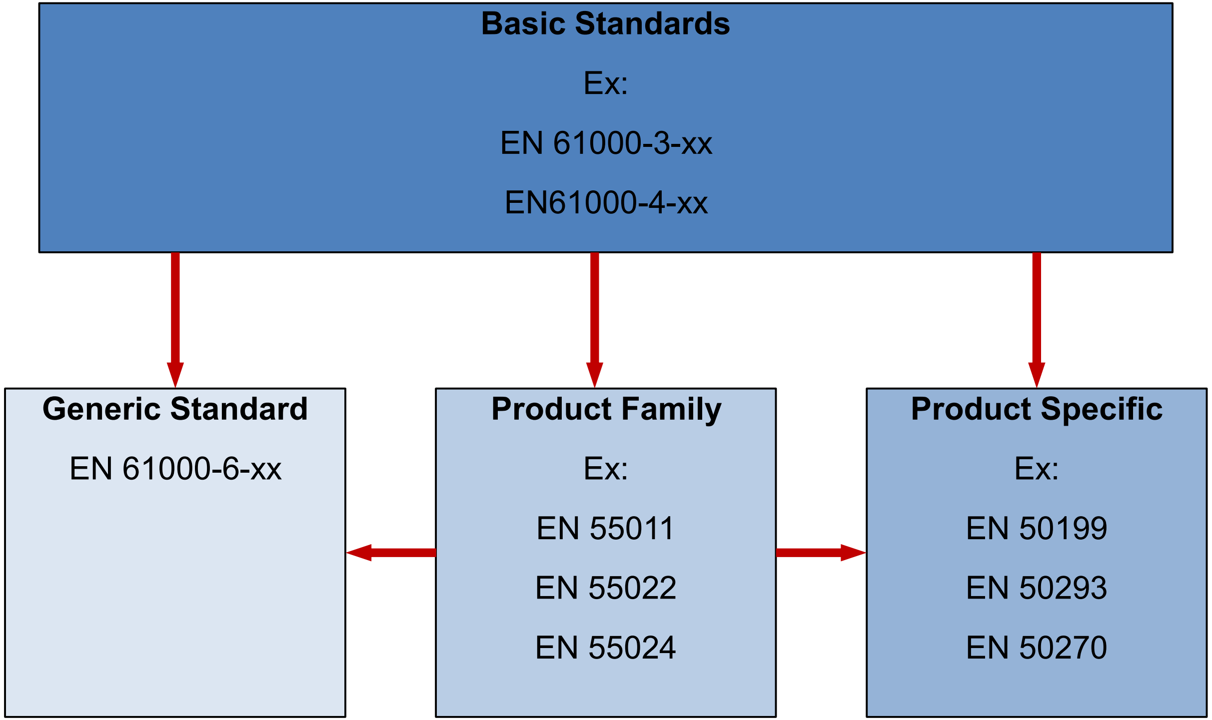
Manufacture

- Performance of EMC qualification tests
- Redesign and retest where necessary
- Preparation and submittal of EMC test report or declaration

Test

STEP 1: Identify the Requirements

a). Standards, customer requirements, environment, etc.



Basic Standards

Ex:

EN 61000-3-xx

EN61000-4-xx

Generic Standard

EN 61000-6-xx

Product Family

Ex:

EN 55011

EN 55022

EN 55024

Product Specific

Ex:

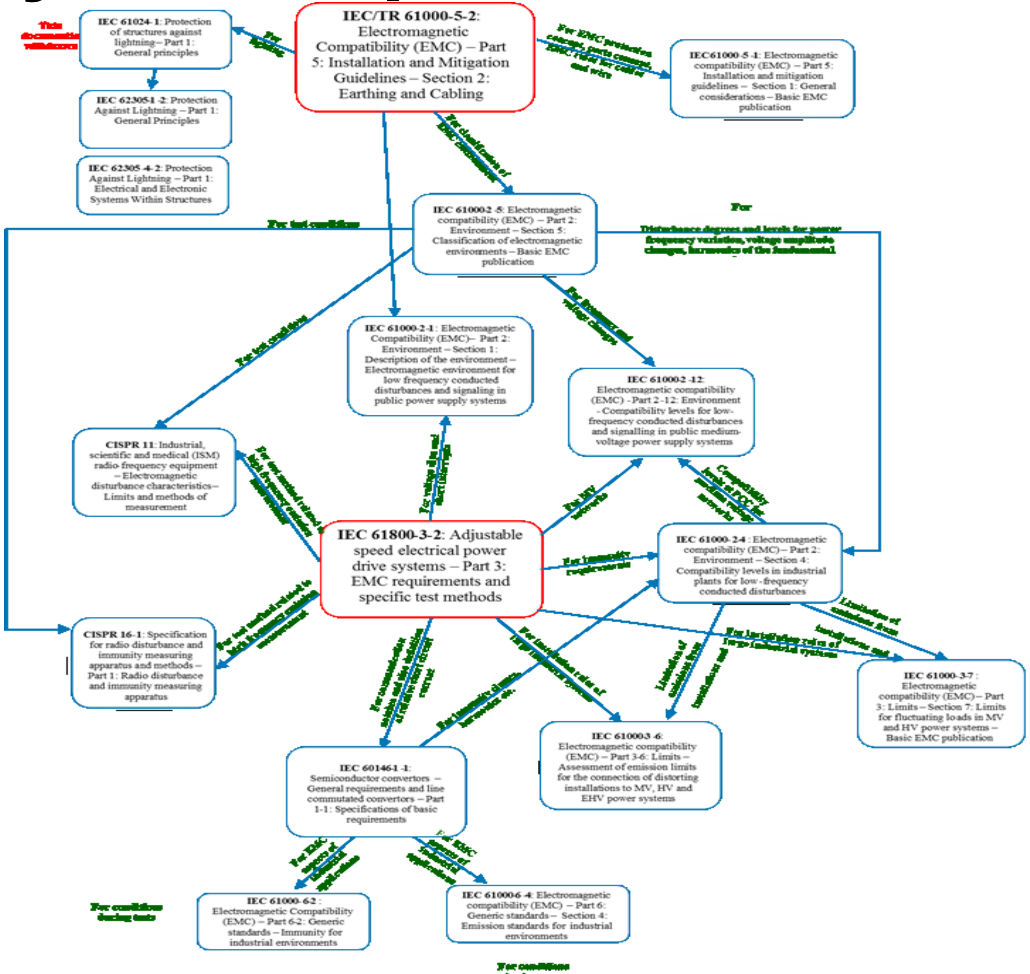
EN 50199

EN 50293

EN 50270

STEP 1: Identify the Requirements

a). Standards, customer requirements, environment, etc.



IEC/TR 61000-5-2: Electromagnetic Compatibility (EMC) – Part 5: Installation and Mitigation Guidelines – Section 2: Earthing and Cabling

IEC 61024-1: Protection of structures against lightning – Part 1: General principles

IEC 62305-1-2: Protection Against Lightning – Part 1: General Principles

IEC 62305-4-2: Protection Against Lightning – Part 1: Electrical and Electronic Systems Within Structures

IEC61000-5-1: Electromagnetic compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 1: General considerations – Basic EMC publication

IEC 61000-2-5: Electromagnetic compatibility (EMC) – Part 2: Environment – Section 5: Classification of electromagnetic environments – Basic EMC publication

IEC 61000-2-1: Electromagnetic Compatibility (EMC)– Part 2: Environment – Section 1: Description of the environment – Electromagnetic environment for low frequency conducted disturbances and signaling in public power supply systems

IEC 61000-2-12: Electromagnetic compatibility (EMC) - Part 2-12: Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public medium-voltage power supply systems

CISPR 11: Industrial, scientific and medical (ISM) radio-frequency equipment – Electromagnetic disturbance characteristics – Limits and methods of measurement

IEC 61800-3-2: Adjustable speed electrical power drive systems – Part 3: EMC requirements and specific test methods

IEC 61000-2-4: Electromagnetic compatibility (EMC) – Part 2: Environment – Section 4: Compatibility levels in industrial plants for low-frequency conducted disturbances

CISPR 16-1: Specification for radio disturbance and immunity measuring apparatus and methods – Part 1: Radio disturbance and immunity measuring apparatus

IEC 61000-3-7: Electromagnetic compatibility (EMC) – Part 3: Limits – Section 7: Limits for fluctuating loads in MV and HV power systems – Basic EMC publication

IEC 61000-3-6: Electromagnetic compatibility (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems

IEC 60146-1-1: Semiconductor convertors – General requirements and line commutated convertors – Part 1-1: Specifications of basic requirements

IEC 61000-6-2: Electromagnetic Compatibility (EMC) – Part 6-2: Generic standards – Immunity for industrial environments

IEC 61000-6-4: Electromagnetic compatibility (EMC) – Part 6: Generic standards – Section 4: Emission standards for industrial environments

STEP 1: Identify the Requirements

b). System category

Power System Categories – IEC 61800-3-2

Category C1: Converter system of rated voltage less than 1kV, intended for use in the first environment (ex. household products).

Category C2: Converter system of rated voltage less than 1kV, which is neither a plug in device nor a movable device and, when used in the first environment, is intended to be installed and commissioned only by a professional (ex. UPS for offices).

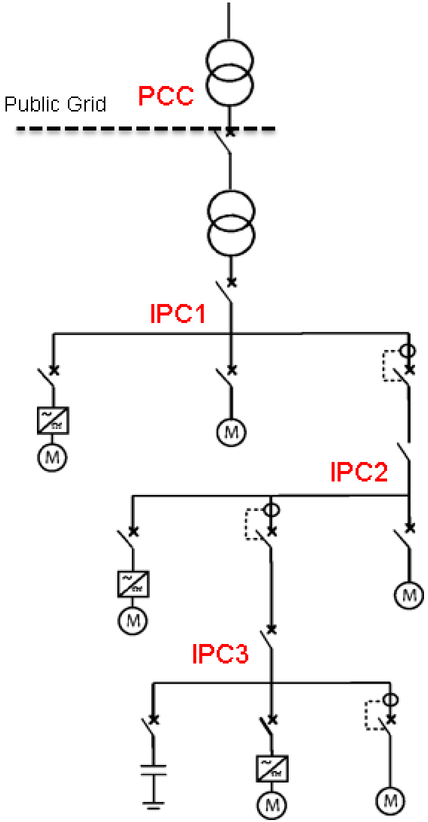
Category C3: Converter system of rated voltage less than 1kV, intended for use in the second environment and not intended for use in the first environment (ex. low voltage STATCOM).

Category C4: Converter system of rated voltage equal to or above 1kV, or rated current equal to or above 400A, or intended for use in complex systems in the second environment.

ref: ABB

STEP 1: Identify the Requirements

c). Electromagnetic classes



PCC: Point of common coupling
IPC Internal point of coupling

Electromagnetic Classes – IEC 61000-2-4

CLASS	DESCRIPTION	THDv (%)
CLASS 1	This class applies to protected feeders and has compatibility levels that are lower than the level of the public supply system. It is related to the use of the equipment very sensible to the supply distribution distortions, as the electric instruments of technological laboratories, some kind of automatic equipment and protection equipment, some computers, etc.	5%
CLASS 2	This class applies generally to **PCCs** and to **IPCs** in the environments of industrial and other non-public power supplies. The compatibility levels of this class are generally identical to those of public networks. Therefore, components designed for supply from public networks may be used in this class of industrial environment.	8%
CLASS 3	This class applies only to **IPCs in industrial environments**. It has higher compatibility levels for some disturbance variables than Class 2. For example, this class should be considered when one of the following conditions applies: • The main part of the load is supplied via converters; • Welding machines are used; • Large motors are started frequently; • Loads vary quickly	10%

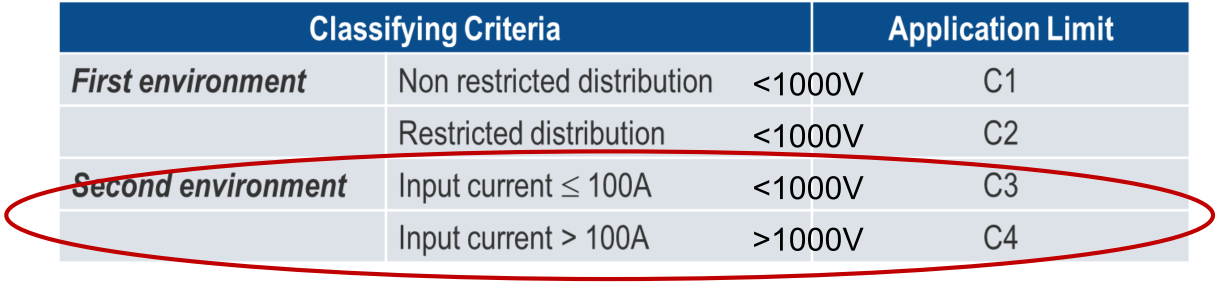
STEP 1: Identify the Requirements

d). Environment classes

Environment Classes – IEC 61800-3-2

First Environment includes domestic premises. It also includes establishments directly connected without intermediate transformer to a low-voltage power supply network which supplies buildings used for domestic purposes.

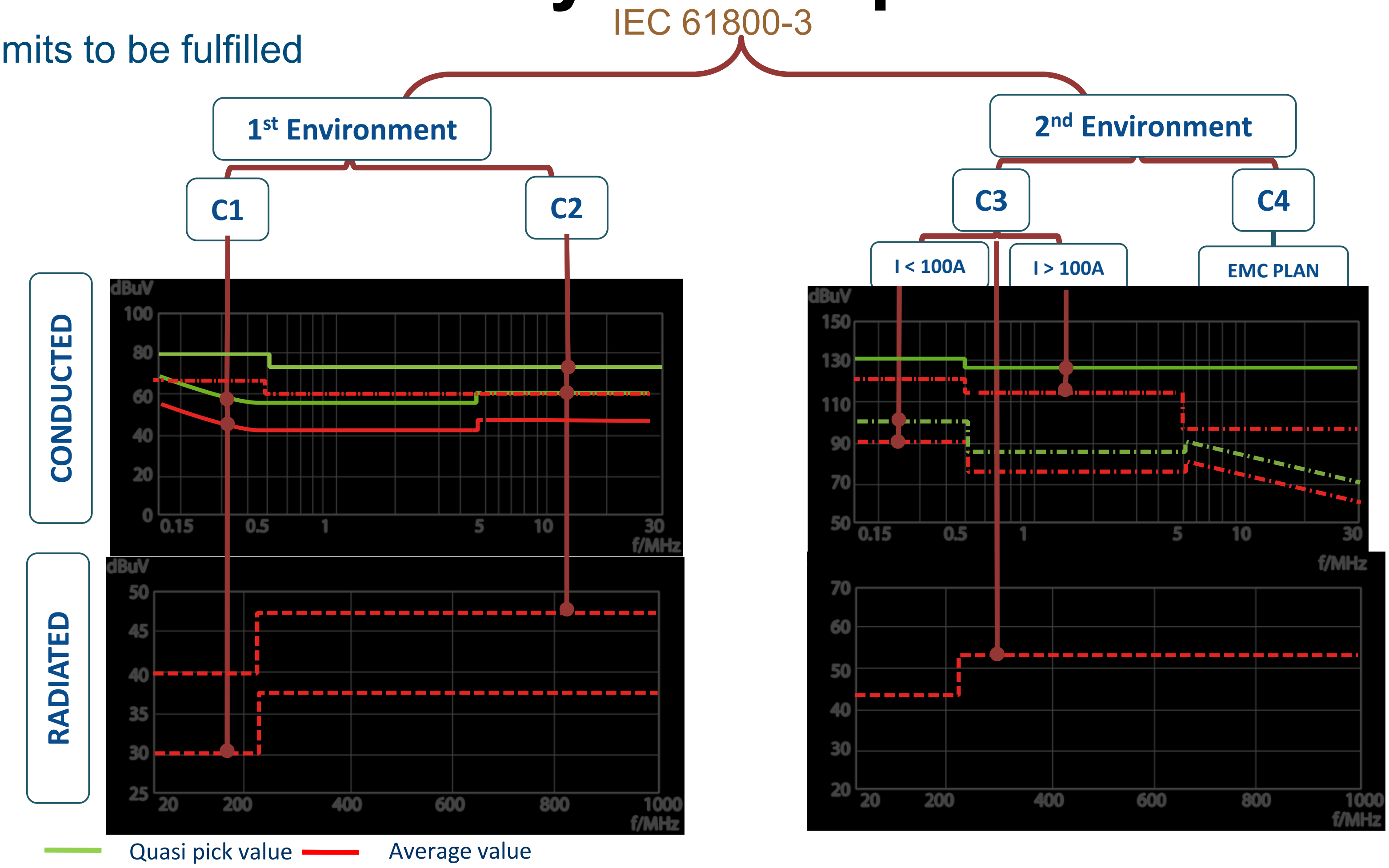
Second Environment includes all establishments other than those directly connected to a low voltage power supply network which supplies buildings used for domestic purposes.



