Chapter 16

Systems EMC

16.1 System versus product EMC

The title of this book is *EMC for Product Designers* and that is its primary focus. But many individual products, that is electronic equipment and apparatus, are actually put together in systems which are required to function as a whole. This then changes the EMC context. There are now two aspects to consider: the compatibility with each other of the various items of equipment within the system, which we can call *intra*-system EMC; and the compatibility of the whole system with its environment and with other systems and apparatus in that environment, which we can call *inter*-system EMC. A complete view must take into account both aspects.

Designers of products which are going to be used in this way need to be aware of the two aspects, as do the designers and installers of the systems themselves. A companion book to this one, called *EMC for Systems and Installations* [19], treats the subjects raised by EMC at this level in much greater detail, and the systems designer is recommended to that book for further reading. Meanwhile, this chapter will serve as an introduction to the issues that face systems designers, from the point of view of a product designer whose projects must be capable of installation and interfacing at the systems level. Some of these issues have to do with the EMC compliance of the whole system, but more of them are related to interactions between equipment that may be installed either in close proximity or in different locations, and which therefore require EMC precautions that go beyond simple compliance.

16.1.1 Compliance requirements

As we have seen in Chapter 2, the 2nd edition EMC Directive noticeably extended the requirements that apply to fixed installations. The substantive requirement is:

> A fixed installation shall be installed applying good engineering practices and respecting the information on the intended use of its components, with a view to meeting the protection requirements. These good engineering practices shall be documented and the documentation shall be held by the responsible person(s) at the disposal of the relevant national authorities for inspection purposes as long as the fixed installation is in operation.
>
> – [194] Annex 1(2)

To help to meet this requirement, whenever practicable the project manager, system designer or installation engineer should use recognized practices and procedures for EMC as given in international, European or national standards, technical reports, specifications or codes of practice. There aren't that many of them, but this chapter makes reference to the few standards that exist and discusses some of the methods recommended by them.

16.1.2 Functional requirements

Irrespective of the need for compliance with external compatibility legislation, a system or installation must actually work properly. Part of this is that its sub-systems should not interfere with each other. Issues arise when equipment either is located in close proximity to disturbance sources or victims, or is subject to disturbances which are developed in other parts of the installation and unintentionally coupled in by structural components. Under these circumstances, the construction of the interconnections and layout within a system becomes important [38][67]; earthing, bonding and cable layout must be designed rather than allowed to go by default, and they should be designed to separate the unavoidable interference currents from the required functional interfaces.

The installation techniques described in this chapter can be regarded as best practice. Nevertheless, it is still true that the best equipment design will be one which puts fewest restrictions on earthing, cable routing and separation – i.e. one where the major EMC design measures are taken internally. There are many application circumstances when the installation is carried out by unskilled and untrained technicians who ignore your carefully specified guidelines, and the best product is one which works even under these adverse circumstances.

16.2 Earthing and bonding

16.2.1 The purpose of the earth

In a system context we can identify four purposes for earthing.

16.2.1.1 Safety earth

The purpose of the safety earth is to guarantee personnel safety under fault conditions. The IET Wiring Regulations (BS 7671, [207]) define "earthing" as:

> Connection of the exposed conductive parts of an installation to the main earthing terminal of that installation.

Earthing provides a low-impedance path in which current may flow under fault conditions. Exposed conductive parts are those conductive parts of equipment which may be touched and which may become live in the case of a fault. The earthing connection prevents such live parts from reaching a hazardous voltage. The protective conductor (typically colour coded green-and-yellow) provides an electrical connection which maintains various exposed and extraneous conductive parts at substantially the same potential under both operational and fault conditions, and also connects the conductive parts to the installation's main earthing terminal. The prospective touch voltage within the installation is then the product of the impedance of the protective conductor and the earth fault current.

This creates a zone within which exposed and extraneous conductive parts are maintained at "substantially" the same potential. Although the voltages within such a zone may be safe, they are not necessarily, and not even usually, zero. Continuous currents from various sources, including equipment earth leakage, are likely to be flowing, even in a "healthy" circuit. (Allowable earth leakage levels from individual items of equipment are covered in section 14.2.3.3.) Such an "equipotential" zone may protect people but is not guaranteed to protect equipment or wiring.

Protection against electric shock is typically provided by earthing in conjunction with automatic disconnection of the supply. For this purpose, the protective device must be co-ordinated with the installation's earth fault impedance, to disconnect quickly enough to prevent the touch voltage from reaching a hazardous level. The sizing and hence resistance of the earth protective conductor will therefore be determined largely by the prospective fault current available from the rest of the system. Since the concern is low frequencies, it is resistance rather than inductance which determines the conductor impedance; this is not the case for high frequency earths.

16.2.1.2 Functional earth

For an electrical circuit to interface correctly with other equipment, there must be a means both of relating voltages in one equipment to those in another, and of preventing adjacent but galvanically separate circuits from floating.

This is the purpose of the functional earth, and it must be distinguished from the safety protective earth. Because of the threat of circulating currents and potential differences between earthing zones, there may be practical constraints on the widespread use of functional earthing on large systems, especially since there is normally no explicit requirement for conductor cross-section to maintain low impedance. Signal circuits of equipment should normally be specified for a maximum common mode voltage, which will be the voltage that appears between different parts of a functionally earthed system. If this is impractical or inadequate, isolated circuit interfaces are the normal solution.

16.2.1.3 Lightning protection earth

In building installations, a further important safety-related earthing function is to provide a return connection for currents induced by a lightning strike. In many respects this is the *only* correct use of the term "earth", since this function is normally provided by ensuring a low-impedance connection throughout the building fabric to the literal earth on which the building sits. Since lightning potentials are built up between the cloud structure of a thunderstorm in the atmosphere and the surface of the Earth, connection to earth is the correct way to complete the circuit in the shortest manner.

Standards for lightning protection have been published by the various standards bodies (e.g. IEC 62305) and you should look to these for detailed advice (Table 16.1). Section 16.6 reviews the main principles.

Table 16.1 Standards for lightning protection

	Protection of structure	**Protection of contents**	**Risk assessment**
IEC/ CENELEC	IEC 62305-3: 2010 EN 62305-3: 2010	IEC 62305-4: 2010 EN 62305-4: 2010	IEC 62305-2: 2010 EN 62305-2: 2010

16.2.1.4 EMC earth

The EMC earth has the sole purpose of ensuring that interfering voltages are low enough compared to the desired signal that incorrect operation or excessive emission does not occur [145]. It has no explicit safety or operational function. Because of this, and because of the wide frequency range over which it must work, earthing for EMC usually takes advantage of distributed structural components that are part of the whole system – typically, chassis members, enclosure panels and so on. The value of an EMC earth is directly related to its physical geometry. This means that design and implementation of an EMC earthing system is not restricted to the electrical engineering discipline alone – it must also involve constructional aspects, that is, the mechanical designers and installers.

16.2.2 Installation techniques for multi-purpose earthing

16.2.2.1 Three-dimensional meshed equipotential earth-bonding

The preferred earth-bonding method in buildings is the Common Bonded Network, or CBN, shown by Figure 16.1. Complex installations require an equipotential system

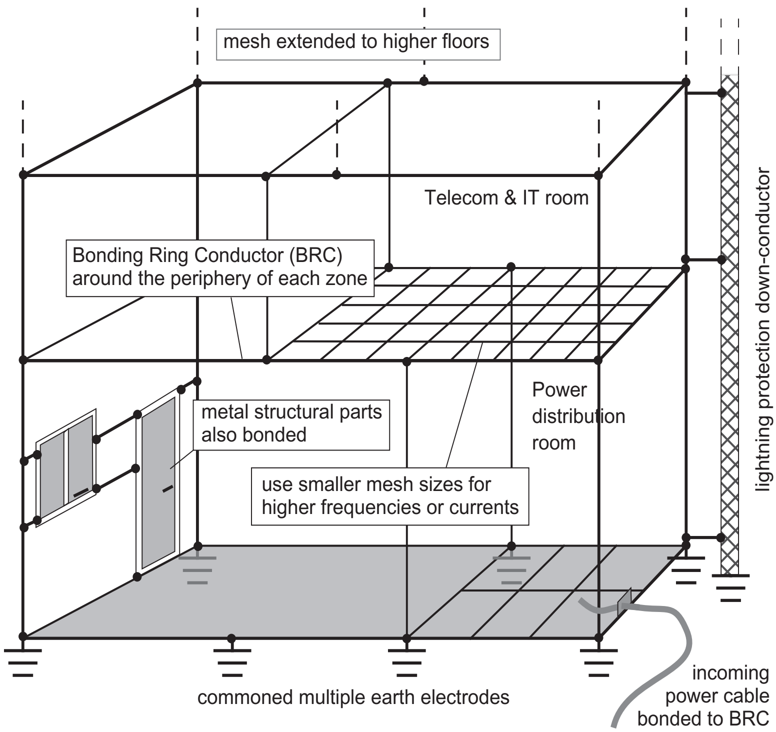


Figure 16.1 Common bonded network

meshed in three dimensions, often referred to as a MESH-BN (for Mesh Bonding Network). This bonds every piece of structural and non-structural metalwork together to make a very highly interconnected system, which is then connected to the lightning protection system (LPS) at ground level and possibly other floors. Whilst Figure 16.1 shows the application within buildings, the principle applies to an installation in any circumstances: aircraft, ships and vehicles should all follow a similar practice. For aircraft, DEF STAN 59-113 [220] provides a detailed set of design and test requirements for lightning protection in this environment, and FAA Advisory Circular 20-136B [234] gives management guidance.

