Power Quality Application Guide

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Earthing & EMC

A Systems Approach to Earthing

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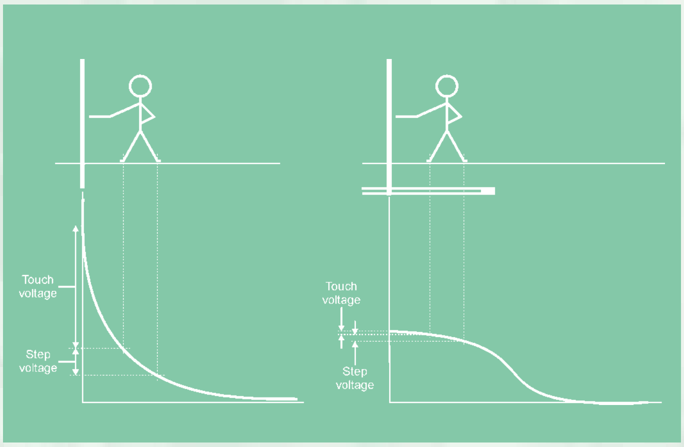

Earthing & EMC

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Earthing & EMC

A Systems Approach to Earthing

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May 2002

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Acknowledgements

This project has been carried out with the support of the European Community and International Copper Association, Ltd.

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A Systems Approach to Earthing

Introduction

Earthing of installations and equipment is an issue that crosses the boundaries of the various disciplines involved in the construction and equipping of a modern commercial or industrial building. Construction engineers need to talk with instrumentation engineers and IT professionals need to discuss matters with electrical engineers and so on. Sometimes, however, these individual engineers do not speak the same technical language or are not even aware of the needs of each other's installations. In this document an overall earthing approach is presented to serve as a basic guideline for earthing and interference suppression that can be used by multi-disciplinary teams.

In general any earthing system needs to satisfy three demands:

- **Lightning and short circuit:** the earthing system must protect the occupants, prevent direct damage such as fire, flashover or explosions due to a direct lightning strike and overheating due to a short-circuit current.
- **Safety:** the earthing system must conduct lightning and short-circuit currents without introducing intolerable step-voltage and touch-voltages.
- **Equipment protection and functionality:** the earthing system must protect electronics by providing a low impedance path to interconnect equipment. Proper cable routing, zoning and shielding are important aspects and serve the purpose of preventing sources of disturbance from interfering with the operation of electrical equipment.

Although requirements for these three aspects are often specified separately, the implementation of them requires an integrated systems approach.

A systems approach

The original purpose of the protective earth was to ensure the safety of people and property within the zone served by the earthing system. This requires a high current capacity path with relatively low impedance at the fundamental frequency so that voltages developed under high fault current conditions are not hazardous.

It is very easy to make a good low impedance connection to ground. All that is needed is a high conductivity, corrosion resistant conductor (copper is a good choice) buried in the earth at such a depth that it will neither freeze nor dry out, large enough to contact a suitably large volume of earth, covering a sufficiently large area and in such a position that it is not influenced by other earthing systems. A large volume of earth reduces the current density in the soil and therefore the resistance to earth. A large area connection allows shaping of the electric field to be accomplished, reducing touch and step voltages (as discussed later in this note). This is a clean earth – at least, as clean as it gets.

Problems arise as soon as equipment is connected to it. In practice, the cleanliness of the earth is affected by other, nearby, earthing systems and, usually more seriously, by the equipment of the installation itself.

The use of a combined protective earth and neutral (PEN) conductor, as used in a TN-C system, cannot be reconciled with the principles of good design outlined in this application note. In a TN-C system neutral currents - including third harmonics - and earth currents mix in neutral conductors, protective conductors and connected metalwork. Installations should always be TN-S, even if they are derived from TN-C systems on the supply side of the point of common coupling (PCC). The presence of a single earth-neutral bond is very important.

Traditional installation practice focuses, correctly, on safety. Originally, it was thought sufficient to simply provide a low impedance path to earth. Modern practice requires 'shaping' of the field in the ground to control the voltage gradients around the earth electrode.

