TECHNICAL REPORT

IEC 61000-5-2

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1997-11

Electromagnetic compatibility (EMC) –

Part 5: Installation and mitigation guidelines – Section 2: Earthing and cabling

Compatibilité électromagnétique (CEM) –

Partie 5:
Guides d'installation et d'atténuation –
Section 2: Mise à la terre et câblage

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

2) The formal decisions or agreements of the IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested National Committees.

3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical reports or guides and they are accepted by the National Committees in that sense.

4) In order to promote international unification, IEC National Committees undertake to apply IEC International Standards transparently to the maximum extent possible in their national and regional standards. Any divergence between the IEC Standard and the corresponding national or regional standard shall be clearly indicated in the latter.

5) The IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with one of its standards.

6) Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. The IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. In exceptional circumstances, a technical committee may propose the publication of a technical report of one of the following types:

- type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;
- type 2, when the subject is still under technical development or where for any other reason there is the future but no immediate possibility of an agreement on an International Standard;
- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

Technical reports of types 1 and 2 are subject to review within three years of publication to decide whether they can be transformed into International Standards. Technical reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

IEC 61000-5-2, which is a technical report of type 3, has been prepared by subcommittee 77B: High frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility.

The text of this technical report is based on the following documents:

Committee draft	Report on voting
77B/168/CDV	77B/183/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

INTRODUCTION

IEC 61000-5 is part of the IEC 61000 series, according to the following structure:

Part 1: General
General considerations (introduction, fundamental principles)
Definitions, terminology

Part 2: Environment
Description of the environment
Classification of the environment
Compatibility levels

Part 3: Limits
Emission limits
Immunity limits (insofar as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques
Measurement techniques
Testing techniques

Part 5: Installation and mitigation guidelines
Installation guidelines
Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into sections which are published either as international standards or as technical reports.

These sections of IEC 61000-5 will be published in chronological order and numbered accordingly.

The recommendations presented in this technical report address the EMC concerns of the installation, not the safety aspects of the installation nor the efficient transportation of power within the installation. Nevertheless, these two prime objectives are taken into consideration in the recommendations concerning EMC. These two primary objectives can be implemented concurrently for enhanced EMC of the installed sensitive apparatus or systems without conflict by applying the recommended practices presented in this technical report and the relevant safety requirements such as those of IEC 60364. As each installation is unique, it is the responsibility of the designer to select the relevant recommendations most appropriate to a particular installation, with corresponding implementation by the installer.

It is important to note that the recommendations presented in this technical report do not seek to preclude existing installation practices, when they have been shown to perform satisfactorily. Special mitigation methods might not be necessary when the equipment satisfy applicable emissions and immunity standards. In particular, some installation practices such as a "Star Network" or "Isolated Bonding Network" for earthing are based on different approaches to EMC that have been found satisfactory for specific installations when correctly applied and the **topology maintained** by competent specialists. Nevertheless, the approach recommended here is more generally applicable to all types of facilities, especially when signals are exchanged between different apparatus.

Clauses 1-3 provide the usual general information of the IEC 61000 documents on EMC.

Clause 4 provides an overview and introduction of the general approach to applying EMC concepts in the design of installations.

Clause 5 provides recommendations on the design and implementation of the earthing system, including the earth electrode and the earthing network.

Clause 6 provides basic information on the design and implementation of bonding for apparatus or systems to earth or to the earthing network.

Clause 7 provides recommendations on the selection, erection, and connection practices for cables used for low-voltage a.c. and d.c. power supply, for input and output signals serving control and command, as well as those used for other communications within the premises.

Clause 8 provides information on related mitigation techniques.

Clause 9 provides information on verification and test methods.

Informative annexes provide information on the supporting concepts, including bibliographic citations, from which the recommendations of this technical report have been drawn.

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 5: Installation and mitigation guidelines – Section 2: Earthing and cabling

1 Scope

This technical report (type 3) covers guidelines for the earthing and cabling of electrical and electronic systems and installations aimed at ensuring electromagnetic compatibility (EMC) among electrical and electronic apparatus or systems. More particularly, it is concerned with earthing practices and with cables used in industrial, commercial, and residential installations. This technical report is intended for use by installers and users, and to some extent, manufacturers of sensitive electrical or electronic installations and systems, and equipment with high emission levels that could degrade the overall electromagnetic (EM) environment. It applies primarily to new installations, but where economically feasible, it may be applied to extensions or modifications to existing facilities.