Classifying Criteria			Application Limit
First environment	Non restricted distribution	<1000V	C1
	Restricted distribution	<1000V	C2
Second environment	Input current ≤ 100A	<1000V	C3
	Input current > 100A	>1000V	C4

STEP 1: Identify the Requirements

e). Limits to be fulfilled

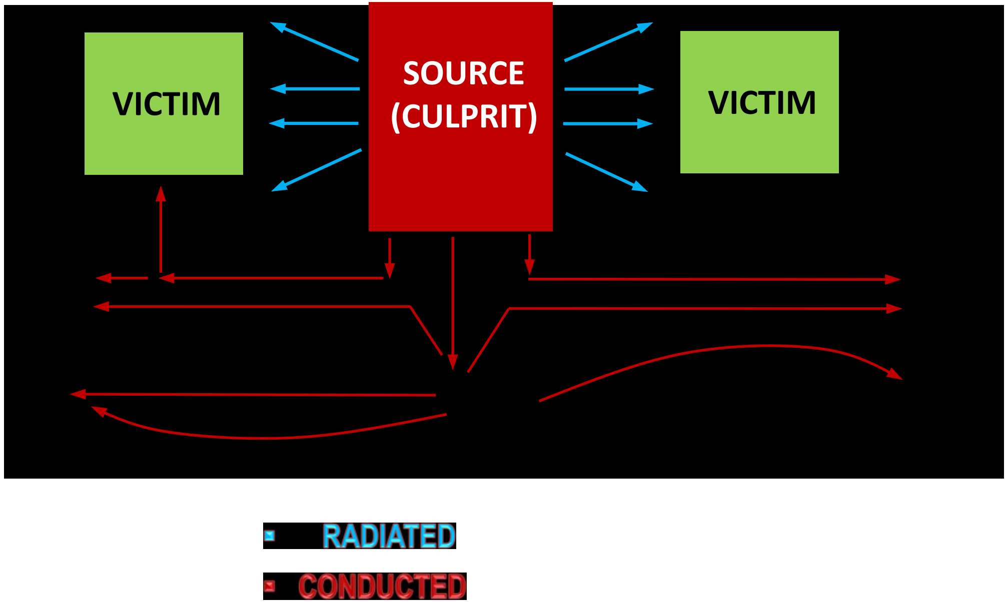


IEC 61800-3

- 1st Environment
  - C1
  - C2
- 2nd Environment
  - C3
    - I < 100A
    - I > 100A
  - C4
    - EMC PLAN

STEP 2: Change Noise Characteristics at „Source“

System has to deal with two kind of emissions:



STEP 2: Change Noise Characteristics at „Source“

- ✓ Decrease high di/dt current → I ↙
- ✓ Slow down switching action → f ↙
- ✓ Reduce high frequency path enclosed area → A ↙
- ✓ Minimize stray inductance in the power path

$$\boxed{E \propto \underset{\swarrow}{f^{2}} \cdot \underset{\nearrow}{\frac{1}{r}} \cdot \underset{\swarrow}{I} \cdot \underset{\swarrow}{\mathrm{A}}}$$

Ref: http://incompliancemag.com

STEP 2: Change Noise Characteristics at „Source"

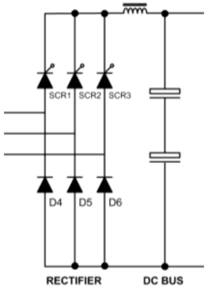
a). Topology

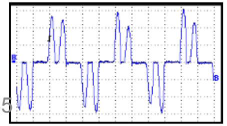
- ✓ Decrease high di/dt current
- ✓ Slow down switching action
- ✓ Reduce high frequency path enclosed area
- ✓ Minimize stray inductance in the power path!!!

$$E \propto f^2 \cdot \frac{1}{r} \cdot I \cdot A$$

DC CHOKES

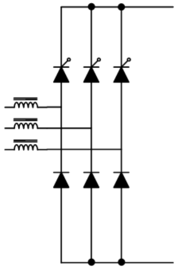
THDi ≈ 40%

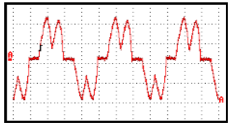




CHOKES 3%

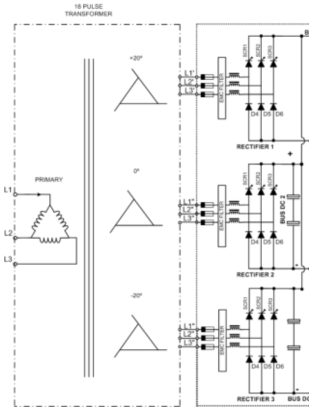
THDi <35%

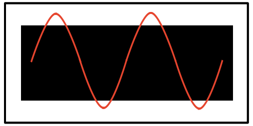




MULTIPULSE

THDi <15%

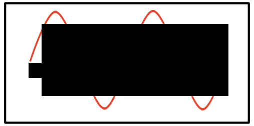




NOTCH FILTER

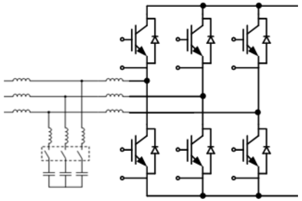
THDi <5%

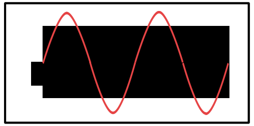
[redacted]



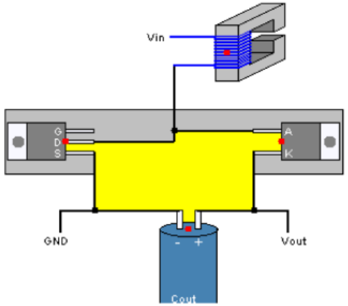
AFE

THDi <4%

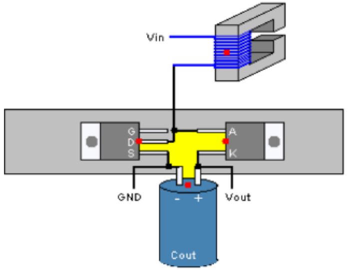




STEP 3: Reduce Switching Path Enclosed Area

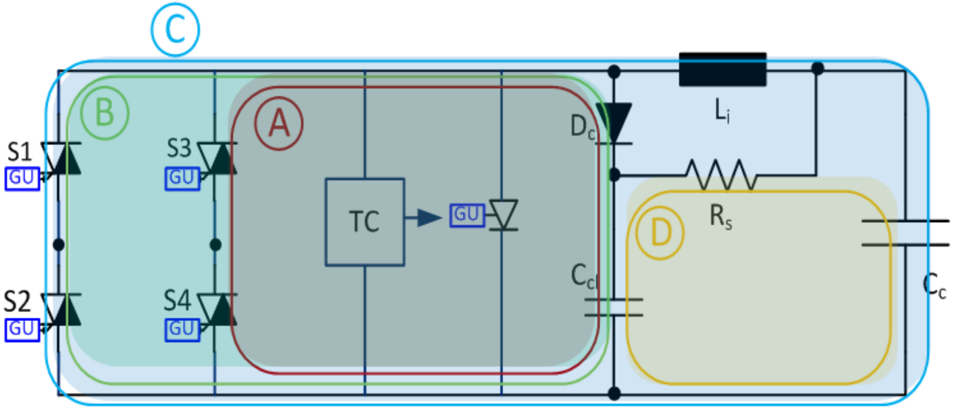


Overvoltage 75%

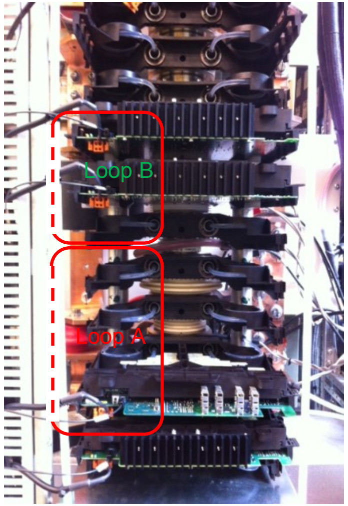


Overvoltage 32%

$$\boxed{E \propto f^2 \cdot \frac{1}{r} \cdot I \cdot A}$$



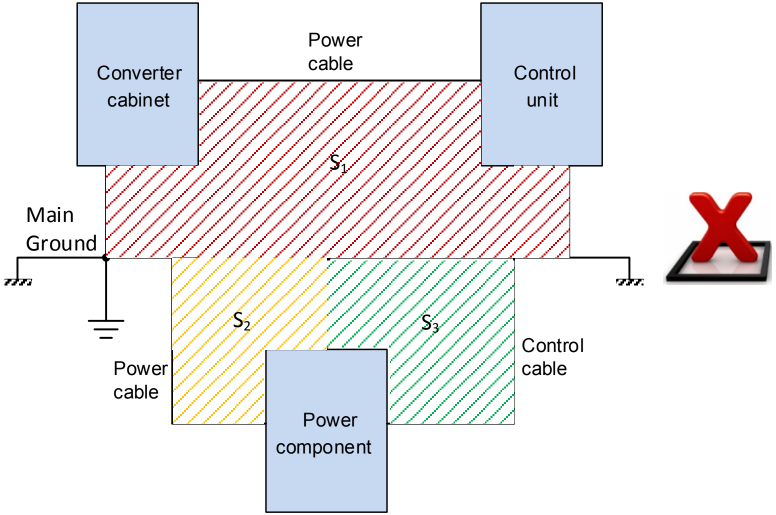
○ circuit inductance

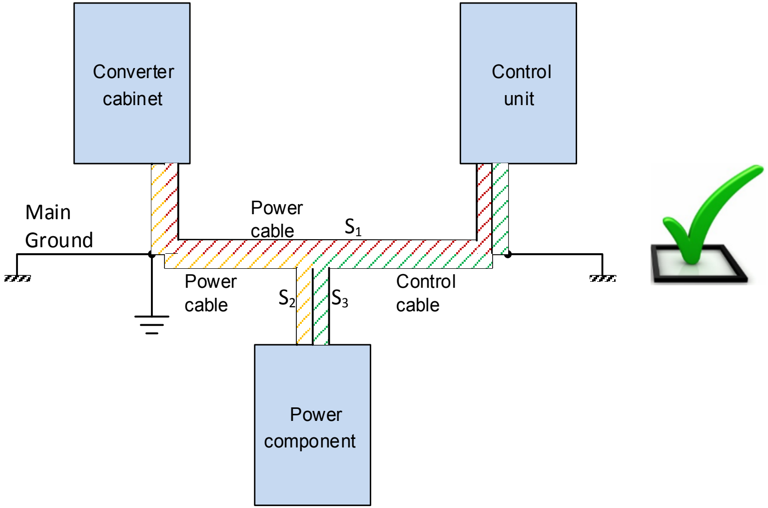


ref: ABB

STEP 3: Reduce Switching Path Enclosed Area

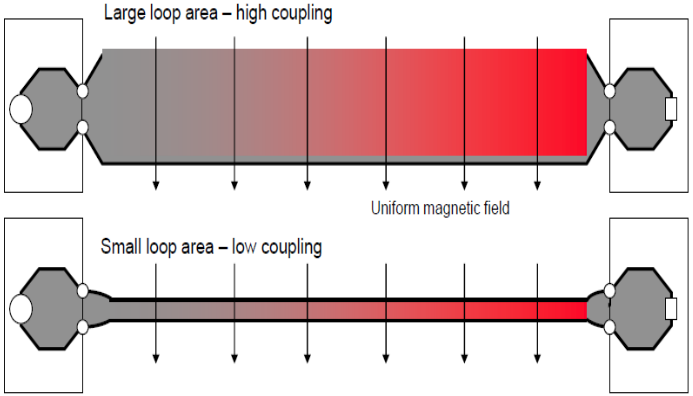
$$\boxed{E \propto f^2 \cdot \frac{1}{r} \cdot I \cdot A}$$

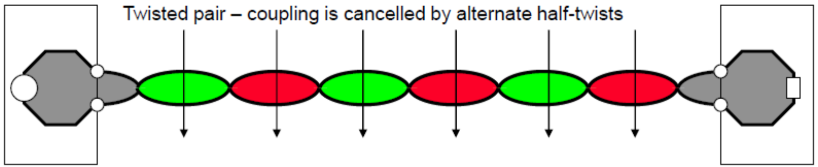




STEP 3: Reduce Switching Path Enclosed Area

$$\boxed{E \propto f^2 \cdot \frac{1}{r} \cdot I \cdot A}$$



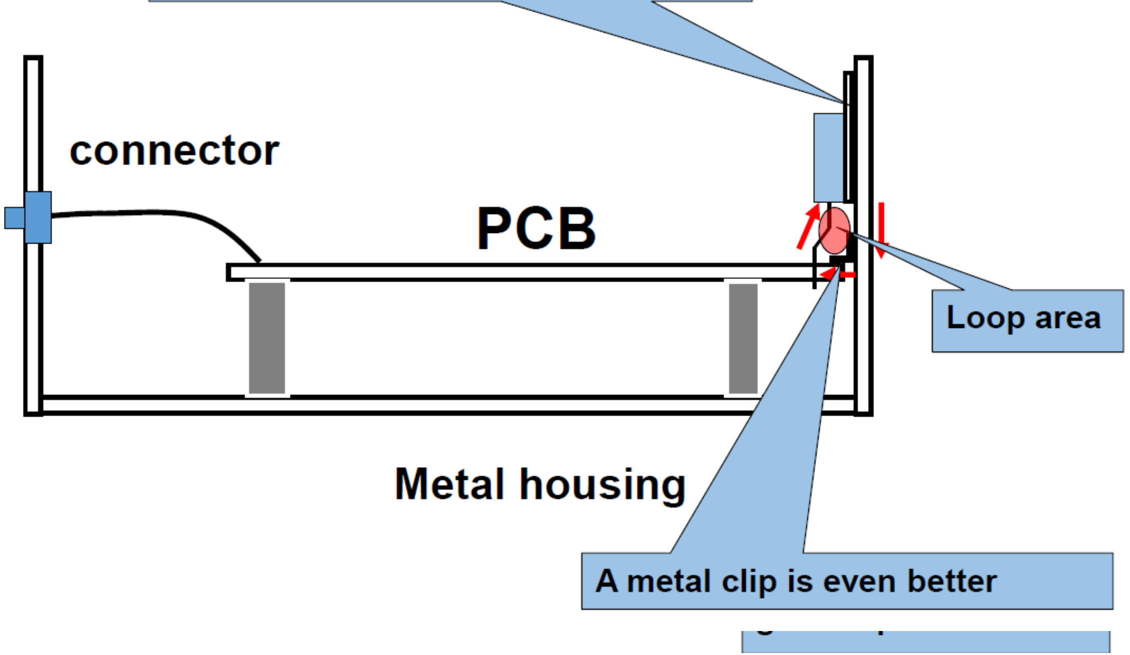


STEP 3: Reduce Switching Path Enclosed Area

$$E \propto f^2 \cdot \frac{1}{r} \cdot I \cdot A$$

Example 2

Parasitic capacitor (insulation between heat sink and housing)

