Chapter 2

Grounding & Shielding

Safety, system protection and performance are the three main reasons to earth a system. Not all electronic equipment needs to be connected to earth to work, satellites are an example. Sometimes wrong grounding configurations, oriented to satisfy the special power and performance requirements of electronic loading equipment, can compromise safety rules generating dangerous situations for personnel and equipment. Personnel safety, equipment safety and performance grounding issues have to be analyzed together. In any case, safety rules must not be violated. All these concepts as well as the relations between ground issues need to be clarified before passing on to a higher level in the control of the electromagnetic emissions of the system. Along the present chapter, concepts like safety grounding, signal or ground reference plane as well as grounding topologies to achieve electric safety and good performance of the system, are presented. The characteristics of shield structures, shielded power cables as well as their connections to ground are also presented. Finally in the last section, some recommendations to design the CMS detector grounding are included. The grounding design of the detector constitutes the first of several steps to be followed for the detector integration under a electromagnetic compatibility plan.

2.1 Grounding generalities

As described in [1] [2] and [3], proper grounding techniques are necessary for safety, equipment operation and performance. The integrity of both the facility grounding and the proper equipment operation depends on the proper bonding of the grounding electrode system, proper system grounding of service equipment and separately derived sources and proper equipment grounding for operational frequencies (DC or AC-mains) as well as higher frequencies. It is recommended that the grounding design and installation be compliant to all applicable codes and standards [4][5]. The grounding is not designed as an active component of the power supply (PS) distribution system, hence this path must be free of any operational current.

Metal parts of equipment enclosures, racks, raceways and equipment grounding conductors susceptible of being energized by electrical currents (due to circuit faults, electrostatic discharge, and lightning), must be effectively grounded for reasons of personnel safety, fire hazard reduction, equipment protection and equipment performance [6][7]. Grounding these metallic objects facilitates the operation of over-current protective devices during ground faults and permits return current from electromagnetic interference filters and surge protective devices, connecting line to ground or line to chassis, to flow in proper fashion. All metallic conduits and raceways in areas containing electronic load equipment have to be carefully bonded to form an electrically continuous conductor.

All mechanical equipment in the electronic equipment areas should be carefully bonded for an electrical safety and for noise current control. Such equipment should be grounded or bonded to local building steel using direct or higher frequency grounding and bounding means. When located in the same area as the electronic load equipment, mechanical equipment should be bonded at multiple points to the same ground references as the electronic load equipment. Heating, ventilation, air conditioning, process cooling equipment, related metal piping and electrical conduits are recommended to be bonded to the same ground reference serving the electronic load equipment.

Once the grounding complies with the safety rules, the ground connections have to be improved to obtain a good performance of the system. It is important to keep in mind that for operational reasons one should imagine that at low frequencies the ground system is a kind of low resistive divider in which all noise currents usually flows everywhere. However at high frequency the ground impedances start to increase mainly due to the inductive effect, flowing the noise only through the lowest impedance path. Therefore, the ground connections should be tackled in two steps. The first step is oriented to low frequency currents where it is important to avoid ground loops because once these currents are established they can flow everywhere, decreasing the performance of the system. The second step is focused on the noise at high frequency, where one could imagine that everything in the system is connected (through real or parasitic impedances) designing the ground path and connections in an specific way that gives a low impedance path to HF noise currents and thus avoiding the flow of these currents through sensitive parts of the system.

2.2 Grounding for fault and personnel protection.

2.2.1 System grounding or earthing

System grounding or earthing involves the ground connection of power services and separately derived systems. They include generator, transformers, uninterruptible power systems (UPS). The system earthing is the intentional connection of a circuit conductor (typically the neutral on a three phase, four wire system - Protective earth (PE)) to earth. The purpose of the system grounding [3] is for electrical safety of personnel and equipment as well as fire safety reasons. Safety is basically governed by the electrical codes and standards as adopted by government agencies and commercial entities. System grounding also impacts the performance of electronic load equipment for reasons related to the control of the common-mode noise and fault currents, however the personnel and the equipment protection is the primary task of the grounding as it is described in [8].

The grounding of power systems is, from a safety standpoint, oriented to limit the potential difference between grounded objects, to provide a good operation of over-current protective devices in case of ground fault, to stabilize the phase voltages with reference to ground and to limit transient voltages due to lightning and load switching.

There are two basic requirements for grounding power services and separately derived systems or sources (transformer, generators, UPSs, etc.). The first requirement is to bond the neutral or secondary grounded circuit conductor to the equipment grounding terminal or bus. For power services entrances, the incoming neutral conductor is connected to the equipment grounds bus in the switchboard by means of the main bonding jumper. For separately derived sources, the neutral must be bonded to the equipment grounding terminal or bus. The second requirement is that the equipment grounding terminal or bus must be connected to the nearest effective grounded electrode by means of the grounding electrode conductor. To illustrate the grounding connection of a separately derived source, figure 2.1 shows the grounding connection for an isolation transformer. If no effective grounded electrode or building steel is available, then the separately derived source should be connected to the service entrance grounding point via a grounding electrode conductor installed in the most direct and shortest path practicable. In the case that metal interior piping is present near the separately derived source, a supplemental grounding electrode conductor should also be installed from the equipment grounding terminal or bus of the separately derived source to the metal interior water piping.

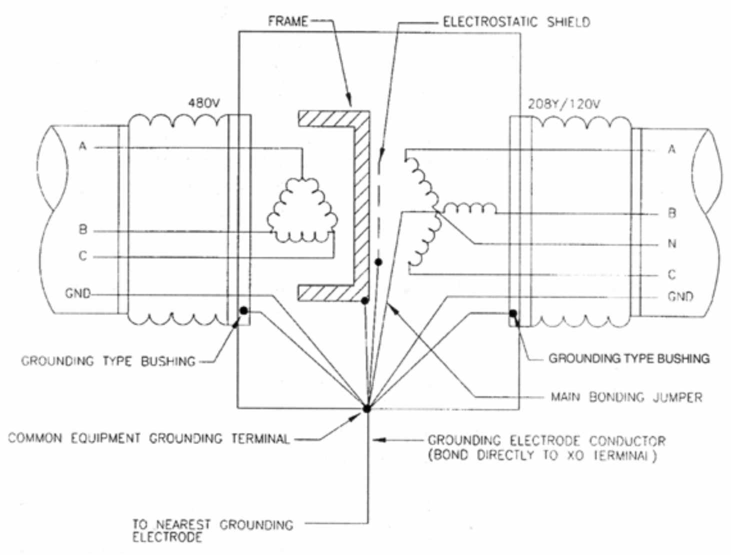

Figure 2.1: *Isolation transformer grounding layout.*

From a performance standpoint, solidly grounded power systems are recommended practice to ensure the existence of effective conductive paths for the return current of filters and surge protective devices connected line to ground or line to chassis. These filters and surge protective devices may be an integral part of the electronic load equipment or may be separately mounted devices located in the building electrical distribution system. It is recommended in the design to aim at the lowest reasonable impedance between the load equipment containing a filter or surge protective device and the associated power system source. Low-inductance wiring methods should also be used.

2.2.2 Equipment grounding

As described in [9][10][11] and [12], electrical or electronic circuits do not need to be earthed in order to work. Satellites, spacecraft and mobil phones, all work properly without earthing. The earthing or system grounding is a requirement necessary for safety. Electrical safety concerns all electrical design work. Safety requirements cannot be compromised to satisfy the special power and grounding requirements of electronic loading equipment. One should always try "*to make the system design safe and then try to make it work*". This ground philosophy is widely explained in [7], [13] and [14].

The term "equipment grounding" refers to the connection to power system ground of all non-current carrying metallic parts of a power system that may come into accidental contact with circuit phase and neutral conductors. These metallic parts include raceways, conduits, equipment grounding conductors, equipment enclosure and racks. All these items are ultimately grounded together at the grounding electrode of the power service or a separately derived system. Equipment grounding is required for both personnel safety and power systems protection. From a personnel safety point of view, properly grounded system components minimize potential differences that may exist between various system components under transient and fault conditions. From a system protection standpoint, properly grounded system components provide a low impedance path for ground fault currents and promote the timely operation of over-current protective devices in case of ground faults.