The 'protective conductor' must also provide a functional earth to the equipment operating on the system - that is, it has to provide a path for the leakage currents (at the fundamental frequency) and the high frequency noise currents arising from, for example, switched mode power supplies via radio frequency interference (RFI) filters as well as being a voltage reference for signal interfaces.

The magnitude of leakage currents varies around the installation. Since the earth leakage current originates mainly from single-phase equipment on each of the three phases, balanced components of the fundamental from each phase will tend to cancel, so that the current in the protective conductor may increase or decrease as circuits are combined along a distribution system. Often, it is worst at a (single-phase) final circuit supplying IT equipment. Leakage currents are harmless while flowing to earth, but can easily reach lethal levels if the connection fails and therefore a high-integrity design is required. In essence this requires duplicate paths (each capable of carrying the full fault current) and robust and reliable connections – for example, long-life, corrosion-resistant, copper conductors installed by electricians rather than steel cable trays installed by building workers. Where the armour of cables is used as one of the routes, special attention is required to ensure that reliable connections are achieved and maintained at glands. High integrity design principles must extend throughout the system, including right up to the desktop, by fitting sufficient socket outlets for example, so that extension blocks, with their single, low integrity, protective conductor, are not required.

High frequency currents can be a bigger problem as far as functionality is concerned. Much of the equipment that produces noise on the earth is also sensitive to it – but there is a difference; the equipment produces noise *currents* and it is sensitive to noise *voltages*. If the noise currents can be transported to earth without producing noise voltage drop, all will be well. This requires a connection to earth that has low impedance at all frequencies. To decrease radiated noise, the earth path for the noise current should run close to the supply conductors. It should be noted that in this context we are more concerned about the impedance of the connection to the earthing system, which represents the equipotential surface we colloquially call 'earth', rather than to the physical earth itself. This is different from the contexts of safety and lightning protection where the impedance to the earth itself is of critical importance.

When the amount of equipment installed was small it was common to run a separate large size earth lead straight back to the main earth terminal, or even to a separate earth rod (also bonded to the main earth terminal to comply with local regulations). This was usually satisfactory, partly because these systems and their peripherals were co-located in a geographically small area and so could be maintained at an equipotential (if there is such a thing), rather than at zero potential. The noise return path was also close to the supply conductors, reducing radiated noise. However, the long radial earth connections exhibit quarter-wave resonance[1] effects that increase impedance at some frequencies, making this an unsuitable technique for modern widely distributed installations. Modern computer systems usually extend throughout several floors of a building. Maintaining an 'equipotential' (at high frequency) between these scattered devices requires a better solution.

It is a fact that most distributed computer systems work. As microelectronic devices have developed and operating voltages have reduced, the energy required to switch logic states and the immunity to voltage noise have generally decreased making them more sensitive to noise. The effect of this trend has been offset by improvements in system design to improve noise immunity. These measures include the use of differential interfaces and better software design, such as the use of error detecting and correcting protocols on networks. These techniques are very effective, but reduce network throughput by sending redundant (error control) data and requiring re-transmission of failed data packets. As the electrical noise increases, the error rate increases, and throughput decreases until useful communication ceases completely. To the user it appears as if the system has suddenly failed, whereas in fact it has merely degraded so far that the recovery mechanisms provided can no longer cope. If the electrical noise can be reduced to a low enough level, the error rate will reduce also and data transmission will again be possible. High noise levels reduce throughput by requiring repeat transmission and reduce efficiency. Clearly, network efficiency is related to

[1] *The design of the earthing system of a building, including the lightning protection system, requires great care if all the objectives are to be met. It is, as usual, best and cheapest if it is designed correctly from the start, rather than having to be re-engineered after the building has been occupied.*

data processing efficiency, which is related to business efficiency. As with many things, efficiency is worst when the need is greatest – when the network is busy. Reducing the level of electrical noise in the data processing environment is crucial to increasing efficiency. It is unfortunate that, in speculative developments, the most popular data cable for networks is unshielded twisted pair. For IT-intensive buildings and for 100 Mb/s data rates, the use of shielded twisted pair cable (STP) should be preferred.

