Electromagnetic Compatibility (EMC)

An introduction with particular focus on essential cable parameters and implications for a variety of applications
Part 0  Some Prerequisites
Part 1  Desired cable properties
Part 2  Conducted Noise, Filters
Part 3  Radiated Noise and screening
Part 4  EMC relevant cable parameters
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Prefixes

• Prefixes are pure factors to represent a large range of physical values.
• EMC engineering uses many of them
• EMC mixes dB and prefixes for practical reasons

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Exponent</th>
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<tbody>
<tr>
<td>yocto-</td>
<td>$10^{-24}$</td>
</tr>
<tr>
<td>zepto-</td>
<td>$10^{-21}$</td>
</tr>
<tr>
<td>atto-</td>
<td>$10^{-18}$</td>
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<tr>
<td>femto-</td>
<td>$10^{-15}$</td>
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<tr>
<td>pico-</td>
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<tr>
<td>nano-</td>
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<tr>
<td>micro-</td>
<td>$10^{-6}$</td>
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<tr>
<td>milli-</td>
<td>$10^{-3}$</td>
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<tr>
<td>(none)</td>
<td>$10^0$</td>
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<tr>
<td>kilo-</td>
<td>$10^3$</td>
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<tr>
<td>mega-</td>
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<tr>
<td>giga-</td>
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<td>zetta-</td>
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<tr>
<td>yotta-</td>
<td>$10^{24}$</td>
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</table>
The decibels behind EMC

- The decibel is no unit. It’s a factor.
- The decibel always indicates a power ratio.

References and Formulae

- 0 dBA (acoustics) is 1 pW (picowatt)
- 0 dBm is one milliwatt (1 mW) into 50Ω, or 224 mV

Mathematically the power ratio is given by

- Gain[dB] = 10log(P1/P2) for power or
- Gain[dB] = 20log(U1/U2) for voltage

EMC spans many orders of magnitude. Therefore values and ratios are often represented in dB. It is imperative to understand the reasoning behind.

- Zero decibel (0dB) is the reference of this comparison. The reference is always a power.
Most of the EMC phenomena respond to the laws of radio frequency.

Basic electricity responds to laws that omit a large part for reasons of simplicity.

\( \mathcal{E} \) electricity:
Voltage remains constant. Current defined by load.
source impedance=const, **load impedance changes**

\( \mathcal{E} \) radio frequency and EMC:
**Impedances remain more or less constant.**
Voltage change provokes current change.
Opening of a wire connection will not completely stop current flow.
The current source

Definition:
I = constant
Zs = source impedance
(theoretically infinitely high)

The value of the current is independent of the load impedances.

Removing a load impedance causes the current to share only 3 paths instead of four.
EMC almost exclusively deals with high impedance (noise) sources. The determining element is almost always a (noise) current.

The (noise) currents are usually small but their spectrum (i.e. frequency span) is very wide. Noise currents find their way EVERYWHERE. (That's why they are difficult to find).

**Noise currents share all available paths.**

That's conductors, screens, ground, metallic structures, neighbouring circuitry and FIELDS.
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Part 1 Desired cable properties

Cables ideally should

• Have infinite lifetime under CERN conditions
• Be cheap (material and commercial question)
• Have a perfect fire behaviour
• Be robust (mechanical, installation stress)
• Have the technical parameters required
Cables spec's and EMC

A cable can
• transport most of your signal, or energy
• keep the shape of your signal, or hold the insulation
• screen certain types of noise
• Defend itself against moisture, impact, chemicals, UV

A cable cannot
• Screen everything
• Work outside its spec's (physics: leakage, frequency)
• Patch up design errors (installation path, connectors, equipment)
**EMC Errors (superficial EMC)**

Looking for the noise source
Lack of immunity is quite common. Excessive noise production is comparably rare.

Ground opening
Should you suspect a ground connection to import noise prove it by measurement. It is, by the way, illegal to open ground connections.

Star ground
The star ground is a Safety measure.
It has nothing to do with EMC.

Cable screens and expensive filters
Screens and filters need to be engineered for the application.
A lot of money is wasted in this domain.
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Part 2 Conducted Noise

- Common & Differential Mode
- Conversions
- Suppression Levels & Methods
- Shorting Common Mode
- Origins of common mode
- Filters, baluns, ununs & and symmetric lines
Cables bring "conducted noise"

**Near fields** end up mostly as "common mode"
- along cable trays
- by passing in the vicinity of alternating magnetic fields
- Transients generated by power cuts and short circuits

**Far fields** are a local disturbance with limited impact
- mobile telephone, TETRA, remote controls
- particle showers
- all radiated noise (corona, ringing, RF-leakage)
Cables transport (almost all the) noise

Cables not only deliver power and signals

Cables conduct noise from and to equipment

Cables pick up noise under certain conditions

Cables radiate noise (mostly near-field)

Cables also may generate noise
Common and Differential Mode

One of the ways to explain common mode, and its cancellation by a transformer.
Common and Differential Mode on the Oscilloscope

Upper tracks: Common mode displayed as voltage on two different conductors of the same circuit.