This highly meshed three-dimensional system is then interconnected to the screens and armouring of all electrical cables, and the frames or chassis of every piece of electronic equipment. Where existing metalwork or conductors do not already exist, heavy gauge conductors are added to complete the mesh either vertically or horizontally so that nowhere is the mesh size greater than about 3 or 4m. The main earthing terminal for the incoming power supply to the building needs a number of bonds to the MESH-BN.

The MESH-BN gives safety, functional, and EMC earthing, all at the same time – an integrated earth-bonding system. With it you can achieve the various aims of safety, signal integrity, equipment reliability, and EMC, which are often seen as being in conflict, at reasonable cost in a reasonable time, without compromises, and without restricting future modifications.

Although each of the MESH-BN elements will resonate and disturb the earth bond at the resonant frequencies – refer to section 12.1.3.4 which discusses this phenomenon – its highly interconnected nature will ensure that there are alternative current paths that are not resonating, and so provide a high degree of equipotentiality over a wide frequency range. One consequence of this is that very regular bonding structures should be avoided, since all their elements would exhibit similar resonances at the same frequencies.

To limit voltage differences in the earth structure at higher frequencies for the same level of power, or at higher powers for the same frequency, the mesh size of the MESH-BN needs to be smaller. With the different types of apparatus having been segregated according to whether they are "noisy" or "sensitive", the building should then be partitioned into areas with different earth mesh sizes, depending on the earthing needs of each [173], as shown by Figure 16.1.

Note that each segregated apparatus area with its individual meshing or bonding is surrounded by a complete conductor. These are known as bonding ring conductors (BRCs) and protect the apparatus in an area against lightning transients, earth faults, and other low frequency surges originating outside of their area.

16.2.2.2 The bogey of ground loops

A common objection to the meshed earthing system is that it creates "ground loops" (equally known as "earth loops"). Historically, currents flowing in ground loops, and their associated driving potential differences across different parts of the earth network, have been found to be particularly serious contributors to interference problems, and therefore a practice has developed of trying to eliminate all such loops. This practice, although often superficially successful, is unfortunately misguided.

In a situation where high earth potential differences exist, closing a loop between two such earth points will allow a high current to flow in the structure. If the conductors in that loop include a segment which either forms part of, or is closely coupled to, a signal or low-level power cable, then substantial interference can be induced in the circuits of that cable. If the loop is opened, the current no longer flows, and the interference disappears – although the high potential differences remain, ready to create problems again when another loop is closed somewhere else. This is the principle which is formalized in the star or single point earth regime: remove all ground loops and live with the resultant high voltages between different parts of the earthing system.

Such an approach is fairly easy to implement and quite successful in simple low-frequency systems, but it represents a retreat from best practice. With interference frequencies measured in MHz rather than Hz, it is untenable. This is because the star earthing conductors present a high impedance to these frequencies and therefore *de*couple a system from earth, rather than couple to it. Also unfortunately, larger star systems tend to degenerate into accidentally ground-looped systems as time passes and systems and buildings are modified and added to, requiring a heavy management and control burden to maintain their efficiency and ensure safety and equipment reliability.

In these circumstances the only reliable earthing system is a mesh. The mesh does indeed provide a multiplicity of ground loops, but they are small and controlled: voltage differences between parts of the structure are minimized, resulting currents are low and the interference consequences, if any, are negligible.

16.2.3 Earth conductors

16.2.3.1 Short fat straps

Elsewhere in this book we have discussed the impedance of wires and structures (section 12.1.3.4). In the context of systems earthing, a number of points are relevant:

- any length of wire becomes predominantly inductive above a few kHz; short fat wires have a higher transition frequency than long thin ones;
- the inductive impedance of typical lengths of wire reaches ohms at around 1MHz, and tens of ohms in the tens of MHz range;
- the impedance of a length of wire connected at one end to an earth reference plane reaches a resonant maximum when its length is a multiple of a quarter wavelength, and falls to a resonant minimum at multiples of a half wavelength;
- the exact frequencies at which these resonant peaks and nulls occur are strongly affected by layout; if any of them coincides with a susceptible or emissive frequency of the equipment, surprising and unpredictable variations in equipment performance will be brought about simply by moving such a wire by a few centimetres.

The general rule with earth wires is: short fat straps have the lowest impedance, as suggested in Figure 16.2. But even short straps are not perfect. A tinned copper braid 10cm long by 9mm wide by 2mm thick, for instance, still has substantial impedance in the hundreds of MHz. Its merit is that those resonances which still exist are pushed much higher in frequency and exhibit a much lower Q, thus reducing their impact usually to negligible proportions.

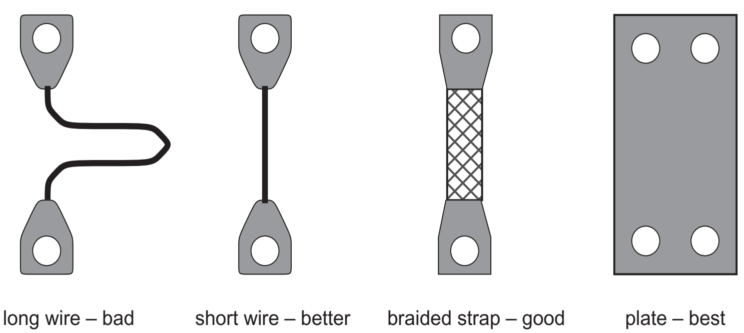


Figure 16.2 Hierarchy of earth conductors

16.2.4 Bonding techniques

The safety bond – a length of green-and-yellow wire interconnecting panel and frame, or different structural parts – is familiar to system builders. It is vital to realize that *this is not adequate* for EMC bonding. The purpose of a wired safety bond is to prevent different parts of the structure from assuming different potentials and hence presenting an electric shock hazard at power frequencies: it has no other purpose. It cannot give a low-impedance connection at RF.

This is not to say that the safety bond is forbidden for EMC purposes: it can coexist quite happily with a proper EMC bond. But the one is no substitute for the other. If you are intent on building an RF-adequate enclosure or structure, then full metal-to-metal connection at all joints is required:

- bonds are best made by surface-to-surface conductive contact at frequent intervals, or preferably continuously along a seam; "bonding" straps, although necessary in many circumstances and preferable to wire connections, are a second best option;
- bonding between parts requires removal of insulating layers, for instance paint or anodizing, and often the treatment of mating surfaces to ensure conductivity, for instance zinc plating or chromate conversion;
- positive pressure is required to make a bond; fasteners will provide this but usually the gap between two fasteners does not allow pressure to be maintained, hence the use of conductive gaskets;
- once a bond is made between two surfaces, it should be protected from corrosion by being made gas-tight or by applying some type of overall coating.

16.2.4.1 Bonding of equipotential mesh structures

As described in section 16.2.2.1, a three-dimensional earth structure is required to provide equipotentiality over a wide range of frequencies.

All structural metalwork and cable supports should be RF bonded across all their joints, and RF bonded between each other whenever they are close enough, to make a three-dimensional earth mesh. Plumbing, pipework, air ducts, chimneys, re-bars, I-beams, cable trays, conduits, walkways, ladders, ceiling supports, etc., should all be RF bonded, as shown in Figure 16.3. Building steel and reinforcing rods should have welded joints and a sufficient number of access points to them for frequent bonds to the earthing network to create the appropriate mesh size for the MESH-BN.

The length of the connection between a structural item and the common bonded network should not be more than 0.5m, and an additional connection should be added in parallel some distance away. Connecting the earthing bus of the electrical switchboard of an equipment block, or the earth bonding bar of a local AC power distribution cabinet, to the bonding network, should use conductors of under 1m length and preferably under 0.5m. Achieving good signal integrity and EMC performance at frequencies of 100MHz and above requires direct metal-to-metal bonds at multiple points, preferably seam-welded, for each joint.