The best way to reduce noise to a minimum is to use a copper grid ground plane. This technique was often used for 'computer rooms' when data processing was centralised and is still frequently the only viable solution. It works because there is an infinite number of paths through the grid with different apparent electrical lengths – while some of these paths may be multiples of a quarter wavelength, there will undoubtedly be many other parallel paths which are not. The result is a low impedance connection over a wide frequency range. Such a grid should cover the whole of the area of the installed equipment – these days usually the whole building – and it should not be forgotten that this applies to the vertical direction as well as the horizontal. There is little point in having horizontal meshes on every floor connected to a single vertical downlead. Grids are normally constructed using flat strip to keep skin effect to a minimum. Where structural elements are used as a grid, such as the supports for a raised floor that have been selected for their mechanical rather than electrical properties, it is important to ensure that the elements are electrically bonded together – using *short* copper braids – at each intersection.

It may be thought that a complete copper grid installation is rather expensive for ordinary commercial buildings – particularly in the case of speculative buildings. However, the cost is not great and it is obvious that the lowest overall cost is achieved by incorporating grids at the design stage, and that the most expensive route is to retrofit grids after occupation. An effective earthing system ensures that the building is suitable for a wider range of uses and is thus more marketable. The building can attract a higher rent, justified by the reduction in the frequency (and cost) of problems to tenants and the consequent operating costs.

Putting the concept into practice

The ground electrode

The design of the ground electrode - its size, shape and disposition - are critically important, not only for producing a sufficiently low impedance but also for controlling the shape of the electric field on the surface of the ground.

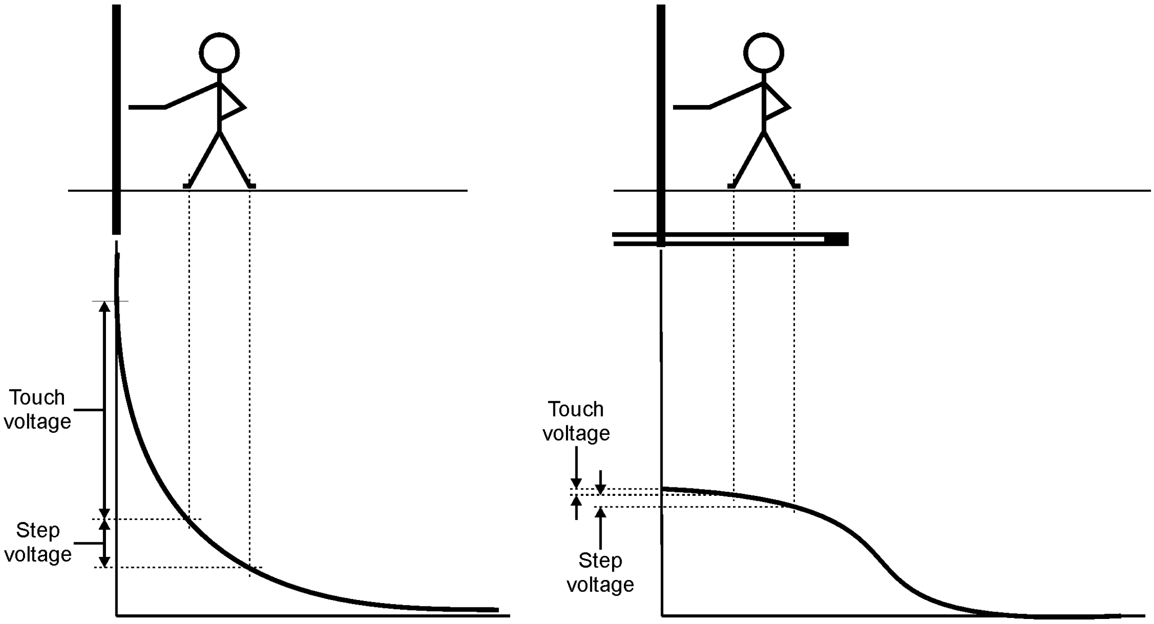

Figure 1 - Step and touch voltages

The resistance of the earthing electrode system and the current into the soil determine the voltage difference between the system and the ground. For large fault currents this voltage will be very high at the electrode and will decrease with distance from the earth conductor as the volume of earth through which the current is flowing increases. This ground potential rise (GPR) can result in dangerous situations.