2 Reference documents

IEC 60050(161):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 161: Electromagnetic compatibility*

IEC 60050(826):1982, *International Electrotechnical Vocabulary (IEV) – Chapter 826: Electrical installations of buildings*
Amendment 1: 1990
Amendment 2: 1995

IEC 61000-2-5:1995, *Electromagnetic compatibility (EMC) – Part 2: Environment – Section 5: Classification of electromagnetic environments – Basic EMC publication*

IEC 61000-5-1:1996, *Electromagnetic compatibility (EMC) – Part 5: Installation and mitigation guidelines – Section 1: General considerations – Basic EMC publication*

IEC 61024-1:1990, *Protection of structures against lightning – Part 1: General principles*

ISO/IEC 11801:1995, *Information technology – Generic cabling for customer premises*

Note that other documents are listed in the Bibliography in informative annex D. This bibliographic listing includes documents that were used in developing the present report, documents cited in support of a recommendation, and documents suggested as further reading for complementary information.

3 Definitions

For the purposes of this technical report, the definitions given in IEC 60050(161) and IEC 60050(826) apply, as well as the definitions listed below.

A list of acronyms is provided at the end of this clause.

3.1
bonding
the act of connecting together exposed conductive parts and extraneous conductive parts of apparatus, systems, or installations that are at essentially the same potential [new WG2]

NOTE – For safety purposes, bonding generally involves (but not necessarily) a connection to the immediately adjacent earthing system.

3.2
common mode voltage
the mean of the phasor voltages appearing between each conductor and a specified reference, usually earth or frame [IEV 161-04-09]

3.3
common mode conversion
the process by which a differential mode voltage is produced in response to a common mode voltage [IEV 161-04-10]

3.4
common mode circuit
the full current loop or closed circuit for the CM current, including the cable, the apparatus, and the nearby parts of the earthing system [new WG2]

3.5
differential mode voltage
the voltage between any two of a specified set of active conductors [IEV 161-04-08]

3.6
differential mode circuit
the full current loop or closed circuit for the intended signal or power, including a cable and the apparatus connected to it at both ends [new WG2]

NOTE – Instead of “differential mode”, the terms “normal mode” and “serial mode” are sometimes used.

3.7
(electromagnetic) disturbance level
the level of an electromagnetic disturbance existing at a given location, which results from all contributing disturbance sources [IEV 161-03-29]

3.8
equipotential bonding
electrical connection putting various exposed conductive parts and extraneous conductive parts at a substantially equal potential [IEV 826-04-09]

3.9
earth; ground (USA)
the conductive mass of the earth, whose electric potential at any point is conventionally taken as equal to zero [IEV 826-04-01]

3.10
earth electrode
a conductive part or a group of conductive parts in intimate contact with and providing an electrical connection with earth [IEV 826-04-02]

3.11
earthing network
conductors of the earthing system, not in contact with the soil, connecting apparatus, systems, or installations to the earth electrode or to other means of earthing [new WG2]

3.12
earthing
the act of connecting exposed conductive parts of apparatus, systems or installations to the earth electrode or other elements of the earthing system [new WG2]

3.13
earthing system
the three-dimensional electrical circuit which performs the earthing [new WG2]

NOTE – The earthing system includes two parts: the earth electrode and the earthing network.

3.14
electrically independent earth electrodes
earth electrodes located at such a distance from one another that the maximum current likely to traverse one of them does not significantly affect the potential of the others [IEV 826-04-04]

3.15
(electromagnetic) compatibility level
the specified electromagnetic disturbance level used as a reference level for co-ordination in the setting of emission and immunity limits [IEV 161-03-10]

3.16
facility
something (as a hospital, factory, machinery...) that is built, constructed, installed or established to perform some particular function or to serve or facilitate some particular end [new WG2]

3.17
immunity margin
the ratio of the immunity limit to the electromagnetic compatibility level [IEV 161-03-16]

3.18
immunity level
the maximum level of a given electromagnetic disturbance, incident in a specified way on a particular device, equipment or system, at which no degradation of operation occurs [IEV 161-03-14]

3.19
parallel-earthing conductor (PEC)
a conductor usually laid along the cable route to provide a low-impedance connection between the earthing arrangements at the ends of the cable route [new WG2]

3.20
port
specific interface of the specified apparatus with the external electromagnetic environment

3.21
surface transfer impedance (of a coaxial line)
the quotient of the voltage induced in the centre conductor of a coaxial line per unit length by the current on the external surface of the coaxial line [IEV 161-04-15]

3.22
transfer impedance (Z_t)
the ratio of the voltage coupled into one circuit to the current appearing in another circuit or another part of the same circuit [New WG2]

NOTE 1 – For the purposes of this technical report, the separate circuits may be physically separated but closely spaced cables, or the same cables operating in different modes.

