Chapter 15

Systems EMC

15.1 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* [22], 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.

15.1.1 Compliance requirements

As we have seen in Chapter 2, the 2nd edition EMC Directive has 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.
>
> – [183] 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.

15.1.2 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 [39][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 no restrictions on earthing, cable routing and segregation – 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.

15.2 Earthing and bonding

15.2.1 The purpose of the earth

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

15.2.1.1 Safety earth

The purpose of the safety earth is to guarantee personnel safety under fault conditions. The IEE Wiring Regulations (BS 7671, [175]) 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 13.2.3.3.) 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.

15.2.1.2 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 normaly 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.

15.2.1.3 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.

Several standards for lightning protection have been published by the various standards bodies (e.g., BS 6651 [172]) and you should look to these for detailed advice (Table 15.1). Section 15.5 reviews the main principles.

Table 15.1 Standards for lightning protection

	Protection of structure	**Protection of contents**	**Risk assessment**
IEC/ CENELEC	IEC 62305-3: 2006 EN 62305-3: 2006	IEC 62305-4: 2006 EN 62305-4: 2006	IEC 62305-2: 2006 EN 62305-2: 2006
BSI	BS 6651:1999	BS 6651:1999 App C	BS 6651:1999

15.2.1.4 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 [135]. 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.

15.2.2 Installation techniques for multi-purpose earthing

15.2.2.1 Three-dimensional meshed equipotential earth-bonding

The preferred earth-bonding method in buildings is the Common Bonded Network, or CBN, shown by Figure 15.1. Complex installations require an equipotential system

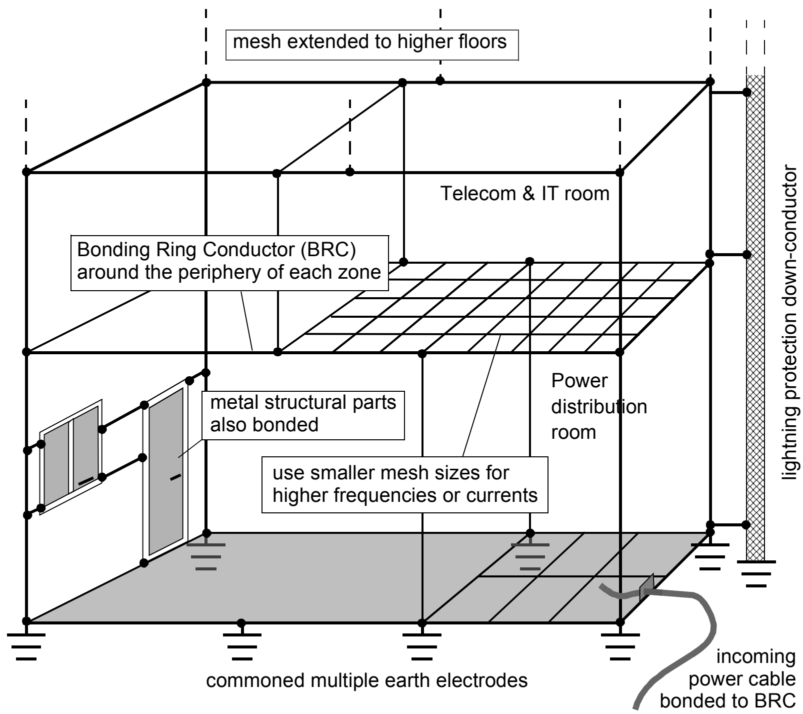


Figure 15.1 Common bonded network

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 15.1 shows the application within buildings, the principle applies to an installation in any circumstances: aircraft, ships and vehicles should all follow the same practice.

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 11.1.3.4 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 [156], as shown by Figure 15.1.

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.

15.2.2.2 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.

15.2.3 Earth conductors

15.2.3.1 Short fat straps

Elsewhere in this book we have discussed the impedance of wires and structures (section 11.1.3.4). 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 15.2. 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.

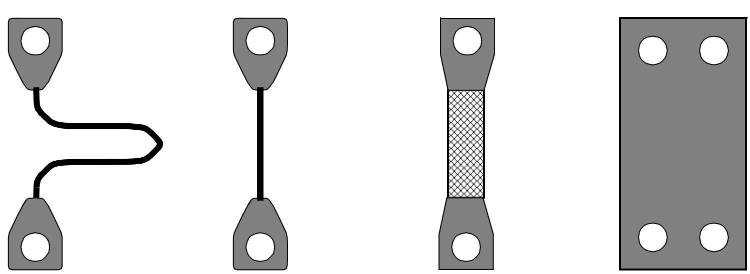


Figure 15.2 Hierarchy of earth conductors

15.2.4 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.