Before examining the issue further it is necessary to define some terms (see Figure 1). 'Touch potential' is the voltage difference between the earthed structure and a person standing on the ground within touching distance of the structure. 'Step potential' is the voltage between the feet of a person (assumed to be 1 metre apart) standing on the ground. The maximum touch and step potentials are limited by various Standards.

It is quite possible to achieve a low impedance - under the right soil conditions – with a single earth rod. A typical field pattern is shown on the left hand side of Figure 1. Note that the ground potential slope is very steep – i.e. the step and touch voltages would be high – so this is not a suitable choice of electrode. Figure 1 shows (right hand side) the effect of adding a guard ring 1 metre outside the perimeter, buried 0.5 metres deep, to the system. Not only does this reduce the impedance and therefore the GPR (because a greater volume of earth is carrying the current), but the shape of the field is also controlled within the guard ring reducing step and touch voltages.

As can be seen, the step and touch voltages around the building are much smaller when an earthing ring is used. The top of the 'potential mountain' is made wider and flatter by the field shaping characteristics of the ring in the soil. When no ring is used the 'mountain' is steeper and higher, especially near a grounding rod or concrete pile, thus possibly leading to dangerous situations.

The buried earth electrode ring around the building should be located at a distance of least 1 metre from the exterior wall. It should be deep enough to ensure that it will not be affected by freezing in winter and will not dry out in summer. Where there is no applicable local guidance the depth should be at least 0.5 metres. The earth ring should be made of copper with a cross-sectional area of at least 50 mm^2 .

The earth electrode ring must be connected to a meshed network under the structure and to the meshed network around the structure if applicable. Connections between the ring and the rest of the earthing system of the building or site must be made at several points.

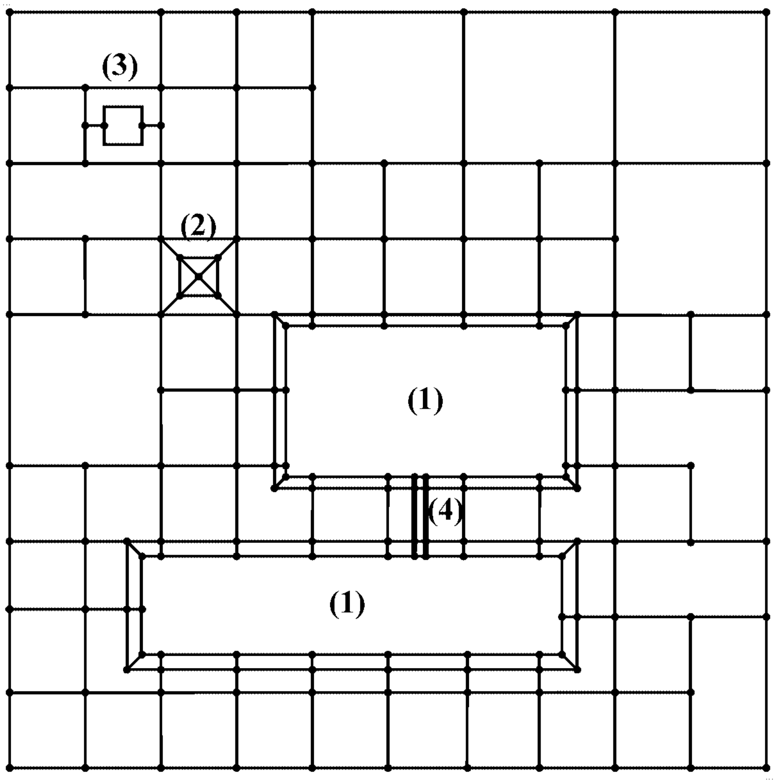

Figure 2 - Earth grid (after Figure 8 of IEC 61312-2)

Site-wide earthing system

A low impedance path to earth is required to conduct lightning and short circuit currents into the soil. This main earthing system has to be a network that provides a low impedance connection between all objects and a good distributed contact with the soil. It must be able to conduct all possibly occurring currents while avoiding dangerous touch voltages and large currents on cables connecting remote objects.

