Earthing of Physics Detectors

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Earthing of High-Energy Physics Detector Systems

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Abstract

The paper discusses earthing with a special focus on safety and compatibility aspects. Attention is paid to active and passive noise reduction. Reasons are given for the limited degrees of freedom of detector designers.

1) Introduction

No electrical circuit needs to be earthed in order to work. A simple torch light, the more complex automobile and aircraft electrical circuits, the portable radiotelephones, all work properly without earthing. Even the famous Faraday-cage used to stop the electrical field and hence electromagnetic waves to penetrate into a conductive enclosure works without earthing.

Galvanic earthing of accessible conductive parts is a requirement necessary for safety. For system design earthing rather fulfills the role of mutual earth voltage referencing. It is precisely this role that makes systems exchange unwanted energy via earth currents. In principle earth reference and signal return are entirely different things. Mixing the signal return function with the earth circuits sets off many risks. The risk of noise is but one.

Galvanic interconnections should be made such that they help routing disturbing currents away from sensitive circuits. When defining the earth voltage of a Faraday cage using a galvanic interconnection the desire is to eliminate most of the capacitive coupling to the surrounded volume. The connection point carries capacitive currents and needs to be chosen with care.

Galvanic earthing is not required everywhere. For special purposes and under certain conditions the insulation of electric circuits from earth is permissible. It is generally understood that the galvanic earth connection may become an unwanted stray path between systems. In large electrical systems surrounded by and built with metallic structures there are inherent small earth voltage differences between any two points of the structure. Earth voltage differences originate from various effects including electrochemical reactions, induction, filter earth currents and many others. Earth voltage differences cover the entire spectrum from DC into the microwave range. Any additional interconnection of two earth points in a system forms a new set of earth loops.

Earth loops closing via sensitive parts or signal returns of a system worsen noise immunity, earth loops avoiding sensitive parts improve noise immunity.

From point of view of safety a maximum number of interconnections with as little amount of current as possible is desired. In case of electric fault the resulting transient earth voltage differences must be such that there is no risk of ignition or threat to the health of personnel [1]. Repetitive and non-repetitive surge effects via earth are design parameters of electrical power systems. Accidental earth faults must neither pose any health or fire risk nor destroy the equipment. All the points mentioned also apply to experimental installations such as low voltage or extra low voltage or high voltage power supplies for physics detectors[1]. **The clear distinction between power return and earth is therefore also a safety requirement.** The very same distinction assures minimum common impedance coupling between systems.

Often the safety earth connection interferes with other requirements. Earth loops and retransmission of dynamic magnetic fields into enclosures and screens may be a consequence of badly routed loop currents. Earth loop opening or dampening is not always possible without sacrificing safety requirements. Conditional opening is discussed in chapter 3.

Badly routed earth loops are considered the primary source of interference. Knowledge about earth loops belongs to the domain of electromagnetic compatibility [3, 5, 7, 8, 12, 14]. It is based on rules that cover emission limitation and noise immunity requirements [4]. Some of the published rules are legal requirements too. Co-ordinators of detector systems should adopt a set of internal compatibility rules. There are good standards that advise on conducted noise, active and passive radio-frequency sensitivity, surges, magnetic pulsing and others. The mere existence of a requirement saying that IEC-1000 level 4 must be respected does not mean that all equipment needs to be run through the mill of standardisation. It simply would lead the way to the solution when a lack of compatibility renders inevitable a technical modification. An EMC-type regulatory statement would alert researchers and provide them with useful technical parameters. As the domain of

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[1] Voltage definition according to CERN Safety Instruction #33 (IEC 364)

electromagnetic compatibility is not well known in physics research it is important to disseminate hints on how to measure the most important EMC-parameters on elements, systems and installations. In situ measurements are not foreseen in the standards because of the problem of reproduceability. In situ campaigns are limited to gathering comparative data on exotic problems that are not covered by standards.

2) Earthing in experimental areas

2.1) General Remarks on Power and Earth

The electricity consumption in large experimental areas is in the order of a few MW. In general there is an electricity substation which strictly follows the rules of high-power high-voltage design[1] and operation[2]. Earthing is done using a local earthing system interconnected with the distribution transformer at its secondary star point. This point is the departure of the local mains neutral conductor (“N”) and, at the same time, the earth conductor (“PE”) leading to the metallic structures and enclosures of all connected electrical equipment. The main difference between “N” and “PE” is that the neutral carries all the return current whereas the earth conductor is supposed to be free of any operational return current[3].