15.2.4.1 Bonding of equipotential mesh structures

As described in section 15.2.2.1, 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 15.3. 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.

15.2.4.2 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 (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.

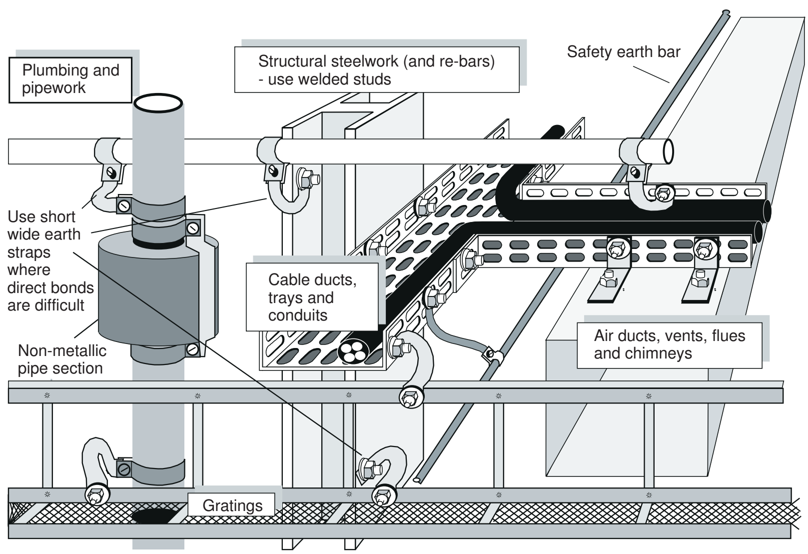


Figure 15.3 Bonding structural components of the equipotential earth mesh

Cable trays, ducts, and conduits will be required to act as Parallel Earth Conductors (PECs), as described in section 15.4.2. 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 15.4). 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.

15.3 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;
- 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,

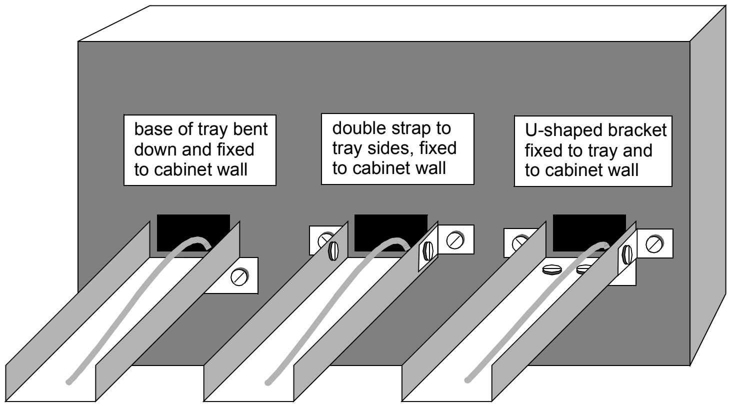


Figure 15.4 Methods of bonding cable trays and ducts to equipment cabinets

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.

15.3.1 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.

15.3.1.1 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.

15.3.2 Layout and placement within the enclosure

15.3.2.1 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 15.5), 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 15.4.2.)

To minimize coupling of cables with each other, segregate different classes of cable and run them with at least 150mm (see section 15.4.1) of separation. Do not allow long runs of closely spaced cable of different segregation classes.

15.3.2.2 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 segregation 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 15.6 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

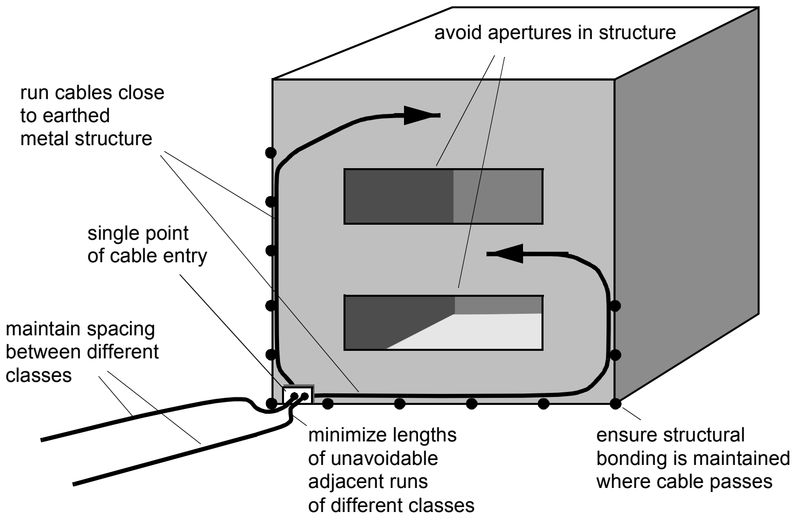


Figure 15.5 Cable runs within the enclosure

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 [84]. 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. Similar considerations apply for other "noisy" transducer drivers, such as RF-stabilized welding, spark erosion, and Class D audio amplifiers.