Lower track: By subtracting one voltage from the other (like a transformer, or an OpAmp do), the common mode disappears and the differential mode remains as result.
Common Mode (CM) passes through ground

Differential Mode (DM) remains inside circuit.
Origins of common mode

Magnetic near fields (transient or permanent)
- a) close to power lines
- b) inside magnets, close to the air gaps
- c) action of power cuts

Parallel cabling (or detector channels):
Coupling impedance makes energy to leak out of one cable, and to sneak into the next.

Specific common mode generators such as SMPS:
- SMPS generate common and differential mode
  Lack of symmetry in symmetric lines generates common mode, so does bad cable termination

In general we say:
- Truly symmetric lines
- Low noise generation

Unavoidable common mode requires:
- Adequate common mode immunity and adequate common mode return paths
Common mode – electronics vs EMC

Electronics usually talks about voltages.

Common mode in electronics suggests a voltage common AND IN PHASE with signal and return.

Common mode (voltage) does not appear at the output of an OpAmp. The CMRR is given in dB.

In EMC common mode is a current, i.e. its source impedance is high.

Common mode travels on all conductors according to their impedance with respect to the common return: the CBN.

Common mode cannot be rejected because it acts like a current source. Either you do not generate it, or you deviate it to paths less sensitive to parasitic currents: The CBN. Or the local loop.
**Induced Common Mode**

**Origin of induced common mode:**

- Induction

**ELF cabling, transformers or chokes induce voltages COMMON to all surrounding conducting elements.**

**The effect depends on the load and the degree of asymmetry in 3-phase networks.**

**Induction cannot be battled much by cable shields.**

Either one leaves the induced voltage "standing" (no current) or one installs additional conductors (e.g. a good CBN) that make loops. The loop currents oppose the field and thereby cancels it.

Please do not confuse ELF common mode with anything else. Refrain from voltage measurements in a perturbed system, especially voltage to ground. Determine the exciting field, then decide how to get it off your system.
**Common to Differential Mode Conversion**

Even without considering Cstr1/2 the slightly different cable lead impedances $Z_{c1,2}$ provoke differential signals in presence of common mode noise sources. Stray (or amplifier input) capacitances Cstr1,2 of again different values aggravate the situation.

Elimination: When dealing with RF symmetrization has limits inherent in circuit design. Additional shielding+filtering remains the only alternative.
Any imbalance causes the noise voltage to appear as part of the signal. In EMC language: We face a (partial) common to differential conversion. Noise voltage, impedance and frequency range are unknown.
ELF stray field added to CM

Without CBN the induced voltage will drive a loop current from the instrument via both lines and the other noise source, whatever it might be. No earthing will help, no shielding, no filter.

Lowering or cancelling the magnetic field is possible by using a circuit independent low impedance loop. Or a good CBN assuming the same job. Best: A metal plate.
Common mode decreases substantially when shorted together between cable screens. Screen currents resulting from this action should not run close to, or, worse, into the electronics.

Length behind grounding should be kept as short as possible.
Screen connections done properly

High frequency tight screen connections are laborious – but good. The pigtail is not a good solution.

Example of a so-called EMC-cable for optimum protection and minimal transfer impedance.
Pigtails versus coupling

Coupling of various lengths of pigtails.

Coupling of a properly connected coaxial line.

Coupling of an open wire.
**Common mode from UPS**

UPS convert battery power into three phase AC.
Conversion technology:
Power semiconductor switches, followed by filters.

UPS need to comply with EMC-Directives. Coverage starts at 9 kHz. So they usually operate at 8 kHz. Common mode exhibits fundamental and harmonics of 8 kHz. These frequencies are very difficult to filter because of bulky components.
EMC Filters need engineering

Filters cannot make disappear anything. Noise energy filtered must be put somewhere.

Choice of filter depends on electrical parameters

- Voltage
- power
- short-circuit withstand
- number of leads

and EMC-parameters

- Frequency range
- required damping
- CM, DM or combined noise source
- Common bonding network
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Part 3 Radiated Noise

• Fields, field strengths, field measurements, field probes, antenna factor
• Theory of screens
• Practical methods of (good) screening
• Screening of ELF magnetic near fields
Intentional EM fields

Inside physics laboratories strong RF-fields from outside are rare. However, we generate tremendous near-field background.

ERP = effective radiated power [W]
Fields close to objects

Near Field versus Far Field

\[ \log Z_w \]

120\(\pi\)Ω

Near Field

Far Field

Log \(r\)

\[ \lambda/2\pi \]

Electric source

Magnetic source

\[ Z_w = |E|/|H| \]

\[ r_o = 2\pi r/\lambda \]

Magnetic source

Electric source

\[ Z_w = 120\pi r_o / \sqrt{r_o^2 + 1} \]

\[ Z_w = 120\pi \sqrt{r_o^2 + 1/r_o} \]
Building Attenuation

![Diagram of building attenuation over frequency bands]

**NOTES:**
1. Buildings surveyed are business-type, with metal girders.
2. Suggested extrapolation for E field attenuation—H-field attenuation decreases significantly below 1 MHz, to approach 0 dB around 10 kHz.
The Faraday Cage and its derivatives

The Faraday cage can do a lot but not everything.