In a similar way there must be clear separation between power return and earth inside physics experiments and subsystems thereof. Power return, signal return and high voltage return are somewhere connected to what is called earth. This connection does not carry, under normal circumstances, any operational current. Sharing a conductor between power return and earth is possible but one must be aware of the consequences. Per definition the earth connection is a voltage reference. No current, i.e. no power, comes across. The safety function of an earth connection comes into play when there is an earth fault. The earth fault, the accidental contact of live wiring with earth, must not produce lethal voltages in adjacent metallic structures. That is why the earth wire cross section and loop resistance are standardised design parameters.

In principal removing and connecting the earth should not alter system performance. **The earth connection will never swallow noise**. If the connection to earth alters the noise performance of a system there must be a reason for this effect. Earth currents, the main reason for earth dependent noise performance, may easily be measured. Current amplitude vs. frequency plots are required for analysis.

A clear line should be drawn between earth voltage and earth current. For all considerations concerning noise performance the earth current is the relevant parameter. However, for considerations concerning safety of persons the resulting earth voltage or the voltage difference between adjacent structures must be limited to $U < 70$ V during the worst case transients.

2.1.1) Quiet Earth

Often the term "quiet earth" is mentioned although the quiet earth does not exist. Contrary to widespread belief there is no remedy in being precisely on zero earth voltage. A techncial apparatus that wanted to be precisely on earth voltage would have to actively compensate any earth current across the earth impedance, an extremely unpractical undertaking of purely academic importance.

The only reason, why a separated earth connection is more quiet than the nearby metallic structure of some physics apparatus is the introduction of additional (earth) impedance into an otherwise directly closed earth loop. The additional earth impedance of an independent earth decreases the loop current. However, it dramatically increases the risk of fatal voltage differences between

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[1] At CERN: French Standard NF C 13 200

[2] At CERN: French Publication UTE C 18 510

[3] TN-S configuration; applicable at CERN but not necessarily elsewhere

neighbouring metallic structures. The noise configuration is altered when using a separate earth. Very much the same positive effect can be had by introducing any additional loop impedance which automatically decreases the currents in the earth loop. In other words, the quiet earth can be found using a simple resistor instead of a direct connection. As both methods, the separate earth and other arbitrary earth impedances, are not safe in an industrial environment some hints are given in chapter 3 on how to safely increase the earth loop impedance for small voltage differences whilst keeping the ability to sustain high fault currents without the consequence of fatal voltage differences.

2.2) Physics Detector Subsystems in Experimental Areas

A subsystem is the setup found in abundant numbers inside high-energy physics detector systems. The typical subsystem consists of a (extra) low voltage power supply, a (extra) low voltage power busbar, a high voltage supply[1], cabling for power, signals and monitoring, the actual electronic devices (preamplifier, shaper, driver, receiver, the enclosures housing the electronics) and the detector element containing some kind of sensor element that delivers electrical signals.

As the surrounding metallic structures serve as the screen the voltage difference between this screen and the most sensitive point of the setup, usually the sensor, must be kept to a minimum in the whole frequency range the sensor is responding to. This requirement leads to maximum broad band coupling between sensor earth point and structure, but also to minimum coupling to anything elsewhere, in particular to the remote power feed. Screening and earthing are entirely different things and should be treated separately. The screening requirements are defined by ambient fields, crosstalk considerations and the susceptibility at the various devices and their interconnections. Screening power cables is not necessary in most cases because the energy needed to disturb a power circuit is hard to find inside high energy physics detectors. If, however, switching power supplies feed power via long parallel cable runs the cables act as a low pass filter. A cable screen prevents some of this energy to couple into the vicinity of the cable run.