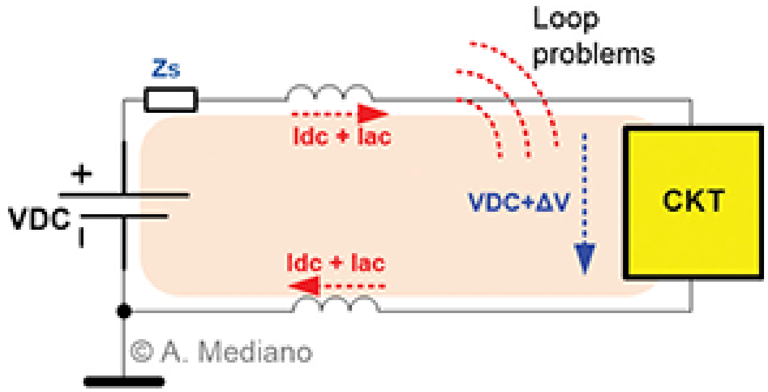


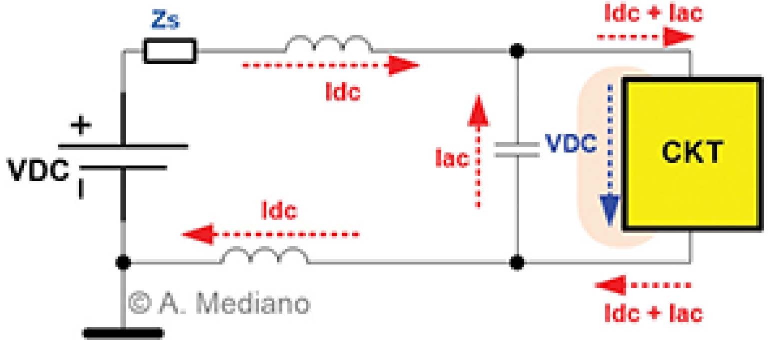
Loop area

A metal clip is even better

Ref: “*Common mode current currents in power devices: do you know where they flow?* “, Lex de Rijck, ECPE´17

STEP 3: Reduce Switching Path Enclosed Area





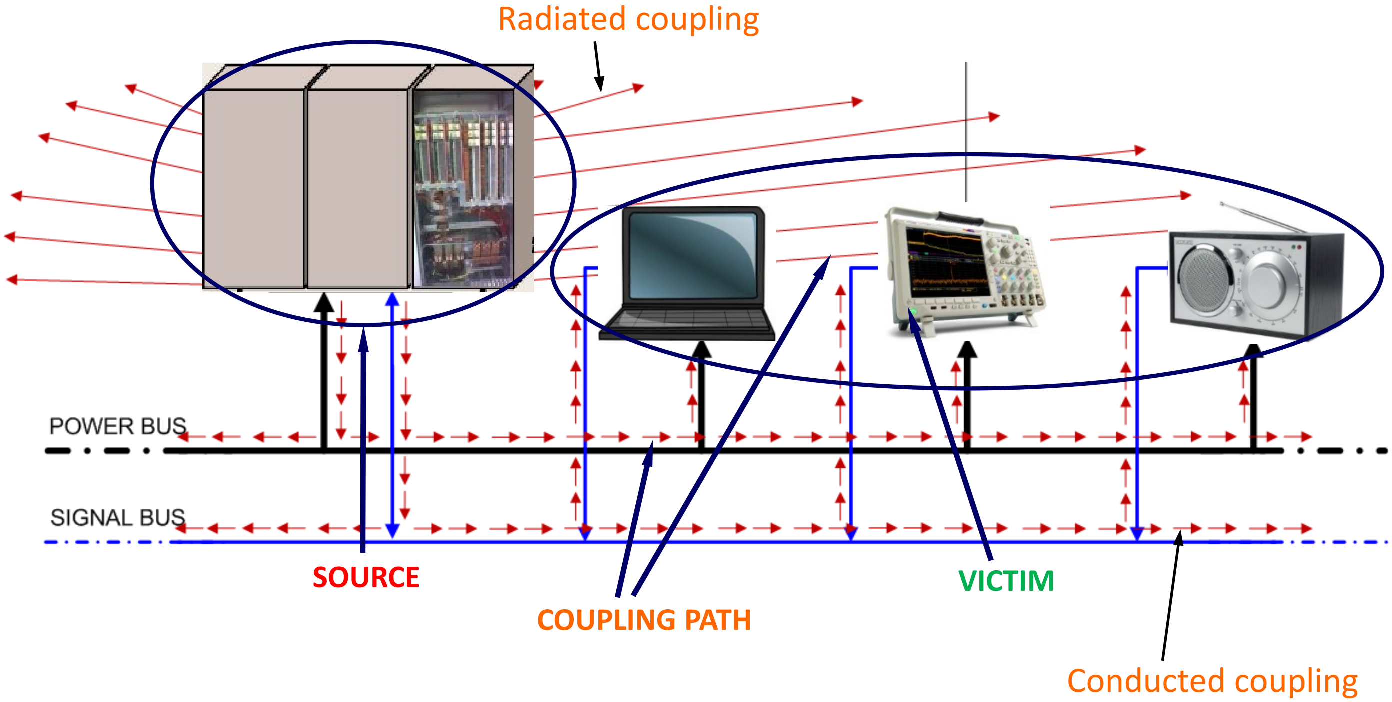
A simple capacitor (100nF) has traditionally been an effective solution for the frequency range below 30-50MHz to decouple the circuits but for higher frequencies it gets more complex.

Ref: http://incompliancemag.com/article/using-capacitors-in-parallel-dangerous

STEP 4: Zoning

a). Sources, victims, coupling paths?

Define the culprits (sources), victims (sensitive circuits) and possible coupling paths.



STEP 4: Zoning

b). Group components depending on their ZONES

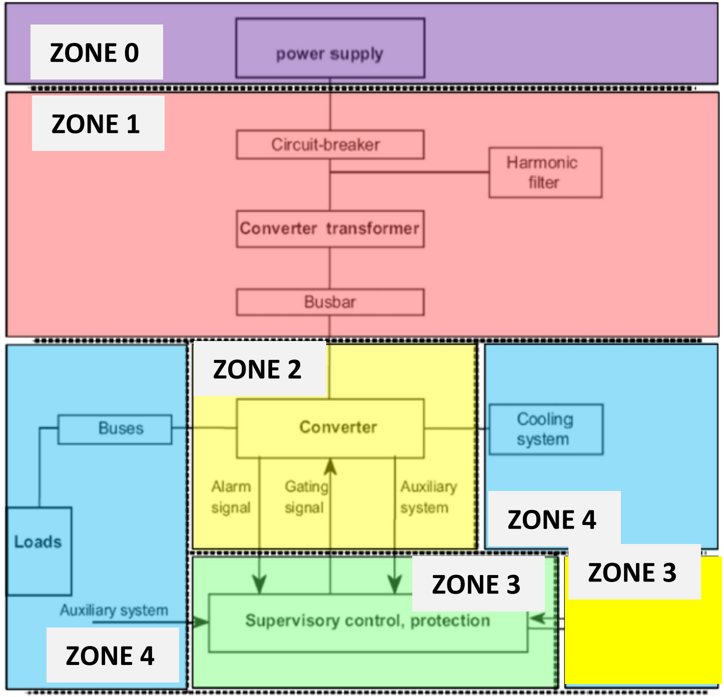
Zone 0: HV transformer, disconnectors, circuit breakers, busbars etc. belong to Zone 0.

Zone 1: MV transformer, disconnectors, auxiliary power supply transformers (if connected to MV), cables/busbars, filters etc. belong to Zone 1.

Zone 2: The environment with the highest pollution from electromagnetic interference is located in this section in which the converter is also placed itself.

Zone 3: Processors and low voltage components that are operated at high frequency and/or sensitive to conducted or transmitted EM fields. It shall be designed as far as possible as a Faraday cage and special attention is required for the incoming and outgoing lines of this zone.

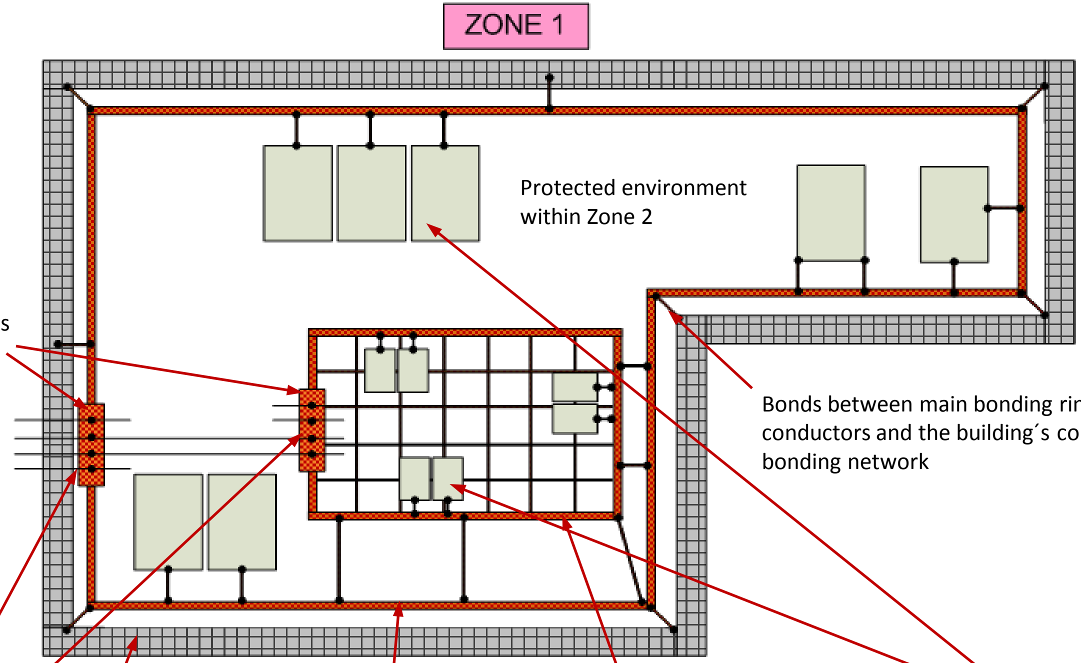
Zone 4: Cooling system, loads, etc. belong to this zone.



Ref: IEC 61800-3

STEP 4: Zoning

c). Prepare grounding layout for each zone



Protected environment within Zone 2

Main earthing terminals

All metallic services and shieldings are bonded to the main earthing terminals when entering to a new zone

Bonds between main bonding ring conductors and the building´s common bonding network

Walls

Electrical or electronics equipment

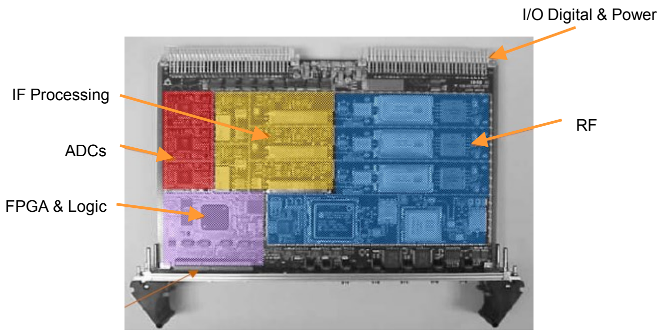
All the cables entering to a different zone should be electrically bonded at the zone´s boundary

Bonding ring conductor surrounds zones that do not use a seamless metal shield

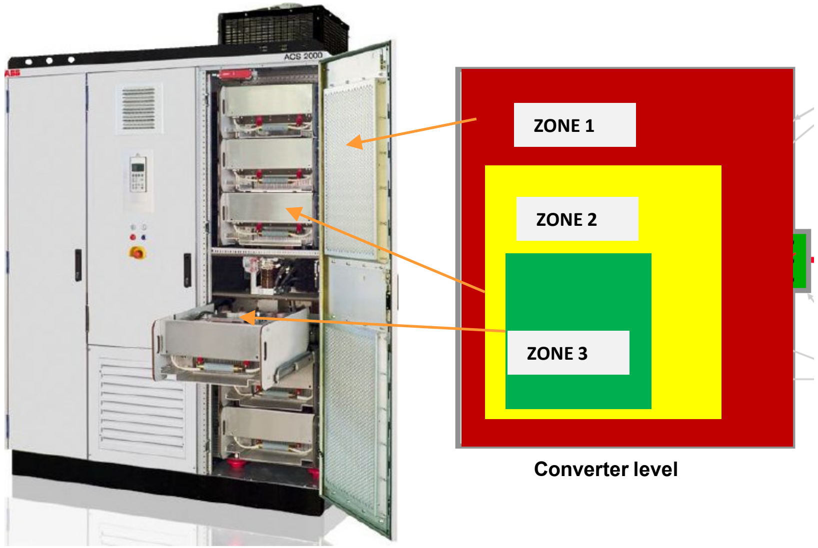
Bonding ring conductors for the segregated area (for sensive components)

STEP 4: Zoning

d). Place the ZONES accordingly



PCB level



Converter level

STEP 5: Cabling

a). Classify the cables

Cable classes:

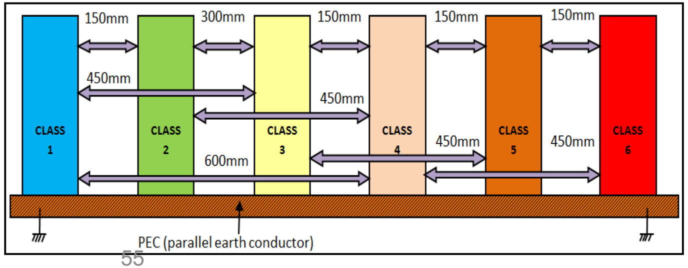
Class ① Very sensitive signal and data cables. High quality twisted pair cables with 360° shielding are required.

Class ② Slightly sensitive signals (4-20mA or 0-10V), analogue signals, low rate digital signals (RS422, RS485). 230/415V can also be treated as Class 2 inside an enclosure, after it has been filtered in the cabinet.

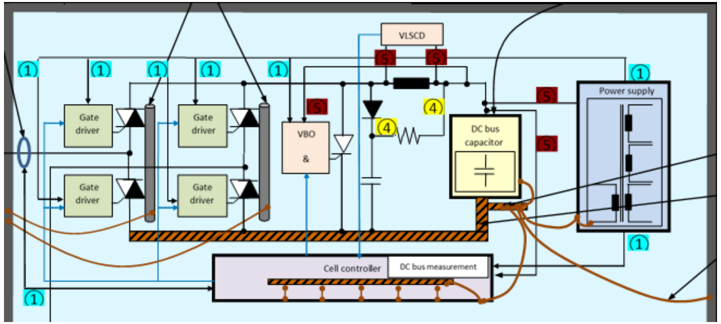
Class ③ Slightly interfering cables, AC cables (230/415V), DC cables, control circuits with resistive and inductice loads. They can be shielded, twisted cables highly required. Screw terminals are allowed as long as the exposed conductors are less than 30mm long.

Class ④ Power cables with a high noise level (e.g. motor cables, welding equipment etc.) with U > 230 V. ..1 kV. Pigtails are not allowed. The conductors should be twisted. Relays solenoids, contactors, etc. may use unshielded twisted pairs only if they operate infrequently (t >> 5min).

Class ⑤ Class ⑤ Medium-voltage and high voltage cables with U > 1 kV. These cables are more exposed to external disturbances (lightning, powerful surges, transients etc.)

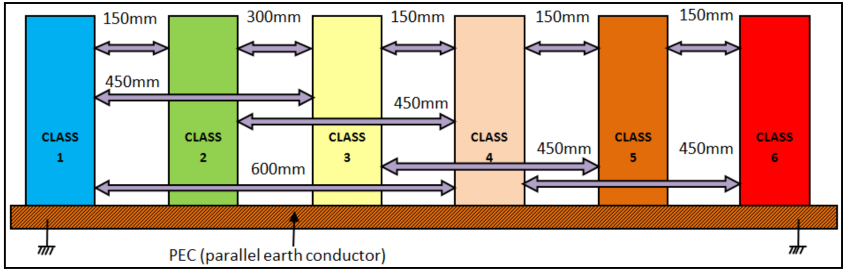


*where the cable are not shielded an L > 30m



STEP 5: Cabling

b). Separate the cables



Larger spacing may sometimes be required for classes 5 and 6 for insulation purposes, or for preventing damaging flash-overs during fault conditions.