NOTE 2 – Different localized contributions stem from the cable proper and from the apparatus.

3.23
acronyms

a.c.	alternating current
CM	common mode
d.c.	direct current
DM	differential mode
EM	electromagnetic
EMC	electromagnetic compatibility
HF	high frequency
IM	intermediate mode
LF	low frequency
PE	protective earth
PEC	parallel-earthing conductor

4 General EMC considerations on installation of earthing and cabling systems

4.1 General

Different types of standards are available to define conditions for compliance with EMC requirements for electrical and electronic products, ranging from basic standards to dedicated product standards. However, these standards might not be sufficient, or appropriate, when EMC for sensitive installations is concerned. Therefore, installation guidelines are necessary to adapt to a maximum of situations. Mitigation methods might not be necessary when the equipment themselves have sufficiently high immunity levels.

Three main areas can be considered with regard to EMC:

– emitters: the source of the disturbances, influenced by the apparatus design;
– coupling paths: influenced by installation practices;
– susceptors: the potential victims, influenced by the apparatus design.

In order to assure EMC, three types of steps should be applied as necessary:

– at the source of disturbances: reduction of emissions;
– at the coupling: reduction of coupling;
– at the victim: increase of immunity.

This technical report addresses principally the mitigation achievable by reduction of the coupling through appropriate practices on the implementation of earthing and bonding, and the selection and installation of the various cables used in the facility.

4.2 EMC and safety (insulation) installation requirements

Attention is drawn to the fact that EMC protection and insulation/safety requirements can have common aspects, such as earthing and protection against overvoltages and lightning. It is important to bear in mind that the safety aspects procedures for personnel protection take precedence over EMC protection procedures. In some cases, there might be an alleged conflict between safety-related procedures and EMC-related procedures. ***Safety must always prevail, so that in such cases alternate EMC-related measures must be sought*.**

4.3 Equipment and installation ports

To provide a transition from the overall concept of coupling between environment and apparatus to the detailed specifics, it is useful to consider the concept of “ports”, as discussed in IEC 61000-5-1. By identifying such ports, protective steps can be specifically related to the nature of the EM phenomenon, its coupling path, and its impact on the functional elements of the apparatus (immunity) or its impact on the environment (emissions).

The IEC 61000-5 documents address in detail the mitigation and installation practices with consideration the ports and the associated EM phenomena. In the present technical report, clauses 5 and 6 deal with the earth port, and clause 7 deals with the power ports and the signal and control ports.

5 Earthing and bonding

5.1 Requirements concerning safety

The primary goal of an earthing system is to assure personnel safety and protection of installations against damage. Two important phenomena are lightning and power system faults. These can cause circulation of large currents, which might create hazardous voltages in installation structures. An important point to be noted is that these two phenomena are external to installations (as a general rule for the power system) and the earth (soil) is the only path for currents to return to the sources. In some countries the neutral conductor is also a path for these currents.

The amplitude of currents is comprised between a few amperes and tens of kiloamperes for power system faults and lightning. From the frequency spectrum viewpoint, these two phenomena produce signals whose frequencies are between 50/60 Hz to several megahertz.

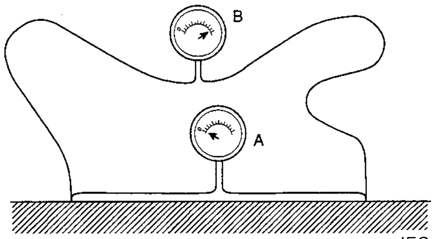
The task of the earthing system, in these conditions, is to be a path to the soil for currents, while maintaining voltage differences between any two points of an installation (touch and step voltages) as low as possible. Generally, national regulations specify maximum voltage values for personnel safety including provision for protective earth (PE) conductor practices. However, these PE conductors alone are generally not sufficient to fulfill the EMC requirements.

