

# THE BENEFITS OF APPLYING IEC 61000-5-2 TO CABLE SCREEN BONDING AND EARTHING

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## INTRODUCTION

It is sometimes said that EMC engineers divide into two camps:

- Those concerned with power, surges, lightning, and electrical installations
- Those concerned with radio frequencies (RF) and electronic products

This paper will hopefully be valuable to both camps.

Issues of cables screen bonding and earthing are becoming more important because...

- The frequencies used in electronics are increasing
- The environment is becoming more polluted with noise at mains harmonic and radio frequencies
- Electronic devices are becoming more complex and also more vulnerable to interference
- EMC regulations are increasing world-wide

Screened cables only provide their full performance at high frequencies when their screens are correctly terminated to their equipment's Faraday cage or local 'earth' reference *at both ends*.

This paper discusses the design and installation issues involved in terminating screens at both ends, with particular reference to the excellent guidance given by IEC 61000-5-2 [1]. The following topics are covered here:

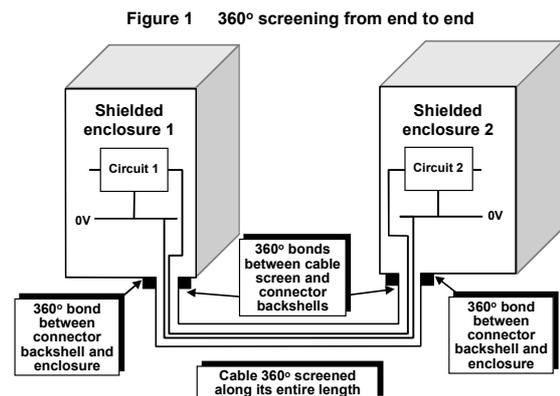
- Terminating screens at both ends to control RF
- Never use 'pigtailed' for screen termination
- Terminating screens at one end exposes electronics to damaging overvoltages
- Meshed earth bonding is better than single-point
- The parallel earth conductor (PEC) (prevents excessive currents when cable screens are terminated at both ends)
- When screens cannot be terminated at both ends
- Copper communications between buildings

## TERMINATING SCREENS AT BOTH ENDS TO CONTROL RF

Developments in electronic technologies, including microprocessors, wireless communications, switch-mode power conversion and variable-speed motor drives, plus developments in EMC regulations, mean that we now have a general requirement to control frequencies above

150kHz, called radio frequencies (RF) here. This need is becoming more demanding as electronic technology continues to progress and as applications increase to include areas not previously under electronic control, including safety-related functions. At the moment most environments, other than in some military and scientific applications, require control of RF up to at least 2GHz (2,000MHz) because of the cellphone systems operating near that frequency.

To realise the full RF screening potential of a screened cable there must be no gaps in its screen along its entire length, including its connectors at both ends. This is often called 'end-to-end 360° screening', and Figure 1 illustrates its general principles.

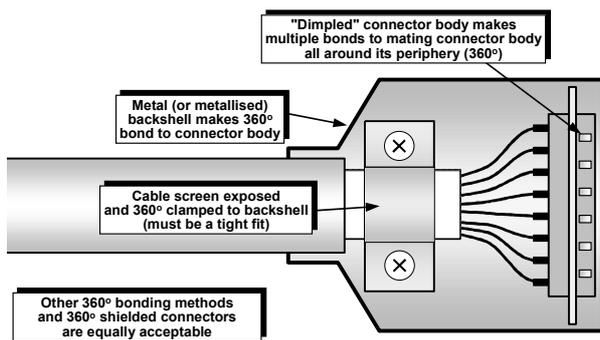


Achieving effective screening at RF is rather like plumbing – any gaps or incomplete seals (including at all couplings and joints) that would leak if the system was filled with water under pressure, would leak RF.

The RF screening performance of cable screens and their connectors is characterised by their surface transfer impedance:  $Z_T$ . A low value of  $Z_T$  implies a good screening performance. Section 7.2.2 of Williams and Armstrong [2] describes the  $Z_T$  of different types of cables, and shows that the tiny apertures in the braid or foil of screened cables causes  $Z_T$  to rise at frequencies above 1MHz or so. But since there are no apertures in solid copper screened cables their  $Z_T$  falls above 1MHz.