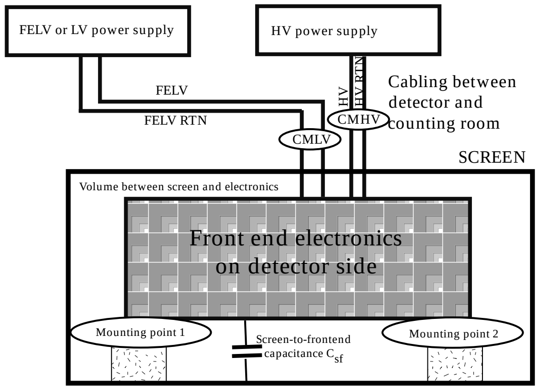

Fig. 2.1 Common mode exchange points

Once the screening requirements are understood the common mode currents need to be analysed (typical common mode exchange points see fig. 2.1). There is no point worrying about common mode voltage levels because capacitive coupling is small due to the small voltage swings encountered in physics detector frontends. High noise risks do appear, however, when common mode voltages are allowed to drive currents across sensitive parts of a system, in particular currents through cable screens. Once generated, common mode currents run across all interconnections and stray capacitances. The number of interconnections between the elements of a subsystem may become very confusing when an attempt to assessing the earth current distribution is made. **Earth loops are formed by multiple connections or multiple coupling to earth or both**. Multiple mounting points, such as the ones drawn in fig. 2.1, do the same. **Earth star points or partial insulation of apparatus therefore do not remove all earth loops** because of residual capacitances closing loops for medium to high frequency ranges. **Contrary to another widespread belief partial insulation of major parts of a physics apparatus is a thing of the past**. In the past analogue signals carried all the measurement information out of a physics detector. Today we

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[1] IEC-364 classification; dry environments only.

deliver fast digital signals, the susceptibility has shifted from ELF-humming to fast transients destroying digital packets.

2.2.1 DC and low frequency

The low frequency problems must be treated first because they are the ones that are the most difficult to correct. They have two origins. Firstly, the much feared earth loops are the direct consequence of multiple earthing. Secondly, low frequency currents straying in or induced from elsewhere must be sustained. This includes mains, harmonics of the mains, and induction during power cuts and lightning. Low frequency exposure is an existing, inalterable environmental parameter. **Low frequency exposure needs to be mastered by proper electronics design and not by partial insulation of an apparatus**.

For DC-effects and low frequency effects it is important to find a largely simplified schematic showing only the earth connections relevant for low frequencies. It goes without saying that neither power returns nor signal returns should be used for earthing purposes. The earth schematic should identify all interconnection points from the environment to the wiring of the subsystem. The schematic may be derived from the configuration shown in fig. 2.2.

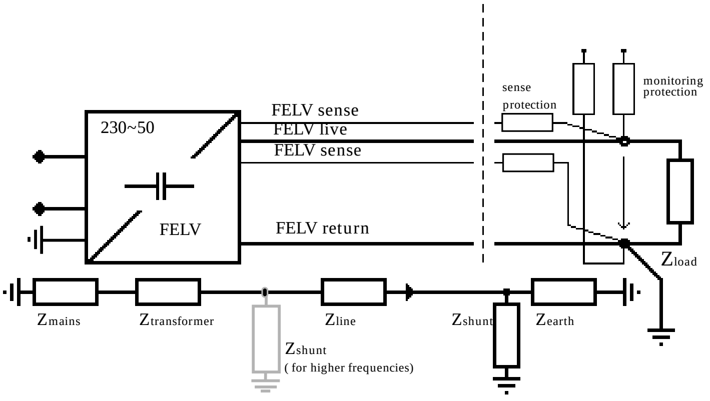

Fig 2.2 Low frequency model for a subsystem

In order to avoid low frequency currents to propagate anywhere in the system it is desirable to keep the earth voltage of the bus-bars supplying power to sensitive equipment close to the earth voltage of the metallic structure, even though the DC power supply is located at some distance. In order to achieve this the earth currents need to be small and the connection to the metallic structure must have an impedance as low as required by the system's screening effectiveneness. Earth currents across the earth connection should be minimised over the frequency range the subsystem could be troubled with. Whatever the distance between power supply and feed point, the earth coupling of the DC-circuit at the location of the power supply should be as loose as possible in order to avoid low frequency loops sharing noise and return currents.

Interconnection of the earth of the experiment, all screens, FELV-returns and cabling should be such that there is minimal effect onto the subsystem itself. There are many possible subsystem earth configurations. The one represented in fig. 2.2 is a typical example. The only galvanic earth connection is located close to the detecting element that is represented in fig. 2.2 by its load equivalent Z_{Load}. Fig. 2.2 also shows that removing all but one galvanic earth connection does not cancel out all loop effects. Z_{mains} establishes the most evident capacitive earth link. The power supply would close the loop via appr. 1 nF winding-to-winding capacitance. RFI-capacitors add on to the problem. Sometimes the monitoring path (FELV sense wires) is entirely different from the power path in which case the impedances called monitoring protection must be selected with care. This suggests RF-filtering with chokes and appropriate capacitors at the feed point of the printed circuits boards, which is state of the art.