15.3.2.3 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 15.7). 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 14.13 on page 399). 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.

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

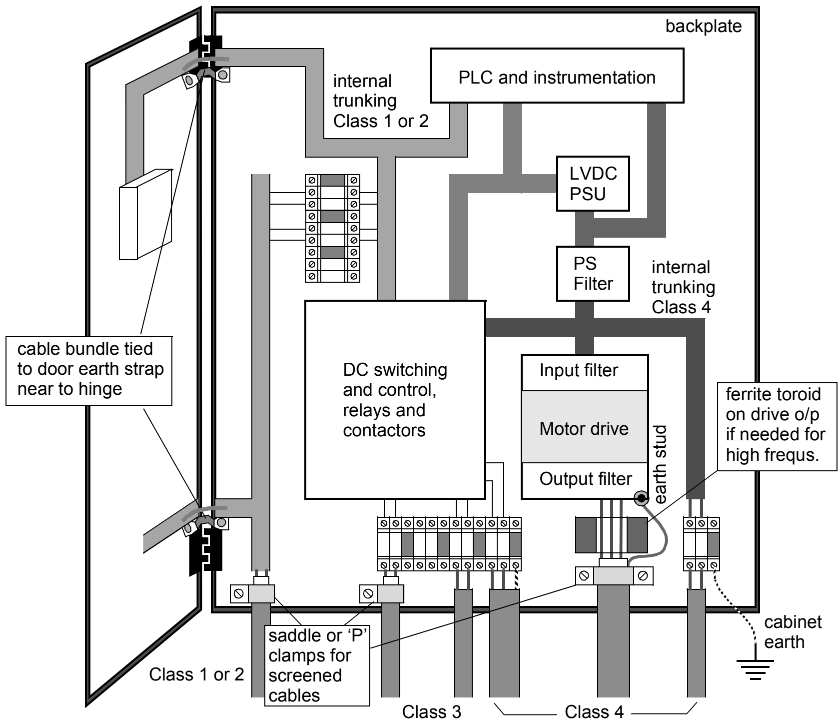


Figure 15.6 Layout and cable routing internally in cabinet

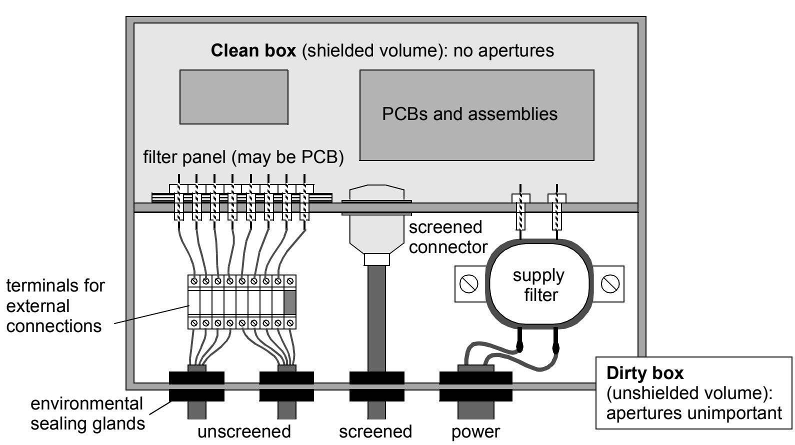


Figure 15.7 The "clean/dirty" segregated shielded cabinet

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.

15.3.3 Conductive hardware

Whilst conductive gaskets are widely available for mating two surfaces, and have been covered in section 14.2.1, there is also a growing range of more specialized products for particular shielding applications.

15.3.3.1 Cable penetrations

All cables entering or leaving an 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 15.8. 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 15.8 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.

15.3.3.2 Ventilation panels

Fully shielded enclosures will often require ventilation. Pre-packaged units (Figure 15.9) known as "honeycomb panels", using waveguides below cut-off as discussed in section 14.2.3.2, 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.