Connectors have a similar problem – any apertures in their screening causes their  $Z_T$  to rise above a certain frequency, which is why so-called 'EMC D-types' (see Figure 2) have rows of dimples all around their bodies – to make multiple screen connections when mated – to reduce the size of the gaps in their overall screening.

Figure 2 Terminating cable screens in connector backshells  
Example of a D-type



At a cable connection there are a number of possibilities for large gaps to appear in the screening – e.g. cable screen to cable connector backshell; backshell to mating connector; mating connector to its cable screen or enclosure shield.

Cable screens are often bonded at one end to preserve single-point earthing schemes and prevent ‘hum loops’ from affecting signals. But single-point earthing is an old technique that cannot control screen currents at RF and is now no longer preferred, as discussed below. A paper by Armstrong and Waldron [3] explains why using circuit and equipment design practices known before 1995 mean that multiple earth bonds are a real benefit for signal quality.

When a cable screen is only terminated at one end, a large gap in the screen exists at its other end. This creates a number of problems:

- The gap ‘leaks’ a great deal at RF, compromising the screening performance of the whole cable
- When the length of a cable exceeds one-sixth of a wavelength the screen will begin to act as a resonant antenna – worse than having no screen at all
- High-speed data communications use transmission line techniques, and breaking their screen anywhere creates impedance discontinuities which harm signal integrity and data rates
- No screening is provided against magnetic fields with certain orientations

The best RF screening performance of connectors or glands is only achieved if their assembly does not require the cable screen to be disturbed. Screen termination arrangements that do not disturb the lie of the screen are preferred, and an example of a D-type connector is shown in Figure 2.

The military have a lot of experience with RF control, and the need for 360° bonding of cable screens at both ends is clearly expressed in two military EMC installation guides from the US Department of the Navy [4] and the UK’s Ministry of Defence [5]. Commercial and industrial EMC best practices in bonding screens at both ends are described in detail in [1], IEC 61000-5-6 [6] and by Armstrong [7].

**Never use pigtailed for screen termination**

Traditionally, terminating a cable screen was done by connecting it with a wire to an appropriate terminal. These wires are often called ‘pigtailed’ and they ruin the cable’s screening performance at RF. Pigtailed inside equipment are often around 100mm in length, but are sometimes found to be over 300mm. In installations, pigtailed of several metres length are sometimes seen.

The inductance of a pigtail is very significant at high frequencies. A 100mm long wire has an inductance of around 100nH (0.1µH), which has a reactive impedance of 19 ohms at 30MHz and 190 ohms at 300MHz.

But resonance of a pigtail’s inductance with the cable screen’s capacitance causes a much greater reduction in performance. Pigtailed just 25mm long have been seen to completely ruin any shielding effect in a 3 metre long cable at frequencies above 30 MHz.

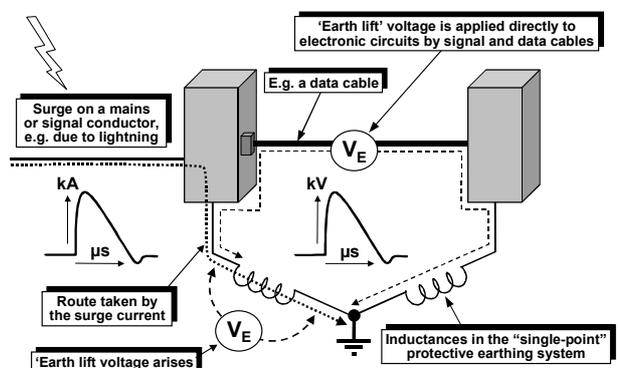
Respected EMC guides [1] [2] [4] [5] [6] and [7] all warn against the use of pigtailed for screen termination. Their bad effects on RF control have been well-known in EMC circles since at least 1985.

**TERMINATING SCREENS AT ONE END EXPOSES ELECTRONICS TO DAMAGING OVERVOLTAGES**

During transient electromagnetic disturbances – such as those caused by lightning, earth faults, the switching of large inductive loads, and HV circuit breaker operation – large potential differences can exist between the protective earth conductors in different parts of the same structure. These potential differences are caused by the flow of transient currents through the inevitable impedances of the common bonding network (CBN, sometimes called the protective earthing network).