In the past, the power system fault current was generally used to define the earthing system (Kouteynikoff, 1980 [1]; Kuussaari, 1978 [2]; Lu, 1980 [3])[1]. An unfortunate consequence of this situation is the fact that the resistance of this path became the usual criterion. This approach may still be correct for phenomena with a typical frequency of 50 Hz or 60 Hz but is certainly inappropriate for high-frequency aspects, where the inductive phenomena along the path may be predominant. Today, it would be better to characterize the earthing system by its impedance.

5.2 Requirements concerning EMC

The secondary goal of an earthing system is to serve as a common voltage reference and to contribute to the mitigation of disturbances in installations with sensitive and interconnected electronic and electrical systems.

The objective of an earthing system which presents, in all situations, an absolute voltage reference is obtainable only in theory, as shown in figure 1 (case A). Sometimes, an attempt is made to describe the ideal objective of zero volt voltage difference between any two points by the word “equipotential”. However, the concept of potential is applicable to static electricity and d.c. only. In practice, induction makes the voltage between any two points greater than zero. In the case B of figure 1, the path followed by the voltmeter leads adds an inductive voltage to the near-zero voltage of case A. Likewise, interconnections between equipment, located some distance away from each other, and depending upon having a common reference, might be routed as in case A or as in case B. The extraneous voltage induced in the loop of case B can then produce a shift in the reference voltages which will depend on the actual routing. Even at 50 Hz or 60 Hz, this situation already exists in earthing systems. In theory, only a large, solid, well-conducting plane could be considered as a voltage reference. This condition would be measurable only if the voltmeter leads were run tightly against the reference plane. This concept will be discussed further and applied in clause 7.



NOTE – In case A, the voltmeter leads are maintained close to the reference plane, and the difference of voltage indicated by the voltmeter is low. In case B, the lengthy path of the voltmeter leads allows induction of an extraneous voltage in the loop.

Figure 1 – Demonstration of the fallacy of the "equipotentiality" concept as a universal rule, especially at high frequency

The earthing system contributes to the mitigation of disturbances by the fact it is the path for return currents, between a source of disturbances (see IEC 61000-2-5 for a list and description of sources) and sensitive electronic apparatus or systems and also a voltage reference for protective devices (filters, etc...). In other words, disturbances may be described in terms of currents, even in the case of radiated fields where the electromagnetic energy is transformed into current by the sensitive apparatus or systems which act as an antenna.

For the EMC aspects, modern electronic apparatus or systems are sensitive to currents and voltages many decades lower than those taken in consideration for personnel safety. This difference of point of view should be recognized, especially for technologies depending on low-level signals.

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[1] Figures in square brackets refer to the bibliography given in annex D.

5.3 Design of the earthing system

The requirements described in 5.1 and 5.2, that is, shunting of unwanted power-frequency and high-frequency currents, and lowering the voltage difference between two points of the system, are the same for:

– lightning;

– personnel safety;

– installation protection;

– EMC.

Each one of these considerations places constraints on the design:

– lightning and personnel safety dictate the design of the earth electrode;

– safety and installation protection dictate the size for the earthing conductors;

– the EMC behaviour requirements determine the layout of the earthing network.

5.3.1 Earth electrode

For the earth electrode design, the first step should be the knowledge of the resistivity of the soil. This resistivity is a function of nature and homogeneity of soil, climatic conditions etc. Soil resistivity values versus nature of soil vary on a large scale, from a few ohm·meters to 10 000 Ω·m. For more details see the documents listed in the bibliography (annex D).

The earth electrode geometry should be adapted to the importance of the installation. A limited earth electrode (such as a cable or rod) may be used only in the case of very small installations such as a room or stand-alone apparatus or system.

In general, for buildings or plants, the best solution for the electrode is a meshed network buried under and around the building or the plant. In old buildings where these objectives may be difficult to attain, other measures and more careful attention to EMC concerns will be necessary. It is important to note that this recommendation does not seek to preclude existing installation practices, when they have shown to perform satisfactorily.