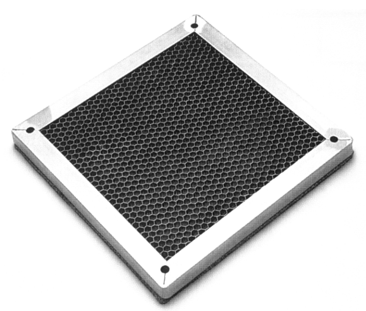


Figure 15.9 Honeycomb ventilation panel (TBA ECP Ltd)

15.3.3.3 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 14.2.3. 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.

15.3.4 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 15.10).

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.

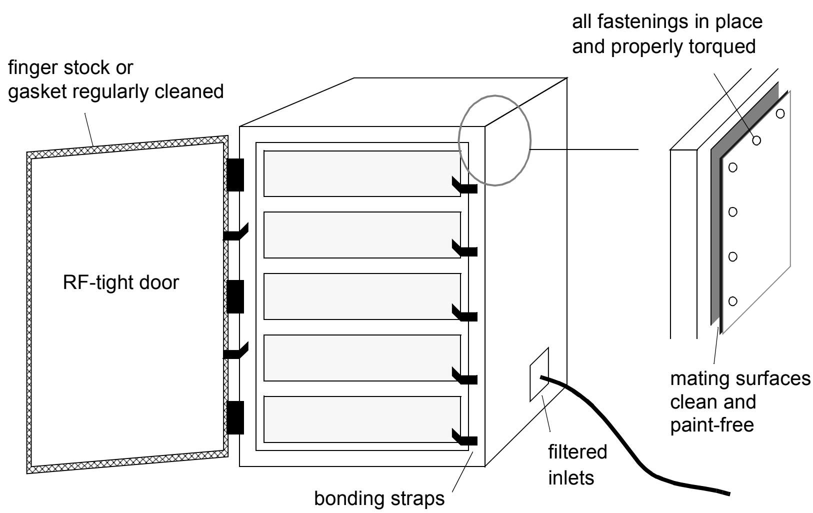


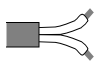
Figure 15.10 Screened enclosure maintenance

15.4 Cabling

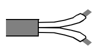
Chapter 13 discusses cable issues in some detail and what it says will not be repeated here. Rather, we will consider the aspects of cable installation that are more specific to systems. These include cable classification, segregation and routing, and use of a parallel earth conductor.

15.4.1 Cable classification, segregation and routing

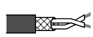
To minimize crosstalk effects within a cable, the signals carried by that cable should all be approximately equal (within, say, ±10dB) in current and voltage. This leads to the grouping of cable classifications shown in Figure 15.11. Cables carrying high frequency interfering currents should be kept away from other cables, even within shielded enclosures, as the interference can readily couple to others nearby. See Figure 10.4 on page 226 for the effect on mutual capacitance and inductance of the spacing between cables.



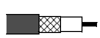
Class 4 Noisy: AC power and return, chassis ground, high-power RF and wideband signals; power inputs, outputs and DC links of adjustable speed motor drives, welding equipment, and similar electrically noisy equipment



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 15.11 Cable classification

15.4.1.1 Physically segregating 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 segregated from each other to prevent them from interfering with each other. Figure 15.12 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.

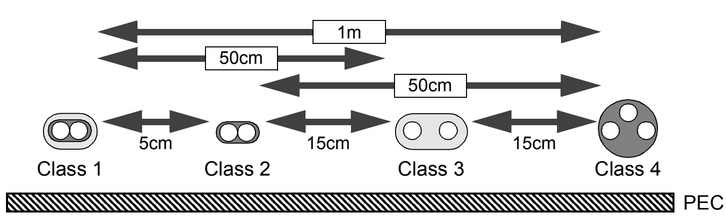


Figure 15.12 Minimum spacings between cable classes when run over a single PEC

Alternatively, IEC technical report IEC 61000-5-2 [156] on the installation of cables and earths in buildings simply recommends that cables should be segregated 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.

15.4.1.2 Segregation within classes

This discussion of segregation 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 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 segregation 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.