Cable screens are traditionally only terminated at one end so as to preserve the single-point earthing scheme and prevent ‘hum loops’, but Figure 3 shows how single-point earthing exposes electronic input and output devices to the transient overvoltages caused by (for example) a lightning-induced current surge.

Figure 3 ‘Earth lift’ in single-point earthing systems



When a lightning surge (for example) is experienced by one item of equipment, the inductance in its earth connection causes it to experience a local ‘earth-lift’ potential. But the other item of equipment does not experience the earth-lift, so the differences between the

'earths' of the two items is applied in common-mode to the electronic circuits at their interconnected input and output (I/O) ports.

A typical simulated lightning surge, used for compliance testing to the EMC directive, would result in between  $\pm 500\text{V}$  and  $\pm 2\text{kV}$  of earth-lift for a single-point earthed equipment with a 10 metre long protective earth conductor. In real life most single-phase equipment is subjected to lightning-related surges of up to three times higher than this, so for the above equipment we should expect earth-lift voltages somewhere between  $\pm 1.5\text{kV}$  and  $\pm 6\text{kV}$ . Some three-phase and other equipment could be exposed to even higher levels of lightning-related surge and consequent earth-lift.

Such common-mode transient voltages can cause signal and communication errors, but can also cause the electronic circuits to fail. Actual physical damage can occur, increasing the risks of electric shock and other safety hazards such as toxic fumes, smoke, and fire.

A lighting protection expert has described seeing the unterminated screens at the ends of long cables arc to the equipment frame during a thunderstorm – hardly a recommendation for safety, never mind equipment reliability.

So we can see that the age-old practice of single-point grounding and its consequent requirement to only terminate cable screens at one end is poor for EMC, poor for surge protection and reliability, and poor for safety.

### A practical example of earth-lift

In [8] van der Laan and van Duerson gave an example of how the overvoltage exposure of an instrumentation unit varied with the bonding of its cable screen and related metalwork. A temperature sensor monitored a HV (150kV) transformer, and was connected by a 23 metre cable to the temperature indicating electronics in a control room.

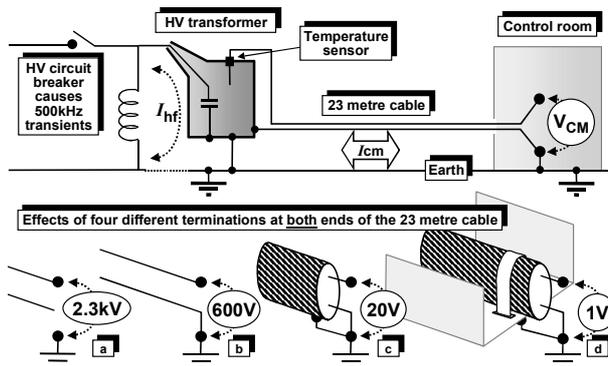
When the HV circuit breaker which connected the transformer to the 150kV busbar opened, its flash-over created an intense ringing wave of around 250A at 400kHz. This induced significant voltages into the temperature electronics in the control room, via the 23 metre multi-conductor cable carrying the sensor signal. The results of their investigations into the effects of bonding at both ends are shown in Figure 4.

With the sensor signal conductor and its associated armour and steel duct connected at the HV transformer end only, opening the HV breaker exposed the temperature electronics in the control room to 2.3kV. This was probably a great deal more than the designer of the temperature electronics had expected.

When one of the other conductors in the 23 metre cable was bonded to the CBN at both of its ends (the HV transformer and temperature electronics equipment frame), the overvoltage was reduced to 600V. Bonding the cable armour at both ends then reduced the overvoltage to 20V, and when the steel duct was also bonded

at both ends the overvoltage during the opening of the HV breaker was reduced to under 1V.

Figure 4 'Earth lift' case study by van der Laan and van Duerson



### MESHED EARTH BONDING IS PREFERRED TO SINGLE-POINT EARTHING

The traditional technique of single-point earthing (sometimes called star earthing) is clearly a problem – it prevents us from directly terminating cable screens at both ends to get the best EMC performance, and it does nothing to protect electronic devices to overvoltages.