**Main features:**
- Attenuation vs. frequency (80 dB typ.)
- Cable feed-throughs with 80dB filters
- Ventilation ducts
- Wall material
- Door technology
Every magnetic circuit running AC has a stray field (also called fringe field).

For power conversion 50 Hz, its harmonics, and for switch-mode conversion frequencies from 25 kHz to more than 1 MHz are used.

Cables running through such stray fields cannot be screened because these frequencies penetrate into the cables.

Similar fields are issued by AC-coils, power cables, UPS, SMPS.

Transient fields of similar shape are caused by lightning, switch actions and short-circuits.
Means against Dynamic Magnetic Near Fields (ELF)

**Equipment or cables placed into the field volume are subject to induction.**
The voltage induced is a function of magnetic flux density, frequency and the loop surface.

Cable screens do not help against induction, except they are allowed to form a loop that is strong enough to create a counter-field.

**Three ways exist to lower the effect:**

1) **Shorting by loops.** Loops carry current, the current causes a field opposing the exciting one.
2) **Field conversion into heat.** Metal is placed into the field. Eddy currents convert the field into heat.
3) **Avoid currents driven by the induction.** All loops are kept open, all cables are twisted pairs.
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- Coupling impedance
- Kind of screen
- Screen density
- Screen cross section
- Nr. of twists per unit length
- Characteristic impedance/termination
The current on the screen is related to the voltage on the conductor by an impedance that varies over frequency:

\[ Z_T = \frac{V}{I \cdot L} \quad (\Omega m^{-1}) \]  

The voltage resulting from the screen current will be superimposed to any other voltage present on the cable.

The return of a coaxial cable is the screen.

A noise related change of the screen current will add the noise to the signal.
**Coupling Impedance: char. values**

Impedance is given per unit length.

The impedance of the connectors needs to be added.

The way the connectors are mounted is detrimental to the final transfer impedance.

Open screens are not discussed because the signal return then takes the same path as all common mode.
**Coupling Impedance: connectors**

Connectors often dominate the coupling impedance, especially for short cables.

<table>
<thead>
<tr>
<th></th>
<th>DC to 10MHz</th>
<th>100MHz</th>
<th>1,000MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BNC connector</strong></td>
<td>1 to 3 mΩ</td>
<td>10 mΩ</td>
<td>100 mΩ</td>
</tr>
<tr>
<td><strong>N or SMA (threaded)</strong></td>
<td>&lt; 0.1 mΩ</td>
<td>1 mΩ</td>
<td>10 mΩ</td>
</tr>
<tr>
<td><strong>Ordinary MultiPin Connector</strong> (metallic shell, just pluggable, or non-threaded bayonet style)</td>
<td>10 to 50 mΩ</td>
<td>10 to 50 mΩ</td>
<td>300 mΩ</td>
</tr>
<tr>
<td><strong>Pigtail, 2.5 cm</strong></td>
<td>Z = 1.5 mΩ + j. 0.15Ω x FMHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The LEMO connector is not mentioned because it was never made for analogue signals.

The "ordinary multi-pin" corresponds to our Burndy connector.

The pigtail describes a looping wire connection of the screen.
This comparison is shown because at low frequencies all cables show increasing transfer impedance, owing to the magnetic field penetration of the screen material.

"1 Ohm/m" means that 1mA of screen current will add 1mV/m to your signal.

1: single mesh
1a: optimized single mesh
2: Aluminium/Mylar foil
3: massive copper
4: double mesh
5: optimized double mesh
5a: triple mesh
6: double mesh plus single $\mu$-metal layer
7: triple mesh plus double $\mu$-metal layer
Kinds of screens (shields)

The screen (shield) must match requirements. See coupling impedance and screen currents to expected.

Screens without ferromagnetic materials will not cope well with low frequency exposure.
Screen density (coverage)
Screen cross section

Very good RF screen design
foil for 100% coverage, braid for return current (low Zt)

CERN: I never saw a screen specification.

The overall cross section of the braid determines the coupling impedance.

CERN special cables, with shield or even with double shield:

It is highly recommended to know or calculate the required EMC parameters. The purpose of the screen must be known prior to ordering.
Looking at a perfect cable, connected in perfect symmetry, the diff. transfer imp. rises with frequ. (meas. by Charoy):
Twisting has its limitations, entails some cost and does not solve everything. Low and also too high frequencies remain problematic...

Curves are applicable under the assumption of perfect circuit symmetry.
## Coupling impedance

Noise source: parallel unscreened cable running 0.6 Amps sine wave in the kHz range (simulated switching power supply noise without harmonics of switching frequency).

Coupling: Primarily inductive near field coupling.

### Cable noise performance

Cable noise performance depends very much on how it is used.