There are two different grounding configurations associated with the connections of the equipment to the PE point; the standard ground configuration and the insulated ground configuration.

- For the standard equipment grounding configuration, a supplementary ground conductor provides an additional low impedance ground path in parallel with the metallic conduit or raceway from the equipment to the power system.
- For the isolated grounded configuration, the electronic or electrical load is not connected to the metallic enclosure and this metallic enclosure is earthed through an independent conductor to the start point of the safety ground. The insulated equipment grounding conductors run with the other circuit conductors feeding electronic load equipment. In an isolated ground configuration, the additional equipment grounding conductor provides the sole grounding path from the electronic or electrical load equipment to the power system or separated derived system.

In either case, the insulated equipment grounding conductor should run in the same raceway or conduit as the phase and neutral conductors. Grounding configurations provide equalization of potentials between grounded objects at the operative frequency. As the frequency increases, other grounding means must be considered to cover the high frequency range.

Robust design of the electronic load equipment for immunity to disturbances on the grounding circuit is a good method to get a good grounding [15]. Particularly for distributed computing and telecommunication electronic loads, using optical signaling interfaces reduces the sensitivity to disturbances on the ground circuit. As it is implemented in the CMS detector, the processed data from the detector is transmitted out of the detector via optical devices, and the slow control signals are isolated from the detector via opto couplers.

2.2.2.1 Standard equipment grounding

The standard equipment ground configuration [13][14][16] uses one equipment grounding conductor (PE or G), in green color, running with the phase and neutral conductors to supplement grounded metal raceway and conduit. This configuration is shown in figure 2.2.

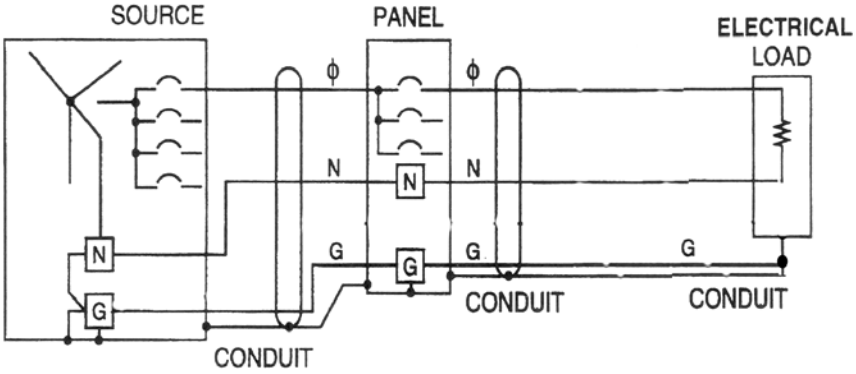

Figure 2.2: *Standard ground configuration.*

The standard equipment grounding conductors are usually sized according to the table of standards for equipment grounding conductors and are properly connected and bonded to each metal enclosure that it passes through from the separately derived system or power service to the electronic load equipment. These metal enclosures include all distribution panel boards, safety switches, circuit breaker enclosures, transformers and branch circuit panel boards, as well as pull boxes, junction boxes and metal outlet boxes.

The conduit and raceway system may depend on the integrity of mechanical connections at conduit and raceways joints, panel boards, junction boxes and at the receptacles themselves. The non-uniformity and bad performance of the grounding paths can compromise personnel safety as well as the operation of surge suppressors and filters located in the electronic load equipment. In addition, currents flowing on grounded surfaces may take less desirable paths, such us through load equipment and associated data cables. The purpose of the installed equipment grounding conductor is to increase the reliability of the grounded metal conduit system.

2.2.2.2 Isolated grounding

The isolated grounding configuration [16][17] uses an insulated equipment grounding conductor, typically green color with yellow stripe, running with the phase, neutral and PE conductors from the electronic load equipment to the equipment grounding terminal of the power system or separately derived system. As opposed to the standard equipment grounding configuration, this additional insulated equipment grounding conductor typically connects the isolated ground receptacle (IGR) only to the equipment grounding terminal or bus of the power system source or separately derived system. This equipment grounding conductor extends radially downstream to the chassis of the electronic load equipment without contacting any grounded metal surfaces such as metal conduits and race ways, panel boards, and outlet boxes for receptacles. This configuration is shown in figure 2.3.

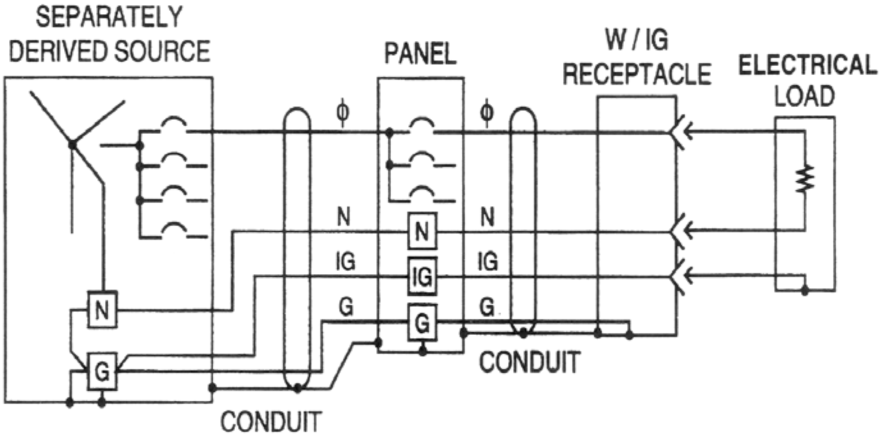

Figure 2.3: *Isolated ground configuration.*

The isolated equipment grounding conductors are sized according the table of standards for equipment grounding conductors and are properly connected and bonded to the metal enclosure at load level as explained in the standard equipment grounding. This type of equipment grounding configuration is only intended to be used for reducing the common mode (CM) electrical noise on the electronic load equipment circuit as described in [13] and [17].

This type of configuration may produce better or worse noise conditions than when a standard equipment grounding configuration is used to serve electronic load equipment. Noise effects will be somewhat proportional to the overall length of the circuit [17]. Under power system fault conditions, the potential difference between the electronic load equipment and grounded objects may be sufficient to cause a safety hazard or to disrupt the electronic load equipment performance.

The isolated grounded configuration is only directly applicable to metal-enclosed wiring means and has no useful purpose with nonmetallic wiring systems. Non-metallic wiring systems are at least partially constructed as if they are isolated grounding types, since no metal conduit or raceway is involved in the wiring path or is bonded to the equipment grounding conductor of the circuit. In any case, the non-metallic wiring system does not provide electromagnetic shielding for the enclosed circuit conductors and should not be used.

The application of the isolated ground configuration may provide beneficial effects to circuits supplying electronic load equipment that do not otherwise connect to grounded objects. However, if the electronic equipment contains other connections to grounded objects as in the standard ground configuration, the performance of the isolated grounding configuration decreases. These connections to ground may be either intentional or unintentional. Typical examples of these connections are interconnections of various equipment through grounded shields of data cables and bonding of equipment chassis to grounded metal equipment racks.

2.3 High frequency grounding configuration

The grounding configurations described above provides the necessary connections to ensure the overall electrical safety of the system. When two or more components of an interconnected system are installed in an area where there is a physical space between them and across their separation data input/output cables and inter-unit power circuit cables (DC, AC or both) are routed, there exist indirect bounding problems ranging from DC to several tens of MHz or higher that can compromise the system performance. A reasonable grounding system has to be designed, without compromising electrical safety, by defining a ground reference structure over a broad range of frequencies. For separated equipment or units is necessary to place all of them on a single sheet of metal in the form of a signal reference plane and then to use direct grounding or bonding techniques to connect the entire perimeter of the base of the unit to signal reference structures (SRS). These reference structures can be built as reference planes (RP) or grid structures (GS). Linear brazing or welding around the perimeter of the unit's base is one method for grounding to the structures. However, such direct connections are not often practical, and the next best approach is to use multiple indirect bonding straps of minimized length to connect individually the plane to each unit locally.