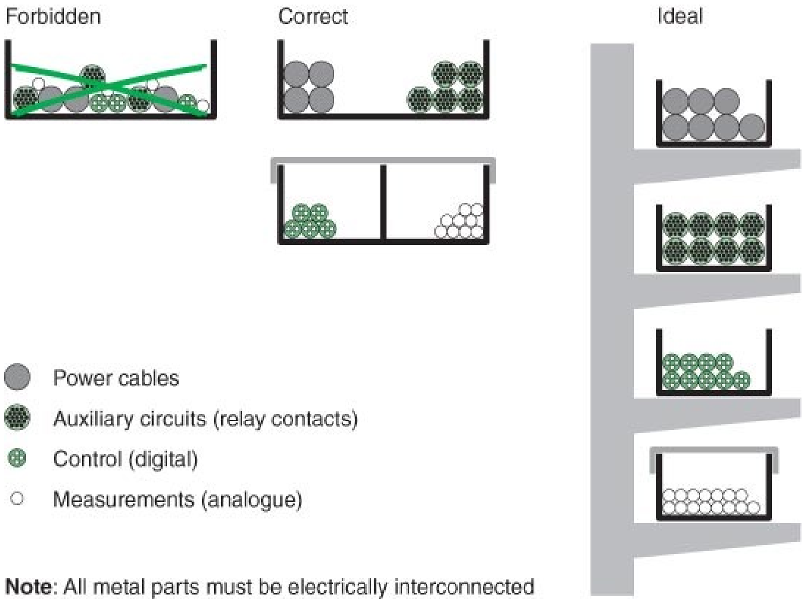
Cable list and cable deails

Use	Class	Minimum distance between neighbor cable (or busbar)	Shield	Shield connection	Installation type
Current transducer cables	1	1-4 → 40mm 1-5 → 50mm	yes	Connected to cell controller's minus potential from cell controller's side, the other side is floating	Same grounding potential with the cell
Busbars inside the converter	5	5-1 → 50mm 5-4 → 10mm	no	-	Insulated, no direct contact with grounded metal parts
24Vdc and 48Vdc auxiliary cables	1	1-3 → 240mm	yes	Cable shield will be connected to ground on both sides	From converter base frame side it will be connected base frame common grounding busbar. On the controller side it will be connected to the common grounding busbar in the frame. Needs 360° shielding connection.

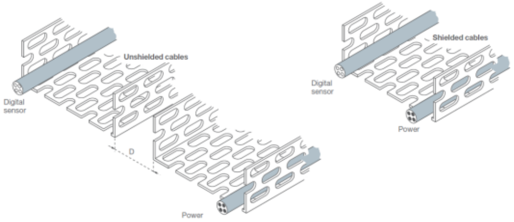
STEP 5: Cabling

b). Separate the cables

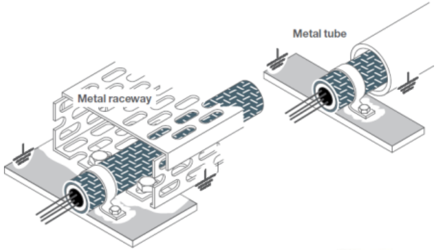
- Cables on the same class may be bundled.
- If there is no PEC, spacing between classes of **at least ten times the diameter of the larger bundle** (l > 10 x d) is required.
- When the cable is too close to the EMI source the shield should be bonded several times or capacitors can be used instead of direct bonds.



Note: All metal parts must be electrically interconnected

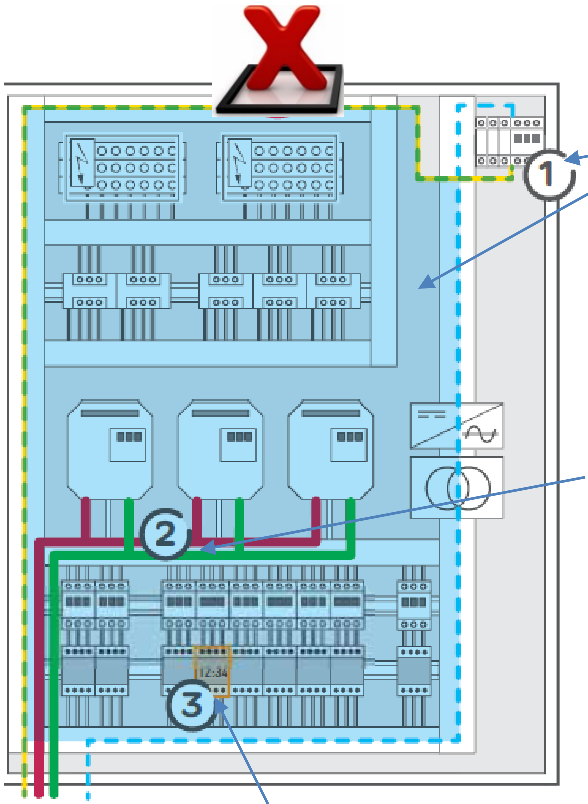


separate raceways if the cables are unshielded (D > 5 cm)



STEP 5: Cabling

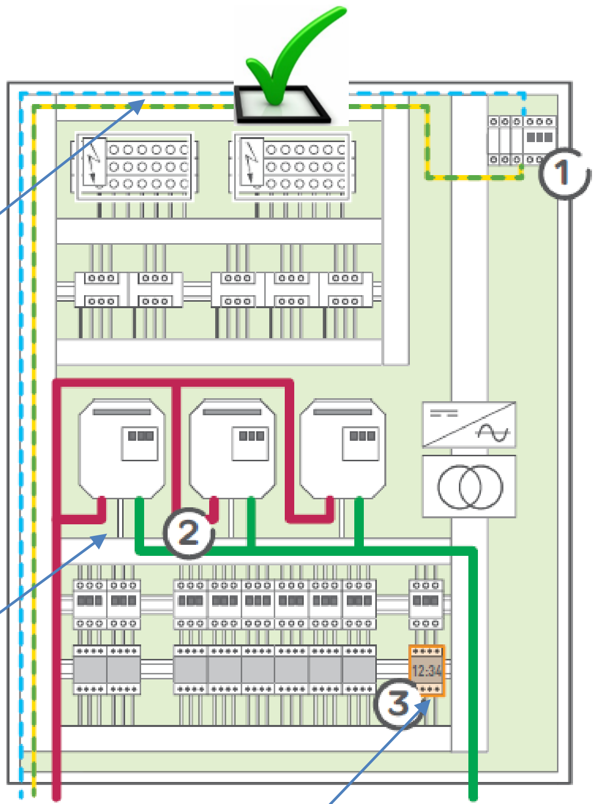
c). Make a cable routing plan



The power and earth cables form a large loop.

The upstream and downstream power cables of the variable speed drives run alongside one another creating a transfer of disturbance.

A time switch is installed between two contactors, it risks malfunctions during contactor switching.

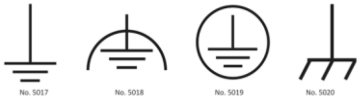


The cables are held against one another to reduce the surface area of the inductive loop.

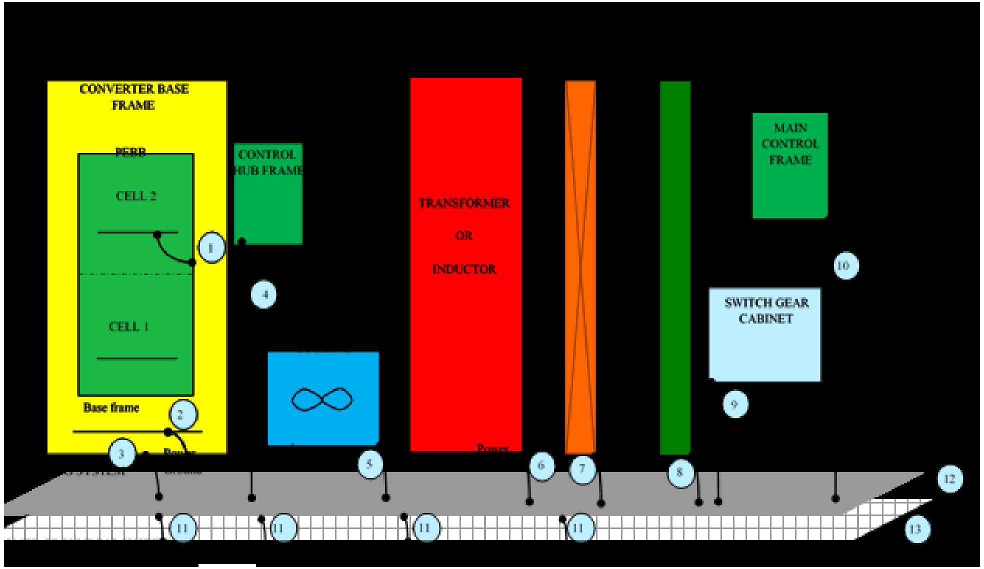
The upstream and downstream cables follow seperate paths. If necessary the cross another at night angles.

The time switch is remote from the contactors.

STEP 6: Grounding

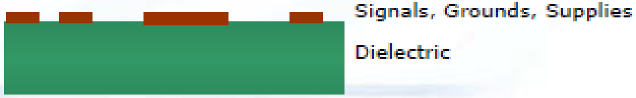


When you see these symbols there is always an EMC work to be done around!...

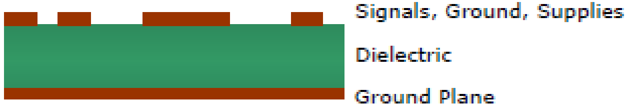


- System grounding should be **less than 0.1Ω**.
- Ground rod length, number, placement, and spacing affect the resistivity of the path to earth.
- Separate the clean and dirty grounding.
- All classified groundings should be connected directly to the meshed grounding.

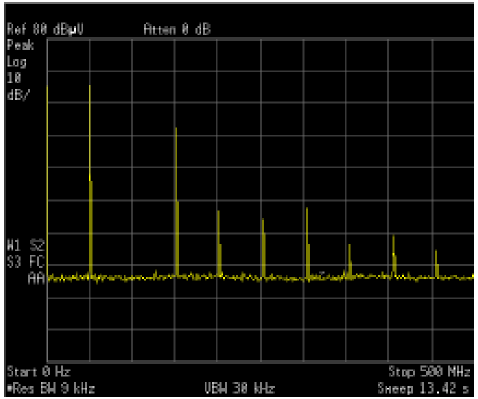
STEP 6: Grounding

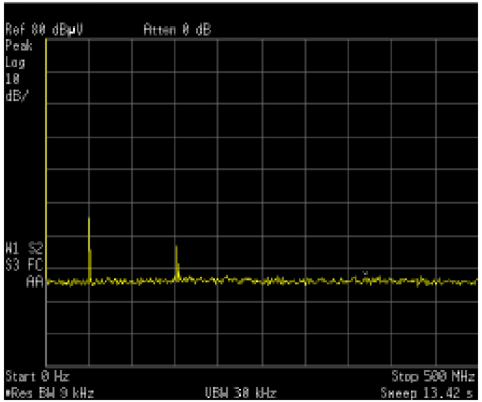


One Sided



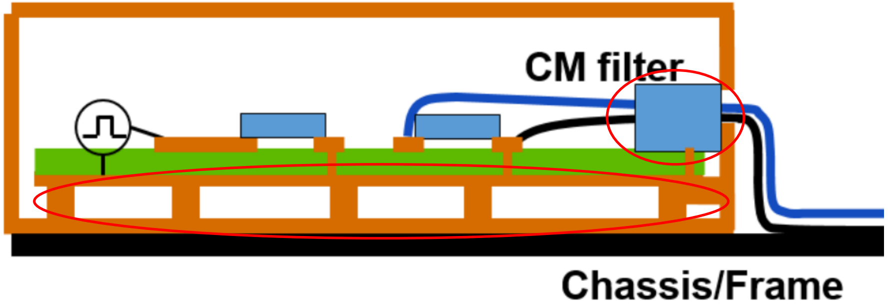
Two Sided

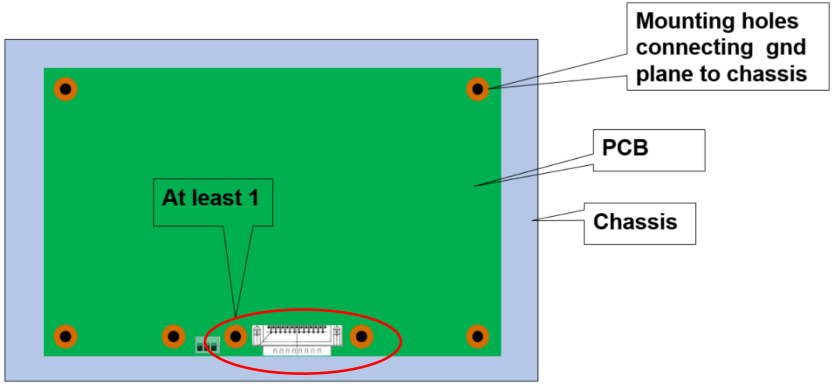




Adding ground plane reduces emission of fundamental ≈ 40 dB

STEP 6: Grounding

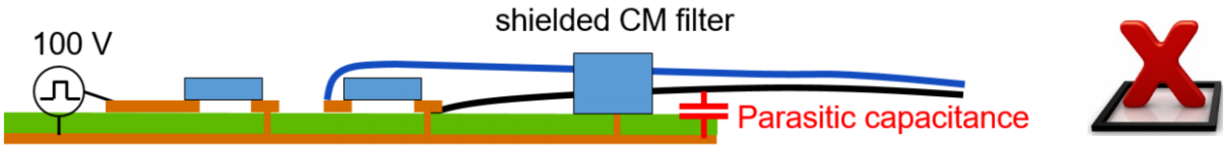


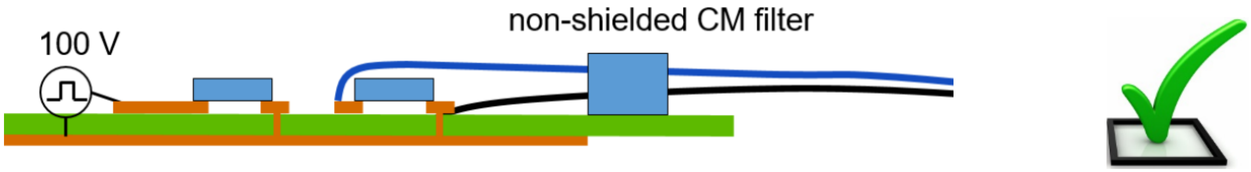


- Connect the ground plane of the PCB with multiple metal studs to the housing or metal plate.
- Use CM-filters at the entry point of cables going in or out.
- Place ground-plane-to-housing-studs near connectors

Ref: www.acradac.com

STEP 6: Grounding

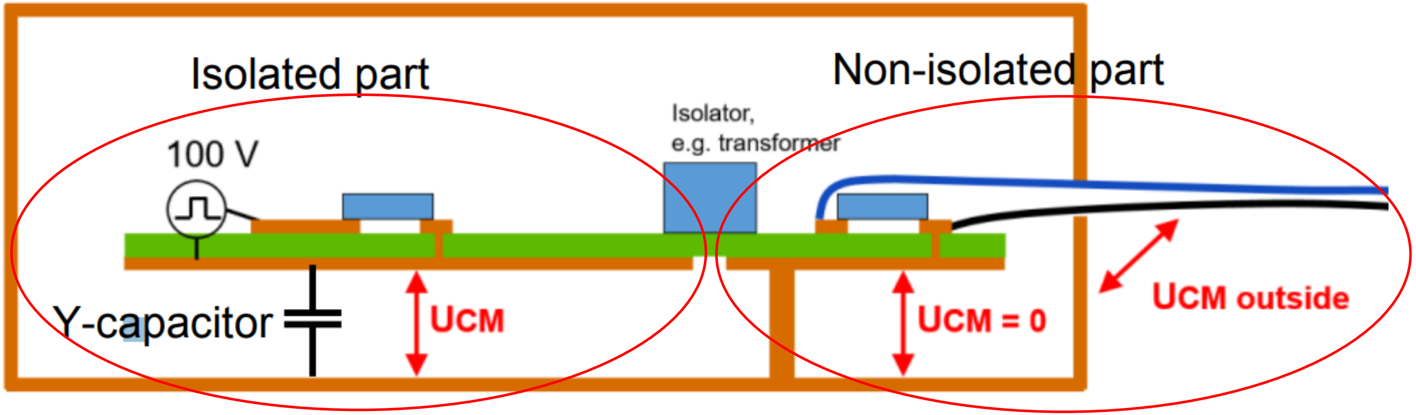




- The end of the ground plane will have a parasitic capacitance between the plane and the outgoing cables.
- Use a non-shielded CM-filter at the entry point of cables going in or out.
- Retract the ground plane under the filter.