16.2.4.2 Bonding cable trays and ducts

Galvanized cable trays and rectangular conduits are best jointed by seam-welding, but it is often acceptable to use U-brackets with screw fixings every 100mm or less around the periphery of the U instead. Using lengths of wire will only control low frequencies

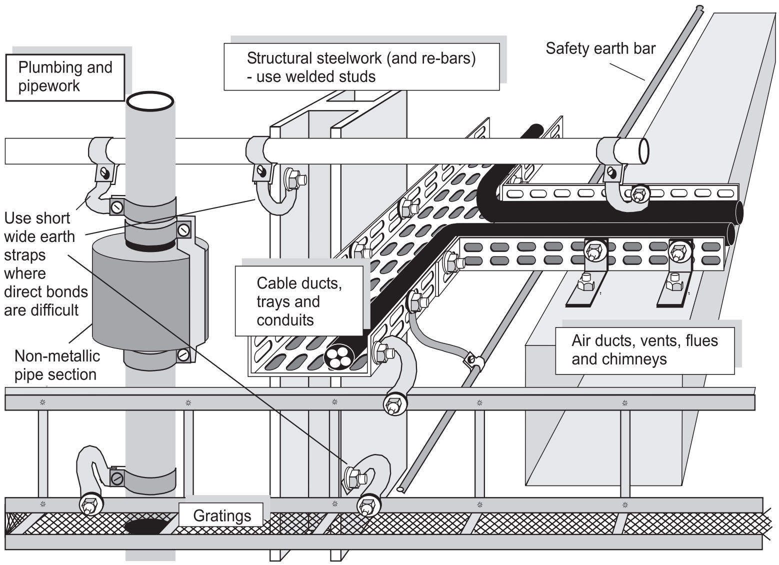


Figure 16.3 Bonding structural components of the equipotential earth mesh

(such as 50/60Hz). Shorter wires, or short fat braid straps, or multiples of each, all reduce impedance and so help increase the frequencies (or power levels) at which interference can be controlled.

Cable trays, ducts, and conduits will be required to act as Parallel Earth Conductors (PECs), as described in section 16.4.2. The bonding methods at their joints and end terminations should also be appropriate for the frequencies to be controlled. Where a rectangular cable tray or duct terminates at the wall of an equipment cabinet (or similar) two or more straps will give better control of higher frequencies (Figure 16.4). An alternative is to cut away a few inches from the sides of the tray, bend the remaining floor section over and bolt it to the cabinet wall in at least two places. A U-bracket may also be used.

Circular conduits are best jointed (either inline or at corners or junctions), using standard screwed couplings which make a 360° electrical bond. Similar 360° bonding glands should be used wherever a round conduit is terminated at cabinet walls, other types of cable ducts, or similar metal surfaces. These will generally employ some type of conductive gasket in their internal construction.

16.3 Cabinets, cubicles and chambers

In the context of systems EMC, a metal enclosure can have a number of purposes as well as its primary one of providing physical protection and mounting:

- to provide a local earth reference for the internal equipment;
- to provide and demarcate a zone of increased EM protection;

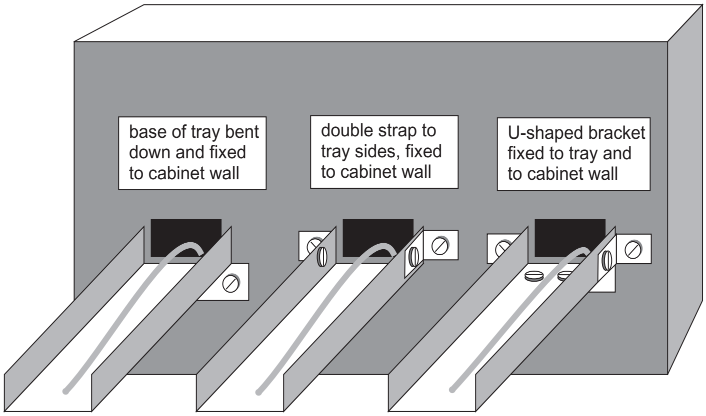


Figure 16.4 Methods of bonding cable trays and ducts to equipment cabinets

- to prevent radiated field coupling to and from the internal equipment.

You will notice that the conventionally understood function of a metal cabinet – to provide shielding – is placed last in the above list. This is deliberate. As we will see, many examples of metal housings are likely to function very poorly as shields, because of their surfeit of inadequately treated apertures and seams. But this doesn't mean they have no EMC function. In fact, the first purpose – to provide a local earth reference – is nearly always the most important. This can be achieved by an enclosure which is effectively *un*shielded, provided that care is taken to use the bulk metal of the cabinet in the right manner. Such an approach is very cost-effective, since many of the assembly, installation and maintenance implications of a fully shielded enclosure can be dispensed with.

Simply constructing a metal cabinet or cubicle to house the equipment in the physical sense, is not adequate for electromagnetic purposes. The constructional and assembly methods of the individual structural parts, and the provisions for cable entry/exit, are at least as important as the mere fact of a conductive enclosure. Interference currents in the structure are expected and have to be controlled. So, electrical interconnections between the parts must be fully specified, and any discontinuities in the form of apertures, seams and cable penetrations must be avoided or controlled.

16.3.1 Transfer impedance of the earth reference

The function of providing a local earth reference is critical to the effectiveness of a metal enclosure, whether this enclosure is deliberately intended as a shield or not. The previous section already looked at the principles of earthing and the next will look at cable layout. In between is the area where the cables and equipment are terminated. This area must provide the lowest possible transfer impedance to the internal circuits and equipment, so that interference currents do not couple between the enclosure and the sensitive or noisy circuits within it.

16.3.1.1 Cabinet backplate earths

After a cylindrical or rectangular enclosure, a large flat plate over which the relevant circuits are mounted gives the best transfer impedance performance. Industrial control cabinets in general include a backplate for physical mounting, whilst smaller enclosures provide some sort of metal chassis. Telecomms and IT cabinets have an internal support structure. Mounting all electronic modules on, and terminating all cable screens and parallel earthing conductors to, a backplate or similar chassis provides the lowest achievable transfer impedance in practical terms. But since using the backplate in this way means that it must carry interference currents, the way in which contacts are made to it, and its conductivity, become significant. Zinc plating, and clamp-style cable screen connections, are both recommended.

At high frequencies only a metal area (mesh or plate) can give a reliable low-transfer-impedance earth, so you are best advised to use a solid backplate or chassis of an enclosure as the earth for all internal electronic equipment *instead of* using green/yellow wires to a star point. This calls for heavy zinc-plated metalwork, not painted; at the cost of some inconvenience, you can use painted metalwork as long as the following precautions are taken for all the earth connections:

- remove the paint;
- use star washers to bite into the metal;
- apply suitable corrosion protection after the joint is made.

Terminations of screened cables to the backplate or chassis should be carefully planned and implemented so that all common mode interference currents flow directly through it, and not into the circuits mounted on it.

16.3.2 Layout and placement within the enclosure

16.3.2.1 Cable runs

Coupling of external fields to internal cables, and of local electric and magnetic fields between cables, is greatly affected by the route a cable follows around a system. To minimize coupling of cables with external fields, run the cables close to a well-bonded metal structure which can act as a low-impedance earth reference – this is usually the backplate or chassis. Where a cable leaves the backplate/chassis, ensure that it follows a conductive structure which is electrically bonded to the backplate/chassis. Avoid running cables near to apertures in the structure or enclosure or near to breaks in the bond continuity (Figure 16.5), as the localized fields around these points are high. (This advice is really the same as saying that the internal construction of the enclosure acts as a continuation of the PEC for the cables, as described in section 16.4.2.)

To minimize coupling of cables with each other, segregate different classes of cable and run them with at least 150mm (see section 16.4.1) of separation. Do not allow long runs of closely spaced cable of different separation classes.

16.3.2.2 Module placement

Carefully position the various items on the backplate/chassis to keep sensitive units such as PLCs, computers or analogue instrumentation away from electrical noise sources such as switches, relays or contactors, and to help achieve separation of the different cable classes. The important principle here is to assess each item for its interference potential, and to specify the internal layout accordingly.

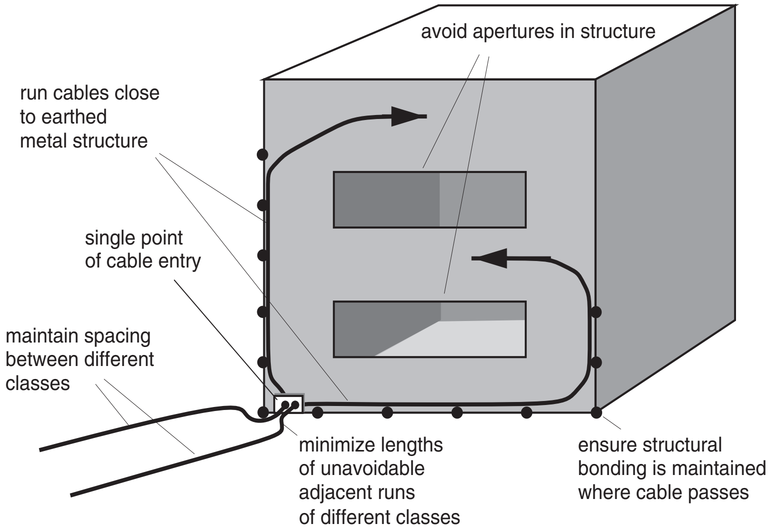


Figure 16.5 Cable runs within the enclosure

Figure 16.6 describes an industrial enclosure, showing the cable route to door-mounted equipment, with cables strapped along the short earthing braid between door and cabinet wall; and an example of backplate layout in a motor drive area. The purpose of the cable following the earth strap across the door opening is to minimize coupling of the cable with the door aperture. The earth strap provides continuity across the aperture, and hence keeps a low transfer impedance between the cable and the cabinet.