The SRS is not intended to be dielectrically or galvanically insulated or isolated from the safety grounding conductor (PE) system that is part of the fault/personnel protection grounding system. The principal purposes of the SRS are:

- To enhance the reliability of signal transfer between interconnected items of equipment by reducing inter-unit common electrical noise over a broad band of frequency.
- To prevent damage to inter-unit signal circuits by providing a low-inductance, and hence, effective ground reference for all of the externally installed AC and DC power, telecommunications, or other signal level, line to ground/chassis connected equipment that may be used with the associated equipment.
- To prevent or minimize damage to inter-unit signal circuits and equipment power supplies when a power system ground fault event occurs.

The need of an SRS is minimal when all of the inter unit signal and telecommunication circuits are interfaced to the associated electronic equipment via optically or isolations transformer coupled means. It is used in CMS detector, where these interfaces have good common mode voltage breakdown characteristics.

However, the need for an SRS may easily rise to that of a requirement in the event any of the following three conditions are given:

- When the logic AC-DC power supplies used in the associated electronic equipment are installed with one of the terminals connected to the equipment's metal frame/enclosure. This is typical and recommended practice in the equipment industries.
- When the signal-level circuits and logic AC-DC power supply common terminals are dielectrically insulated or galvanically isolated from the equipment ground against recommended practice, and are instead connected to an insulated ground terminal that is intended for connection to an externally installed signal ground reference circuit.
- When there are actual performance problems occurring with the equipment, which can be assigned to common mode electrical noise or similar common mode interference related to the equipment's existing grounding system, whatever its design, or the signal-level

Improved HF grounding for data signaling cables between (non-contiguous) areas can typically be accomplished by reducing the open loop area enclosed by the cable and its grounded surroundings. This is typically accomplished via the use of metal conduit or electrically continuous, solid-bottom, metal cable tray, wire-way, or similar forms of signal transport ground-plane constructions.

The main advantages of the SRS are:

- Low-impedance return path for RF noise currents
- Containment of EM (noise) fields between their source (cable, etc.,) and the plane
- Increased filtering effectiveness of contained EM fields
- Shielding of adjacent equipment

An SRS may be typically constructed using one the following methods (in decreasing order of effectiveness), which are well described in [16]:

- Solid covering of sheet metal (RP).
- Grid of cooper straps (GS).
- Grid of cooper and aluminium wire (GS)
- Rised flooring substructure (GS).

Hybrid forms of SRS employing mixtures of signal reference grid and signal reference planes for varied construction and improved overall performance are also useful. They are used where the benefits of each type of SRS are needed for the collective support of a variety of interconnected electronic load equipment that is susceptible to CM noise current.

The use of RP may be recommended for some applications where the subject system operates at a higher frequency than the typical GS signal design cut-off frequency. Although the RP does not offer a zero impedance path across its surface, it does offer several orders of magnitude of improvement over any signal or ground of large-cross section wires that might be used for bonding between units. The general equation for determining the impedance between two points on a plane is:

$$Z_{gp} = (R_{DC} + j \cdot Z_{RF}) \cdot \left[1 + \tan\frac{2 \cdot \pi \cdot d}{\lambda}\right] \qquad (2.1)$$

where R_{DC} is the DC resistance of the ground plane using the Ω/m^2, Z_{RF} is the impedance of the ground plane in Ω/m^2. and d the distance between two points.

Accordingly, the impedance between two points on a ground plane should be approximately equal to the ohms per square value of the material of which it is composed and of the length such that the distance d is short compared with wave length λ of the highest frequency of interest in the design. Finally, the ground plane must be at least as wide as d. Based on this concept, it may be seen that the impedance value between points across dimensions d is constant at DC level and gradually rises as the applied frequency of the current is risen. Finally, isotropic rise in impedance may be expected at the first resonant point encountering 0.25λ on the plane and at each succeeding odd-order multiples 0.5λ of the first resonant point generally approaching the expected impedance along the projection of Z_N. This is shown in figure 2.4. The most favorable area of operation for the ground plane is in the range where $1 < 1/20 \cdot \lambda$ at the highest frequency of concern.

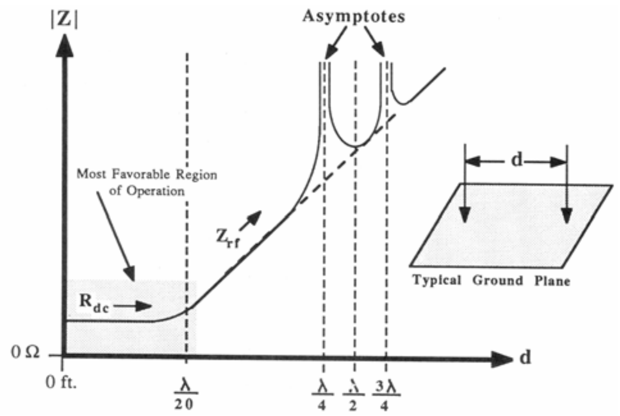

Figure 2.4: *Frequency response of a ground plane.*

Often the solid form of a ground plane cannot be obtained and a mesh or grid form must be a substitute for it. GS may be thought of as a plane in which holes, whose dimensions have been kept below a critical value, have been placed in a repeating pattern. In general only grounding grids using squared cells are recommended for use for HF currents. One of the most important issues related to grounding grids operating in the HF area, as opposed to DC and AC power frequency areas, is the need for minimizing the reactance in the path of the grounding grid instead of the resistance.

2.3.1 Multipoint and single point grounding connections

There exist different grounding configurations according to the connection of the different components or units to a signal reference system. Although they are well explained in [14] and [16], some details of the most important configurations, the single point and the multipoint connections are now presented. The determination to use single-point grounding or multipoint grounding typically depends on the frequency range of interest. Analog circuits with signal frequencies up to 300 kHz may be candidates for single-point grounding. Analogue/Digital circuits with signal frequencies in the MHz range should use multipoint grounding.

2.3.1.1 Single point

As it is shown in figure 2.5, the single point grounding is the easiest configuration of grounding. It is very useful in small systems. Nevertheless, if the real configuration of the single point grounding is analyzed (figure 2.6), it is the most undesirable ground system from the EMC point of view. Firstly, because of the big inductance that the ground path presents, the ground loops and the stray capacitance associated with the system. Secondly, because of the unreasonable large amount of wire necessary.