Ref: www.acradac.com

STEP 6: Grounding

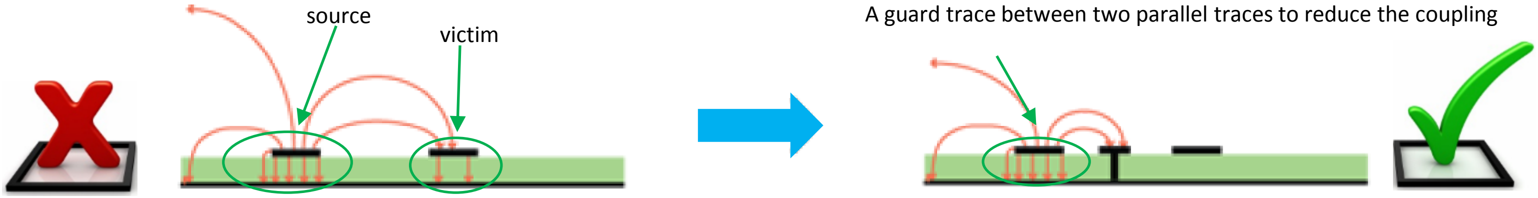


- Connect the ground plane of the non-isolated part with the metal housing or metal plate.
- The isolated part can be connected to the housing via Y-caps to further reduce EMI.

Ref: www.acradac.com

STEP 6: Grounding

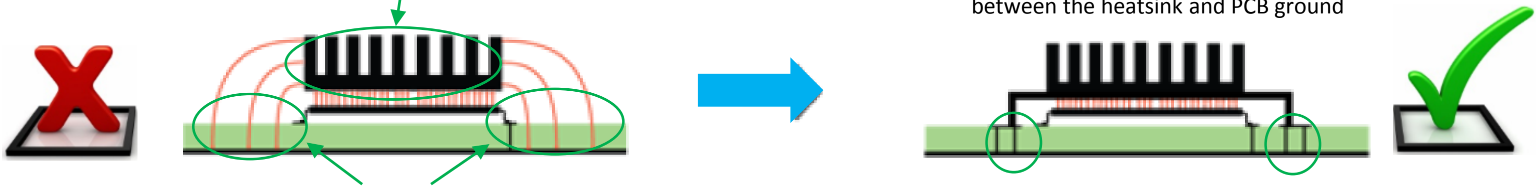
a). Grounding at circuit level



A guard trace between two parallel traces to reduce the coupling

STEP 6: Grounding

a). Grounding at circuit level



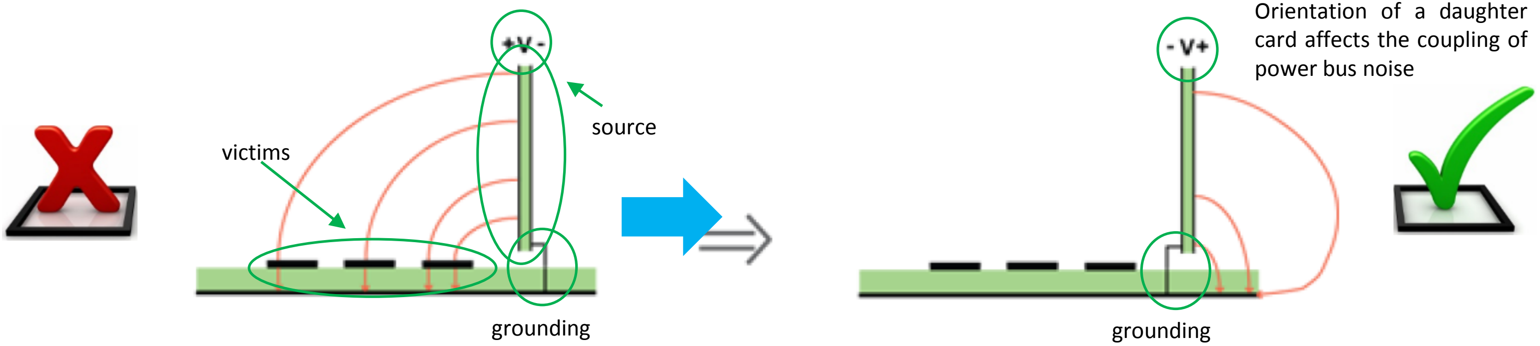
source (ungrounded heatsink)

victims

Grounding a heatsink attenuates the electric field between the heatsink and PCB ground

STEP 6: Grounding

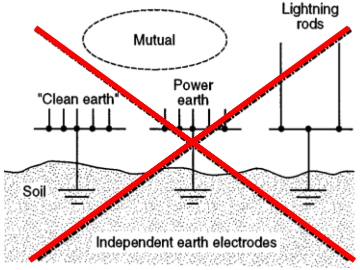
a). Grounding at circuit level



Orientation of a daughter card affects the coupling of power bus noise

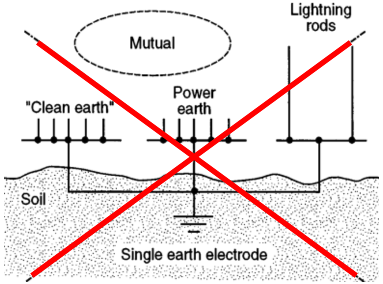
STEP 6: Grounding

b). Grounding at system level



In case of lightning or system fault, dangerous transient voltages can occur between the isolated earthing and the other independently earthed networks.

a). Independent earth electrodes (not suggested).



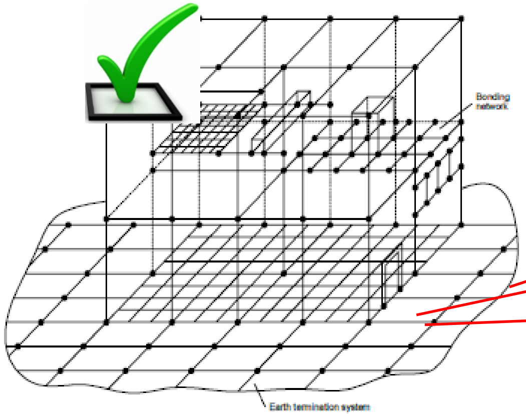
Disturbance signals can circulate between dirty power earthing and clean signal earthing, not suitable for EMC reasons.

b). Single earth electrode (not suggested).

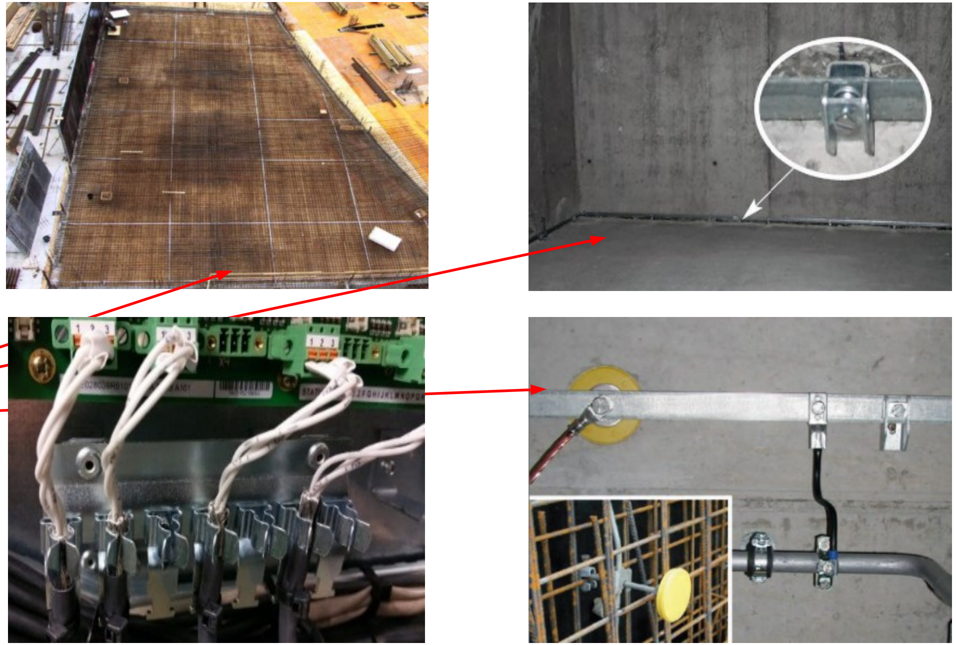
EN 50174: MESH
IEC 61000-5-1: Installation and mitigation methods

STEP 6: Grounding

b). Grounding at system level



c). Bonded earth electrodes (suggested).

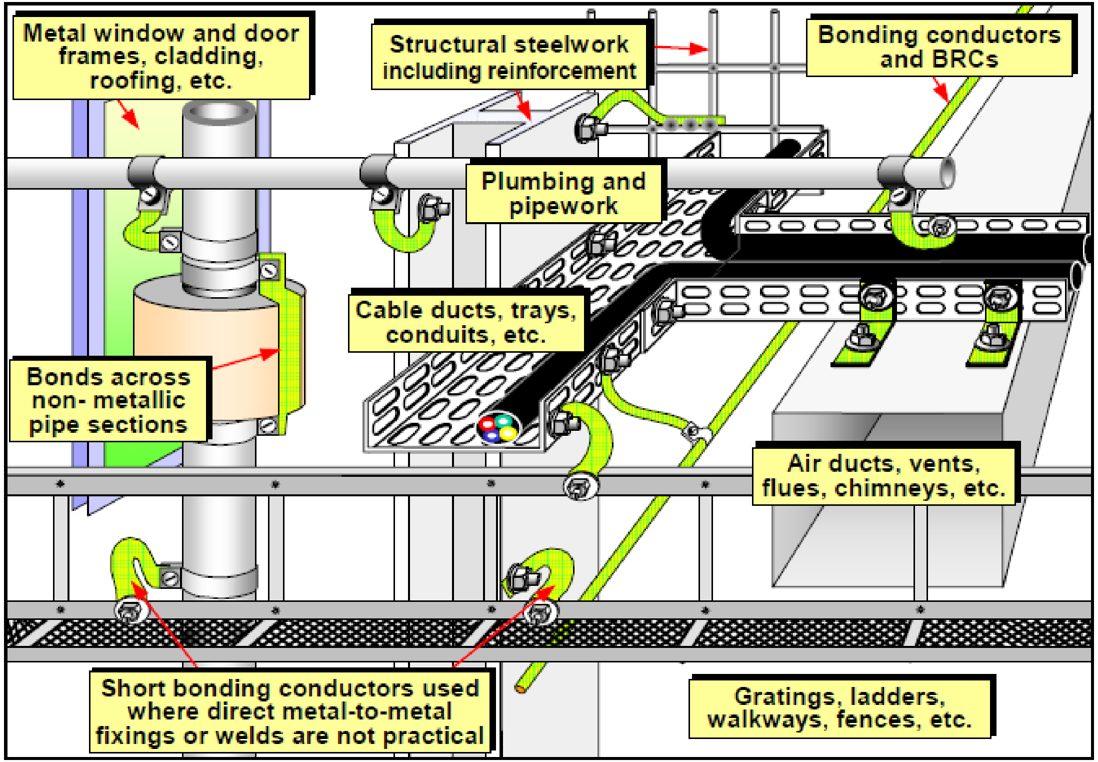


EN 50174: MESH
IEC 61000-5-1: Installation and mitigation methods

STEP 6: Grounding

b). Grounding at system level

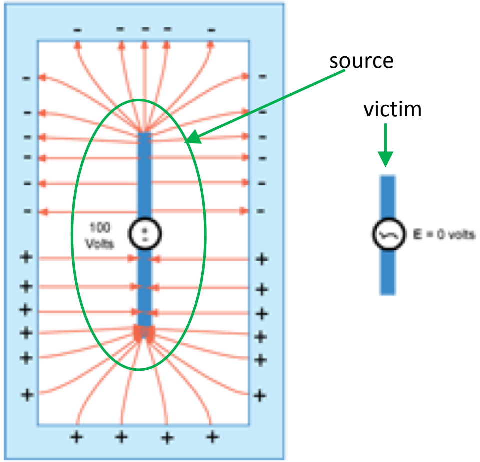
Creating a MESH-CBN by bonding 'natural' metalwork



STEP 7: Improve the Immunity of Receptor

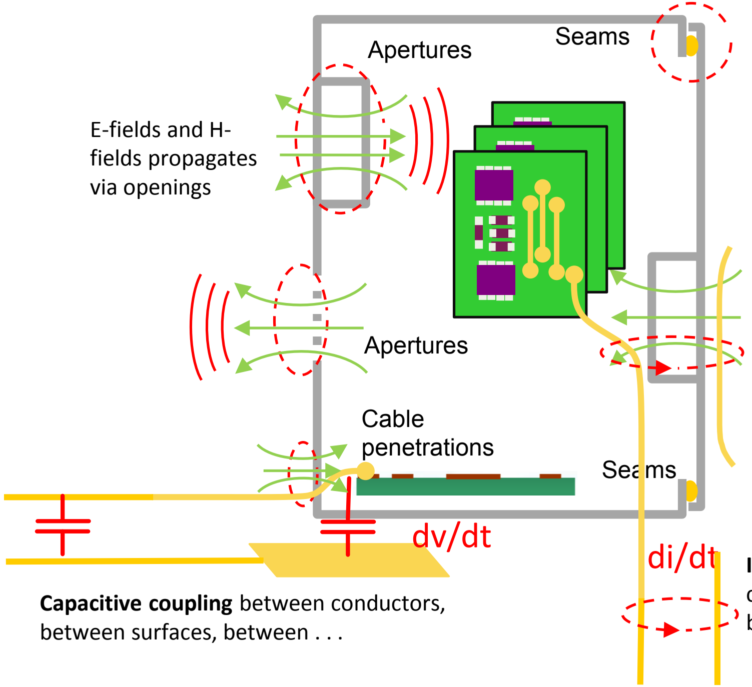
Shielding, apertures, seams, cable penetration…

Every **seam**, every **aperture** and every **cable penetration** have to be evaluated carefully to ensure that no significant interfering signals are allowed to pass from one side to the other.



STEP 7: Improve the Immunity of Receptor

Shielding, apertures, seams, cable penetration…



E-fields and H-fields propagates via openings

Capacitive coupling between conductors, between surfaces, between . . .

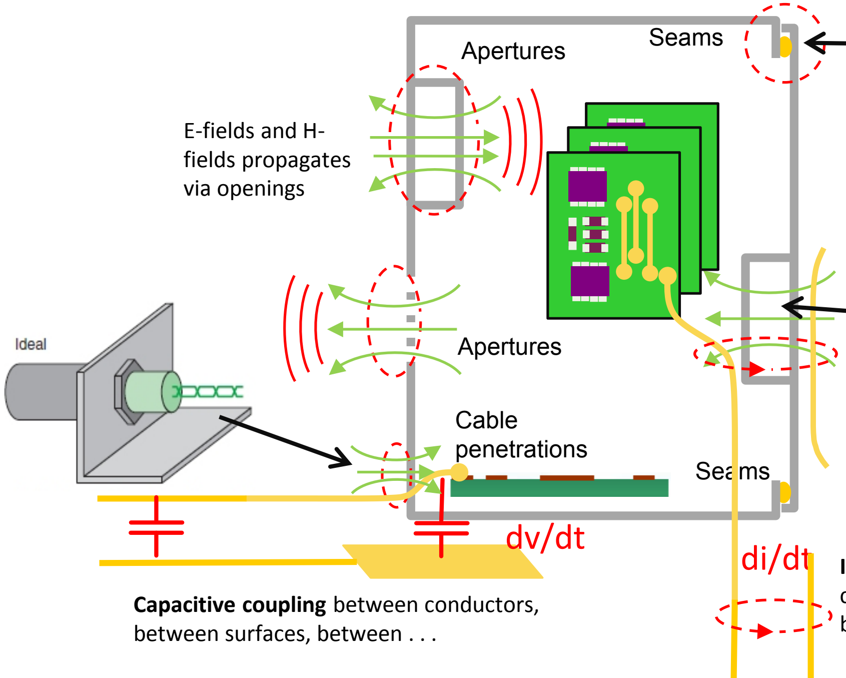
Inductive coupling between conductors, between cable shields, between . . .