Because of their extremely aggressive emissions, inverter drive motor connections are always important [88]. A local return path to the filter has to be provided for the switching noise currents which are flowing back down the earthing conductor and/or the screen of the cable to the motor. These currents can easily pollute the rest of the cabinet and even other equipment in the immediate area of the drive-to-motor circuit, if proper high frequency earth bonding between the cable screen and the filter is not provided – see section 16.5. Similar considerations apply for other "noisy" transducer drivers, such as RF-stabilized welding, spark erosion, and Class D audio amplifiers.

16.3.2.3 The clean/dirty box approach

A frequent and effective approach for industrial and other enclosures is to segregate the enclosure into a "clean" compartment and a "dirty" compartment (Figure 16.7). Either the cabinet can have a partition welded into it, or an additional "dirty" enclosure can be bolted or welded to the side of the main "clean" cabinet instead of a dividing plate.

The "clean" compartment is then used for all the electronics which must be shielded from the external environment. All apertures in this part of the enclosure are rigorously controlled. Connections through to the clean volume must be made via 360° screen bonds to the partition plate, or via effectively earthed filters – no untreated cables are allowed (compare this with Figure 15.13 on page 451). Through-bulkhead filters present no problem, but chassis-mounting filters must keep the leads passing through the partition plate as short as possible and preferably should be treated with ferrite sleeves to minimize HF propagation across the partition.

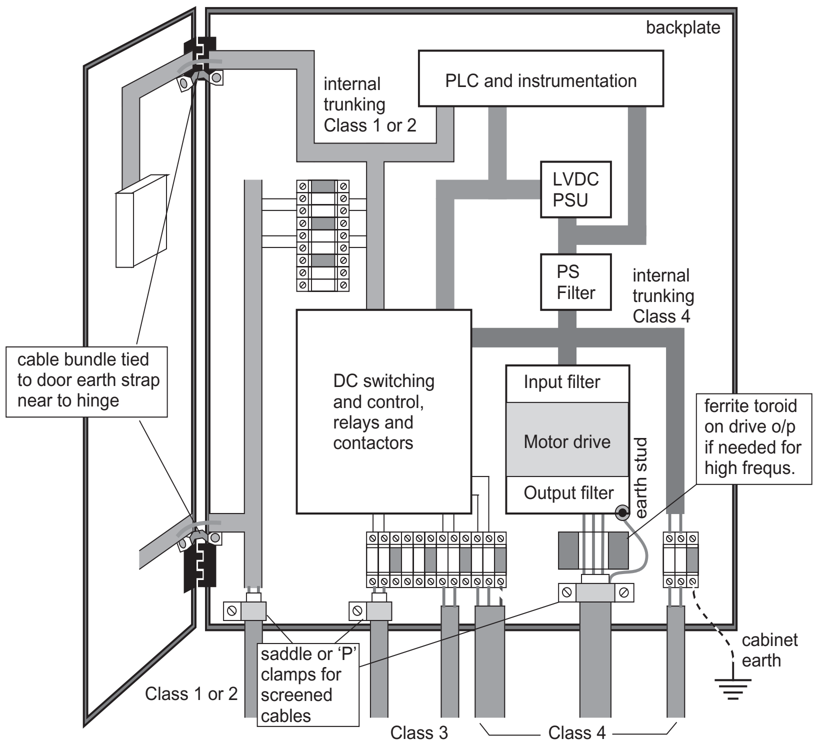


Figure 16.6 Layout and cable routing internally in cabinet

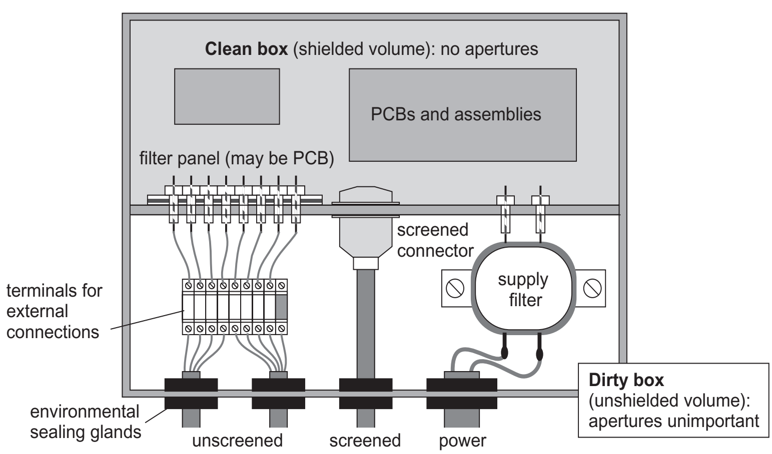


Figure 16.7 The "clean/dirty" segregated shielded cabinet

The great advantage of this approach is that the dirty volume can be used for many or all of the field-installed connections. The interface through the partition can be pre-wired and checked before the system is shipped from the factory. Then, all of the strictures about ensuring correct installation practices are taken out of the hands of the installation technician and given to the system assembler and designer. This is of particular benefit if the system supplier does not control the installation methods at all.

16.3.3 Conductive hardware

Whilst conductive gaskets are widely available for mating two surfaces, and have been covered in section 15.2.1, there is also a growing range of more specialized products for particular shielding applications.

16.3.3.1 Cable penetrations

All cables entering or leaving a shielded enclosure should have their screens properly terminated to the enclosure wall. (*Un*screened cables should enter or leave via a suitable filter if the shielding effectiveness is to be maintained.) This means that full 360° contact should be maintained around the outer surface of the cable screen.

Mechanisms for ensuring this are similar to conventional cable glands for environmental sealing, except that the appropriate parts are fully conductive. Most of the traditional manufacturers of cable accessories are now aware of the importance of EMC aspects, and provide EMC-specific cable glands as part of their stock range. A typical construction using an iris-type spring compressed against the cable screen outer surface is shown in Figure 16.8. This is one of the most common methods of clamping to the screen, but others are possible, including collet or other clamping mechanisms, elastomeric compression modules, folding the screening braid back over a conductive tube or even passing the bare screen through a box of copper shavings.

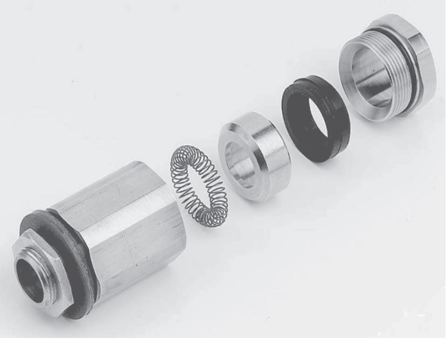


Figure 16.8 Construction of a typical shielding cable gland assembly (KEC Ltd)

Aspects which you need to consider when specifying a screening cable gland system are

- mechanical compatibility: the cable screen outer diameter must match the gland's construction, often within quite tight tolerances;
- electrochemical compatibility: the materials used for screen, gland and enclosure panel should discourage corrosion;

- ease of assembly, especially if unskilled or poorly trained technicians are expected, or the working area is restricted;
- conductivity across the joints, which directly affects shielding effectiveness;
- least disturbance of the screen;
- whether or not an environmental seal is also required.

16.3.3.2 Ventilation panels

Fully shielded enclosures will often require ventilation. Pre-packaged units (Figure 16.9) known as "honeycomb panels", using waveguides below cut-off as discussed in section 15.2.3.2, can simply be fitted into the wall of an enclosure (observing the proper precautions regarding bonding all around the periphery of the assembly) to give any reasonable level of ventilation. These are much more effective at screening than a mesh of holes of the same open area in a thin panel, but of course are more costly and require some thickness in addition to the panel.

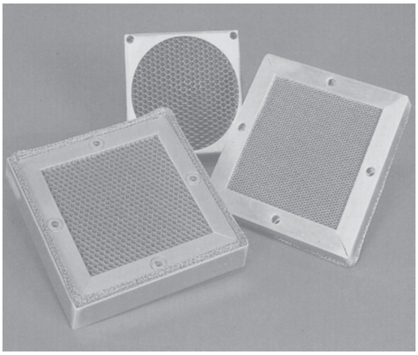


Figure 16.9 Honeycomb ventilation panel

16.3.3.3 Shielded windows

Viewing apertures can represent the largest size hole in the apparatus. If the display behind the window is a serious source or victim of disturbances, then the entire aperture needs to be shielded. Special conductively treated windows are available for this purpose; they need to be installed, as always, with great care to ensure that they are bonded to the surrounding panel all the way around the edge. The conductive treatment must be brought out to the edge of the window in such a way that good contact can be made to it with no breaks – a metal or metallized frame is often the best way of ensuring this.

Shielded window materials are discussed in section 15.2.3. Whatever the material, there is a trade-off to be made between electromagnetic protection and transparency or light transmission; generally, the more transparent a window, the less shielding effect it can give.