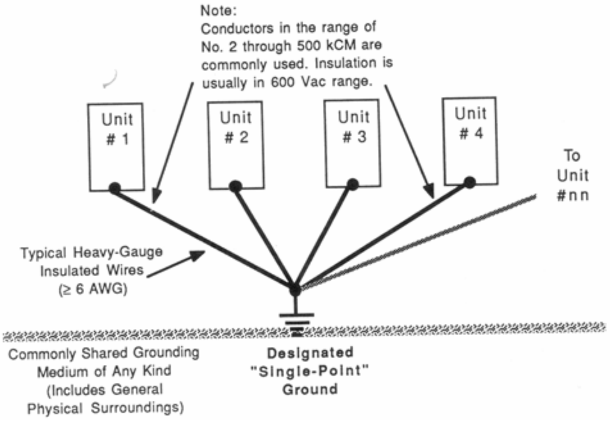

Figure 2.5: *Single point grounding configuration.*

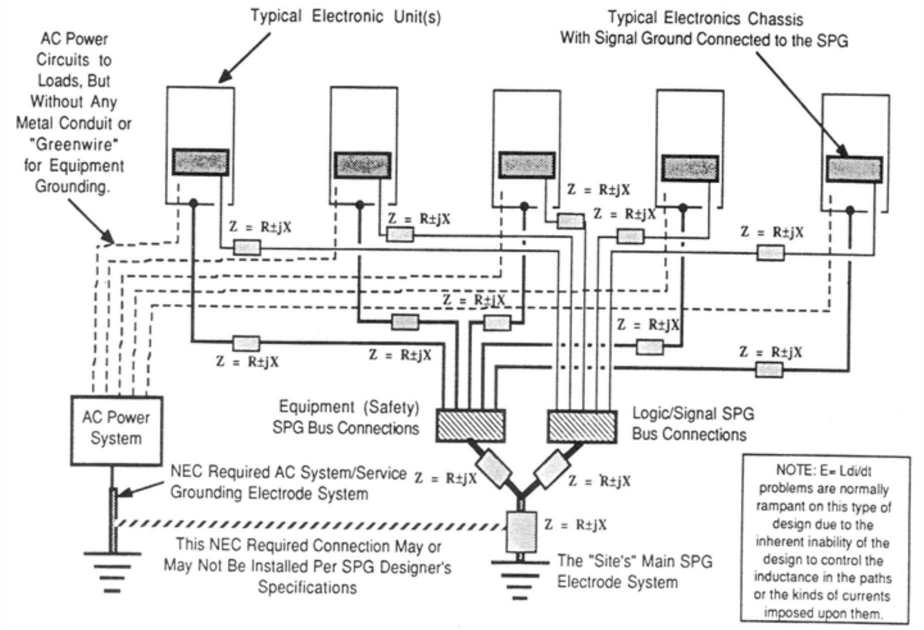

Figure 2.6: *Real single point ground configuration.*

Single point grounding cannot be easily implemented in SRS since these structures depend on a multiplicity of connections. Single-point grounding is usually implemented with a physical bus or bulkhead form of construction, where all conductors are connected prior to entering or leaving the signal reference grid area. A potential violation is to have a single-point ground area where one additional grounding connection occurs at a remote point within the electronic load equipment that is normally designed to be grounded only at one point. Such a connection may be intentional or unintentional. This configuration would provide a well defined and concentrated current path through the electronic load equipment, which could cause performance problems or component damage. More details about this kind of designs are shown in [19].

2.3.1.2 Multipoint

The recommended practice for signal reference systems (SRS) is multipoint grounding. Multipoint grounding requires that all metallic objects crossing or intersecting the signal reference system are effectively bonded to it. This type of grounding is shown in figure 2.7

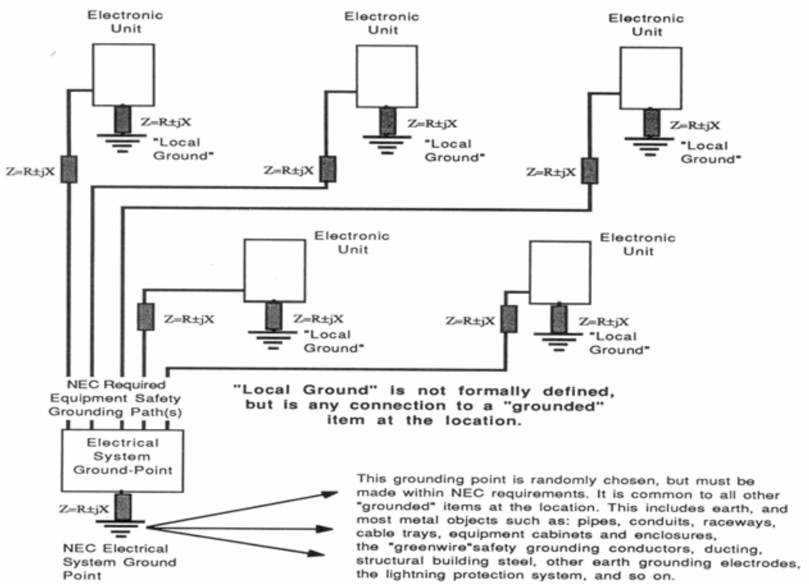

Figure 2.7: *Multi point ground configuration.*

Multipoint grounding to the SRS minimizes the possibility for all types of electrical currents flowing in the signal reference grid to be unwanted onto a few conductors of the signal reference system (this controls near-field conditions and potential difference as well). Based on this type of grounding, it is strongly recommended to separate at the origin the ground (reference or return) of analog signals, digital signals, power supplies and racks and afterwards connect them in a specific way that minimizes the differential of potential between different grounds. This is valid at system or board level. More details can be found in [16] and [18].

2.3.2 Bonding and straps

All equipment, especially electronic load equipment, should be connected to the signal reference system through a low-inductance path. The connections can be made at both the facility and equipment level by means of indirect bonds or direct bonds. The indirect bond is the connection in that a wire, strap or bus bar is used to interconnect the items or units together, whereas in the direct case, the bonding connection is made by direct connection using screws or solder joints. Indirect bonding is discussed in this section.

The purpose of bonding two items is to equalize potential between the items and to ensure that a minimum of potential can be developed between them over a broad frequency range, typically from DC to several tens of MHz and beyond. To achieve this goal, the design of bonding strap must be one providing low impedance across the desired frequency range for AC and very low resistance for DC. There is always resistance in the metallic path and for high frequency currents the impedance increases due to skin effect and inductive effects.

Bonding path installed on the site and intended for use at or near the power main frequency, such as for ground fault currents, need not consider much more than the resistance of the material being used together with its heating and fusing characteristics. Thus simple wire resistance and capacity tables are normally adequate for the determination of the path's performance with regard to the sizing and minimizing of ground fault voltage drop across the bonding path. However for longer ground fault path lengths, wire impedance tables that account for the slightly increased impedance due to skin effect and reactance at the power fundamental frequency must be used. When unwanted AC signals are present in the grounding / bonding path, things are somewhat different. In these cases the need to minimize the potential developed across the bonding path under high frequency (HF) voltage and current conditions of all kinds is of major importance. This need entails the consideration of the path impedances and with the reactance of the bonding path being of greatest importance.

In general the total impedance of a bonding conductor is given by:

$$Z = R_{DC-AC} + j \cdot \omega \cdot L \tag{2.2}$$

The most important term of the above equation is the inductance L. The magnitude of the inductance L is calculated based on the concept of 'partial inductance'. The partial inductance assumes that a current flowing through a segment of unitary length defines a virtual loop, where the opposite segment is at infinity. Based on figure 2.8, the partial inductance L_{pij} is the ratio of the magnetic flux penetrating the surface between segment i and the infinity and the current j that produces it.

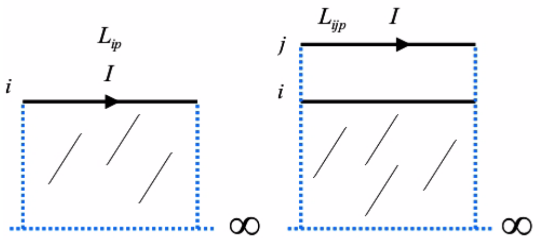

Figure 2.8: *Partial self and mutual inductance loops.*

This definition is used to represent the eventual loop interaction without the prior knowledge of the current loop. Based on this definition it is possible to calculate partial self and mutual inductance. The total or loop inductance is equivalent to the sum of the partial self-inductance and mutual inductances of the segments, as shows equation 2.3.

$$L = \sum_{j=1}^{N} \pm L_{pij} \tag{2.3}$$

where the loop contains a total of N segments in which the loop has been divided. Each segment supports a current I_j, and the sign of each term corresponds to the relative orientation of the currents assigned to segments j. A detailed definition and analysis about partial and total inductance can be found in [12][20][21][22] and [23].

Based in the definition above mentioned, it is possible to calculate the partial inductance of a single round bounding.

$$L_{\mu H} = 0.002 \cdot l \cdot \left(\ln\left(\frac{4 \cdot l}{d}\right) - 0.75 \right) \tag{2.4}$$

where l is the length in centimeters and d is the diameter of the wire also in centimeters. Basically the value of this inductance depends on the length and the diameter of the bounding, increasing the diameter of round conductors has a limited effect on the HF impedance presented by the strap. On the other hand, if a rectangular bonding strap is considered as a flat-strap, the following equation applies:

$$L_{\mu H} = 0.002 \cdot l \cdot \left(\left(\ln\left(\frac{2 \cdot l}{b + c}\right) \right) + 0.5 + 0.2235 \cdot \frac{b + c}{l} \right) \tag{2.5}$$

where l is the length in centimeters, b is the width of the wire in centimeters and c is the thickness of the strap. The length to width ratio of a strap may be significantly altered to benefit a bonding path's performance, whereas altering the diameter of a round wire cannot produce useful improvements. Basically, it is much better to do the ground connections with flat-straps than with round conductors. It is also well known that the inductance increases by winding a conductor into a coil or similar form where the magnetic lines of force along the conductor may be concentrated causing an interaction among them. Thus, it must be expected that the best performance is achieved on a bonding path or with only a minimum and gentle bends in the winding conductor. Loops and sharp angles must be avoided unless an inductance is deliberately being created at the point of path discontinuity.