STEP 7: Improve the Immunity of Receptor

Shielding, apertures, seams, cable penetration…

To provide shielding, currents must flow on the surface of the enclosure. To have a good shielding:

- ✓ Minimize size and number of apertures and seams
- ✓ Use gaskets/spring-fingers to seal metal-to-metal interface
- ✓ Interfaces free of paint and debris
- ✓ Ground contact should always be effective 360 around the cable termination.



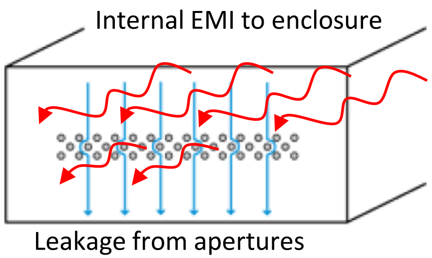
Capacitive coupling between conductors, between surfaces, between . . .

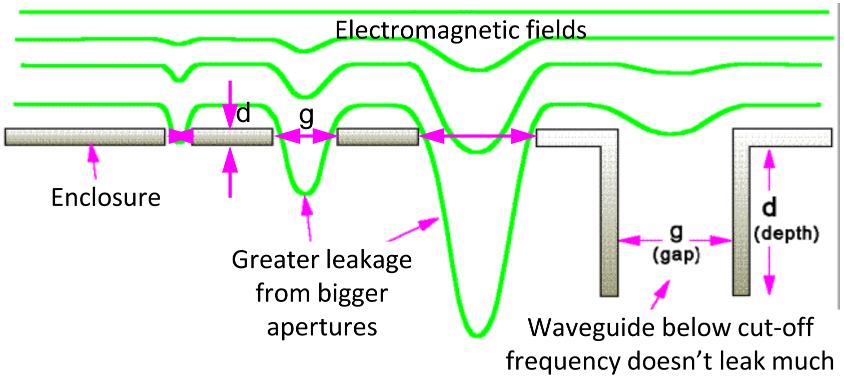
Inductive coupling between conductors, between cable shields, between . . .

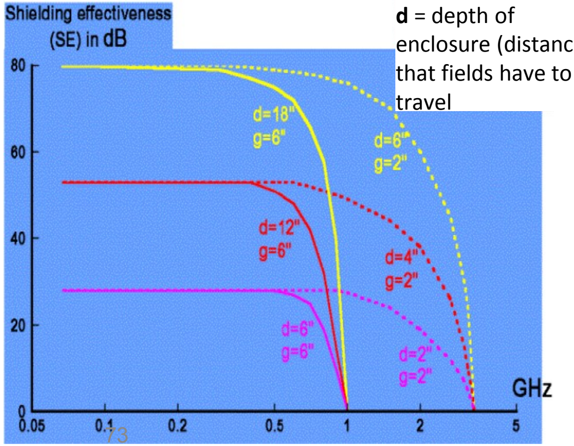
STEP 7: Improve the Immunity of Receptor

a). Aperture size

To provide shielding, currents must flow on the surface of the enclosure. However, apertures with maximum dimensions that are much smaller than a wavelength provide very low attenuation.







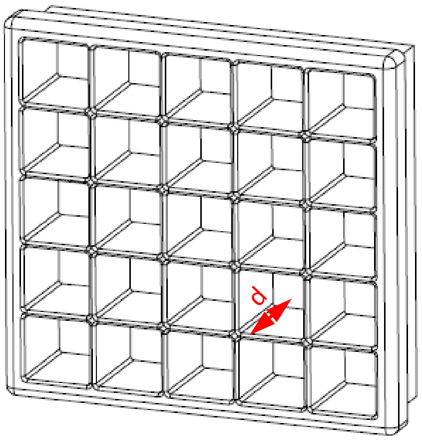
g = aperture width
d = depth of enclosure (distance that fields have to travel

The waveguide EMI performance depends on two parameters:

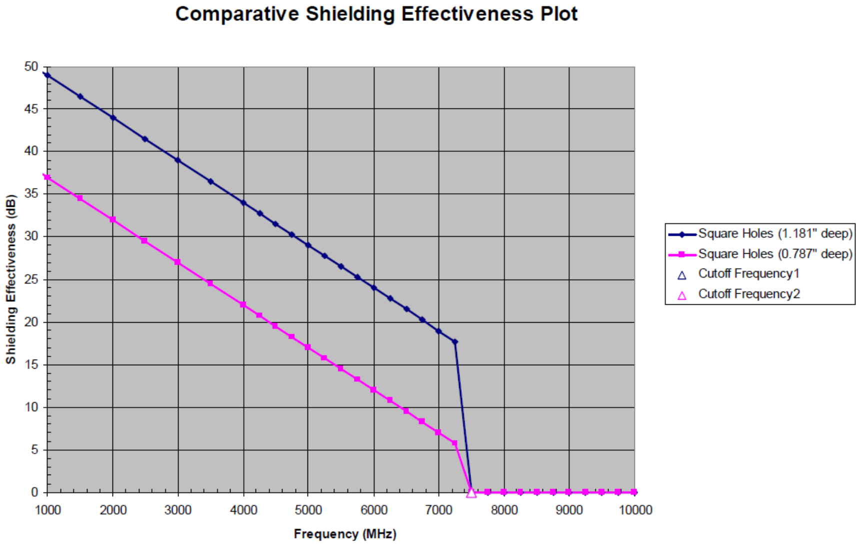
- Cutoff Frequency (fc), which determines the maximum possible frequency of effectiveness.
- Shielding Effectiveness (SE), which determines the magnitude of the EMI attenuation and is a function of frequency.

STEP 7: Improve the Immunity of Receptor

b). Increase the depth of apertures



$$SE \approx 27.\frac{d}{a}.\sqrt{1-\left(\frac{f}{f_c}\right)^2}$$



Panel 1:
g = 20 mm **square**
d = 30 mm deep
Number of holes = 50 holes total
fc = 7,493 MHz

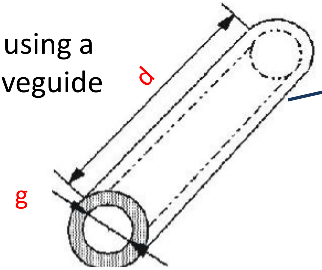
Panel 2:
g = 20 mm **square**
d = 20 mm deep
Number of holes = 50 holes total
fc = 7,493 MHz

In the case shown above, a depth change from 1.181” to 0.787” for square holes results in a 12dB change in performance up to the Cutoff Frequency

STEP 7: Improve the Immunity of Receptor

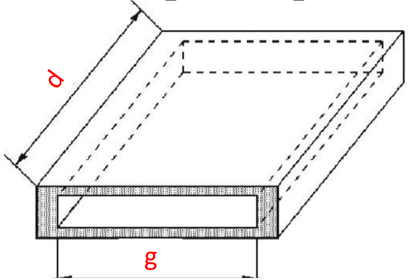
c). Aperture geometry

Derivation using a circular waveguide

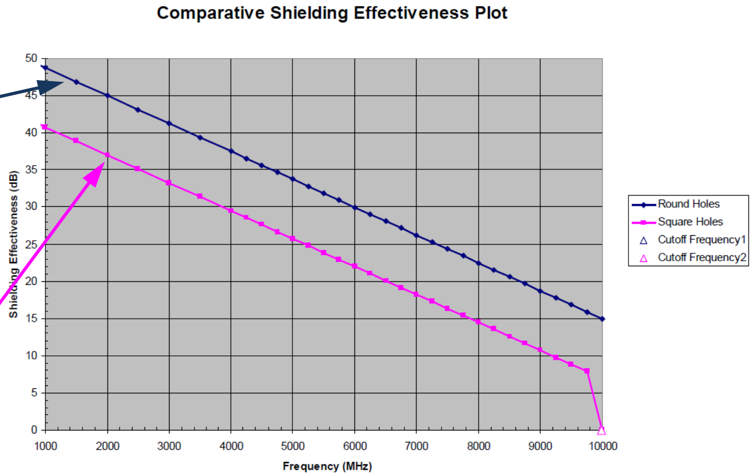


$$SE \approx 32.\frac{d}{a}.\sqrt{1-\left(\frac{f}{f_c}\right)^2}$$

Derivation using a rectangular waveguide



$$SE \approx 27.\frac{d}{a}.\sqrt{1-\left(\frac{f}{f_c}\right)^2}$$



Panel 1:
g = 15 mm **round**
d = 15 mm deep
Number of holes = 50 holes total
fc = 11,684 MHz

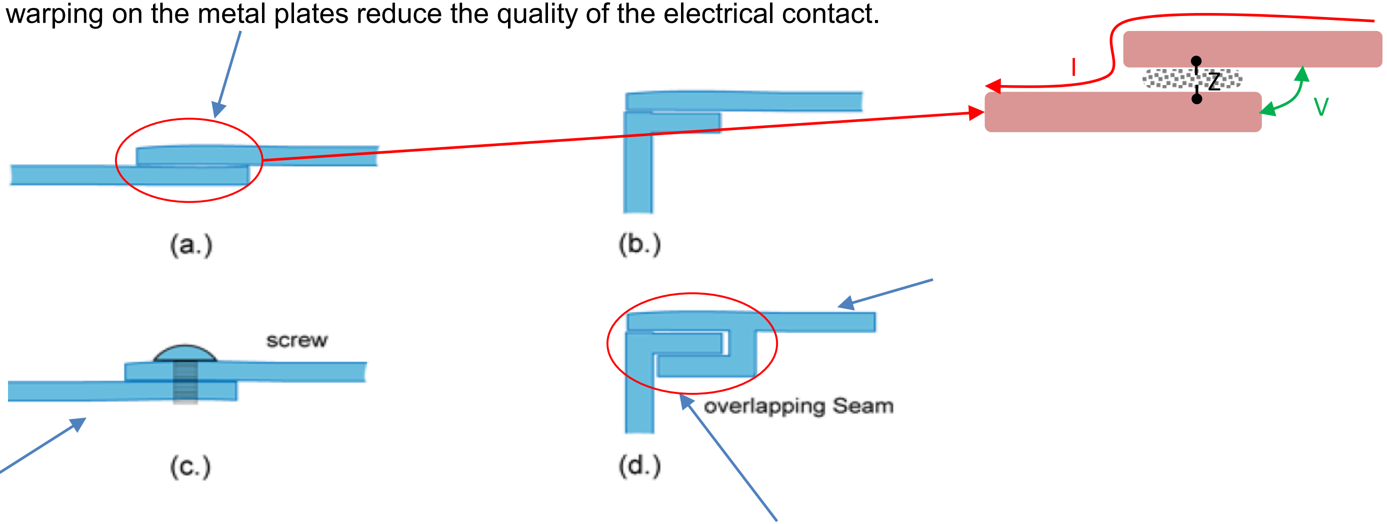
Panel 2:
g = 15 mm **square**
d = 15 mm deep
Number of holes = 50 holes total
fc = 9,991 MHz

A change from round holes to square holes reduces Shielding Effectiveness by approximately 8dB.

STEP 7: Improve the Immunity of Receptor

d). Seam shape

Simply pressed metal surfaces rarely provide sufficiently reliable contact at high frequencies. Surface oxidation, corrosion and warping on the metal plates reduce the quality of the electrical contact.



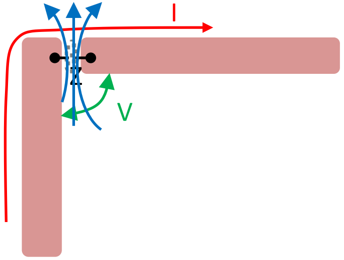
Screws or rivets can provide a good electrical contact, but they do not necessarily improve the connection at locations between fasteners.

Overlapping both sides of the plates reduces the impedance of seams.

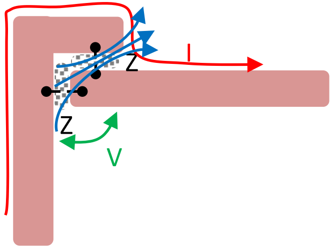
STEP 7: Improve the Immunity of Receptor

d). Seam shape

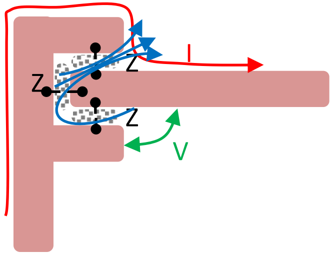
Shape A

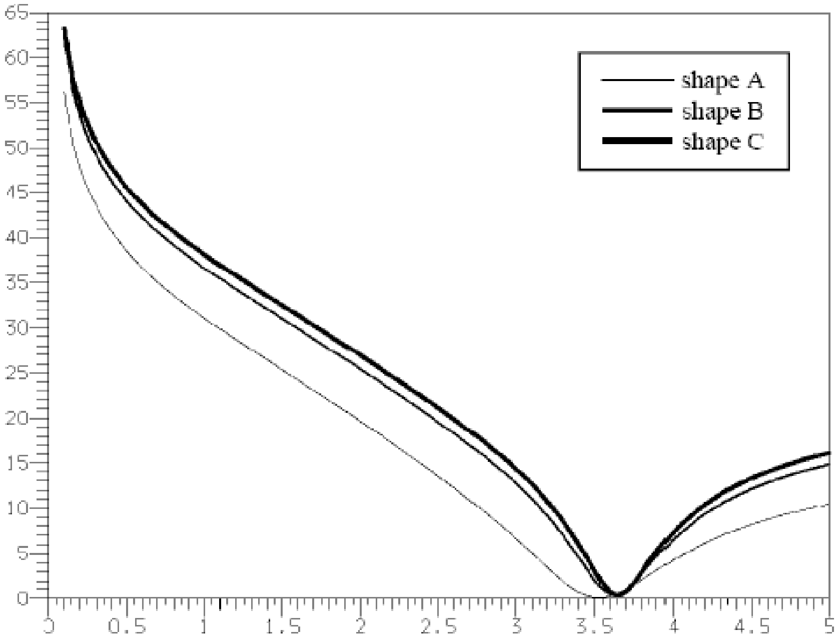


Shape B



Shape C

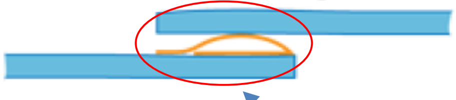


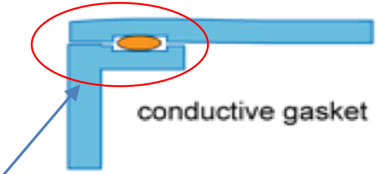


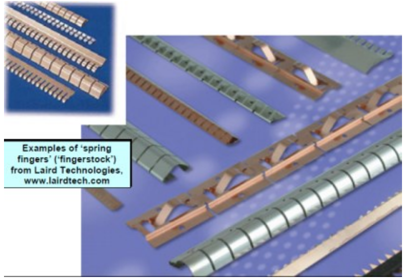
Slot resonant at 3.6GHz, SE at 5 cm away from the slot

STEP 7: Improve the Immunity of Receptor

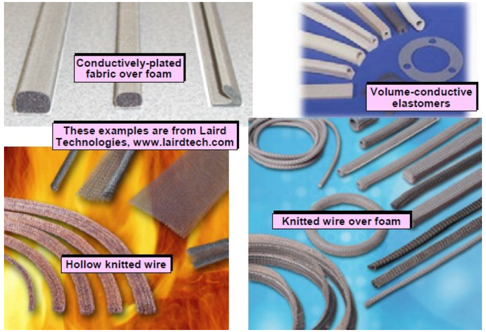
d). Seam shape







Finger stock or gaskets have the best performance to reduce the impedance of seams



STEP 7: Improve the Immunity of Receptor

e). Cable penetration

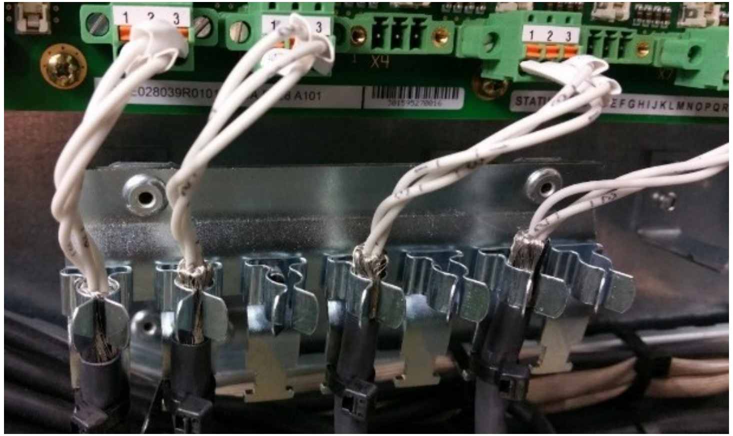
An unshielded, unfiltered wire penetrating can completely eliminate any shielding benefit.