16.3.4 Installation and maintenance of screened enclosures

As apertures and seams in screened enclosures such as racks and cabinets can affect the screening performance drastically, it is very important to ensure that measures which are taken to control their effects at the system design stage are not degraded by installation and maintenance procedures (Figure 16.10).

Bonding integrity must be maintained continuously. Any surfaces which are intended to mate must not be allowed to corrode and must never be painted until after they have been assembled. Normally you will use a robust conductive finish, but if the environment is corrosive (such as in a naval installation) then more specialized measures, and more frequent maintenance, will be needed. Where fastenings provide a conductive path they must all be kept in place and at the correct torque. Replacement of short, wide bonding straps by loops of wire is unacceptable.

Doors, panels and hatches which make contact via gaskets or spring finger stock must be installed and treated with care so as not to damage or distort the contact surfaces, which should be regularly checked and cleaned if necessary. Filtered inlets and shield penetrations must make assured 360° contact to their host panels; a DC continuity check is rarely adequate to confirm that this is present.

It should be clear by now that *requiring* a cabinet or other enclosure to exhibit good shielding is not a simple or inexpensive option. The requirement affects all aspects of the installation throughout its intended life cycle. Also, maintenance, installation personnel and even users need to be trained in the principles and techniques involved, since they may otherwise unwittingly compromise shielding integrity just by following their own established practices, such as leaving a cabinet door open. For these reasons, shielding is best regarded as a means of last resort if other, lower-cost EMC options are unavailable or inadequate.

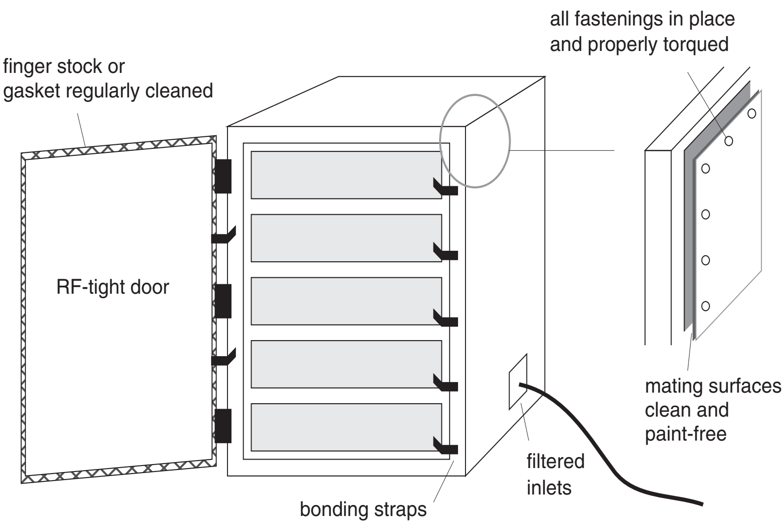


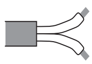
Figure 16.10 Screened enclosure maintenance

16.4 Cabling

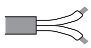
Chapter 15 discusses cable issues in some detail and what it says will not be repeated here. Rather, we will consider the aspects of cable installation that are more specific to systems. These include cable classification, separation and routing, and use of a parallel earth conductor.

16.4.1 Cable classification, separation and routing

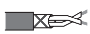
To minimize crosstalk effects within a cable, the signals carried by that cable should all be approximately equal (within, say, ±10dB) in current and voltage. This leads to the grouping of cable classifications shown in Figure 16.11. Cables carrying high frequency interfering currents should be kept away from other cables, even within shielded enclosures, as the interference can readily couple to others nearby. See Figure 11.4 on page 263 for the effect on mutual capacitance and inductance of the spacing between cables.



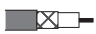
Class 4 Noisy: AC power and return, chassis ground, high-power RF and wideband signals; power inputs, outputs and DC links of adjustable speed motor drives, welding equipment, and similar electrically noisy equipment



Class 3 Slightly Noisy: DC power, suppressed switched loads, filtered AC; externally supplied low-voltage AC or DC power which does not also supply other noisy equipment, contactor and solenoid coil circuits



Class 2 Slightly Sensitive: low-power low frequency signals, low bit rate digital data; analogue instrumentation (e.g. 4–20 mA, 0–10V) and slow digital bus communications (e.g. RS232, RS422, RS485, Centronics); switched I/O such as limit switches, encoders, and the outputs of internal DC power supplies



Class 1 Sensitive: low-level analogue signals such as thermocouples, thermistors, RTDs, strain gauges, load cells, microphones; also wideband digital and analogue communications such as Ethernet, video, RF receiver inputs; and all other signals with full-scale range less than 1V or 1mA, or with a source impedance > 1kΩ, or signal frequency > 1MHz

Figure 16.11 Cable classification

16.4.1.1 Physically separating cables by their classes

The purpose of determining which class a cable belongs to is to be able to choose the correct cable type and terminations, but it is also so that different classes of cables may be run separated from each other to prevent them from interfering with each other. Figure 16.12 shows the minimum separation distances that should be maintained between the different cable classes. This assumes a continuous flat metal PEC (parallel earth conductor) under them all.

Alternatively, IEC technical report IEC 61000-5-2 [173] on the installation of cables and earths in buildings simply recommends that cables should be separated according to the type of signal they carry. Each loom should be 0.15m from the next if it is carried on a metallic conduit used as a PEC, and 10 times the diameter of the largest loom if it has no PEC.

16.4.1.2 Separation within classes

This discussion of separation has assumed that all the cables in a class may be bundled together, but this may not always be advisable, especially for the more extreme classes. Sensitive analogue Class 1 cables should not be bundled with high-rate digital signals in twisted pairs and neither of them should be bundled with high-rate digital in coaxial

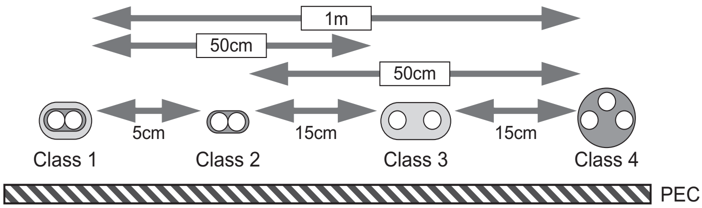


Figure 16.12 Minimum spacings between cable classes when run over a single PEC

cables. These sub-classes should be bundled separately and not run next to each other (separation of at least 10mm between each pair), keeping each bundle as close as possible to the metal surface of the PEC at all times.

Different Class 4 cables may also require individual routings. The cables from adjustable speed inverter drives to their motors may be specified by the drive manufacturers to have 600mm or more spacing from any other parallel run of cable (drives are perhaps the noisiest devices on the planet!). It is difficult to make general rules for separation within Class 4, because a cable may be very noisy in its own right, but still able to pick up sufficient interference from neighbouring Class 4 cables to affect the electronics to which it is connected.

16.4.1.3 Routing

All the cables between items of equipment should ideally follow a single route along a single PEC, whilst also maintaining their separation by class. Figure 16.13 shows the two main principles of cable routing:

- the cables between two items of equipment must always follow the same route, and
- there should be a single interconnection panel for each item of equipment.

Where you need several routes and/or connection panels, each should have its own PEC, and higher PEC earth currents should be expected.

Stacking cable trays along a route

Because of the minimum separation distances required between cable classes, it is generally impossible to run cables of all four classes along one cable tray (they are

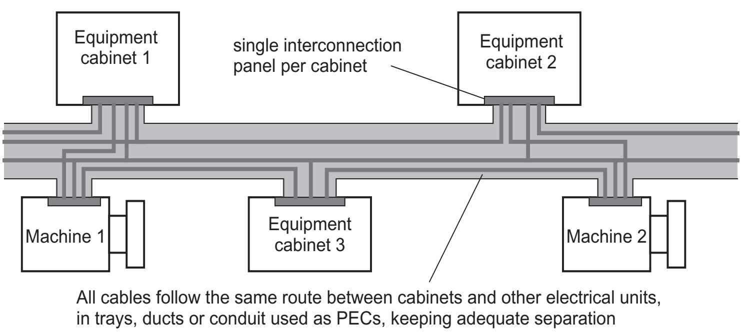


Figure 16.13 Installation cable routing

usually not wide enough). This is overcome by running a "stack" of cable trays. The cable trays are stacked vertically and electrically bonded together at all of their support pillars. They all follow the same route between two items of equipment.

Alternatively, you can segregate source from victim cables in the same conduit using a conductive metal internal wall and/or a mu-metal magnetic screening absorber. The mu-metal absorber technique will be necessary if there are high AC power currents in the source cables coupled with low frequency low-level circuits in the victim cables; mu-metal is effective as an absorber only up to a few kHz. It has to be treated carefully and is susceptible to magnetic saturation, so should not be placed against the source cable but separated from it by at least 15mm. A plain metal wall is fine for high voltage rather than high current sources.

Connections to cabinets

There should only be a single connector panel for a cabinet. All external cables should enter a cabinet at only one side, rear, top, or bottom, and they should also enter the earthed backplate along one of its edges. This is so that, in conjunction with the other techniques described here, the high-level circulating currents flowing in the long cables in many industrial situations will flow from cable to cable via the connector panel or backplate edge via the screen-terminations or filters mounted in that area, and will not flow through the rest of the cabinet or backplate structure and hence affect the electronic units.