<table>
<thead>
<tr>
<th>Screened twisted pair</th>
<th>0 dB (reference)</th>
<th>63 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>100Ω</td>
<td></td>
<td>77 dB</td>
</tr>
<tr>
<td>100Ω</td>
<td></td>
<td>70 dB</td>
</tr>
<tr>
<td>100Ω</td>
<td></td>
<td>55 dB</td>
</tr>
<tr>
<td>100Ω</td>
<td></td>
<td>28 dB</td>
</tr>
<tr>
<td>100Ω</td>
<td></td>
<td>13 dB</td>
</tr>
<tr>
<td>100Ω</td>
<td></td>
<td>0 dB</td>
</tr>
</tbody>
</table>

- **Coaxial cable**

<table>
<thead>
<tr>
<th>100Ω</th>
<th>1 MΩ</th>
</tr>
</thead>
<tbody>
<tr>
<td>100Ω</td>
<td>1 MΩ</td>
</tr>
<tr>
<td>100Ω</td>
<td>1 MΩ</td>
</tr>
<tr>
<td>100Ω</td>
<td>1 MΩ</td>
</tr>
</tbody>
</table>

- Full pickup (reference)
- Full pickup (magnetic near field cannot be screened)
- Current via screen (coupling impedance)
- No pickup on screen (no current via screen)
- No current on screen but no symmetry either same
- Current via screen and one leg
- No screen current (full CMRR) same but better screen
- Screen current but cancelled

Screen pickup partially cancelled
In terms of high (radio) frequency each cable has a characteristic impedance.

This impedance should have an ohmic value and remain constant over the cable's operating frequency range.

The impedance is a function of cable materials and geometry.

Damaged cables (squashed, kinked, scratched, pulled) alter their impedance locally.

Characteristic impedance, termination

\[
Z_0 = \sqrt{\frac{R + jwL}{G + jwC}}
\]

Equivalent circuit per unit length

- \( R \) is resistance of wire/track
- \( L \) is the inductance
- \( C \) is the capacitance
- \( G \) is the conductance of the dielectric
Electricity: 
The voltage is kept constant. Also the source impedance. The load impedance varies. It is given by the load.

Radio Frequency: 
Voltage and current vary with power but the IMPEDANCE is kept constant. The impedance is inherent in all high frequency cables.

Termination: 
The load impedance should be equivalent to the cable impedance and should not exhibit capacitive or inductive elements.

EMC: 
When termination is different from the above ringing will occur. The cable "generates" noise.
Ringing on high frequency cables (electrically speaking: "transmission lines")

Cables react in the same way. Once the termination deviates from the characteristic impedance, energy gets reflected and bounces on the cable, generating noise, losses, signal degradation and more crosstalk.

Quality assurance:
Cables with badly mounted connectors, cables that are destroyed by pulling or plying, by squashing and by corrosion are no more transmission lines with constant impedance but instead show impedance deviations, all with the abovementioned consequences.
Ringing on high frequency cables (example for long cables)

Shorted (or open with inverted polarity, or badly matched) coaxial cables will provoke reflection and superposition of waves.

Badly mounted connectors make the cable appear as either open, or shorted, or badly matched.

RF work needs high quality, 360 degree screen connections into connectors matching the cable.
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- Cable “mechanics”
- Parallel Cabling
- Cable Screens
- Cable geometry vs. EMC-behaviour
- RF: Cable termination
Cable “mechanics” and EMC

**Improved EMC by**
- a) cable bending radius within manufacturer’s specifications
- b) mating connectors
- c) physical separation of signal & power

**Diminished EMC by**
- d) Reeling
- e) sharp bends or squashing
- f) disconnected screens
- g) wide area loops in circuit
Exposure of cables to ambient noise

Configuration for zero screen current and immunity against even very severe noise, including ELF.

Normal configuration. Screen can carry some current coming from external sources, such as induction. The coupling impedance $Z_t$ describes the amount that is transferred to the inner conductors.
Cable “mechanics” and EMC

Example of metallic cable tray with proper separation of power, controls and measurement cables.

EMC performance can be dramatically improved by vertical metallic separation walls between services.

Câbles de puissance

Fils de contrôle-commande

Conducteurs de mesure avec écran

$d =$ quelques centimètres
Once you have a given cable:  
It's the **distance from a conductive surface** that determines how well external fields may be attenuated.  
Don’t forget about conversions...

**Flying cables**

**Note:**  
Below 1 MHz currents induced into ground loops dominate for cables far from conductive plane.  
Above 1 MHz the difference disappears.
Leads of symmetrical cables should have equal impedances to ground. They never have.

**Symmetric lines**

**Note:**
Below 10 MHz shield currents and asymmetry dominate over geometry. Above 10 MHz the difference disappears.
Open (unused) conductors

It is unsafe and very bad in terms of EMC to have loose conductors.

Unused cables or conductors need to be earthed at both ends.
Both ends of the screen: Earth!

Screen earthing on one end kills high frequency shielding.
Attention: The open screens have surprising antenna effects.