Figure 2 shows the top view of a meshed earthing system of a plant. For buildings (1), the steel reinforcement forms a fine meshed network, which is connected to a buried bare copper ring around the building to avoid step and touch voltages. Elsewhere, a meshed earthing system is installed. The mesh spacing directly around the buildings is 5 metres. A tower (2) and stand alone equipment (3) are also connected to this meshed network. Every object is connected to the earthing system by multiple connections. Between the buildings a cable tray (4) is used as protection for cables running between the buildings.

Lightning capture system

To limit damage due to a direct lightning strike to a structure, a low impedance path must be provided from the top of the structure down to the earth. At ground level, the lightning protection system is connected directly to the ground electrode and the rest of the earthing system. Figure 3 shows a typical structure for a building.

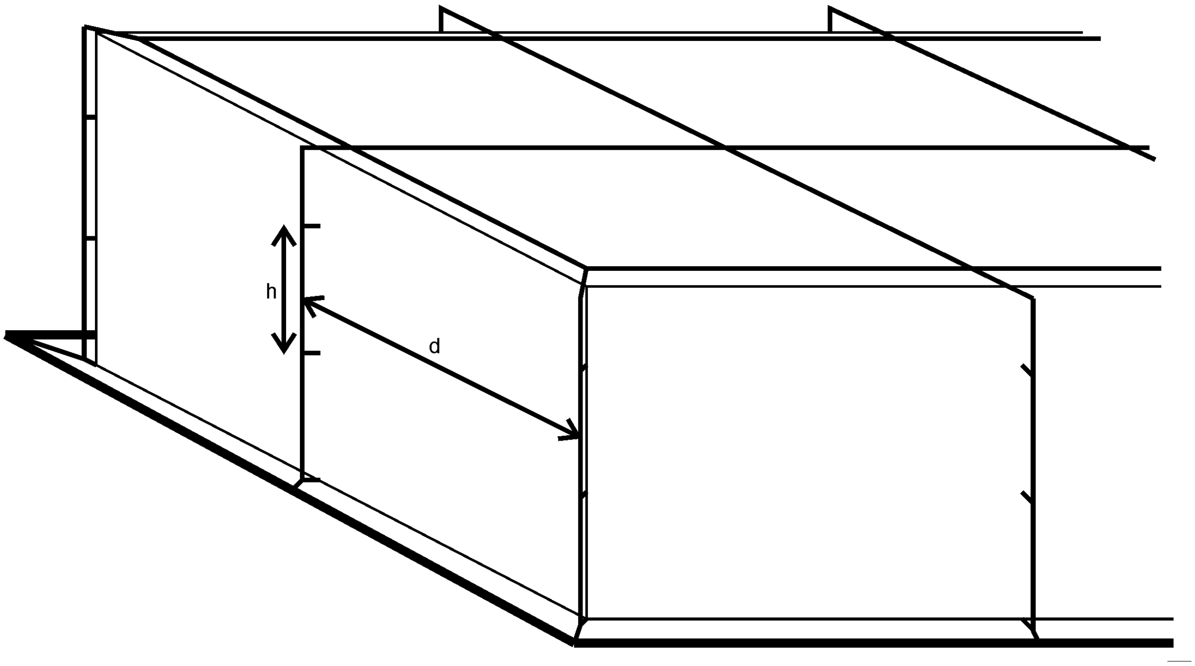

Figure 3 - Lightning conductor downlead positioning

The maximum vertical conductor spacing, d, is 10 metres for normal protection and 5 metres for high level protection. At least two vertical conductors must be used, with a cross-sectional area of at least 20 mm^2. Preferably at each floor, but at a maximum of 20 metre intervals, the vertical conductors should be connected to the earthing system of the building. The objective is to provide a Faraday screen around the building comprising the external array of vertical conductors and the horizontal connections at each floor level, establishing local 'equipotential' zones for each floor.

It must be remembered that lightning is a transient event so inductance and skin effect must be kept low by using flat strip conductors installed in straight lines.