16.4.2 Parallel Earth Conductor (PEC) techniques

Modern best practices for EMC in installations (according to IEC 61000-5-2 [173] and EN 50174-2 [160]) require the use of cable trays, conduits, and even heavy-gauge earth conductors as Parallel Earth Conductors (PECs) to divert power currents away from cables and their screens. From the equipment designer's point of view, the cabinet and backplate should provide the means for the connection of the necessary PECs.

16.4.2.1 Constructing PECs

The first function of a PEC is to divert heavy earth loop currents from both screened and unscreened cables. Since earth currents are usually at 50/60Hz, and the surges from lightning events have most of their energy below 10kHz, it is enough for this purpose that the PEC has a very low resistance and a sufficient current-carrying capacity: inductance here is secondary. Most cable support systems have enough metallic cross-sectional area to provide this low resistance and current capacity. Cables must be run very close to the metal of their PEC throughout the length of their run.

Any screen or earth conductor external to a cable should be treated as a PEC and bonded to earth at both ends. Cable armouring can be used as a PEC, but there must be no breaks in the electrical continuity of any armour used for this purpose. Cable installers traditionally regard armour merely as mechanical strengthening or protection, and may not be used to the idea of electrically bonding it at joints and to the local earth at both ends.

PECs can also control higher frequencies. Figure 16.14 shows a variety of types of PECs, and ranks them by high frequency performance. (Compare this to Figure 12.5 on page 303.)

A cable tray is usually perforated with slots to make cable fixing easier, but these can detract from its high frequency performance. The problem is exactly the same as has been described in section 15.1.3 on shielding effectiveness: slots and gaps interrupt

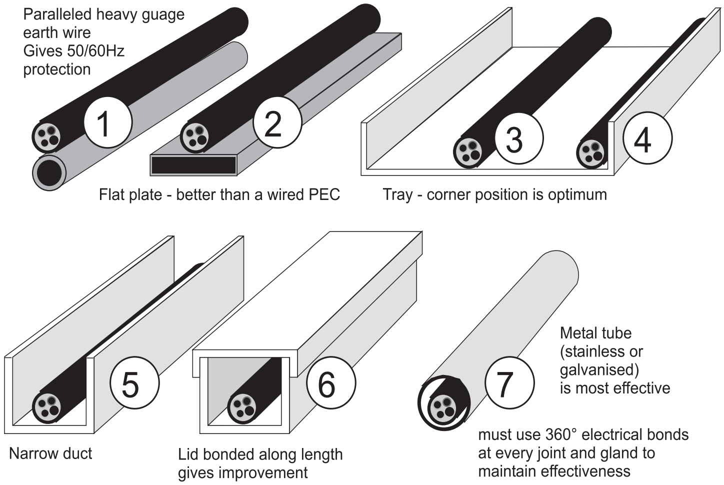


Figure 16.14 Some types of parallel earth conductors (in order of increasing HF effectiveness)

current flow and therefore increase the transfer impedance of the structure. Due to their open construction, ladder- and basket-type cable support systems are poor as PECs.

In extreme environments PECs may have to carry high continuous currents, and should do this without overheating or other damage, so they must have an adequate metallic cross-section. Conductively coated plastic conduit or trunking will obviously not be adequate, for this reason, and if used will require a heavy-gauge copper wire PEC inside to handle any heavy currents. On the other hand, in a building installed with a designed-in equipotential earth mesh any of the interconnected metalwork may be used as a PEC (I-beam girders, building steel, etc.).

16.4.2.2 Bonding PECs

PECs must be electrically bonded to the local equipment earth at each end, and to all their support structures and any other earthed metalwork at every available opportunity. This helps to create a meshed earth structure, and it also helps the PEC to function effectively.

Joints and end-terminations in PECs must be bonded using appropriate methods. Cable trays and rectangular conduits will need to make electrical bonds directly to the cabinet wall (or floor, top, or rear) using U-brackets or similar with multiple fixings. Round conduit can bond to the cabinet wall with circular glands (see 16.3.3.1), remembering to remove the paint first (to ensure a 360° bond) and apply corrosion protection. For plain wire PECs, a cabinet will need appropriately sized and positioned earth terminals.

16.5 Switching converter installation

Energy efficiency has assumed a high profile in the last ten years. One consequence of this is the push to improve the efficiency and flexibility of large electrical machines, which has seen the major use of variable speed drives. Another is the increasing installation of alternative electricity generating sources, particularly wind and solar. Both of these applications use switchmode converters at high power levels to achieve their purpose. But as we know, switchmode converters are a significant source of RF interference emissions.

These emissions have to be controlled by the same methods that have been discussed earlier in this book for general product design, that is, by filtering and the control of common mode current return paths. It is worth a short digression to see how these techniques might be deployed in the implementation of a high-power switching converter system: the example used here is a variable speed drive (VSD).

16.5.1 The emissions path

The drive module itself is not an important source of direct emission, because its dimensions are much less than a half wavelength over the relevant frequency range. On the other hand the power wiring distribution can be extensive and may form an effective antenna for the generated frequencies.

The power *output* connections carry the highest level of high-frequency voltage. But since the cable connecting the unit to its load is a dedicated part of the installation, its route can be controlled to avoid sensitive circuits, and it can be screened. Provided the screen is connected correctly at both ends, emission from this route is then minimised.

The power *input* connections also carry a high-frequency potential which is mainly caused by the current flowing from the output terminals to earth through the capacitance of the output cable and load parasitics, and then returning via the supply side network. Although the interference voltage level here is lower than at the output, control measures may be needed because these terminals are connected to the extended mains supply network. Most commonly a radio frequency filter of some kind is installed here.

Note that these current paths are in common mode, i.e. the current flows in the power conductors and returns through the installation structure. Installation earthing

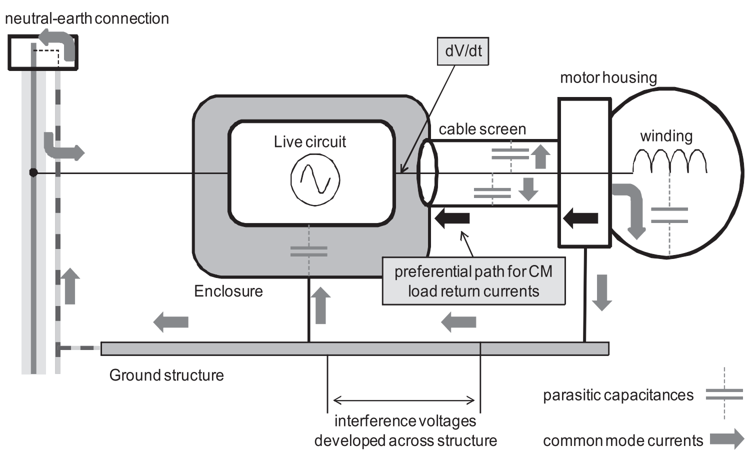


Figure 16.15 Parasitic common mode paths from a VSD

details are therefore particularly important for good EMC. Much of the installation practice aims at controlling the earth return paths and minimising common impedances in the earth system which cause unwanted coupling.

The main cause of high frequency common mode emissions is the current flowing from the output terminals to earth through the capacitance of the load cable and the load parasitics (in the case of a variable speed drive, the motor winding-to-case capacitance) to earth. In many such applications, the output is switched in PWM fashion with the full dV/dt being passed to the load.

Figure 16.15 summarizes the main emission routes for high-frequency emissions. The capacitance of a motor winding to its frame may be in the range 1nF to 100nF, depending on its rating, and the capacitance from the cable power cores to the screen is generally between 100pF and 500pF per metre. These values are insignificant in normal sinusoidal supply applications, but will cause large current pulses at the edges of the PWM waveform where there is a high dV/dt. The peak current can to a first order be estimated from the standard equation for capacitive coupling:

$$I = C \cdot dV/dt$$

so for example, with 5nF of capacitance and voltage waveforms of 400V peak with a risetime of 50ns, the peak current pulse at each edge of the waveform is 40A. If all of this current is forced to flow in the ground structure and the supply earth network it can cause serious interference with other equipment. It can also be seen why cable length is an important installation parameter, since it directly influences the total capacitance from the cable cores to earth.

To control the return path of the common mode current, and pass it preferentially directly back to the converter, we use a combination of filtering and screening. This includes the standard practice of filters on the mains supply, but it is also a good idea to be prepared for filtering on the output.