Multiple screen earthing onto metal plates has maximum EMC effect reaching beyond 200dB of noise damping.
Both ends earthed against one end

The loop area of a cable earthed on one end is equivalent to the loop area of an unscreened cable.

In addition a cable with one earthed end acts as a perfect antenna for wavelengths about 4 times its (electrical) length, plus all odd harmonics.

Further consequence: In the event of a powerful transient there is an efficient energy transfer into the cable and connected electronics, causing malfunction or destruction of components.
Multiple Screen Earthing

In the case of multiple screens at least one screen needs to be earthed on both ends. The inner screens can now be used to suppress crosstalk or as guard-shield to compensate leakage currents.
Cables connected to enclosures

Common mode generation by improper screen connections
Proof of the bad effects of open grounds

Example of a CERN group that fights noise by opening cable screens because they believe in "different grounds".
Proof of the bad effects of open grounds

Some transient event burnt the weakest point by causing an arc!
Proof of the bad effects of open grounds

The same transient also burnt capacitors etc.:
ALL THIS BECAUSE THE EXISTING CBN IS NOT PROPERLY USED, PLUS TECHNICAL CHOICES ARE BAD.
Sensitive Cables

Sensitive cables (we have no identification for this in the cablothèque) need to be put into the corner of continuous metallic cable trays. Cable trays must be interconnected, but not only by a PE-conductor.
Cable trays should be continuous metalwork (and not meshes, or interrupted, or "just ladder mechanics"). Best protection: Iron tubes for extreme EMC troubles, such as pulsing.
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Part 6 Cables as part of equipment and installations

- Principal cable types
- Cables for sensors
- Cables for chambers and vacuum
- Special EMC cables and "CE" conformity
- The forgotten cable parameters
Cable types

• Power cables (not treated here)
• Coaxial/triaxial/screened twisted pair
• Control cables
• Application specific cables (e.g. telecom, welding, physics apparatus, radiation tolerant, high voltage other than power)
• Cables inside equipment
Coaxial: The screen carries the signal return.
Triaxial: The inner screen carries the signal return, the outer screen carries inflicted noise currents.

Alternating magnetic near fields: None of the two cable types is able to suppress these. Allow for standing voltages in the ELF domain.
BNC (and all single ended coaxial connectors)

Grounded or insulated: Screen and signal return use the same path

Screen currents (wherever they come from) mix with the signal return.

CM to DM conversion because screen impedance different from centre conductor impedance
Grounded or insulated: Screen and signal return are now separated

Screen currents (wherever they come from) cannot mix with the signal return.

CM to DM conversion avoided. Also leakage currents when using guard conf.
The main purpose of a guard shield (screen) is to avoid leakage between cable inner conductor and shield, especially in case of high source impedances. The guard buffer provides compensation of the leakage current.
At CERN we do use plenty of shielded cables with a second common external shield.

A common external shield does not allow its use as a guard shield, also for Safety reasons.

Guarded cables must be used only in single cable configuration with a possibility to earth the outer shield.
The guard shield (screen) compensates the leakage between cable inner conductor and shield. Here $R_m$ is measured, which gives $R_s$ by subtracting $R_m$ once disconnected. Voltage across $RL$ is zero.
Measurement of Cable Leakage

RL becomes accessible once you know RS.
RL changes when cables become old or irradiated.
Ionisation chamber with and without Guard

Circuit below compensates cable leakage.
Attention: One cable screen is on high voltage.

EMC: Guarded configuration is more robust against ambient noise.
High impedance voltage source with leakage compensation. All leakage compensation circuits become very problematic when voltages other than DC provoke ringing, phase shifting and even oscillation.

EMC:
Make sure that the CBN is of sufficient quality for the desired frequency range.
Measurement error through shunt impedance

Voltmeter input impedance causes source voltage to be displayed erroneously.

**EMC:**
One may work without shield.
In this case it is advisable to precisely know what could be picked up by the connecting cable.

Do not forget the frequency response of the voltmeter.
Do not assume insulation to be perfect (the stray capacitance is never zero).
Cable leakage introduces measurement errors.

**EMC:**
The cable shield may carry currents that do not belong to your measurement system. They couple into your measurement system via the coupling impedance, which is one of the cable parameters.

\[
V_M = V_S \left( \frac{R_L}{R_S + R_L} \right)
\]
VSD controllers must be **connected in agreement with their conformity documents**. Often the cabling (cable type, max. length, distances to other cables) is directly specified.

The screen continuity is integral part of routing the common mode back to the source ("close the loop"). In case of earthing on the motor side the "PE" network will carry part of the common mode. Order of magnitude: several mA per installed kVA.
All those cable trays are correctly cross-bonded together at every opportunity, including bonding them to the cabinets at both ends, to cost-effectively create the most closely-meshed three-dimensional CBN possible from the existing metalwork.
**Summary on cables**

Below 1 kHz cable screens become transparent for ELF

Perpendicular crossing: almost no influence

Parallel cables: Magnetic and capacitive coupling, screen leakage coupling

Screened cables: Watch out for transfer impedance. It defines the quality.