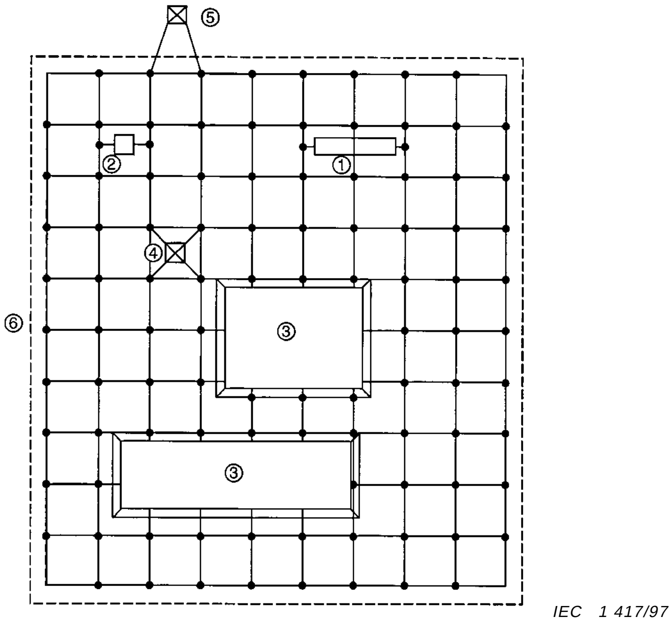
The meshed network of the earth electrode is often complemented by radial cables and/or earth rods at connection points of cables coming from lightning rods, high-voltage apparatus or systems, and apparatus or systems with large fault currents returning through the earthing system.

The earth electrode as a general rule should be set in natural soil, not in backfill materials and, if possible, in damp earth. Figure 2 gives an example of an earth electrode principle diagram for a plant.

Some practical points are important because they influence the long-term electrode quality.

– Solid conductors are preferably used because they are less subject to corrosion than stranded conductors.

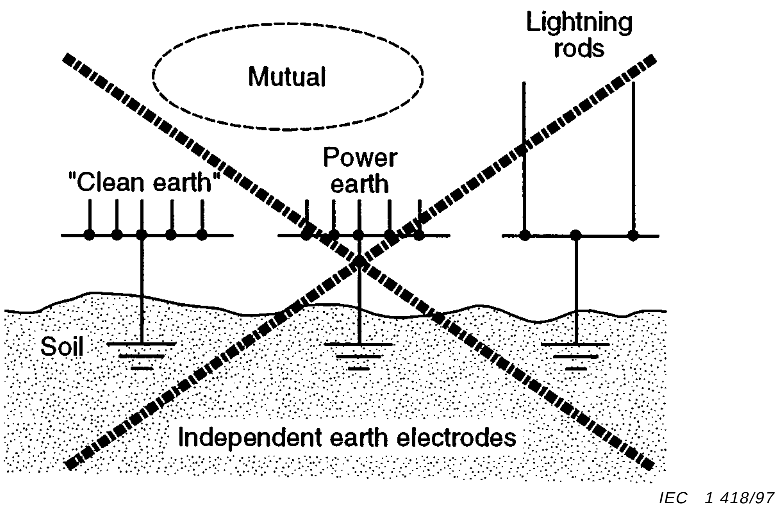
– For the same reason (corrosion), connections between conductors are welded and not implemented by mechanical clamping. Some buildings have a concrete-encased earth electrode. This electrode is located within, and near the bottom of a concrete foundation that is in direct contact with the soil. This solution, correct for residential or office buildings, might not, on its own, have the performances required for industrial buildings.



① Metallic frame ② Stand-alone apparatus or system ③ Building
④ High- or medium-voltage tower inside the plant
⑤ High- or medium-voltage tower near the plant
⑥ Fence

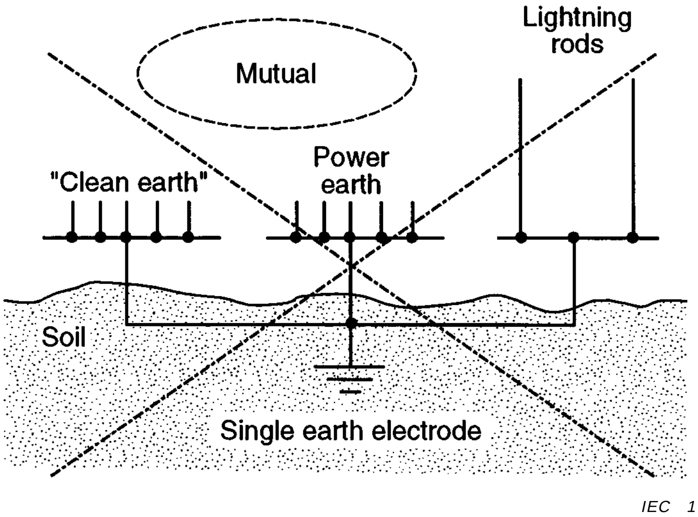
Figure 2 – Schematic plan view of a typical earth electrode