Bounding straps may self-resonate or may resonate with the stray or parasitic capacitance between the equipment and ground. The bonding strap exhibits high impedance near resonance and at resonance it looks much like an open circuit. Hence operation on this area must be avoided. The variation of the impedance with the frequency and the equivalent circuit of the strap are shown in figure 2.9.

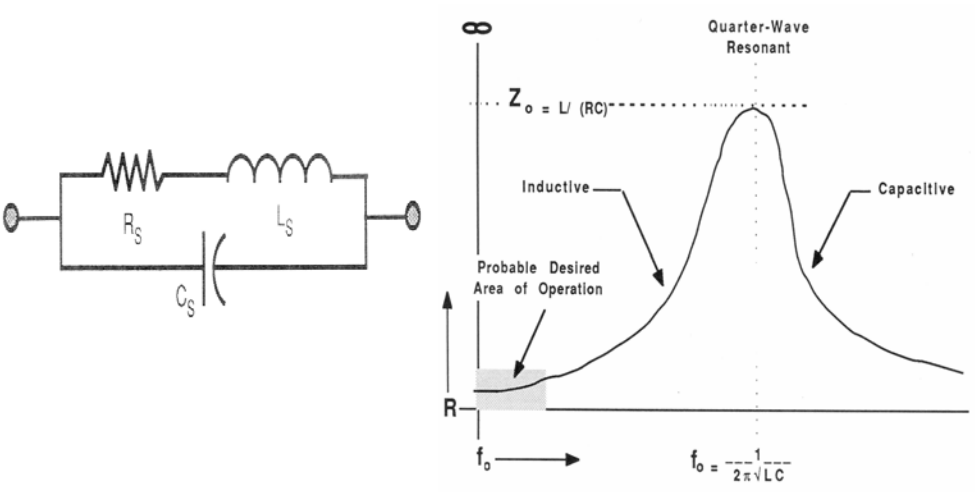

Figure 2.9: *Strap's equivalent circuit and frequency response impedance.*

Radiation to or from a bonding strap is not to be overlooked as a possible problem. However this is a problem only at and very near the actual point of parallel resonance in the strap. Typically any radiator, that is kept to $1 < 1/20 \cdot \lambda$, will not act as a good radiator or receptor. As expected this consideration can also pose major design limitations on the overall length of bonding straps or any conductor used as a ground connection.

Minimizing the impedance between the items being bonded is always important. The use of a single bonding strap between items may make this difficult to accomplish. If multiple, parallel straps are used, the impedance may be reduced between items according to:

$$L_T = \frac{1}{1/L_1 + 1/L_2 \ldots + 1/L_n} \qquad (2.6)$$

Resistance (AC and DC) and inductance are affected in much the same way.

However in the case of the inductance, unless the mutual inductance is also kept to a minimum between parallel straps, they will not act as independent inductances in parallel, the mutual inductance in that case must be considered also. Spacing must therefore be maintained between straps for at least the length of the longest strap employed if this problem wants to be avoided. A detailed analysis of this concept is shown in [16]. Grounding straps should be as short as possible to minimize inductive reactance in the path. The use of at least two bonds widely spaced apart on the same item of equipment is recommended to further reduce the reactance of the grounding path. These straps should be of different length such that they will have different self-resonant frequencies. The straps should never be folded or coiled, nor bent into curves. Even in equipment, lineups where the equipment is bonded together, the recommended practice is to bond each enclosure to the signal reference grid with its own strap or two if it becomes easier. Flat foil strips, which are relatively wide in relation to the length, are the recommended practice. Connections to the equipment frame or a supplied grounding terminal are critical. Paint or other surface contact inhibitors should be removed before bonding straps are directly attached to metal enclosures or cabinet surfaces. Subsequently, the connections should be properly treated to inhibit rust, corrosion and moisture.

2.3.3 Signal reference structure for non-continuous area

The signal reference grid or signal reference plane is appropriate for a single two dimensional area and nearby contiguous areas, but is impractical and not as effective between widely separated areas or buildings, as it is the case of the CMS complex. Recommended practice is to augment the circuits with surge protective devices. Other methods (e.g. optical isolators or suitable wide band common mode current filters) can also provide increased noise and surge immunity for the interconnected telecommunication, data, and signal circuits.

2.4 Shielding

2.4.1 Introduction

The objective of electromagnetic, electric and magnetic shielding is to provide a significant reduction or elimination of incident fields that can affect sensitive circuits as well as to prevent the emission of components of the system from radiating outside the boundaries limited by the shield. The basic approach is to interpose between the field source and the circuit a barrier of conducting or magnetic material.

Shielding effectiveness can be defined as the reduction in magnetic, electric or electromagnetic field magnitude caused by the shield. The effectiveness of a shield depends on the shield material as well as the characteristics of the incident field (far or near field), which is defined by the distance between the source and the victim. So, it is found that techniques for shielding depend on the type of source; whether the source is a magnetic field, electric field or electromagnetic field source. The shielding effectiveness (S) in dB, can basically be calculated as the sum of three components, namely, reflection loss (R), absorption loss (A) and a correction factor (B) used in special cases to consider multiple reflections in the shield.

$$S = A + R + B \tag{2.7}$$

Each component has a different expression and value depending on whether the incident wave is magnetic, electric or electromagnetic field. Although analyzed in detail in [12][24][25][26] some issues are presented in this section. The presence of holes and joints can decrease the effectiveness of a shield and its analysis is well detailed in [12] and [25]. The present study does not provide further analysis on the subject though it should always be taken into account during the design phase. Other important point analyzed in this section is the shielding of cables. Special attention is paid to the connection of the shield at either one or two ends of a cable and the implications that these connections have in the performance of the system.

2.4.2 Electromagnetic field shielding

Although any radiated wave is an electromagnetic wave, the term electromagnetic wave is generally used to describe a far-field, plane wave, where the ratio between the electric field and the magnetic field is defined by the characteristic impedance of the free space (Zo=377 Ω). When an electromagnetic wave passes through a medium, two phenomena, known as absorption and reflection losses, are present. In the former, induced currents generate ohmic loss, heating the material, and producing an exponential attenuation of the amplitude in the direction of the wave propagation [24]. In the latter, when a field arrives at an interface between two media, part of the field can be reflected, introducing new losses. Basically the total loss is a combination of these two losses. The multiple reflection correction term is normally not considered for this type of waves as the reflection loss is high and the correction term is small.

Assuming the electromagnetic wave propagates perpendicular to the shield surface, the absorption and reflection losses (in dB) can be calculated as:

$$A = 131.4 \cdot t \cdot \sqrt{f \cdot \mu_r \cdot \sigma_r} \tag{2.8}$$

$$R = 168 - \left(10 \cdot \log \frac{\mu_r \cdot f}{\sigma_r}\right) \tag{2.9}$$

where t is the thickness of the shield in m., f the frequency, μ_r the relative permeability and σ_r the conductivity. This equation is in close relation to the skin depth of the material. The reflection losses decrease with the frequency, whereas the absorption losses increase due to the skin effect. Based on these equations, it is possible to state that the reflection loss is the primary contributor to the shielding effectiveness at low frequencies. However, at higher frequencies the absorption loss is the primary contributor to the shielding effectiveness at high frequencies.

2.4.3 Electric field shielding

In the near-field, the relation between magnetic field and electric field is not determined by its characteristic impedance in free space (377 Ω). The basic mechanisms of shielding observed for far-field sources are valid for near-field sources, but the type of source is critical for determining the shielding methodology to apply. For sources dominated by high voltages the predominant near-field is characterized by an electrical field, whereas for sources with high currents the dominant near-field is a magnetic field.