Building protective conductor arrangement

The building 'protective conductor' serves several functions:

- To carry fault current back to the earth, so allowing overcurrent protection to operate
- To carry leakage current back to earth
- To act as a signal reference plane so that signal interfaces of interconnected equipment can operate correctly
- To preserve Electro-Magnetic Compatibility (EMC)
- To carry noise currents from RFI filters etc back to earth

All too often the 'protective conductor' is designed as if it were just a protective conductor, the other diverse roles being completely overlooked. It is unfortunate that it is not better named.

Fault current

Designing to cope with fault current is well understood. With properly designed overcurrent and fault protection the duration of a fault current will be limited and the energy 'let through' restricted to safe values. This is standard installation design. In this context, the critical criteria are absolute resistance to earth and the loop resistance of source, cabling and protective conductor.

Leakage current

Leakage currents are often overlooked. They arise mainly from filters intended to reduce RFI and, although the contribution from each item of equipment is small, the combined sum can be significant. These currents originate from a capacitor divider across the supply voltage and therefore have an open circuit source voltage of half the supply voltage. Normally, this source point is grounded to the protective conductor. If a section of the protective conductor becomes isolated, for example a radial circuit protective conductor becomes disconnected at the distribution point, then the isolated protective conductor will float to half the supply voltage. The available source current will depend on the number of connected units - whether turned on or off is usually irrelevant - and may exceed the level at which contact may be lethal. Proper practice is to ensure that the integrity of the 'protective conductor' is improved by providing more than one route from the equipment connection point back to the distribution point. At least one route must be a mechanically robust dedicated conductor while the other conductive path may be provided by cable armouring, conduit or cable trays. Note that if such a path is used, it must be installed and maintained in such a way that the integrity of the connection is assured. Since this type of leakage current is actually a feature of the design of the RFI filter in equipment it is now referred to simply as 'protective conductor current' in some installation codes.

The most important consideration for leakage current is the integrity of the protective conductor. The currents are relatively small, so that resistance is not an issue, but the risk of shock if the connection is lost is very high. The most difficult issue is how the integrity of the protective conductor can be preserved - there is no simple way to discover that the integrity has been compromised by the failure of one of the routes. Similarly, there is no indication of complete failure until an unfortunate user discovers it.

Signal reference plane

For the protective conductor to act as a voltage reference so that interconnected equipment can operate correctly requires very low impedance over a wide frequency range. The concern here is that the whole of the earth system represented by the protective conductor should appear to be an equipotential surface, in other words, over the whole frequency range of interest, over the whole area of the building, the potential difference between any two points should be zero. In practical terms, this means not that the potential difference should actually be zero, but that it should be low enough not to cause any malfunction of the installed equipment. Many signal interfaces use differential voltage levels (network interfaces, RS 485) and are tolerant of relatively high (a few volts) differences in reference voltage. Some older interface standards, such as the RS 232 interfaces used for modems and the IEEE 1284 used for printers, are single ended and are less tolerant.

Figure 4 shows typical single-ended and differential interfaces. A single-ended interface uses a single signal conductor and an earth return path. Clearly, any potential difference between the local ‘earth’ at the transmitter and receiver appears in series with the signal and is likely to cause data corruption. The apparently simple solution of adding another signal conductor between the two earth points is not feasible - a large and undefined current will flow causing interference and possibly damage.

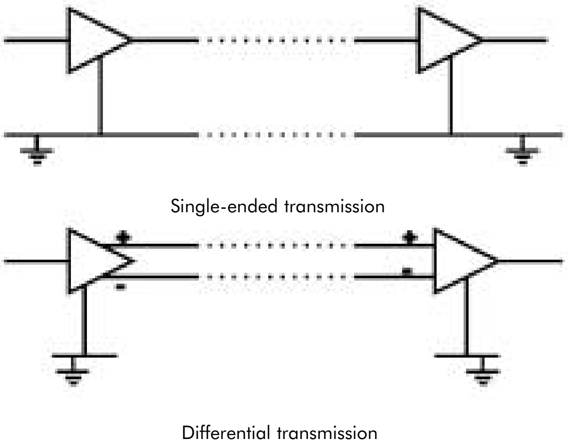

Figure 4 - Single ended (top) and differential signal interfaces

A differential interface uses two signal conductors and data is sent as a voltage difference between them. Ideally the receiver is sensitive only to the differential voltage between the signal lines and insensitive to the common mode voltage (the mean voltage on the signal lines). In practice this is not so and the common mode voltage must still be constrained but at a level of perhaps one or two orders of magnitude higher than that required for a single-ended interface. The ratio of differential sensitivity to common mode sensitivity is known as the common mode rejection ratio (CMRR) and is expressed in dB (voltage). For most semiconductor receivers the CMRR is high at low frequency, but decreases rapidly as frequency rises. In other words, the use of differential interfaces, while helpful in reducing the error rate, does not really relax the requirements of the protective conductor system.