Minimum bending radius: Do not kink cables. Especially RF cables.

Characteristic impedance: Valid for RF-use. It defines voltage-to-current ratio.

Twisted pairs: Cancel interference through induction. Usually symmetric arr.

Symmetric lines: Impedance of leads to earth equal and relatively high.

Loop: Return is not routed down the same path.

**EMC:**

Use cable screens properly. Connect on both ends.
Second shield: Use either for GUARD or for breaking crosstalk.
Do not leave ANYTHING open.
### End of main part

What I left out:

- ESD
- Equipotentiality
- Lightning and other transients
- EMC standards and test procedures

**Still on board in case the audience agrees:**

*Eurolex, Procurement, Equipotentiality and three words on cable chemistry*
Part 0  Some Prerequisites
Part 1  Desired cable properties
Part 2  Conducted Noise, Filters
Part 3  Radiated Noise and screening
Part 4  EMC relevant cable parameters
Part 5  Cabling
Part 6  Cables as part of equipment and installations
Part 1x European Cable Classification
Part 2x Cable Procurement
Part 3x Equipotentiality
Part 4x Cable Chemistry
Part 1x European Cable Classification

• Construction Product Regulation
• Cable certification
• Cables that do not need to certified according to the CPR

EN 50575:2014
Power cables and electric power lines, control and communications cables – cables and lines for general use in construction works as far as concerns the requirements in terms of fire reaction.

EN 13501-6:2014
Classification of construction products and building elements according to their fire reaction - Part 6: Classification using data from reaction to fire tests on electric cables.
**EUROLEX "CPR" – cable classes**

<table>
<thead>
<tr>
<th>Main class</th>
<th>Additional class</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A&lt;sub&gt;ca&lt;/sub&gt;</strong></td>
<td>Heat release</td>
</tr>
<tr>
<td><strong>B&lt;sub&gt;1&lt;sub&gt;ca&lt;/sub&gt;&lt;/sub&gt;</strong></td>
<td>Heat release, Flame propagation</td>
</tr>
<tr>
<td><strong>B&lt;sub&gt;2&lt;sub&gt;ca&lt;/sub&gt;&lt;/sub&gt;</strong></td>
<td>Flame propagation</td>
</tr>
<tr>
<td><strong>C&lt;sub&gt;ca&lt;/sub&gt;</strong></td>
<td></td>
</tr>
<tr>
<td><strong>D&lt;sub&gt;ca&lt;/sub&gt;</strong></td>
<td></td>
</tr>
<tr>
<td><strong>E&lt;sub&gt;ca&lt;/sub&gt;</strong></td>
<td>Flame propagation</td>
</tr>
<tr>
<td><strong>F&lt;sub&gt;ca&lt;/sub&gt;</strong></td>
<td></td>
</tr>
</tbody>
</table>

- **s1a**
- **s1b**
- **s1**
- **s2**
- **s3**
- **d0**
- **d1**
- **d2**
- **a1**
- **a2**
- **a3**

**Smoke generation**

- **Flaming drops**
- **Acidity of gases**
European Cable classification EN13501

EN 13501 shows the test methods and performance criteria for a cable to meet a particular classification (Aca, B1ca, B2ca, Cca, Dca and Eca.)

**Burning behaviour of bunched cables – Scenario 1 (EN 50399)** –
Contribution of a cable to the early stages of development of a fire, under direct exposure to a 20.5 kW flame source.
Classes B2ca, Cca and Dca.

**Burning behaviour of bunched cables – Scenario 2 (EN 50399)** –
Contribution of a cable to the early stages of development of a fire, under direct exposure to a 30 kW flame source. For class B1ca only.

**Burning behaviour of single cables (EN 60332-1-2)** -
This test evaluates the flame spread of a cable under exposure to a small flame. The test is relevant for the classes B1ca, B2ca, Cca, Dca and Eca.

**Smoke production of burning cables (EN 50268)** -
This test evaluates the potential contribution of a cable to obscuration of vision when burning under static air flow conditions. The test is relevant for the classes B1ca, B2ca, Cca and Dca, in association with the additional classification for smoke.

**Acidity levels produced by burning cables (EN 50267-2-3)** -
This test evaluates the potential contribution of burning cable materials to the hazardous properties of evolved gases. The test is relevant for the classes B1ca, B2ca, Cca and Dca, in association with the additional classification for acidity.

**Heat of combustion test (EN ISO 1716)** -
This test determines the potential maximum total heat release of a product when completely burning, regardless of its end use. The test is relevant for the class Aca.
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Part 3x Equipotentiality
Part 4x Cable Chemistry
Part 2x Cable Procurement

- Safety: IS23 (halogen free, smoke limits, flame retarding, radiation tolerance)

- Technical parameters: geometry, impedances, insulation, environmental impacts

- Traditionally missing parameters: copper quality, screen quality (transfer impedance vs. frequency), ban of certain elements (rad. waste production), polymer quality
What does CERN get?