Basically, electric shielding consists of conductive barriers, metal enclosures, metal conduits or cable coverings around circuits. The spatial electric shield acts as a capacitive voltage divider between the field source and the circuit. As it was defined before, for a field propagating perpendicular to the shield surface, the effectiveness of the shield against an electric field is defined by the absorption and reflection losses, in which the absorption term is unaffected by the source, being equal to the equation 2.8. However, the reflection loss factor depends on the source and in the case of an electric field can be approximated by:

$$R = 322 - \left(10 \cdot \log \frac{\sigma_r}{\mu_r \cdot f^3 \cdot r^2}\right) \tag{2.10}$$

where r is the distance between the source and the shield. When the distance is undetermined, the equation showed for the far-field reflection could be used instead, as electric near-field reflection losses are always lower than, or equal to, the far-field reflection losses, hence introducing a certain safety margin. Based on those equations, conclusions for fields with dominant electric component are very similar to those attained for electromagnetic fields. The reflection loss is predominant at low frequencies, while absortion loss is predominant at higher frequencies.

2.4.4 Magnetic field shielding

In the case the magnetic component of the near-field is dominant, and the wave propagates perpendicular to the shield surface, the absortion losses are the same as those for far-field, defined by equation 2.8. However, the reflection losses are different and can be approximated as:

$$R = 14.57 - \left(10 \cdot \log \frac{\sigma_r \cdot f \cdot r^2}{\mu_r}\right) \tag{2.11}$$

Based on this equation, the reflection loss decreases for decreasing frequencies, and is lower than the reflection loss for the plane wave reflection. So, reflection losses are usually negligible for lower frequencies and absorption losses are small for low frequencies too. This fact forces the use of different shielding techniques against low frequency magnetic fields [27][28][29].

Basically, there exist two different ways for shielding against low frequency magnetic fields [12][24].

- Deviation of the magnetic flux with high permeability material.
- The shorted tuned method, which consists in the generation of opposing fluxes that cancel the magnetic field in the area of interest.

To deviate the magnetic flux, it is recommended the use of magnetic material instead of conductor material because it increases the absorption losses, hence improving the attenuation of the magnetic field (as it is the primary shielding mechanism at low frequency against magnetic fields). However, when a magnetic material is considered as material shield, two properties of this material, which introduce some limitations, have to be taken account:

- The permeability of a magnetic material decreases by increasing the frequency.
- The permeability of a magnetic material decreases by increasing the magnetic field strength.

The former depends only on the material, the latter depends on the material and the section of the magnetic circuit. For example mu-metal material has a permeability of over 10000 from DC up to 1 kHz, however at 20 kHz the permeability is not larger than cold-rolled steel. The working conditions of the shield is an important point as it has a serious impact in the selection of the shielding material.

As a summary a magnetic material such as steel or mu-metal makes a better magnetic field shield at low frequencies than does a good conductor such as aluminium or copper. However at high frequencies, good conductors provide better magnetic shielding. For non-magnetic material the shield effectiveness increases with the frequency, therefore, it is recommended to calculate the attenuation for the lowest frequency of interest. On the other hand, for magnetic materials the shield effectiveness may reduce due to the decrease of the permeability with the frequency.

2.4.5 Cable shielding

In the present section the main characteristics of a shielded cable as well as the implications of the shield connections in the performance of the system are presented. The main goal of a shield is to avoid perturbing fields to penetrate into the internal conductors or perturbing currents in the central conductors to radiate. The type of shield material and the shield connections have a direct influence in the performance of the shield.

A shield is made of non magnetic materials, which as it has been shown in the previous section, has very bad properties to attenuate magnetic fields, and specially low frequency magnetic fields. A shield should never be considered as a good shield against magnetic fields unless a current is allowed to circulate through it, which can create an opposite field that tends to cancel the perturbing field. These currents can only circulate if both sides of the shield are connected.

When a shield is not connected to ground or is connected only in one side, the shield attenuates only the electric component of the incident field. In this configuration, the shield can be considered as a capacitive voltage divider as it is shown in figure 2.10. Connecting the shield to ground is required to define the capacitive voltage divider. The shield side closest to the electronic system should be grounded in this case.

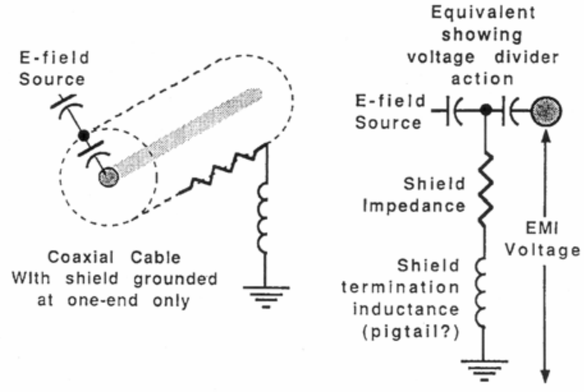

Figure 2.10: *Shield connection.*

This type of connection has been devised in order to prevent conductive "ground loops" from being established, which would cause unwanted current to flow in a shield grounded at more than one place, e.g at each end. This implementation only avoids ground loops when dealing with low frequency signals. At higher frequencies, the parasitic components capacitance between the cable’s shield and the surrounding areas allows flowing currents through the shield. Additionally, the efficiency of the cable shield working as an antenna (receptor or transmitter) starts to play an important role in the emission, propagation and reception of the noise in the system. When a cable’s shield is grounded at one end only the opposing end of the shield is under grounded and it can represent a fire and shock hazard if the cable’s shield becomes energized. Reasons for being energized could be; AC power system ground faults, accidental contact of the shield at some point along its length with a conductor of another system or higher voltage, lightning, etc.

When EMI protection of the signal from near-field with strong magnetic field component is required, it is necessary to ground the cable’s shield at both ends. It allows flowing a shield current induced by the near field magnetic component. This shield current generates a magnetic field opposite to the perturbing magnetic field, attenuating its effect on the central conductors of the shielded cable. This effect does not have any adverse effects on the cable shield attenuation to electric field components.

The attenuation to electric field and magnetic fields is quantified in shielded cables by two characteristic parameters as the transfer admittance and the transfer impedance, respectively. The transfer impedance of a shield is defined as the ratio between the voltage per unit length generated by the circuit formed by the shield and the conductors inside the shield and the shield current. The transfer impedance gives the open-circuit voltage developed between the internal conductors and the shield for one ampere of shield current, in a cable of 1 meter long [25]. On the other hand, the transfer admittance of a shield is defined as the ratio between the current per unit length in the conductors inside the shield and the voltage between the shields and the external structure. The transfer admittance gives the short-circuit current induced in the internal conductors (when the internal conductors are shorted to shield) for one volt between the shield and the external structure, in a cable of 1 meter long [25]. Both the surface transfer impedance and the surface transfer admittance are characteristic parameters of shielded cables and are studied more in detail in chapter 4.

Cable shields grounded at both ends can carry unwanted shield currents due to potential difference between the two grounded ends of the shield. In general, these currents will be related to the power system's fundamental and harmonic frequencies. DC and low frequency currents in the shield, as described above, can be eliminated or significantly attenuated by placing a blocking device between the shield and its ground connection point at one end. For example, a series-connected, back-to-back arranged stack of rectifier diodes or capacitors can be used. When high frequency capacitors are used at one end of the shield, the capacitor blocks the low frequency currents but allows high frequency current to flow through the shield to increase the shield attenuation to magnetic fields at high frequency. Back-to-back diodes or surge diodes can be used when the connection between the shield and the ground point has to be established if the potential between these two structures is higher than the voltage drop of the semiconductor devices [14].

The cable's shield also offers a return path to common currents flowing through the central conductors. The return path is particularly important in shielded power cables to return the common mode currents generated at the output terminals of switching power supplies. If a regular cable without shield is used to connect these power supplies to the load, common mode current will establish between the conductors and the signal reference system (SRS), existing a large radiation loop for these currents. In order to be effective, shields must be grounded via low-impedance paths at the frequencies of interest. Long shields need to be grounded at multiple locations along their length [12][16][17]. To be effective, shields should be grounded using especial connectors that bonds the total periphery of the shield to the chassis or frame where the shield has to be continued.'Pig tail' connection of the shield to the chassis reduces the attenuation of the shield a high frequencies.