Note that what is important is not the absolute impedance to earth but the impedance (over a wide frequency range) between different points on the protective conductor.

Generally, the measures required to provide a good signal reference plane are similar to those required to ensure EMC discussed next.

Electromagnetic compatibility

Every piece of electrical and electronic equipment produces some electromagnetic radiation. Similarly, every piece of equipment is also sensitive, to a greater or lesser extent, to electromagnetic radiation. If everything is going to work, the cumulative level of radiation in an environment must be rather less than the level that will disrupt the operation of the equipment working in that environment. To achieve this goal, equipment is designed, built and tested to standards to reduce the amount of radiation that is emitted and increase the amount that can be tolerated.

EMC is defined in the IEC 61000 series as:

> ‘The ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.’

Maintaining this compatibility in practice requires great care in the design and implementation of the installation and the earthing system. Detailed guidance will be given in later sections of this Guide; here a general overview only is presented.

In traditional electrical engineering separate earthing systems were used, for example, signal earth, computer earth, power earth, lightning earth etc. etc. In today's electrical engineering new insights have been gained on the aspect of earthing and grounding and its relation to instrument protection. The concept of separate earthing systems has been abandoned and the international standards now prescribe one overall earthing system. There is no such thing as 'clean' and 'dirty' earth.

This single earthing concept means in practice that protective earth (PE) conductors, parallel earthing conductors, cabinets and the shields and screens of data or power cables are all interconnected. Also steel construction parts and water and gas pipes are part of this system. Ideally all cables entering a zone must enter at one point at which all screens and other earth conductors are connected.

To reduce interference on equipment the earthing loops between cable-screens and other earthing structures must be kept small. Bonding cables against metal structures makes these structures act as parallel earthing conductors (PEC). Parallel earthing structures are used both for data and power cables. Examples are, in ascending order of effectiveness: earthing wires, cable ladders, flat metal surfaces, cable trays or ultimately metal pipes. The PEC reduces the impedance of the loop formed by the cable and the earthing network. The earthing resistance to mother earth is mostly not important for the protection of equipment. A very effective form of a PEC is a densely woven or completely closed cable screen with a large metal cross-section, connected all around at both ends of the cable.

To keep the impedance of bonding connections in the earthing network small for high frequencies, litz wire (stranded, individually insulated) or metal strips with a length to width ratio smaller than 5 must be used. For frequencies higher than 10 MHz round wires should not be used.

A raised floor can serve as a good equipotential plane. The copper grid underneath it must have a maximum spacing of 1.2 metres and be connected to the common bonding network via many equipotential bonding conductors. The grid should be connected to a 50 mm^2 copper ring placed around the raised floor area, within the boundaries of the floor, at 6 metre intervals. Power and signal cables should be at least 20 cm apart and where they cross, they should do so at right angles.

Conclusion

The earthing system of a building or site is a critical part of the electrical infrastructure and can determine the future viability of businesses operating in it. It is required to deal with short duration fault currents of several hundred Amperes, standing currents of a few Amperes and high frequency noise currents returning them to source or ground with close to zero voltage drop for noise currents and with no risk of damage for fault currents. At the same time, it must protect the equipment and personnel housed in the building during lightning strikes (fast transients in the kiloampere region) in the interconnected earthing system.

The design of the earthing system of a building, including the lightning protection system, requires great care if all the objectives are to be met. It is, as usual, best and cheapest if it is designed correctly from the start, considering the lifetime of the building and, as far as possible, the potentail usage during that lifetime. Re-engineering after the building has been occupied is always an expensive exercise.

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