CERN thinks it gets what it orders:

- Halogen free, flame retarding cables that fulfill some electrical requirements

The reality is a bit different because:

- CERN does not perform any technical check
- CERN allows direct orders from retailers
- Equipment cables are accepted as they are
Areas of possible improvement

Better specifications for the large contracts

Material check of all batches upon arrival

The material check would include

• Chemical analysis
• Quick test of fire behaviour
• Ageing test for 42 days as suggested by standards

Tests could run in parallel with storage.
CERN should have the right to return cables that do not pass
Loss increase through contamination

The copper quality is essential for losses on power cables.

A relatively low contamination brings relatively high losses and, for certain elements, long-lived radioactive waste (e.g. lead and iron isotopes).
Part 0  Some Prerequisites
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Part 3x Equipotentiality

- Earthing - and Loops
- Grounding - and Loops
- (Protective) Earth in Buildings
- Power Return vs. Grounding
- Local Ground Reference
- Common Ground Interference (CGI)
We follow the standards.
We do not follow the religions of equipment insulation, separate earthing, broken Faraday cages, wild cabling, open loops and fear of ground currents.

Following a religion will work in some cases but you will not have full equipment protection and Safety of personnel in case of emergency.
Bonding – the first step to true equipotentiality

Bonding is the practice of connecting all accessible metalwork – whether associated with the electrical installation (known as exposed metalwork) or not (extraneous metalwork) – to the system earth.

Sufficiently dense mesh bonding leads to equipotentiality, depending on mesh size and earth currents.
The false ("raised") floors
When installed correctly false floors act as meshed networks. They provide perfect equipotentiality into the MHz-range.

Racks, cable trays and (outer) cable screens may and should be connected to this mesh.
Why all this bonding?

The more you bond the more leakage and fault current will go away from sensitive equipment, and the more protection is achieved.

Good ground loops are needed and recommended:

Good ground loops close via structures and PE-conductors, racks, massive metal, tanks.

Bad ground loops close via screens that are signal returns, across PCB's, across communication lines.

Bad ground loops need to be avoided.
Ground has many appearances:
Protective earth, metallic structures,
vehicle body, screen connection,
analogue ground, digital ground,
ground plane, PE, CBN, building ground,
chassis ground.

Ground is always a reference common to more than one circuit.
Its purposes:
Equipotentiality
Routing noise back to source "close the loop"
Cancel inflicted magnetic fields and transients
To be avoided:
Ground as signal return
Emergency Bonding (and Earthing)

Bond together objects for mutual Safety.

System avoids sparks, discharges, danger to people

Earth rod only gives ESD Safety, nothing else

Connection to electrical network possible

Follows the general idea of a common bonding network.
No circuit needs to be earthed (grounded) in order to work.

Earth (American: ground) cannot swallow noise.

The Faraday cage does not depend on an earth connection.

Star earth, even more star earth over long cables, has no value in well bonded installations. In badly bonded installations, and only for very low frequencies, the star earth may lower the effects of induction. Capacitive coupling completely annihilates the star earthing idea at higher frequencies. Any noise generated will be "seen" by all neighbours. Such fundamental layout errors are difficult to cure.
CERN kickers use high transient currents originating from discharges. Peak currents reach many kiloAmpères.

Part of the return current runs through the (locally re-enforced) accelerator CBN.

We expect (and see) common mode transients in CBN and all cabling.
Tolerable noise between equipment

In case of trouble over the limit $B$, improve the equipotentiality of the installation.

In case of trouble below the limit $A$, improve the immunity of sensitive equipment.
Impedance of a meshed network

For a conductor, the impedance between the ends increases as its length.

For a 2D grid, the impedance between 2 points does not depend on their distance.

For a 3D grid, the impedance between 2 points decreases with the size of the structure!...
Maximum current in a meshed network

Current for a 1 V maximum common mode noise

Zone of usual total leakage currents for a 10MW installation

Zone of usual CM currents of a large variable speed drive (100kW inverter)

- Current in a 1 m x 1 m grid
- Current in a 2 m x 2 m grid
- Current in a 5 m x 5 m grid
Current required for a 50 V maximum common mode voltage, i.e. the maximum voltage permitted during a transient caused, e.g., by a fuse action or short circuit condition in a sub-station. This corresponds to the maximum voltage between two metal objects that you can touch simultaneously.
Part 4x Cable Chemistry

• Materials – insulation properties
• Jacket Polymer
• Insulation Polymer
• Ageing factors
• What can be predicted today using which tests?
Dielectrically properties of different materials

- Teflon
- Sapphire
- Polystyrene Polyethylene
- FR-4
- Epoxy Board
- Paper
- Ceramics
- Nylon
- PVC
Main Material Properties

Insulating Material:
- FR-4
- Epoxy Board
- Paper
- Teflon
- Ceramics
- Nylon
- PVC
- Sapphire
- Polystyrene Polyethylene