2.5 CMS grounding

In this section only some of the characteristics and rules for the CMS detector grounding are presented. The goal of the chapter is not to provide a receipt to define the detector grounding, but give some direct rules to orient the design. These rules are not fixed and depend on the personal knowledge of the designer and grounding philosophy chosen by the detector. This is one of the reasons why the grounding policy must be done by only one or two persons. Assigning this responsibility to one or more persons per sub-detector can lead to different grounding topologies, which may direct to catastrophic consequences during the integration of the detector. Three major rules have be considered as basic for designing the system grounding and these are:

- Grounding is not required for correct operation of the system.
- No current returns should use reference / safety ground.
- Shielding should divert pick-up currents from FEE.

The detector integration based on the electromagnetic compatibility (EMC) of the different sub-systems has several stages and the grounding design is only one of them. The grounding design of the system constitutes only the first EMC issue in order to achieve electrical safety and good performance for the complete detector. The other issues, as sub-system emission and susceptibility, are oriented to control the interference among electronic units. It is an enormous error to think that a good grounding solves all the problems related to electromagnetic interferences.

Starting with the design of the grounding system to comply with the electrical safety, the CMS detector must follow the CERN electrical safety rules based on European standards. They can be achieved following these steps:

- Connection to ground of all exposed metallic structures and parts.
- Avoid current returns through the ground structure of the complete detector during normal operation.
- During faults, the ground path should be able to carry safely the fault current.

This current path not only has to have the ampacity necessary to carry the fault current but also this path has to present an impedance low enough to activate all the over-current protections properly included in the system to prevent fire during faults.

The main grounding structure of the detector is the own metallic structure of the detector together with the concrete reinforcement structure at ground level. This is the ground reference system of the detector (SRS). All safety and protective grounds have to be connected to these structures. Both are shown in figure 1.3 in green color.

At CMS detector we can distinguish two different areas, where the grounding design can follow different strategies. Those areas are the 'DC-area' around the detector itself and the '400Hz distribution area'. The first area includes very low voltage units, in the range of 2.5V to 10V with current capabilities up to 100A, and high voltage units ranging between 600V and 10KV with very tinny current capability. The '400Hz distribution area' is composed by the three phase 400V power distribution system with a possible installed apparent power of 500-750VA.

As it was described briefly in chapter 1, the '*DC-area*' is composed by all the front-end electronics (FEE) of the sub-detectors. They can be arranged in millions of channels where the sensitive detector is close integrated to the front-end amplifier and signal processor or can be composed by amplifiers that process tinny signals coming from chambers distributed in a vast area of the detector (muon system). In both cases, the metallic structures, boxes or frames containing the electronics and the detection devices have to be connected to the metallic structure of the detector or SRS. The general practice is to use the metallic frame or box as shield or screen for the sensitive electronics, forcing to connect internally the common point of the electronics to the box or frame. Then, when the FEE is considered as a load, each unit has one of the power terminals connected to the metallic box or frame, which is different to the scheme represented in figures 2.2 and 2.3. Additionally, due to the voltage levels and current capabilities associated to the equipment in this area, an independent conductor for PE is not included and each FEE is directly grounded to the SRS. This topology is similar to the multi-point grounding connection depicted in figure 2.7, but the PE o green cable is not included.

Power supplies (PS) for the FEE system, in general, are located outside of the detector, in the CMS case, they will be placed in two areas, one around 20-40 mts away from the FEE and the other about 100-120 m. To avoid the return current from the FEE uses as path the SRS structure of the detector, the outputs of the power supplies are generally floating respect to their frame or case. This frame or case has to be grounded locally to the SRS. This topology is possible in the case of low voltage distributions due to the extreme low voltage involved ($V<45V$). For high voltage power supplies, the output terminals are not completely floating as the low voltage PS and usually resistors or back to back diodes are connected between the common terminal and the PS case. This topology assumes that all the power supplies include a transformer with screen that separates electrically the input terminals from the output terminal, which is in general observed for all practical applications.

Considering the system at the input terminals of the power supplies as individual loads, each one is now in close agreement with the diagram depicted in figures. 2.2 and 2.3. The AC or DC distribution system at this side is perfectly defined by standards [25] and no violations of safety rules are allowed. In the '400Hz distribution area', the PEs run in parallel with the power cables and they are connected together at the secondary star of power distribution transformer. This is shown in figure 2.11, where the proposed grounding topology of the HCAL sub-detector along the power supply is shown.

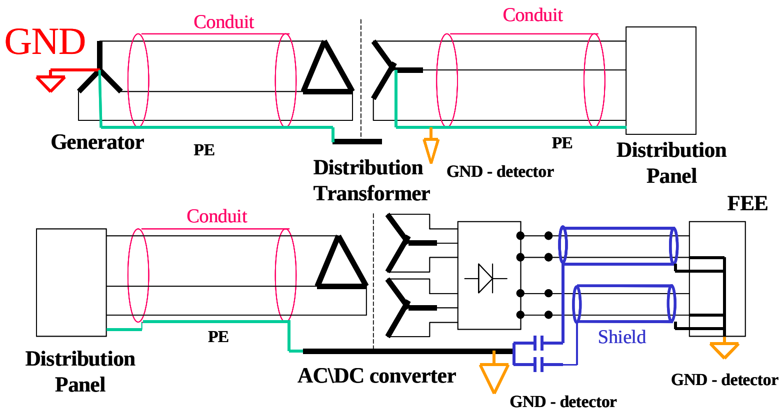

Figure 2.11: HCAL grounding scheme.

The isolation transformer included in the distribution isolates in common mode, the different parts of the system at low frequencies, while this isolation is degraded at high frequency due to the parasitic components of the transformer. The use of this transformer is still not clear, as the system will be isolated from the AC mains (the system will use a set of motor-generator to power the detector or static converters with transformers). The final selection will depend on the definition of the final configuration for the 400 Hz distribution system. The transformer in the AC-DC converter is included to reduce the voltage (400V) distribution to extra low voltage (48V or 10V). These transformers must be able to work into a magnetic field and also isolate the AC-LV area from the DC-extra low voltage area. These transformers should include electrostatic screen, which will improve the rejection of low frequency common mode currents coming from the AC line. The transformer metallic structures and the screen have to be connected to ground.

That overview of the grounding system for CMS basically covers the first two points described above about electric safety. The current capability of all the fault current paths for the '400Hz distribution area' is well described in standards [14][30]. When the design is extended to the 'DC part', special care must be observed in the analysis of the fault path, particularly, its current capability and impedance. When one of the input terminals on the FEE is energized during a fault, the current will flow back to the source using the SRS path. This path is established through the connection between the FEE and the metallic case holding it. This point is critical due to the front-end electronics in general uses the frame or case as screening. From safety point of view, this connection is better at the input power terminal to avoid that the fault current uses as path the FEE where the fault current capability is probably not enough. From performance point of view, it is convenient to connect the FEE to the screen as close as possible to the sensitive amplifier or detector to reduce the parasitic currents coupled to the amplifier. A trade-off between performance and safety occurs in the selection of the connection point between the FEE and the metallic case, prevailing the design based on electrical safety.

The brief description of grounding design based on electrical safety considers a low frequency range, covering from DC to a few KHz. Grounding can affect the performance of the equipment installed and it is necessary to evaluate its impact considering the high frequency behavior of the system. As it was described in chapter 1, data signals from the FEE installed into the detector are transmitted to the counting room via optical links. Slow control signals are electrically isolated via opto couplers. The signal transmission via optical links simplifies considerably the grounding configuration and allows focusing the grounding issues of the detector to the power distribution system. This configuration allows considering the only mechanism of interference among FEE units installed into the detector is conduction and radiation through the power cables.

The electronic load equipment installed on the detector is multipoint grounded to the signal reference structure. Basically, reference terminal or common points of the digital and analog electronics are connected at a convenient point at the board level to optimize performance. Electronics, hardware and power parts are grounded separately at module level and then connected together at a single point, which represents the main ground per sub-detector. As it was pointed before these connection is a trade-off between safety and performance.