2.2.2. High Frequency

With rising frequency the earth schematic will only cover smaller parts of the subsystem more loosely linked to each other. The schematic given in fig. 2.2 would have to be amended by lump elements (dashed impedance Z_{shunt} in fig. 2.2) that represent the coupling to the structure and to neighbouring cables inside wire harnesses. An increased line impedance would geometrically confine the effect to parts that become the smaller the higher the frequency rises. Some noise energy would be radiated off or converted into heat. Noise that is not canceled at its origin by crosstalk elimination will therefore not propagate over large distances. The effects of capacitive coupling between sensitive parts and screens and earth depend on the voltage difference between them. As the galvanic earth connection across considerable cable lengths will not provide sufficiently low impedance one often finds small capacitors between sensitive parts and screens which helps keeping the voltage difference small for high frequency sources. Fortunately high energy physics detectors never suffer from exposure to strong radio frequency. Simulations have shown that even beam tubes do not radiate radio frequency into the detectors [16]. Moderate exposure may be present though, mostly due to badly screened or decoupled high density circuitry. An additional small broad band radio frequency background is generated by charged particles penetrating the physics detector.

The high frequency problems confined to printed circuit boards and integrated circuits cannot be elaborated because this paper does not treat common impedance interference within circuits.

2.2.3. Analogue and Digital Ground

Integrated circuits, printed circuit boards and larger systems use a confusing variety of earth connections called “analogue ground” or “digital ground” or simply “ground”. Without going into further detail all connections used as a power supply return are not strictly speaking earth connections. In practice they end up doing both. The word “ground” suggests this terminal to be used for the local earth reference, i.e. someone has already determined that holding this connection close to the voltage of a surrounding screen or earth plane gives the best noise performance. The separation of analogue (i.e. more quiet) and digital ground suggests possible common impedance interference in case the designer foresees a single return line for both analogue and digital circuitry. Provision for separate return lines gives the desired flexibility for later noise fine tuning.

2.2.4. Electrostatic Screen on Transformers

The electrostatic screen is a separate winding located between primary and secondary of a transformer. The electrostatic screen is connected to a terminal labelled “ES” on transformers so equipped. The electrostatic screen will significantly reduce the common (and differential) mode coupling between the windings in the whole spectrum below 10 MHz. This is important for all power supplies used for sensitive equipment. As the electrostatic screen must stop winding-to-winding capacitive currents it will have to reroute these currents elsewhere. The connection to “ES” is done using the earth of the noisy side because one seeks to screen the sensitive equipment from “incoming noise”. The idea of using a “separated earth” for this purpose is both dangerous and bad because the electrostatic screen and its earth connection must be able to withstand an insulation fault from the primary to the screen.

2.3) Earth Currents (Common Mode Generation and Exposure)

In order to judge on common mode or earth current influence one needs to compare between earth current susceptibility and earth currents measured or expected.

Earth currents are also called common mode conducted noise. When passing through parts of a circuit not meant to carry earth currents, such as the screen of a coaxial cable or a power connection, noise susceptibility vs. frequency will tell at which level a system will be disturbed. The origin of the earth current(s) may well be located outside the system under consideration.

EMC distinguishes between operational exposure and exposure during emergency conditions. During operational exposure no parameters of an exposed system should be altered by earth current exposure, whereas pure survival is sought during emergencies such as power cuts, arc-welding in proximity or the like. For proper layout of a subsystem with focus on earth interconnections and safety two earth current distributions versus frequency should be established. One would deal with common mode generation by the device under test, the other with common mode susceptibility.

Continuous **common mode generators** are switch mode power supplies, asymmetric signal exchanges, induced voltages, the list being far from exhaustive. **Transient common mode** is the consequence of switching operations, lightning and transformer inrush currents.

Earth current paths change with frequency. Earth current routing of frequency ranges considered to be harmful to a system requires a good estimate of the RF-parameters of the system. In doing so one finds that the most difficult challenge is the physics of the wire harnesses.

As a general rule one avoids as much as possible common earth impedances. Earth currents are routed by individual conductors to a common star point. Additional earth connections, e.g. departing coaxial cables, are made earth current tolerant (cf. chapter 3). The common star point is connected to the mains protective earth (PE) by means of a removable link used for test and measurement purposes. This connection, and the star-point behind, actually are safety requirements because the routing of safety-relevant earth currents across screens or equipment enclosures is not allowed.