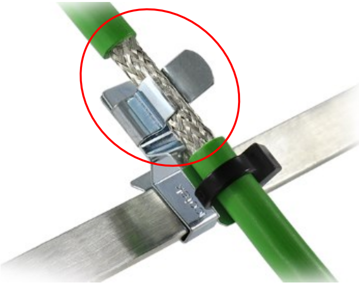
The wire/enclosure pair is often a very efficient antenna at relatively low frequencies.

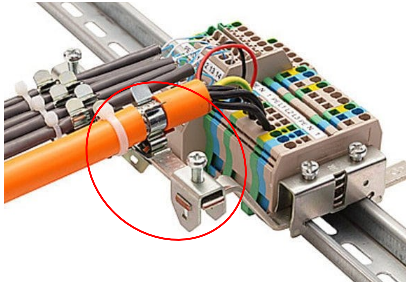
Any wires penetrating the enclosure should:

a.) be well-shielded, or

b.) held to the same potential as the enclosure at all frequencies that may be a radiation problem.



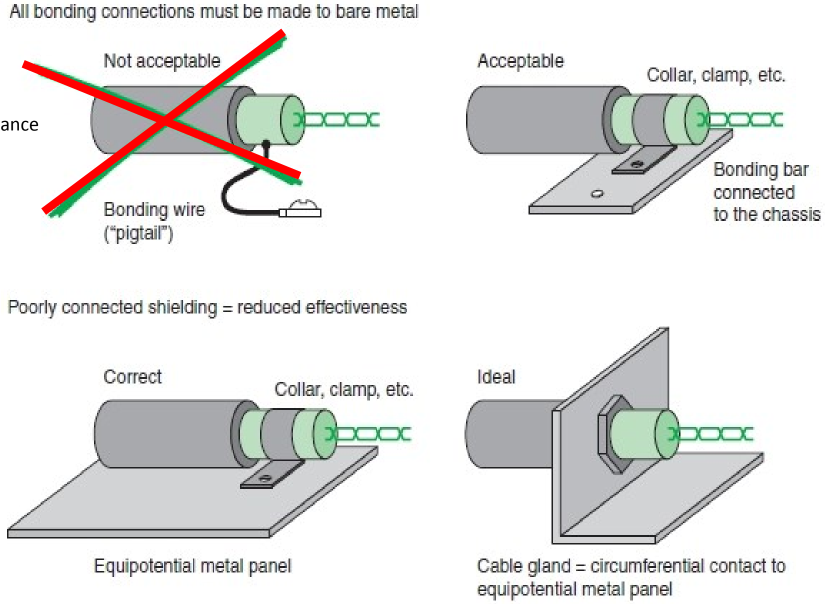




STEP 7: Improve the Immunity of Receptor

e). Cable penetration

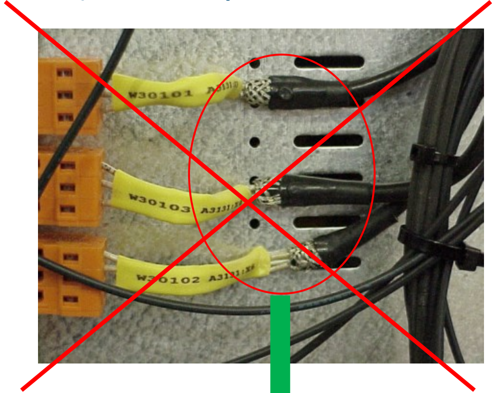
- The cable screen connection is very important for the HF performance.
- In order to provide a low-inductance connection to the shielded enclosure the ground contact should always be effective 360 around the cable termination.

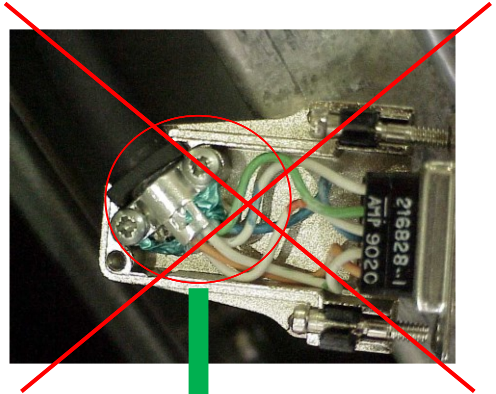


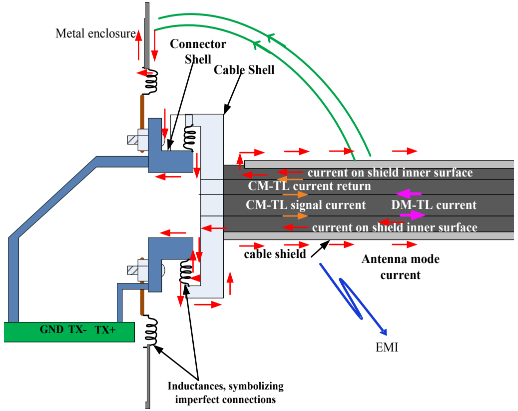
25mm ~few nH inductance

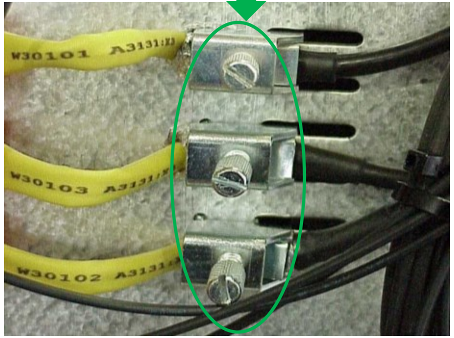
STEP 7: Improve the Immunity of Receptor

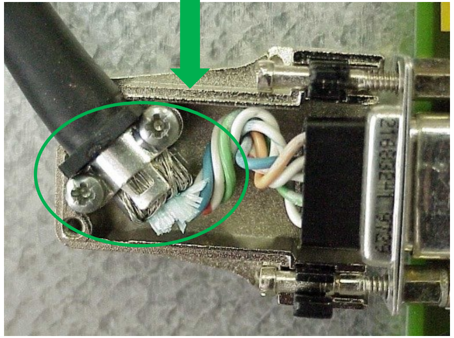
e). Cable penetration

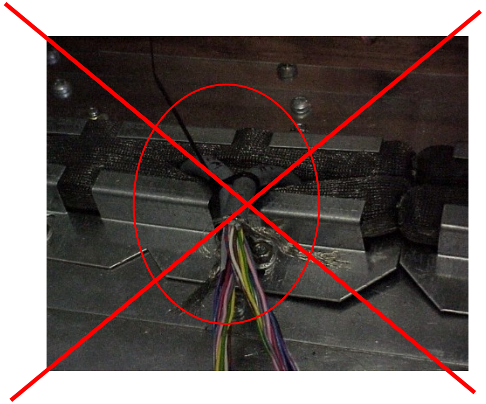












- Shieldings should be mounted to the local ground.

- The isolation around shielding has to be removed.
- The cables should be twisted

- Shieldings should be mounted to the local ground.

STEP 7: Improve the Immunity of Receptor

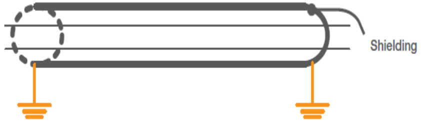
f). Which end to terminate the screen?

Termination at one end:

- Moderate high-frequency protection; as the effectiveness of the screening is reduced above the resonant frequency of the cable.
- Protection against low-frequency electric field.

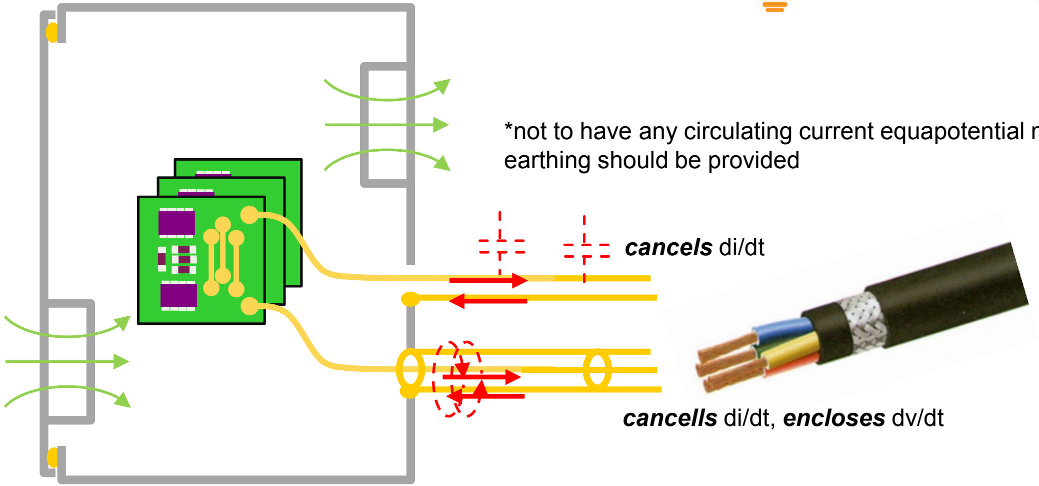
Termination at both end:

- It gives a very good protection against the most severe common mode interference (HF) even at the resonant frequency the improvement remains excellent.
- At low frequency a current my flow in the screen as a result of magnetic fields within the area of the cable. These currents can crosstalk to the interior pair.



No termination:

- No protection, just cost.

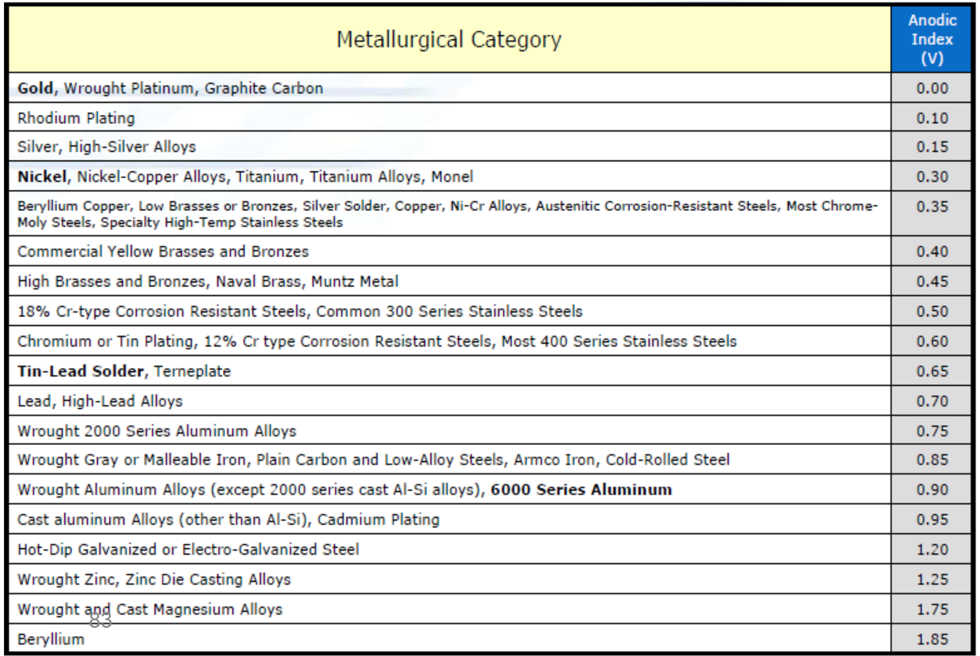


*not to have any circulating current equapotential mesh earthing should be provided

STEP 7: Improve the Immunity of Receptor

g). Corrosion

- Galvanically compatible materials are those that are;
  - For harsh environments
    - Outdoors, high humidity/salt
    - Typically design for < 0.15V difference
  - For normal environments
    - Storage in warehouses, no-temperature/humidity control
    - Typically < 0.25V difference



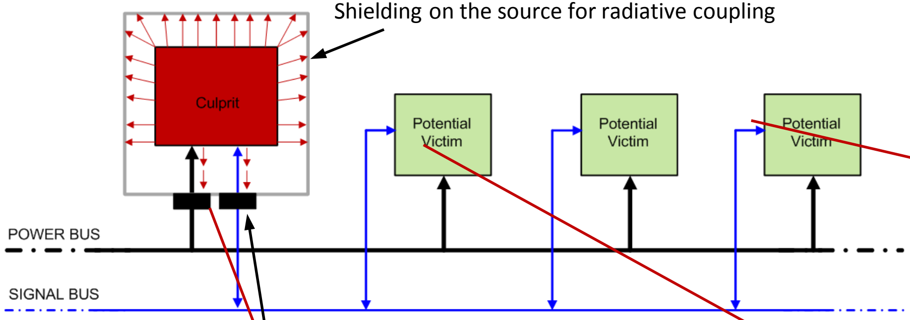
Metallurgical Category	Anodic Index (V)
Gold, Wrought Platinum, Graphite Carbon	0.00
Rhodium Plating	0.10
Silver, High-Silver Alloys	0.15
Nickel, Nickel-Copper Alloys, Titanium, Titanium Alloys, Monel	0.30
Beryllium Copper, Low Brasses or Bronzes, Silver Solder, Copper, Ni-Cr Alloys, Austenitic Corrosion-Resistant Steels, Most Chrome-Moly Steels, Specialty High-Temp Stainless Steels	0.35
Commercial Yellow Brasses and Bronzes	0.40
High Brasses and Bronzes, Naval Brass, Muntz Metal	0.45
18% Cr-type Corrosion Resistant Steels, Common 300 Series Stainless Steels	0.50
Chromium or Tin Plating, 12% Cr type Corrosion Resistant Steels, Most 400 Series Stainless Steels	0.60
Tin-Lead Solder, Terneplate	0.65
Lead, High-Lead Alloys	0.70
Wrought 2000 Series Aluminum Alloys	0.75
Wrought Gray or Malleable Iron, Plain Carbon and Low-Alloy Steels, Armco Iron, Cold-Rolled Steel	0.85
Wrought Aluminum Alloys (except 2000 series cast Al-Si alloys), **6000 Series Aluminum**	0.90
Cast aluminum Alloys (other than Al-Si), Cadmium Plating	0.95
Hot-Dip Galvanized or Electro-Galvanized Steel	1.20
Wrought Zinc, Zinc Die Casting Alloys	1.25
Wrought and Cast Magnesium Alloys	1.75
Beryllium	1.85

- For controlled environments
  - Temperature/humidity controlled
  - Typically design for < 0.50V difference
- Mitigation of Galvanic Corrosion
  - Choosing metals with the least potential difference
  - Finishes, such as MIL-C-5541, Class 3 using minimal dip immersion

If large contact voltages occur, the more anodic material will eventually be destroyed. To prevent this problem, either the gasket material or mating surface, or both, will need to be plated with a material.