16.5.2 Output filtering

Either or both differential or common mode filtering can be applied to a VSD output (Figure 16.16). Output filtering in differential mode follows the same circuit approach as for the input, with capacitors between each line and, if desired, separate chokes in series with each line, and no connection to an earth point. The significant difference here is that the filter components are subject to the full dV/dt of the output switching waveform, and the converter or drive output circuit is subject to the extra reactive

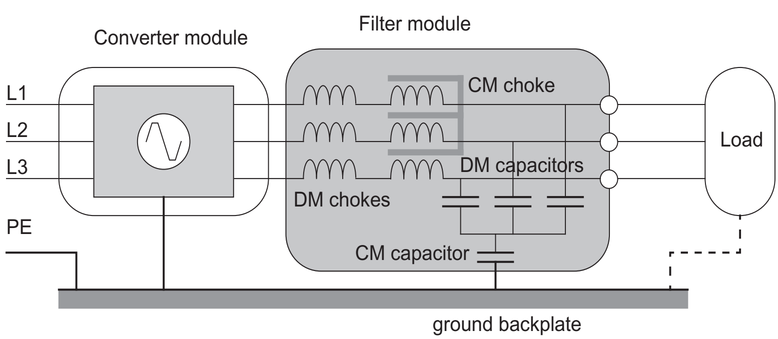


Figure 16.16 Filtering a VSD output

impedance of the capacitors and chokes. This may well put a limitation on the maximum values of such components and it is necessary to carefully match the chosen components with the capabilities and limitations of the converter.

Depending on the need for control of the differential circuit, the output filtering can take one of three forms:

- dv/dt reactor: chokes alone in series with each line; reduces the dv/dt at the load but is limited by resonances between the choke and the load and cable capacitance
- dv/dt filter: chokes and capacitors with a cut-off frequency above the operating frequency of the converter, which maintains the PWM output but softens the rising and falling edges of the waveform; helpful both for EMC and load reliability issues due to ringing on the switching edges
- sinusoidal filter: cut-off frequency below the operating frequency, so that the waveform to the load is no longer switching but is transformed to a near-sinusoid; requires larger components than the dV/dt filter

As well as controlling the high frequency emissions from the output side, such filters can also reduce the stress on the load; particularly, large electric motors driven by variable speed drives may suffer reliability problems from the fast switching edges as well as acoustic noise from the PWM frequency. The sinusoidal filter tends to be used to address these latter issues.

For common mode filtering, the principle is that common mode currents are returned to the module's local earth terminal before they pass out into the cable to the load, by the capacitors; and the choke offers a higher impedance to these currents before they pass to the cable, attenuating them further.

A simple method of implementing a common mode choke, rather than using and wiring in a discrete component or a complete filter, is to apply a ferrite ring around all the output conductors together. The ring fits around the power cores but not the earth, and is most effective if the conductors pass through the ring multiple times – two or three times is typical. The ferrite should be a manganese-zinc type; it is adding resistive loss rather than inductance to the common mode path at higher frequencies, particularly in the 1–10MHz frequency range where motor cable resonance occurs, and this gives useful damping of the resonance. It absorbs the common mode power, and as such may get quite hot. The temperature rise depends on the current at the switching edges and therefore higher common mode capacitance, as created by a long cable or high load parasitics, will increase the size of core that you have to use.

The earth return point for the common mode capacitors is particularly critical (Figure 16.17): it should be as close to the earth terminal for the module as possible, since we are trying to return the noise current via the shortest possible path. The filter must at least be mounted on the same panel as the converter module, and both units must be HF connected to this panel. If the separation between filter and converter exceeds around 30 cm then a flat cable should be used for the HF connection between filter and drive; the optimum technique is to use the "footprint" filters which mount directly underneath the converter module and bond to it.

Any paint or passivation coating between the filter case and the ground plate must be removed to ensure contact. A back-plate of galvanised steel, or other corrosion-resistant bare metal, is preferred.

Note that there may be a high current flowing through these capacitors in operation and therefore there are safety implications to their mounting. In this respect, although

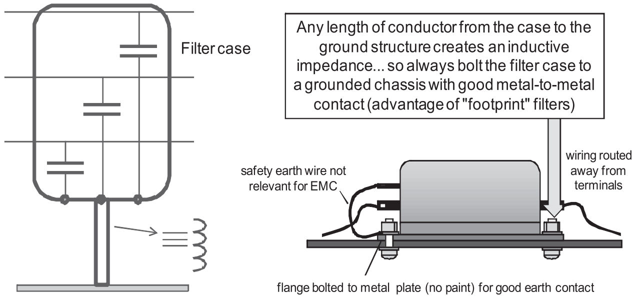


Figure 16.17 Grounding of CM filters

for safety purposes a visible green-and-yellow wire may be required to a safety earth terminal such as a busbar in a cabinet, this does not form any part of the EMC (high frequency) earth. The EMC earth invariably has to be placed in parallel with this safety wire and is effective for both purposes; the safety earth wire is for backup but has no useful function in normal operation.

16.5.3 Output cabling

Because the common mode return currents between the drive/converter and its load are so important, the cabling between the two is an important part of the system design. For any critical installation a screened cable will be needed. The purpose of the cable screen is to provide a preferential return path for these currents. It is not, primarily, to actually "screen" the cable from radiating emissions, although the effect of return current in the screen is largely to cancel these emissions.

It is often assumed that the return current will take the route of least resistance back to its source. This indeed occurs at DC and low frequencies, but as the frequencies increase so *inductance* becomes more important, and a coaxial screen around the inner conductors creates a preferential path due to mutual magnetic coupling. The better the coaxiality, the more effective is the mutual inductance and the lower the apparent impedance of the screen to the return currents.

But to achieve this the low impedance must be continuous through the whole circuit (Figure 16.18): there must be a low impedance connection at each end of the screen, as well as at any junctions along its length. A low impedance connection doesn't include a length of safety earth wire: for the best performance even a short length (a "pigtail") should be avoided. Saddle clamps to a backplate are often the most convenient, and the optimum is a conductive circular gland (Figure 16.8) which makes 360˚ contact all around the cable braid. The point of connection at the load end will be any metalwork enclosing the load, such as a motor housing; at the source end, it should be an earth terminal local to the converter or drive.

In many installations the power to the load has to be carried in armoured cable for mechanical reasons. The common steel wire armouring (SWA) has a higher DC resistance than a copper braid and so its shielding effectiveness in this sense is less than a braid screened cable. On the other hand, the higher permeability and resistivity cause a greater high frequency loss in the armour conductors which damps the wavelength-related resonances along the cable. This has a beneficial effect. Overall, SWA as the

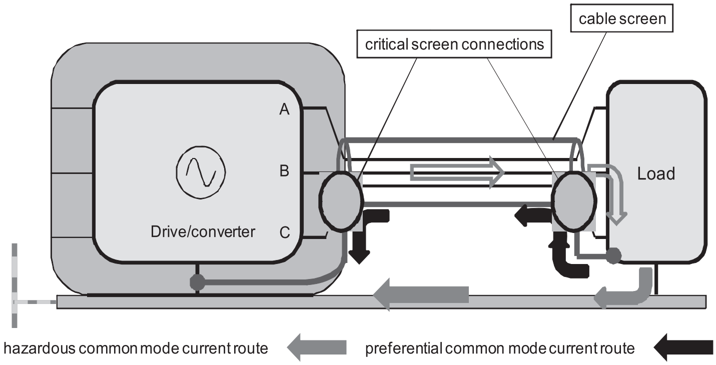


Figure 16.18 Converter-to-load cabling

screen of a cable is useful and acceptable, provided that it is treated as an electrical conductor and fully electrically bonded at each end.

16.5.4 Identifying the need for precautions

In practical installations you will need to identify the degree of threat which may exist from a power converter to other apparatus in the same environment. If there are no sensitive transducers such as proximity sensors or low-level analogue instrumentation, video links or long wave/medium wave/short wave radio receivers, then a relatively high level of emissions can be tolerated. A low power converter with a short cable to the load, or one in which the system is entirely housed in one enclosure such as white goods, may need little more than simple measures to control them.

Table 16.2 Installation precautions for switching power converters

Non-critical environment	Critical environment:
Grounded backplate for converter module, and a fully designed grounding network	
Filter capacitors (0.1–2.2μF) to ground at mains input, or a minimal supply filter	Input filter designed to match the converter unit
Ferrite ring on output cable	Output cable screened, bonded to ground structure at both ends, screen continuous with no interruptions, length minimized Any deviation from optimum output cable configuration should call for an output filter on the module baseplate
Output cable separated from all others (considered as Class 4+)	All cables separated from others in the installation

In a more complex environment or with high power systems then full precautions need to be taken. A complex victim environment includes AM broadcast and short wave radio receivers, analogue instrumentation using very low signal levels (thermocouples, resistance sensors, strain gauges), wideband/fast circuits such as audio or video systems, or unscreened digital data links. All such items are likely to be affected by the harmonic noise generated by the switching converter output.

So the level of precautions may look like that shown in Table 16.2.

16.6 Lightning protection

This short section does little more than review the basics of lightning protection for apparatus in buildings, which is a vast subject all to itself. Personnel safety issues are not covered.