For normal system operation the noise performance is of primary concern. Safety comes into play when assessing possible equipment failures, incidents or human errors. The system behaviour upon exposure to earth currents should be established using measured or calculated parameters of all common mode noise exchange points (fig. 2.1), i.e. the amount of noise and its paths into the system. Likewise it would be extremely **useful to assess the demands on the earth systems for known common mode generators**, such as SMPS, large groupings of asymmetrical signal exchange (i.e. coaxial links) or a confusion between earth and power return.

2.4) Noise and Earth Voltage Tolerance

Known noise paths inside physics detectors include capacitive current flow between sensitive parts and the enclosure or screen, supply voltage feedthrough, RF-asymmetry, near field susceptibility, voltage fluctuations, standing low frequency voltages on lines, earth current feedthrough. The aim is to have a rough estimate of the inherent earth impedances and voltages.

Operational (extra) low frequency earth voltage differences to be sustained will never exceed the 100 mV barrier which has proven to be a good upper limit in high energy physics detectors. Although these voltages may appear very low the associated low interconnection impedances make a cancellation impossible. Subsystems are preferably made such that they are able to tolerate the presence of small earth voltage differences.

Some manufacturers have designed quasi-differential ADC input stages that are able to tolerate and compensate up to 100mV common mode noise on the signal lines. Translated into the context of this paper the manufacturer has found a way to subtract "some noise", i.e. standing ELF voltages, from the signal. This kind of common mode rejection is limited to the frequency range where the circuit exhibits a good CMRR. The above-mentioned commercial designs are able to eliminate low to medium frequency noise of low amplitude.

Differential inputs do not exhibit constant phase delay or gain over the frequency range of operation. Even without the influence of extra-system earth currents the phase inaccuracy causes a split of the differential mode signal into two components, the original differential mode and a new common mode component. The presence of extra-system earth currents has the inverse effect. The resulting effect is commonly known as common-to-differential conversion. It should be noted that once phase inaccuracy is present the conversion is possible in both directions. Common-to-differential conversion has two entirely different origins, one of which is RF-asymmetry. The other one is the voltage drop on the cable's screen provoked by extra-system screen currents. Wherever the effect comes from, once converted into differential mode noise becomes part of the signal. Noise subtraction becomes a frequency domain problem.

2.5) Switch Mode Power Supply Noise

Switch mode power supplies are state of the art and should be used wherever possible because of their high efficiency [13]. SMPS control the power flow by pulse width or pulse frequency modulation or both. The train of power pulses is smoothed using low pass filters (circuit example with major noise paths in fig. 2.3). The ensemble of power semiconductors and their drivers, the inductors and transformers, and the cabling form a powerful noise generator. Both the supplying side (usually the mains) and the supplied side are affected. SMPS noise handling has evolved impressively with modern technology. So has marketing and cost reduction. SMPS noise performance depends on the initial design requirements for a particular SMPS and its installation and use [11]. Noise limiting is a cost factor. Suppliers limit their efforts to legal requirements or they sell components ("modules") which shifts all filtering, safety and protection problems to the user.

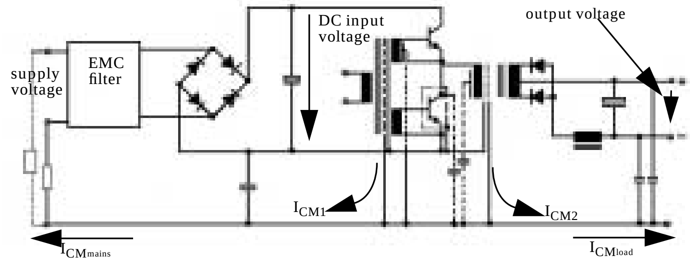

Fig. 2.3 Noise paths inside SMPS

SMPS generate both common mode and differential mode noise at both input and output. These four noise parameters depend slightly on the impedances given by the circuitry connected to the SMPS [11], [13].

SMPS certification[1] [4] is done using standardised networks that define the RF-impedances of the power circuits and coupling network to the standardised measurement receivers [4]. The compliance with standards does not give researchers a blank check for noise performance. Unfortunately SMPS noise depends on more parameters than measured during the certification procedure. Firstly all noise parameters are somewhat load dependent. Secondly SMPS common mode noise generation changes depending on the earth configuration of the mains and the load. Fig. 2.3 shows how the earth line is embedded between mains and load. Due to output and asymmetry earthing of the positive terminal does not give the same noise performance as earthing of the negative terminal. As the common mode source inside the SMPS acts like a current source (I_{CM1} and I_{CM2} in fig. 2.3) moving around fixed charges regardless of most working conditions there also is a dependence on the earth impedance over frequency [11]. Thirdly SMPS show a negative impedance behaviour due to their high efficiency. Increasing the mains voltage causes the mains current to drop over part of the power range. This effect, combined with a leading power factor, is responsible for the damage that occurs when switching off a group of SMPS without using primary over-voltage protections.