15.4.1.3 Routing

All the cables between items of equipment should ideally follow a single route along a single PEC, whilst also maintaining their segregation by class. Figure 15.13 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 segregation distances required between cable classes, it is generally impossible to run cables of all four classes along one cable tray (they are usually not wide enough). This is overcome by running a "stack" of cable trays. The

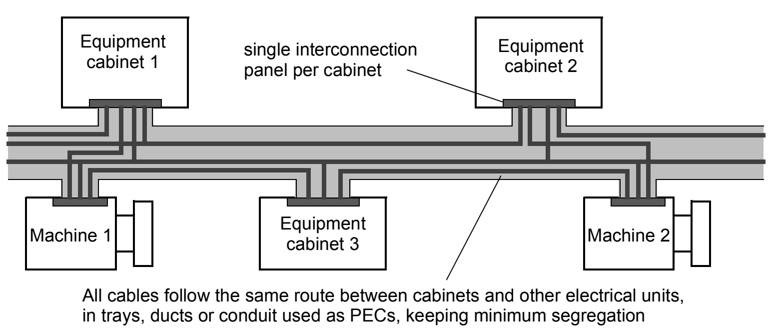


Figure 15.13 Installation cable routing

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.

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.

15.4.2 Parallel Earth Conductor (PEC) techniques

Modern best practices for EMC in installations (according to IEC 61000-5-2 [156] and EN 50174-2 [147]) 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.

15.4.2.1 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. 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 bonding it at joints and to the local earth at both ends.

PECs can also control higher frequencies. Figure 15.14 shows a variety of types of PECs, and ranks them by high frequency performance. (Compare this to Figure 11.5 on page 263.)

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 14.1.3 on shielding effectiveness: slots and gaps interrupt current flow and therefore increase the transfer impedance of the structure. Because of 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.).

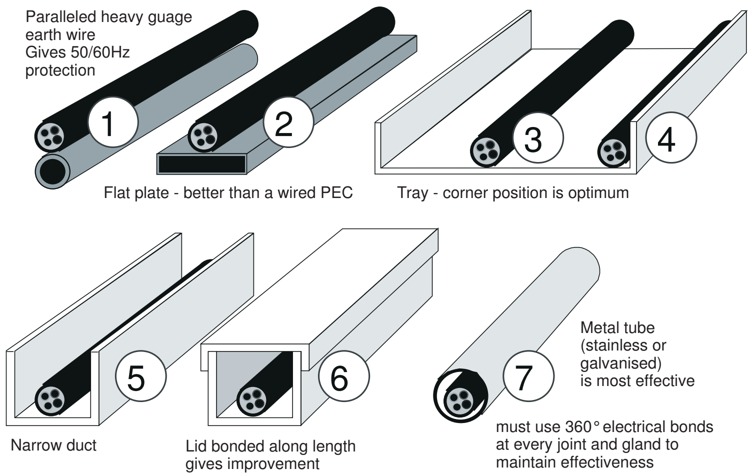


Figure 15.14 Some types of parallel earth conductors (in order of increasing HF effectiveness)

15.4.2.2 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 15.3.3.1), 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.

15.5 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.

15.5.1 How lightning phenomena can affect electronic apparatus

The issues raised by lightning protection for electronic apparatus are addressed by IEC 62305-4 [160] and by Appendix C of BS 6651 [172]. 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 200.10^9A/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 segregation 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.

15.5.1.1 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 7.2.3
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.

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

15.5.2.1 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.

15.5.2.2 Documenting and maintaining an LPS

Both [172] and [160] specify that records are required to be kept throughout the design and construction process. Certain 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.

15.5.2.3 Construction of an LPS

A basic LPS consists of an air termination network, a down-conductor network, and an earth termination network (Figure 15.15). 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.

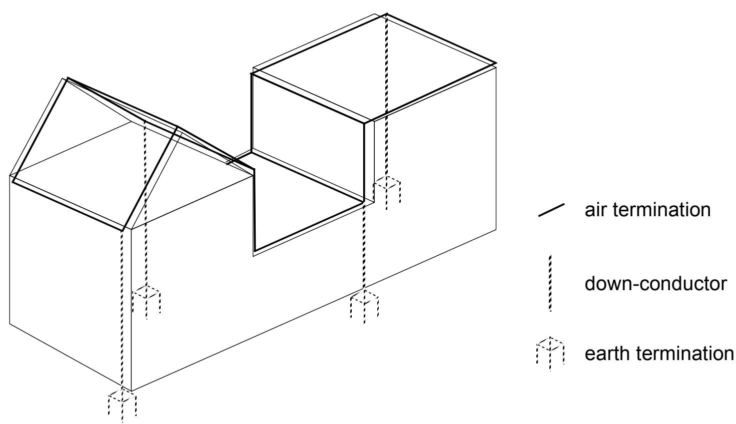


Figure 15.15 Components of building protection

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 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 [172]. [160] recommends that bonds between LPS and CBN take place where there is already a horizontal ring conductor which bonds the LPS down-conductors.