Volume Resistivity (Ω-cm):
- $10^8$
- $10^9$
- $10^{10}$
- $10^{11}$
- $10^{12}$
- $10^{13}$
- $10^{14}$
- $10^{15}$
- $10^{16}$
- $10^{17}$
- $10^{18}$
Material behaviour "under stress"

<table>
<thead>
<tr>
<th>Material</th>
<th>Volume Resistivity (Ohm-cm)</th>
<th>Resistance to Water Absorption</th>
<th>Minimal Piezoelectric Effects&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Minimal Triboelectric Effects</th>
<th>Minimal Dielectric Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teflon® PTFE</td>
<td>$&gt;10^{18}$</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Sapphire</td>
<td>$&gt;10^{18}$</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>$10^{16}$</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>$&gt;10^{16}$</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Kel-F®</td>
<td>$&gt;10^{18}$</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Ceramic</td>
<td>$10^{14} - 10^{15}$</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Nylon</td>
<td>$10^{13} - 10^{14}$</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Glass Epoxy</td>
<td>$10^{13}$</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PVC</td>
<td>$5 \times 10^{13}$</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

**KEY:**
- + Material very good in regard to the property.
- 0 Material moderately good in regard to the property.
- - Material weak in regard to the property.
Polymers in Cable industry

More than 1 500 000 MT of polymers and compounds are consumed by cable industry in EU annually.
Cable jackets

Main functions of Cable jackets are:

- Protection of cable from chemical environment
- Moisture barrier
- To carry out mechanical stress during installation and handling
- Flame protection
- UV protection
Main function of Cable insulation is:

- To provide the dielectric barrier between conductors
# Polymers used in cable industry

<table>
<thead>
<tr>
<th>Polymer type</th>
<th>Where can be used</th>
<th>Nominal Temperature Ratings</th>
<th>Fire Resistance</th>
<th>Chemical Resistance</th>
<th>UV Resistance</th>
<th>Durability</th>
<th>Flexibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE (Polyethylene)</td>
<td>Insulation, Jacket</td>
<td>-50°C to 80°C</td>
<td>E</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>EVA (Ethylene-vinyl acetate)</td>
<td>Insulation, Jacket</td>
<td>-20°C to 125°C</td>
<td>P</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>E</td>
</tr>
<tr>
<td>EPDM (Ethylene Propylene Dimethyl Monomer)</td>
<td>Insulation, Jacket</td>
<td>-55°C to 125°C</td>
<td>P</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>E</td>
</tr>
<tr>
<td>PUR (Polyurethane)</td>
<td>Insulation, Jacket</td>
<td>-55°C to 80°C</td>
<td>P</td>
<td>E</td>
<td>E</td>
<td>G</td>
<td>E</td>
</tr>
<tr>
<td>TPR/TPE (Thermoplastic rubber/elastomer)</td>
<td>Insulation, Jacket</td>
<td>-50°C to 105°C</td>
<td>E</td>
<td>F</td>
<td>E</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>PVC (Polvinylchloride)</td>
<td>Insulation, Jacket</td>
<td>-20°C to 105°C</td>
<td>E</td>
<td>F</td>
<td>E</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>Thermoplastic CPE (Chlorinated Polyethylene)</td>
<td>Insulation, Jacket</td>
<td>-20°C to 105°C</td>
<td>E</td>
<td>F</td>
<td>E</td>
<td>G</td>
<td>F</td>
</tr>
<tr>
<td>Many others</td>
<td></td>
<td>E = Excellent</td>
<td>G = Good</td>
<td>F = Fair</td>
<td>P = Poor</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Are mainly used at CERN*

*Can not be used at CERN due to regulation IS 23 (Halogen free)*
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<td>Nylon</td>
<td>$10^{13}–10^{14}$</td>
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<td>0</td>
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<td>−</td>
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</tbody>
</table>

**KEY:**

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− Material weak in regard to the property.
Cable ageing

By the influence of external factors cable are effected by ageing.

This process leads to:

- Decrease of mechanical properties
- Decrease of elasticity
- Cracking of cable
- Decrease of dialectical properties
- Necessity of cable replacement
Cable aging factors

Factors influencing on aging of cables

- Mechanical stress
- Chemical environment
- H$_2$O vapor
- O$_2$
- O$_3$

UV

Irradiation

Time
Additives are used while polymer processing

- Antioxidants
- Heat Stabilizers
- UV absorbers
- Anti Rads
- Impact modifiers
- Flame retardants

Polymer properties and lifetime

- Oxidation
- Heat
- UV
- Irradiation
- Mechanical stress
- Fire
Cable lifetime prediction

In order to predict life time of the cable that is used under certain conditions the following principles are used

- Condition monitoring by non-destructive methods
- Sampling of materials from an equipment deposit
- Modeling of the conditions by the ageing test
Cable lifetime prediction

In order to evaluate ageing stage the following methods are used:

- Tensile test
- Intender
- Differential Scanning Calorimetry:
  - Oxidation induction time (OIT)
  - Oxidation induction temperature (OITP)
- Term gravimetric analyses (TGA)
- Fourier-transform infrared spectroscopy (FTIR)
- Density Analyses