Differential mode noise caused by SMPS is generally called ripple (or symmetric noise). Filtering is possible down to any level required. Differential mode noise is out of phase on the load lines or supply lines and radiates out only if these lines are not twisted. The frequency range depends on the SMPS. It covers the spectrum between 20 kHz and 100 MHz.

SMPS-generated common mode noise is in phase on input lines and output lines and closes via the earth system ($I_{CMmains}$ and I_{CMload} in fig. 2.3). It is also called asymmetric noise. Twisting lines has no effect on the propagation or radiation. Filtering is much more difficult because in-phase currents can only be made smaller using non-compensated coils. In addition the earth system is always involved. For good noise performance it is imperative to use a SMPS that, by its design, produces a small amount of common mode noise both on input and output lines. The SMPS design is emphasised because common mode noise must not be allowed to stray. As it returns via the earth conductors other systems become exposed. The choice of a SMPS is therefore strongly influenced by its common mode generation.

The spectra for SMPS-generated common and differential mode noise always look very similar [11] which suggests that energy is transferred between the two of them. The amount transferred is

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[1] Certification required by law in Europe: Directive 89/336/CEE

defined by the RF-symmetry of output stage, line and load. For long lines the load symmetry can be neglected.

3) Earthing Methods

3.1. Direct Earthing

Direct earthing via a defined cross section and cable length links the circuit to be earthed to the experiment earth. There is only one earth linking all metallic parts to the building and mains network earth. The earth resistance, i.e. the resistance between building earth and an earth point of a particular system, is required to be below standardised values according to the voltage domain and earth fault current of a system. Physics detectors are large metallic objects which restricts the earth resistance check to making sure that the combination of earth connection and earth fault current does not pose a fire risk and is able to limit transient voltages with respect to earth to standardised values during faults. Some physics detectors (DO, CDF) insulate structural parts from each other for reasons that are not proven scientifically. The quest is earth loop elimination. At CERN such untertaking is forbidden because insulated structural parts cannot carry any fault current in case of indirect electrical contact (i.e. insulation fault). For all cases incurring problems with direct earthing it is worthwile to look for a solution satisfying both safety and physics research requirements. Separate earth grids that supposedly give what is called a quiet earth are both dangerous and expensive. They are not recommended. Electrically speaking one creates a TT-system, which legally translates into making sure that indirect contacts (insulation faults) will not cause health or fire risks. Inside a physics detector it would techncially be impossible to making a proper TT-system.

A final remark on direct earthing concerns the RF-earth, a term created by researchers. As already mentioned previously there is no remote RF-earth. **Anything that has to do with RF-earth cannot exceed the dimension given by a fraction of the wavelengths under consideration. This requirement defines a maximum earth mesh size or a maximum distance from a continuous metallic surface.**

3.2. Impedance Earthing

Insulated Circuits

It is possible to having circuits insulated from earth. Insulated circuits are the preferred choice for safety circuits, magnet power circuits and other special circuits. Safety regulations require an insulated power circuit to be switched off in case of accidental contact to earth. Hence, once you choose a circuit to be insulated from earth voltage a contact to earth employing less than a given impedance (usually a few kOhms) is not allowed any more. This condition needs to be monitored by a device capable of switching off upon earth fault (insulation monitor). Insulated circuits inside physics detectors have been installed successfully, mainly supplying the main coil of magnets.

Electronics running on insulated circuits would need to send data via optical fibres or signal transformers. It is conceivable to finding more insulated circuits using this technique because of the elimination of all loop problems below the MHz-range.

Earth Inductors

Earth coils with or without saturable cores are rare in high energy physics experiments because of their doubtful remedies. For extra low frequencies a coil will not have, at the same time, high inductance and low resistance. Good low frequency coils will not work effectively on higher frequencies. The presence of magnetic fields often precludes the use of coils with ferromagnetic cores. Coils also store energy via the earth fault current. This energy must be disposed of safely which requires damping circuitry. In general coils are not recommended for earthing purposes inside physics detectors.

3.3. Nonlinear Earthing

Circuit earthing via nonlinear elements can fulfill contradictory requirements simultaneously. On one hand a strong desire for circuit insulation may be triggered by earth loop problems and anticipated conducted noise or common-to-differential conversion, on the other hand safety must be guaranteed in case of trouble. Nonlinear earthing elements may not, however, replace missing guard screens or sound system design. **Nonlinear elements are considered a last possibility escape route when additional earth loop impedance cannot be had safely otherwise**.