The noise generated by the PS units can be galvanically coupled to the FEE. This noise is more severe in switched mode power supplies due the high frequency switching of semiconductor devices. This noise has to be filtered by EMI filters included at the input and output of the power supplies. Additionally, EMI filters can be included at the input terminals of the FEE. Although, CM currents can flow through the power cables, the return path for these currents will be the SRS if no shield is used in the cable, increasing the capability of the cables to radiate. Shields reduce the radiation area for these currents and reduce the noise current flowing through the ground of the detector.

The shield of power cables are connected to one end at low frequency (FEE side) and to both ends at high frequency. This can be achieved grounding the shield to the PS side through a capacitor. Cable’s shields connected at both side at high frequency adds screening to the conductor from external electromagnetic fields, avoiding the induced current to flow trough the sensitive parts of the front-end electronics. All auxiliary equipment as cooling system, etc. should be bonded to the signal reference system. The equipment should be isolated from the FEE to avoid antenna behavior.

Each piece of electronic equipment has to be connected to the SRS. The bonding connections should be as short as possible with no sharp folds or bends. Flexible and multiple straps are preferred instead of round conductors. The main goal of these connections is to decrease as much as possible the ground connection impedance as well as to increase the resonant frequency of the strap. As a result, the performance of the FEE is not affected. As example of strap effects, the ground connection between the read-out box (RBX) to a reference copper plane has been studied. The HCAL-RBX is connected during the FEE immunity test via a strap as it is shown in figure 2.12 and the inductance measured. Results are shown in table 2.1

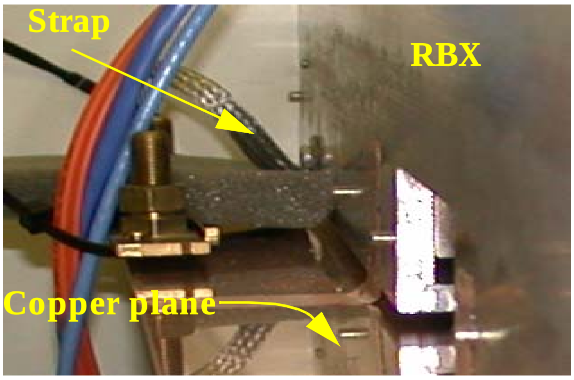

Figure 2.12: *RBX - SRS (copper plane) single strap connection*

	mA – Strap	*mV–Strap*	*L*
At 5 MHz	3.384	22.4	0.209 μH
At 5 MHz	1.298	8.40	0.205 μH
At 10 MHz	0.987	12.2	0.165 μH
At 10 MHz	1.196	13.90	0.187 μH
Average			0.191 μH

Table 2.1 *Strap's inductance of RBX prototype.*

The ground connection presents two resonant frequencies at 18.5 MHz and at 21.7 MHz, associated with the strap inductance and the parasitic capacitance between the RBX to copper plane. Based on equation of figure 2.9 values for stray capacitances associated to the strap and to the RBX are estimated. These values correspond to 380 pF and 275 pF. The problem associated to the strap resonance frequency may be easily solved by decreasing the length of the straps and adding more connections to send the resonance frequency beyond the frequency of interest of the FEE. Also these straps or ground connections should be connected to opposing corners of the equipment and to the nearest, but separate points, on the signal reference grids. This is shown in figure 2.13.

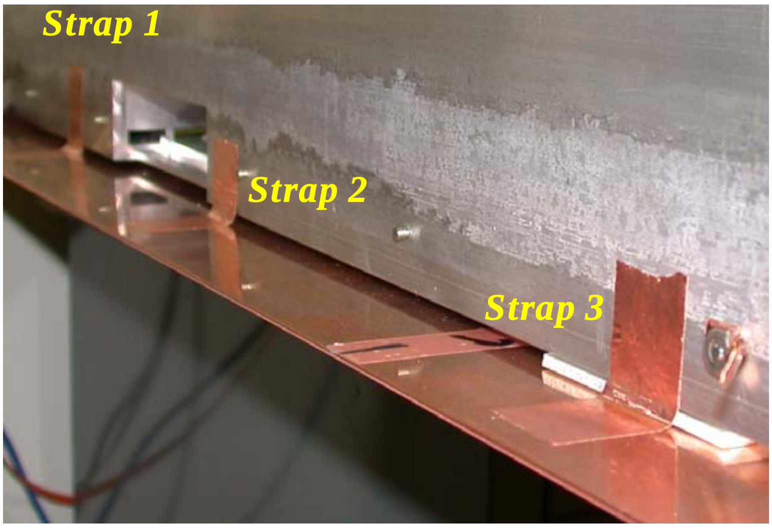

Figure 2.13: *RBX - SRS (copper plane) multiple strap connection.*

2.6 Summary

Grounding is necessary for safety, protection and performance reasons. It is based on standards and no violation of safety rules can be done to improve the performance of the electronics. The metal parts of equipment, enclosures and racks, which are susceptible to be energized by electrical currents must be grounded for personnel safety reasons and equipment protection. No operational currents must flow in this ground (structures and cable). The ground conductor or protective earth must run in parallel with the phase and neutral conductors.

There are mainly two different ways of grounding the electronic equipment, they are: the isolated ground and the standard ground. The main difference between both grounding configurations is that in the isolated ground configuration, the metallic parts holding the load are grounded independently from the rest of the metallic parts of the system, whereas in the standard ground, the metallic box holding the load is directly connected to the general structure of the ground system. The standard ground configuration only needs a simple cable as ground conductor, which is called protected earth. However, the other configuration needs one additional cable, which must fulfill with the typical requirements of the ground conductors, and is used to ground independently some areas of the system.

In cases when two or more components of an interconnected system are installed in an area where there is a physical space between them and across their separation data input/output cables and inter-unit power circuit cables (DC, AC or both) are routed, there are indirect bounding problems ranging from DC to several tens of MHz or higher that can compromise the system performance. To make compatible the grounding with the system performance, electronic components are locally grounded to ground planes or grids known as signal reference surfaces. The main advantage of these structures is to provide a low impedance path for the RF noise current and to contain electromagnetic fields between their source and the plane. The connection layout to the equipment to the reference structures can be made in different ways but the two most important ones are: the single point ground connection and multi-point ground connection. The former use only one point where the components of the system can be grounded. For large systems, this connection is not recommended due to the large amount of cables needed, the large magnitude of the impedances associated with the ground connection and the poor CM rejection due to the parasitic components associated with the system. In the multi-point ground connection each component is grounded at two points; one at load level and other at the safety ground point. This configuration allows a much better control of the noise of the system. Attention should be paid to the generation of low frequency ground loops, which could deteriorate the system performance. The connection of the components of the system to the ground is made by straps. These straps must be as short as possible to minimize inductive reactance of the path. The use of at least two bond straps widely separated on the same equipment is suggested to reduce the reactance of grounding path. These straps should have different lengths.

Shielding of different components of the detectors is necessary to attenuate the electromagnetic, electric or magnetic field that can couple into the system causing performance deterioration or malfunction. The nature of the incident field as well as the frequency of interest is of primary importance to select the shielding method. As an example, magnetic materials are use to attenuate magnetic fields, whereas conductor materials are recommended to attenuate electric and electromagnetic fields.

The selection of shielded cables as well as the connection of the shield to the equipment is very important. The cables's shields are made of conducting materials, so they only can be used to attenuate electric or electromagnetic fields. The attenuation of magnetic fields only can be performed if a current flows through the shield, implying the connection of the shield to ground at both ends.

CMS detector can be separated in two different parts, the AC-400 Hz distribution area and the DC distribution area. For grounding purposes, the former is a standard ground system used in power distribution in which the ’protective earth’ wire runs in parallel with the system. The DC distribution area is characterized by equipment powered by extra low voltage / high current and high voltage / very low current. The ground system is a sub-class of the standard configuration where there is not a ’protective earth’ wire running in parallel with the power distribution cables. The detector structure is used as signal reference surface and the front-end equipment is locally grounded to this structure using straps. In this area it is necessary to take special care about the grounding because it is not standard topology. Ground connections have to be established to provide, in this order, personnel safety, equipment safety (prevent fire hazard) and optimal system performance

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