At the frequencies for which a conductor (including steelwork, metal pipes and ducts, and other conductors) is longer than half of the wavelength, RF disturbances in the environment cause significant currents to flow regardless of its earthing or other type of end termination. 'Stray' capacitances and 'stray' mutual inductances, sometimes between conductors that are some distance apart, dominates the flow of high-frequency current in a system or installation.

So we now see that single-point earthing and terminating cable screens at one end are a method that evolved in the days when high levels of RF were rarely encountered, and is quite unsuited to the modern world.

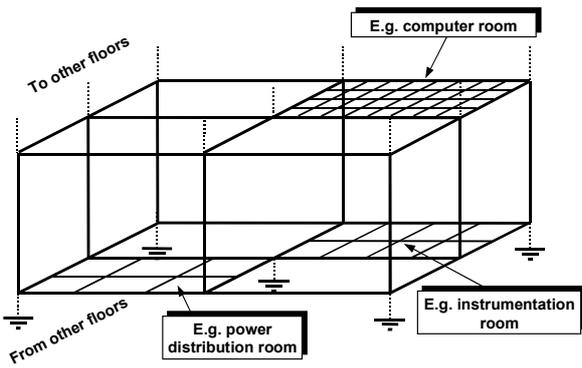
When cable screens are directly terminated to the chassis, frame, or enclosure shield of the equipment at both ends, a meshed common bonding network (MESH-CBN) is created. Where the equipment is also connected to the protective earth for safety reason we could also describe this as a meshed protective earthing system.

Mesh bonding has its drawbacks, but they can be dealt with whereas the drawbacks of single-point earthing in the modern world cannot be dealt with in any practical manner.

Since the cable screens create a MESH-CBN, there is now no reason not to carry on in this vein and gain significant advantages by meshing the protective earthing network too.

Figure 5 shows the scheme recommended by [1] for the MESH-CBN of a building. This achieves a very low impedance at 50/60Hz, and also achieves a low impedance at higher frequencies – depending on its mesh size. A greater number of smaller meshes means a lower inductance, and means a higher frequency of control of systematic RF currents and voltages.

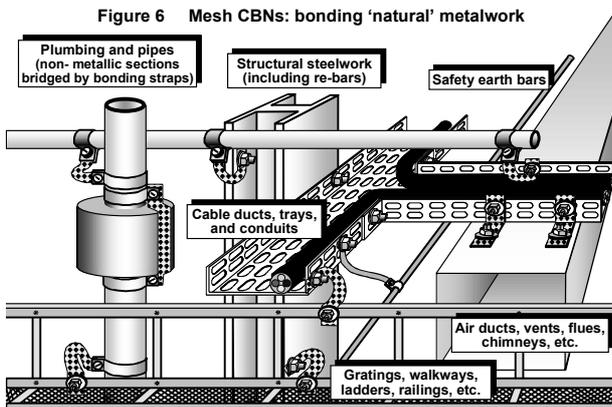
Figure 5 Example of a meshed common bonding network (MESH-CBN)



Heavy current equipment requires a closer mesh to prevent high voltage drops in the case of leakage or fault currents. High-frequency equipment (such as computer or telecommunications systems) requires a small mesh size (often 600mm or less) to help control the high frequencies their interconnections use. Sensitive instrumentation often requires a smaller mesh size to help prevent interference with its signals over a wider range of frequencies.

Meshing creates a lower impedance CBN that reduces earth-lift voltages and so helps to protect equipment from overvoltages. For example, to help provide protection from lightning induced surges it is generally recommended to use a CBN with a mesh size no larger than 4 metres in any dimension (e.g. the mesh diagonals).

So-called ‘natural’ metalwork, such as re-bars, girders, structural metalwork, and any other metalwork can be pressed into service to help achieve a MESH-CBN, as shown by Figure 6.



The ideal MESH-CBN can be thought of as a large number of small earth loops. A lot more on the construction of MESH-CBNs, including the use of bonding ring conductors (BRCs) and the advantages of multiple bonds to the lightning protection system (LPS) can be found in the references.

### Isolated meshed bonding networks

Many older buildings have single-point earthing systems, and these ‘legacy’ systems can make it costly to install new technology that require MESH-CBNs.