Known examples for nonlinear earthing include semiconductor devices, saturable inductances, circuits that are subject to automatic switching upon change of earth impedance or earth current, circuits using gaps for limiting over-voltages etc.

Nonlinear earthing provides for a small and safe degree of freedom. The key feature is low or no current at very low voltages combined with full protection against the classic fault currents of electrical systems (equ. 3.1).

$$I(U_{earth}) = \frac{U_{earth}}{Z(U_{earth})}$$

In most cases $Z(U_{earth})$ is either an exponential function or a step function.

Earthing via anti-parallel Diodes

A set of anti-parallel diodes can be an interesting solution. Apart from a capacitive current no current would be driven if the noise voltage remains below the diode's forward voltage drop which is a valid condition for most physics detectors. It is important to rate the diodes for the short circuit current of the system(s) including all transient energy sources. From point of view of safety diodes of proper rating fulfill all necessary requirements. Equation 3.1. becomes an exponential function.

Earthing via Over-Voltage Protectors

Over-voltage protectors limit the voltage between earth and the circuit to be protected. They are designed to absorb a certain amount of energy during earth faults. Over-voltage protectors are very effective means for safety earth connections of ELV-DC circuits. Although cheap and reliable they do not appear in high energy physics earthing circuits. It should be noted that the choice of such devices needs to take into account the voltage range, the energy the device can safely absorb, its behaviour in case this amount of energy is exceeded, and its speed.

4) System Configuration Examples

4.1. Electronics in spacecraft

Figure 4.1. shows an earth circuit layout designed for the particularly demanding environment of a spacecraft [8].

The separation of earth connections and lines from power return buses and signal returns, the provision for removable interconnections in view of measurements and the clear distinction between screens and structural parts of the spacecraft is obvious. The capacitor from the signal earth to structural earth in fig. 4.1. helps lowering the RF-earth voltage with respect to the structure. This type of capacitor is also present in physics detectors when small ELF AC-voltages need to be tolerated on the signal lines without driving currents that would inevitably convert some energy into differential mode, hence noise. Like in the spacecraft installation the capacitor provides for a low-impedance path in the higher frequency ranges. The design in fig. 4.1 includes a guard shield configuration for what is called signal inputs and outputs in fig. 4.1. The guard shield becomes necessary because a spacecraft uses a number of transmitters, and it is often quite difficult to keeping transmitted signals off measurement channels or logic devices.

Most of the noise impact originating from the nearby DC-DC converter is cancelled by the input signal cable screen used solely for screening purposes. The higher level output signal is less subject to noise impact. There a coaxial cable (combined return and screen) offers a more economic and weight saving design. The timing and control signals travel via symmetric connections using a single screen.

Fig. 4.1 shows clearly how to incorporate a DC-DC converter or SMPS. DC-DC converter as well as DC-AC inverter are equipped with EMI-filters and, for the sake of common mode confinement, with feedtrough capacitors for the respective return lines. This measure limits the common mode propagation without loading too much the local screening arrangement connected by its mounting points directly to the subsystem structure. The EMI-filters are well placed directly at the inputs and outputs of the two power devices for maximum filtering efficiency. A small detail is important but not visible in fig. 4.1. The screen material of the power converter cases is thin steel foil with a galvanised layer of nickel and copper. Iron converts (E)LF into heat because of eddy currents. The spacecraft uses batteries buffered by noisy solar cells as primary ELV DC power. Decoupling from the more sensitive parts using filters and a range of separated return buses is vital.