16.6.1 How lightning phenomena can affect electronic apparatus

The issues raised by lightning protection for electronic apparatus are addressed by IEC 62305-4 [178]. Lightning can cause damage to electronic equipment in a number of ways:

- Resistively induced voltage: the resistance of the soil and of earthing networks, when subjected to intense lightning discharge currents (considered to be between 2kA and 200kA, with 1% of strokes exceeding 200kA) creates potential differences between areas normally considered to be at the same "earth" potential, and this exposes electronics connected to these different areas to excessive surges. Long cables, and especially cables between buildings or structures, are particularly likely to cause damage due to this effect, which is sometimes known as "ground potential rise" or "ground lift".
- Magnetically induced voltage: excessive voltages may be induced into conductors and bonded earth structures due to the radiated magnetic fields from lightning discharge, for strikes at up to 100m distance, due to the rate of change of the discharge currents. A maximum rate of 200kA/µs is accepted for the arc channel itself, with lower values where the lightning discharge current is shared between a number of conductors. Even the pigtails traditionally used for bonding the screens of cables can present a serious risk to their equipment due to inductive voltage coupling (consider $V = -L \cdot di/dt$: a pigtail inductance of 20nH with a di/dt of 200.10^9 A/s would give 4kV).
- Current injection from direct strike: there can be direct injection of the lightning main discharge current into any exposed external equipment and cables. The arcing flashovers associated with a direct strike to external equipment often results in damage to connected internal equipment, but may also cause damage to unrelated equipment by flashovers in shared cable routes or terminal cabinets. Here is another reason for cable separation and good earth bonding at cabinet entries.
- Electric field coupling: the whole area around a lightning strike that is about to happen can be exposed to electric fields of up to 500kV/m (the breakdown voltage of air) over an area of up to 100m from the eventual strike point, with fluctuating fields of 500kV/m.µs occurring during a strike. These fields will induce voltages and currents into conductors and devices, but except for high-impedance circuits do not pose as much of a threat as the high-current effects.

- Lightning Electromagnetic Pulse (LEMP): this is a far field phenomenon, and may be caused by cloud-to-cloud lightning as well as by distant cloud-to-ground lightning. It is usually only a problem for exposed external conductors, and is effectively dealt with by the measures taken to protect equipment from other lightning threats.
- Thermal and mechanical effects from the intense energies associated with a lightning strike: these are more usually problems for the structure's fabric and the design of the lightning protection system itself.
- Multiplicity of the surges in a single "strike": a typical lightning event consists of many discharges (or "strokes"), of which the second one usually contains the most damaging energies. Multi-stroke flashes can exceed ten strokes and last for over a second, which is of great importance in the design of software for error-correction and for the recovery of systems.

16.6.1.1 Assessing the criticality of the apparatus

Lightning damage to electronic equipment can cause safety problems to personnel or damage to the structure, usually through electrocution or fires, but sometimes because the equipment has a safety-related function.

Safety concerns such as fire and electrocution must be addressed as part of the normal health and safety at work procedures. For EMC we are concerned with the response of each item of electrical and electronic apparatus to the effects of lightning. Each item of apparatus should be assessed against the following criteria:

(A) catastrophic failure requiring replacement of the apparatus is acceptable

(B) the apparatus is required merely to survive the lightning event undamaged, with no concern about its functionality during the event

(C) the apparatus must continue to operate during a lightning event, although reduced performance is acceptable (the degree of degradation needs to be specified for each function)

(D) the apparatus must continue to operate without any reduction in performance during a lightning event: safety- or mission-critical equipment.

The same equipment may have different criteria depending on where it is used in a structure, how it is installed (its exposure), and what it is used for (how critical is its function). Co-ordination is then required between three aspects:

a) the apparatus' functional criticality
b) the apparatus' ability to withstand lightning electromagnetic phenomena, which can be derived from surge immunity testing, as discussed earlier in section 8.2.3
c) the lightning electromagnetic phenomena that the installation exposes the apparatus to (especially voltage or current surges).

Apparatus must therefore be designed and tested to achieve the required degree of protection and reliable functional performance depending upon its exposure to various lightning phenomena when installed as specified. This may require the use of surge protection devices (SPDs) at exposed ports, particularly the power supply and any connections to external cables, to deal with both common-mode and differential-mode voltage surges. Meanwhile, the building in which it is installed should benefit from a properly designed lightning protection system.

16.6.2 Overview of design of a lightning protection system (LPS)

16.6.2.1 Basic design of an LPS

The design of a basic LPS for safety and protection of the structure typically requires:

- risk assessment based on lightning exposure and acceptability of consequential losses;
- design of the air termination network and down-conductors;
- design of the earth termination network and earth electrodes;
- either bonding of the metalwork within a structure (the “internal” LPS), and the metallic services entering a structure, to the external parts of the LPS, or separation from them.

The possible utilization of metal parts of the structure – so-called “natural” components – as parts of the LPS should be foreseen in the design of the structure itself, but only used with the agreement of the owner and the structural engineer. All metal parts so used (metal sheets, metal parts of roof construction, gutters, ornamentation, railings, pipes, tanks, etc.) must meet specified minimum requirements. Copper theft can be a serious concern and puts an external LPS at risk, and it is often difficult to persuade owners and their architects that an external LPS enhances the appearance of their building. For these reasons the use of natural components is preferred, although successful application requires consideration right from the start of a building design.

16.6.2.2 Documenting and maintaining an LPS

[178] specifies that records are required to be kept throughout design and construction. Procedures are also specified for the regular inspection, maintenance, and upkeep of the LPS, and records must be kept of these too. These records are generally required to meet the requirements of safety laws and insurers, but are also recommended for aspects of the LPS that concern the protection of electronic equipment.

16.6.2.3 Construction of an LPS

A basic LPS consists of an air termination network, a down-conductor network, and an earth termination network (Figure 16.19). It is possible to construct an isolated LPS that protects a structure whilst being electrically separated from it, but the type of LPS described here is attached to the structure and bonded to its internal CBN.

Air termination network

The air termination network is intended to intercept the lightning strike and divert its currents via the down-conductors to the earth termination network, thereby protecting the structure from the strike. This can be a mesh arrangement of copper or aluminium conductors laid horizontally and vertically on the tops of roofs and the outsides of walls, with minimum spacings between conductors as specified by standards or codes of practice. “Natural” components such as gutters, railings, or metal-clad roofs may be usefully pressed into service and can even take the place of a separately installed air termination network.

Down-conductors

Down-conductors provide a low-impedance path for lightning currents from the air termination network to the earth electrode system, and in general there should be several, equally spaced around the structure to share lightning current amongst

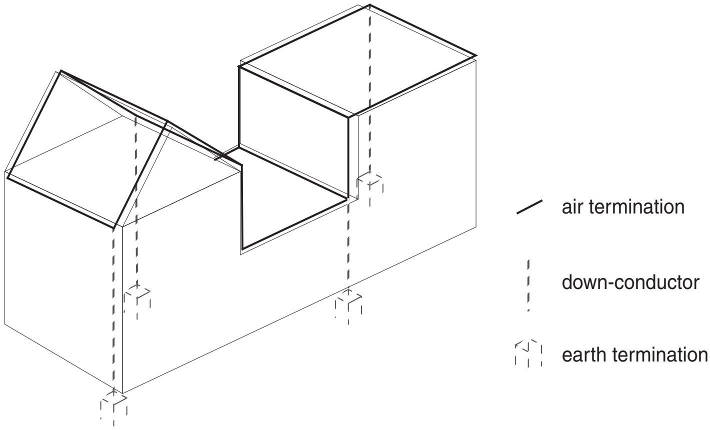


Figure 16.19 Components of building protection

themselves. Metal structures such as radio masts or flagpoles may use their exposed metal structure as all or part of their air termination and down-conductor network simultaneously.

Down-conductors should be straight and vertical, fitted at least at the corners of a structure, equally spaced, and should provide the most direct route to the earth electrodes.

Earth termination network

The earth termination network is the system of earth electrodes which dissipates the lightning currents into the mass of the soil or rock beneath the structure to be protected. All soils and rocks have finite conductivity, which compromises their performance as an earth mass, so care must be paid to the design, construction and maintenance of earth electrodes. The earth termination network for a structure is generally required to provide an earth resistance of under 10Ω, although higher or lower resistances may be allowed or needed in special cases. The lightning standards and codes provide rules and formulae for designing different types of earth electrodes.

A typical earth electrode consists of a copper alloy rod electrode deep-driven vertically into the soil, sited at the foot of each individual down-conductor a metre or so from the boundary of the structure. The reinforcement in concrete foundations (a little while after construction) can achieve a very low earth resistance, especially concrete pilings. This is known as a foundation earth electrode, and it requires the reinforcing bars to be welded, or at least reliably bound together with tying wire, at their crossing points. Strip electrodes may also be used, especially to help reduce voltage gradients around a structure, when they are known as potential grading electrodes.

Bonding

For buildings of just a few storeys, say up to 15m high, with a properly designed LPS, it is usually enough to bond the LPS to the structure's internal common bonding network at ground level only. Structures higher than 20m should bond their non-LPS metalwork to their LPS at top and bottom, and at intervals of no more than 20m in between. [178] recommends that bonds between LPS and CBN take place where there is already a horizontal ring conductor which bonds the LPS down-conductors.