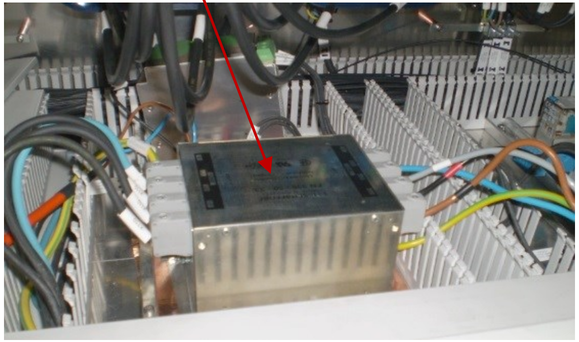
STEP 8: Break the Coupling Path

a). Prevent radiated/conducted interference on culprit side

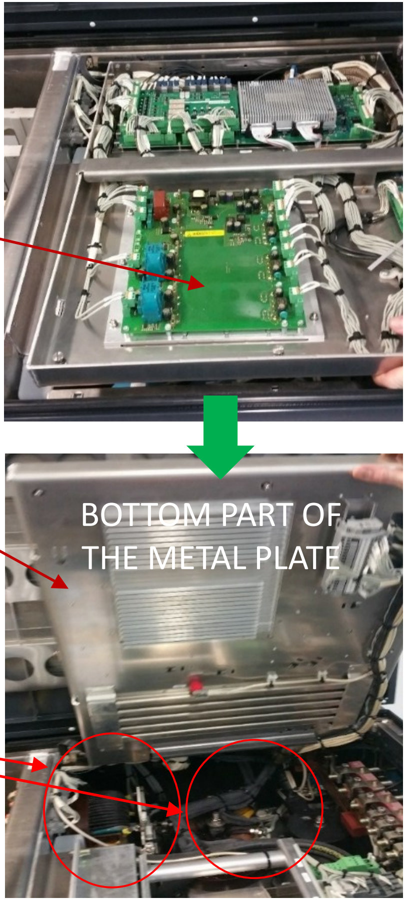


Shielding on the source for radiative coupling

Shielding/Filter on the cabling of source for conductive coupling



filtering (for conducted coupling)

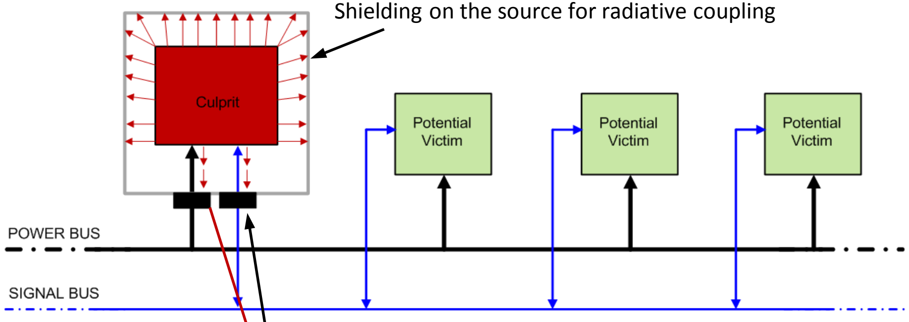


Chokes

shielding (for radiated coupling)

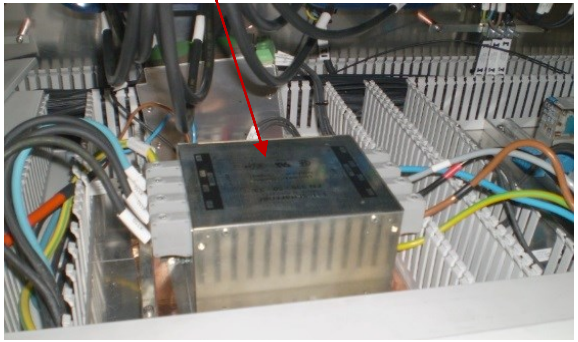
STEP 8: Break the Coupling Path

a). Prevent radiated/conducted interference on culprit side

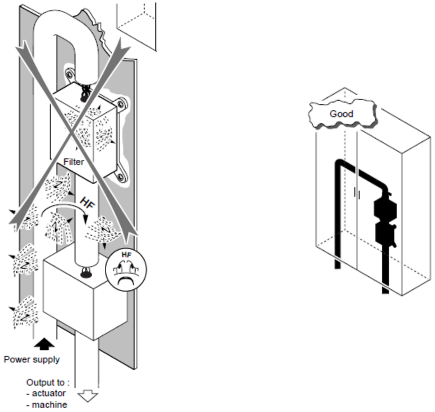


Shielding on the source for radiative coupling

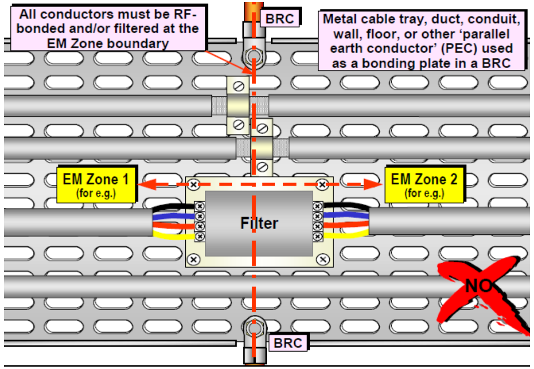
Shielding/Filter on the cabling of source for conductive coupling



filtering (for conducted coupling)



- Filters shouldn't be "bypassed" by input/output cables

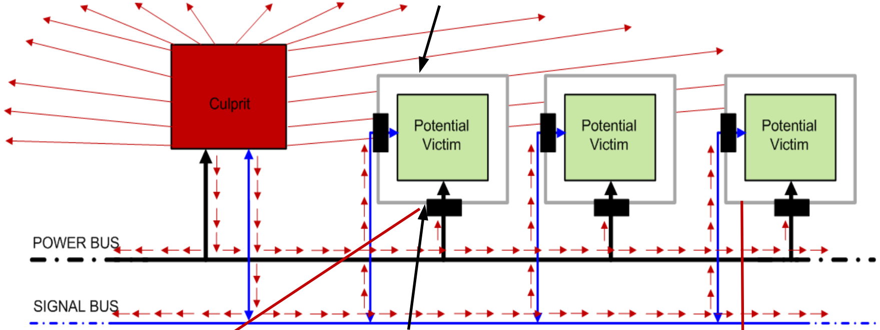


All conductors must be RF-bonded and/or filtered at the EM Zone boundary

Metal cable tray, duct, conduit, wall, floor, or other 'parallel earth conductor' (PEC) used as a bonding plate in a BRC

STEP 8: Break the Coupling Path

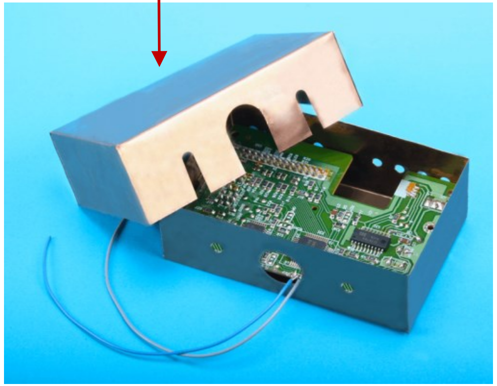
b). Prevent radiated/conducted interference on victim side



Shielding on the cabling of victim for conductive coupling

Shielding/Filter on the cabling of victim for conductive coupling

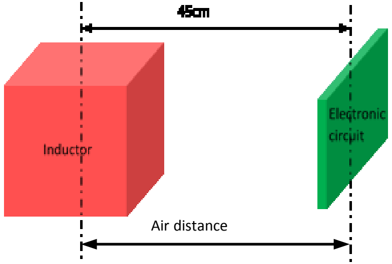
filtering (for conducted coupling)

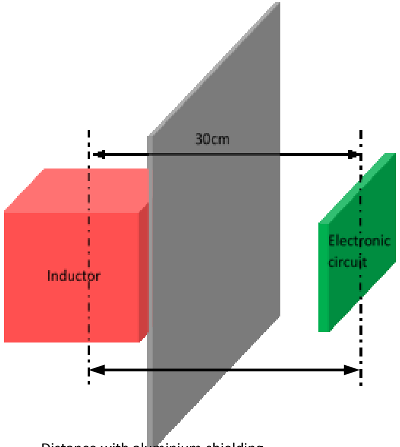


shielding (for radiated coupling)

STEP 8: Break the Coupling Path

c). Spacing





Distance with aluminium shielding

$$\boxed{E \propto I.f^2.A.\frac{1}{r}}$$

For the magnetic components, it’s required to have enough distance for electrical and magnetic clearance. It’s not allowed to have any metallic structure within the magnetic clearance area not induce any unwanted currents in nearby metallic geometries.

→ Distance to small metallic parts d > D/2 (D: coil diameter)
→ Distance to large geometries d > D (rules of thumb)

STANDARDS AND REGULATIONS

Outline

- Introduction
- Overview on Electromagnetic Basics
- Coupling Mechanisms
- Design Process
- Standards and Regulations
- Summary

Regulation Committees

CE - Conformité Européenne

European Conformity
Identifies that a product or machine is compliant with all safety requirements
Requirement not a voluntary process

CE Marking for EMC

- CE is a passport (not approval) to allow free passage of equipment within the EU economic area.
- It´s not an indicator of product quality.
- It´s manufacturer´s own responsibility to declare conformance with a particular directive´s requirements.

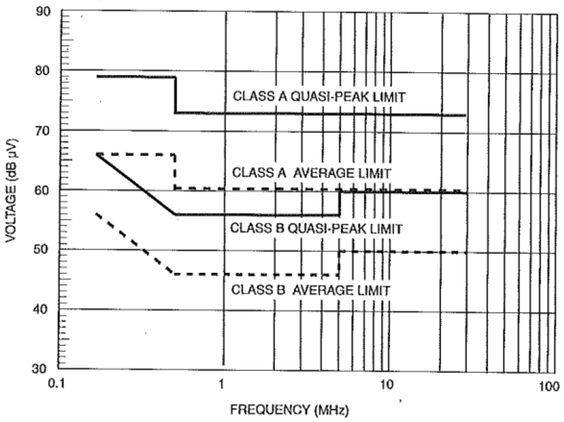
FCC
Federal Communications Commission
United States (The Federal Communications Commission (FCC) is an independent United States government agency, directly responsible to Congress.)
Modems, Printers, and other I/O devices

MIL-STD-416D
Department of Defense
Even harder-to-meet standards than FCC and CISPR
Dependent on reliability of electronic and communication equipment

Conducted vs. Radiated Emission Limits

Conducted

FCC/CISPR Conducted Emission Limits

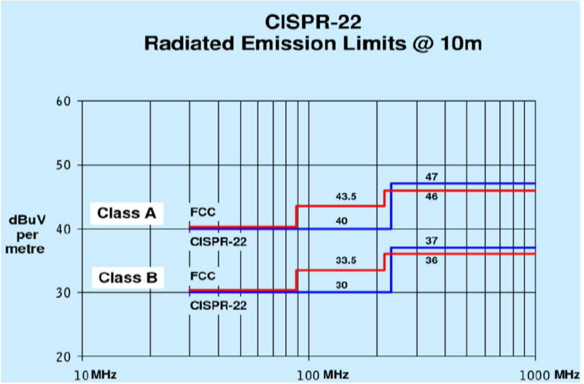


- FCC and CISPR standards the same

Radiated

FCC/CISPR Radiated Emission Limits

Measured at 10m



- FCC and CISPR standards somewhat different
- FCC B (consumer) much more stringent than FCC A (commercial, industrial, and business)

Electromagnetic Compatibility Standards

For Immunity Requirements

IEC61000-2-4
IEC61800-3-2
IEC61000-4-3
IEC61000-4-6

- **IEC61000-2-4:** LV – LF THD, individual harmonic orders, voltage unbalance etc.
- **IEC61800-3-2:** MV – LF THD, individual harmonic orders, voltage unbalance etc.
- **IEC61000-4-3:** LV – HF, against electromagnetic fields
- **IEC61000-4-6:** LV – HF, against electromagnetic fields

Electromagnetic Compatibility Standards

For Conducted Emissions

THDv

IEC61000-2-4
IEC61800-3-2
IEC61000-3-2
IEC61000-3-7

- **IEC61000-2-4:** Industrial and non-public networks.
- **IEC61800-3-2:** LV and MV voltage fluctuations.
- **IEC61800-3-2:** Limits for main terminal disturbance.
- **IEC61000-3-2:** Harmonics and interharmonics.
- **IEC61000-3-7:** MV- Voltage fluctuations.

THDi

IEC61000-3-4
IEC61000-3-12

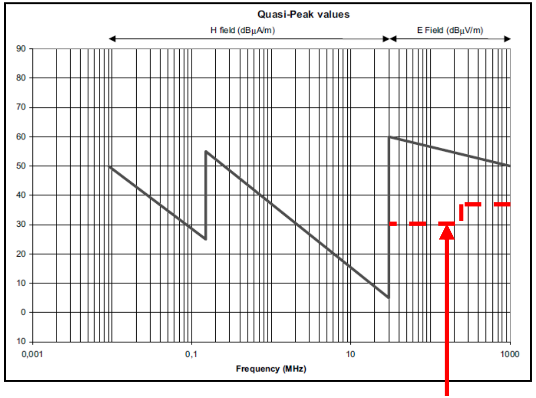
- Public networks up to 600V
- THD and PWHD up to:
    - IEC61000-3-4 <16A
    - IEC61000-3-12 < 75A

Electromagnetic Compatibility Standards

For Radiated Emissions

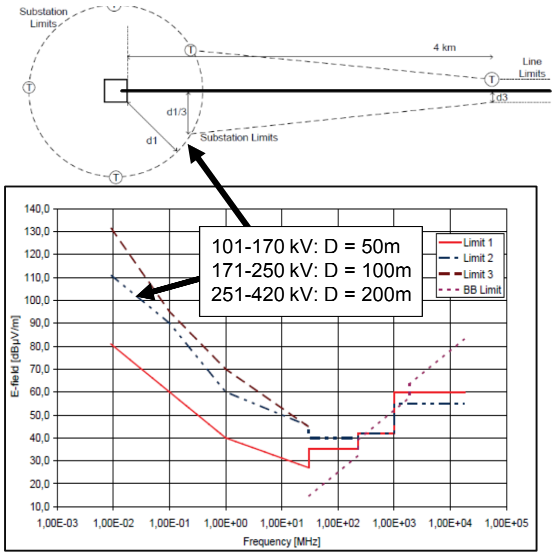
- For HV/high power converter installations there is no truly applicable standard. Directives from **IEC61800-3-2** can be followed.
- **EN 50121** is partly relevant, **Cigre 391** is relevant guideline.

EN50121 Standard for railway substation,
Limit 10m outside outer fence



For comparison, 10m requirement
for domestic environment

Cigre 391 Guide for HV/MV substations



101-170 kV: D = 50m
171-250 kV: D = 100m
251-420 kV: D = 200m

Standards & Regulations IEC61000-2-12

Odd harmonic not multiples of 3		Odd harmonics multiples of 3 (note)		Even harmonics	
Harmonic order (h)	Harmonic voltage (%)	Harmonic order (h)	Harmonic voltage (%)	Harmonic order (h)	Harmonic voltage (%)
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,4	6	0,5
13	3	21	0,3	8	0,5
17 ≤ h ≤ 49	2,27 x (17/h)-0,27	21 ≤ h ≤ 45	0,2	10 ≤ h ≤ 50	0,25 x (10/h)+0,25

Note: The levels indicated through even harmonics multiples of three are applied to the homopolar harmonics. So this, in a 3-phase distribution line without neutral cable with no load connected between a phase and ground, the value of the harmonics order 3 and 9 can be lower enough than compatibility levels, depending on the distribution line imbalance.

SUMMARY

Outline

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- Overview on Electromagnetic Basics
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SUMMARY

$$\boxed{E \propto f^2 \cdot \frac{1}{r} \cdot I \cdot \mathrm{A}}$$

- EMI changes with → ***f, I, A, 1/r***

- **EMC design steps:**
  - **Step 1:** Identify the systems requirements (for harmonics requirements)
  - **Step 2:** Identify the installation environment (for emission and radiation levels)
  - **Step 3:** Choose right type of topology (important for low order harmonics)
  - **Step 4:** Use right type of control to suppress the harmonics
  - **Step 5:** Minimize the switching path enclosed area
  - **Step 6:** Identify source and victims
  - **Step 7:** Place the source and victims based on zone concept
  - **Step 8:** Classify and separate the cables
  - **Step 9:** Make a cable routing plan
  - **Step 10:** Make installation and grounding plan (grounding, earthing, equapotential bonding, shielding)
  - **Step 11:** Separate the clean and dirty grounding
  - **Step 12:** Use right type of apertures and keep sensitive circuits away from the apertures
  - **Step 13:** Identify if /when filter or shielding are required

Thank You for Your Attention

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