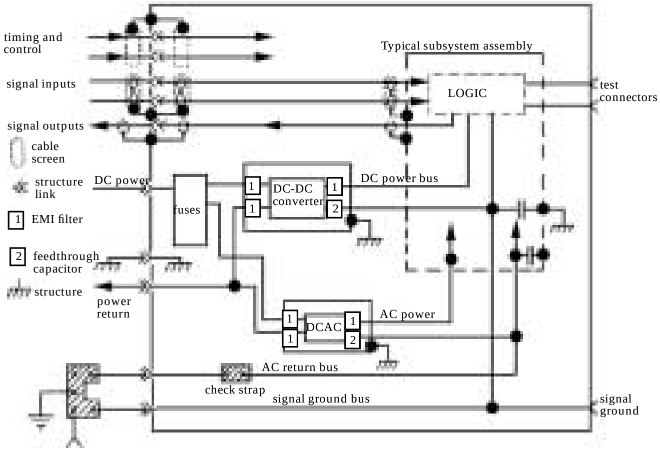

Fig. 4.1. Spacecraft subsystem earth and power return connections

There is, however, no screen for the power lines because the low frequency ripple present would be radiated as a magnetic near field anyway, with or without screen. Due to the fact that the coupling impdeance of screened cables shows a maximum at ELF precautions against magnetic near field radiation are taken where they are more effective. The same is true for the outpoing power lines. The design without screen requires a better specification of the DC-DC converter with regard to adequate high frequency filtering. Note the care that is taken when connecting the earth points of what is called the subsystem assembly, a device similar to a physics detector subsystem.Like in most aircraft and spacecraft design a central earth point (“ground”) is foreseen. For test and measurement purposes earth links may be removed.

4.2. Electronics for a physics detector subsystem

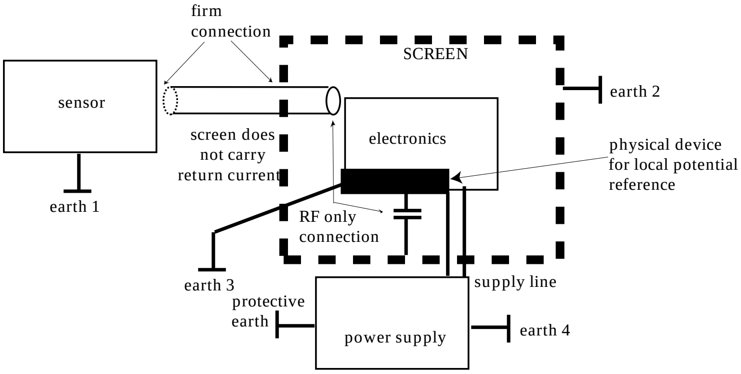

Fig. 4.2 Basic earth configuration inside physics detector

Fig. 4.2 shows the earth and screen connection layout of a typical physics detector. The screen could cover both sensor and electronics, or, as shown in the fig. 4.2, be connected to the sensor’s housing via one or more cable screens (using the same path). It is important to have a local zero voltage reference which is the earth star point. The device used as the earth star point should have a low impedance across its perimeter. All earth connections for equipment close to the device are firm and have low impedance over a large frequency range. All departing earth connections are made such as to be able to tolerate what the environment could carry in. The connections called “earth 1” through “earth 4” in fig. 4.2 are alternative connections and depend on the layout details of the physics detectors and other requirements. Care must be taken when establishing connection “earth 1” in fig. 4.2. The configuration shown in fig. 4.2 could live without “earth 1”. For various practical reasons ‘earth 1” could become the device of zero voltage reference, e.g. in a system involving an ionisation chamber bolted to the detector metallic structure. Experience has shown that in case of a firm “earth 1” connection careful consideration of the link to the electronics must be carried out if “earth 1” cannot be used as the zero voltage reference device.

5) Conclusion

Understanding what good earthing is able to do and, above all, is not able to do, would lead to a professional solution for earthing and noise problems in high energy physics detectors. Remedies and drawbacks of the usual earthing methods are described in this paper, with a strong focus on noise and safety. Safety is integral part of this article because good earthing should be both safe and noise tolerant. Concerning noise it becomes clear that earthing is only part of the story. Ineffective screening renders many physics detectors much worse than they could be. Bad choices of signal cables, and bad routing of noise currents worsen the situation. Considerable software effort is often invested in order to improve resolution, signal-to-noise ratio and background elimination. I am convinced that better screened physics detectors with a well understood earthing system would not only be more reliable, a much desirable feature for LHC, but also better in terms of data quality. The detector parts would also be more accurate and would show more reproduceable results when operated in different environments (testbeam - cavern). One could even imagine that physics detector electronics would continue working with full accuracy with cell phones operating nearby.

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Glossary

ELF	Extra Low Frequency	frequencies below 100 kHz
RF	Radio frequency	frequencies above 100 kHz
ELV	Extra Low Voltage	voltages equal or below 120 V DC
FELV	Functional Extra Low Voltage	
DC	Descending Current	
AC	Alternating Current	at mains frequency 50 Hz
SMPS	Switch Mode Power Supply	
LHC	Large Hadron Collider	future CERN accelerator
CMRR	Common Mode Rejection Ratio	
RF(I)	Radio Frequency (Interference)	

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