One common technique is merely to run every new cable, whether screened or not, with its own dedicated parallel earth conductor (see later), but this can cause problems for sensitive existing equipment when its carefully-honed single-point earthing system is degraded to a poor mesh (e.g. one or two large earth loops).

Where a computer or telecommunications room or other area of modern high-tech equipment is to be installed in an old building, sometimes a *locally* meshed bonding network is used just for its area (sometimes called a bonding mat or system reference potential plane, SRPP). This local mesh is isolated from the building’s earthing system except at a single point of connection (called its SPC). All the cables and services entering or leaving this isolated mesh-bonded area enter / leave near to the SPC and are either directly bonded to the SPC or are fitted with surge protection devices (SPDs) and/or filters which are bonded to the SPC.

This locally meshed technique is often called a MESH-IBN (meshed isolated bonding network). Its biggest problem is that it is easily compromised by craftsmen and engineers and so requires absolute control of all wiring, equipment, and services by a skilled person employed by the site.

MESH-CBNs and MESH-IBNs are described in detail in [1], and also in Chapter 5 of [2] and Part 2 of [7].

### THE PARALLEL EARTH CONDUCTOR (PEC)

Since we can’t generally now avoid the need to terminate cable screens at both ends, a way must be found to prevent cable screen currents from causing overheating. (Note that, as mentioned above, [3] shows that cable screen currents do not cause noise problems when equipment is designed so that screen currents do not flow in internal circuits.)

Where a MESH-CBN as recommended by [1] is fully implemented, it will reduce the potential differences between items of equipment to such low levels that connecting cable screens at both ends does not result in significant levels of screen currents at powerline frequencies, even during earth faults.

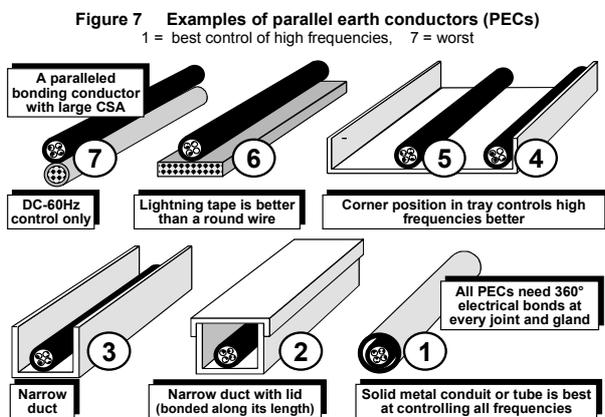
But where an adequate MESH-CBN cannot be fully implemented and if screen currents could be so large as to damage the cables or cause emissions of fumes, the technique recommended by [1] is the ‘parallel earth conductor’, or PEC (although it would have been better to have called it a parallel bonding conductor). As its name implies, a PEC is a conductor connected in parallel with the cable screen.

The largest currents flowing in an earthing system are at power frequency. Given a choice of paths they will prefer to flow in the path of least impedance, and at these low frequencies it is usually only the resistance that matters. So PECs need to have a much lower resistance (hence a much higher cross-sectional area, CSA) than a cable’s screen to reduce the power-frequency currents in that screen to acceptable amounts.

Transient events generally involve considerably higher frequencies than the typical continuous currents which flow in CBNs. Lightning surges have their peak energies at around 10kHz, but can involve frequencies of up to 500kHz. The operation of high-voltage circuit breakers can create currents of 250kA at 500kHz [8]. Earth faults have almost all their energy at the power frequency, but any arcing during the fault or in the fault-clearance devices can create frequencies up to thousands of MHz. At these frequencies the path of least impedance is usually the path of least partial inductance.

So to reduce the levels of transient currents flowing in a cable's screen, its PEC needs to have a much lower partial inductance than the screen, and also must have a high mutual inductance to the screen (achieved by the PEC following the cable's route very closely). PECs with lower partial inductances also provide better control of the RF common-mode currents associated with the wanted signals carried by the cables, thereby improving cable crosstalk and signal integrity and also improving the radiated emissions and immunity of the equipment.

Where a number of cable screens are bonded at both ends to the same items of equipment, they may act as their own PEC. Although each has quite a high resistance and high partial inductance, a number connected in parallel will share the screen currents between themselves and there may be no need for a separate PEC.



Where a building has a MESH-CBN it is often most convenient to use parts of its CBN as PECs, especially cable trays, ducts, and conduits. Where suitable metalwork is not handy, wires with a large cross-sectional area may be used instead. Figure 7 shows a number of common types of PEC, ranking them in order of decreasing partial inductance and increasing mutual inductance, hence their ability to control RF.

A lot more information on PECs is given in [1], for example what types of cable trays perform best and how they should be bonded together. Cable armour can also be used as a PEC, and can have a good response at frequencies above 50Hz (depending on the construction of the armour and the quality of its 360° bonding at its joints and both ends). But ordinary cable armour (e.g. steel wire armour) should not be relied upon alone, to provide any benefits above 1MHz.

One of the problems with using 'natural' metalwork and armour as PECs is that it may be vulnerable to craftsmen and future modifications. If they are only thought to provide mechanical support or protection, their continuity may be compromised in the future by people unfamiliar with their rôle as PECs.

The cabling and earthing recommendations made by IEC 61000-5-2 [1] are referenced, or else duplicated to some degree, by most of the latest standards concerned with the installation of electronics in buildings and other structures, for example [9] [10] [11] [12] [13] [14] and [15].

## WHEN CABLE SCREENS CANNOT BE TERMINATED AT BOTH ENDS

In general, cable screens should be terminated at both ends unless there is a good technical reason not to do so. In the vast majority of cases, including professional audio [3] and other applications involving low signal levels and high signal/noise specifications, bonding screens at both ends and using MESH-CBNs is well-proven to be far superior to more traditional methods.

However, sometimes there is a real practical problem with bonding cable screens at both ends.

In these cases – if signals and data are only communicated at low frequencies – all unwanted high frequencies should be filtered out. It may still be necessary to use a screened cable to help prevent noise and crosstalk within the frequency band of the signals, but this screen will be bonded at one end. Surge protection devices may also be required to protect from transient overvoltages.

However, the best approach is to avoid the use of copper cables altogether. Galvanically isolated fibre-optics (with metal-free cables), infra-red, or wireless communications are all very effective alternatives. These are often dismissed at an early stage in a design on grounds of material cost, but often turn out to have the lowest cost when the overall project is costed taking into account its regulatory compliance, warranty costs, and customer satisfaction. Unfortunately, many designers only begin to appreciate their cost benefits when struggling to solve the reliability problems, interference, or damage created by the use of copper conductors, by which time it is too late to save cost.

Opto-isolator devices on printed circuit boards (PCBs) within equipment are often used for galvanic isolation, but typically are often rated for only 500V. When used on long cables run inside a building covered by a single protective earth-bonding network they need to be able to withstand at least 6kV to protect against transient events.

Sometimes one is faced with an item of equipment which has been designed to permit screen currents to flow in its internal circuitry. If it cannot be modified to a more sensible design that confines potentially interfering screen currents to its chassis, frame, or enclosure shield

it is often possible to use a 'double insulated screen' cable.

The inner screen would be connected at the specified end (even using a pigtail if that is what the supplier's installation instructions required), whilst the outer screen is 360° bonded at both ends as shown in Figure 1 to provide RF control.

## COPPER COMMUNICATIONS BETWEEN BUILDINGS

Generally speaking, the most reliable and safe way to interconnect signals or data between two different buildings, ships, vehicles, or whatever, is to use galvanic isolation which can cope with at least 2MV. Metal-free fibre-optic cables, wireless (radio) links, free-space lasers or microwave links are all suitable candidates and are now provided by a large number of companies.

However, copper cable interconnections may be able to be used, where the functions of or in the buildings (or ships, etc.) will accept an element of risk. This would require each structure has a complete MESH-CBN which extends to the cables between them. The MESH-CBN should be designed to handle the greatest transient events thought to be possible, such as an earth-fault in a nearby HV substation or a direct lightning strike to one of the buildings (or ships, etc.). Chapter 9 of [2] and Part 5 of [7] have more on this issue.

## CONCLUSIONS

The recommendations for cable screen termination and earthing in IEC 61000-5-2 are of very great benefit in helping to control RF as required by systems and installations, in these days of rapidly increasing electronic sophistication and rapidly worsening electromagnetic environment.

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