The use of independent, "isolated" (see definition in 3.14) earth electrodes for computer or electronic systems (figure 3) is not recommended (and may be forbidden in some countries). There are always links by the soil or by parasitic elements (capacitances and mutual inductances) in the installation. In case of lightning or power system fault, dangerous transient voltages (for personnel safety and for EMC) can occur between this isolated earthing system and other parts of the installation.



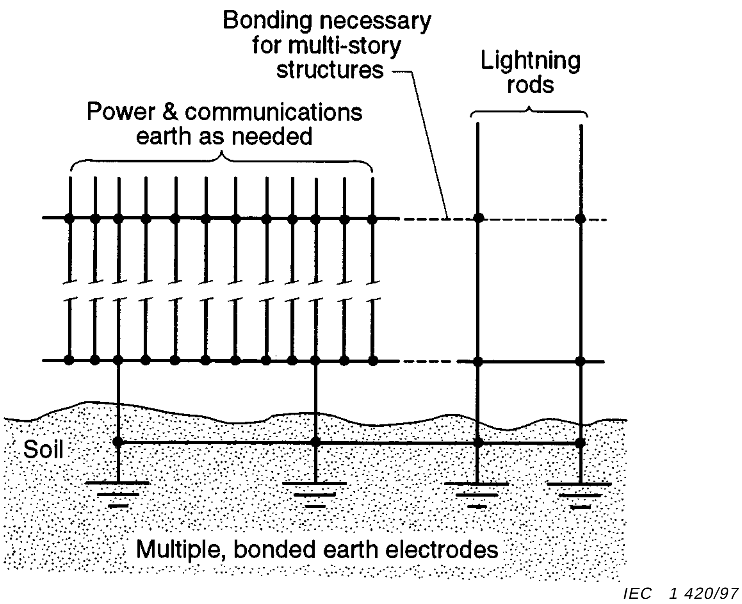
NOTE – In an attempt to obtain a "clean" earthing network, for example to be used as a reference for signals, the earth electrodes have not been bonded. This approach is not suitable for EMC, and is a safety hazard; in fact, regulatory codes prohibit this practice in some countries.

Figure 3 – Misconception of “dedicated”, “independent”, or “isolated” earth electrodes



NOTE – In an attempt to obtain a so-called "clean" or "instrument" earthing network, for example to be used as a reference for signals, the earthing network is separated into a signal and a power earthing network. When properly installed ***and the topology maintained***, this approach has been found satisfactory, but it is not recommended for general use. It is suitable for safety (at power frequencies); it is generally not suitable for high-frequency EMC concerns.

Figure 4 – The concept of a single earth electrode



NOTE – This two-dimensional conceptual representation, similar in format to figures 3 and 4, is actually a three-dimensional network, as shown in figure 7. It is the recommended approach in the general case, for safety as well as for EMC. As noted for figure 4, this recommendation does not exclude other, well-demonstrated and well-maintained special configurations.

Figure 5 – Recommended configuration for the earth electrodes and earthing network

5.3.2 Earthing network

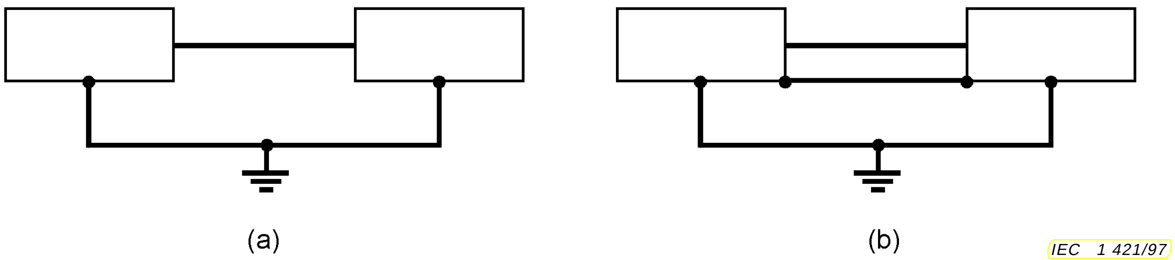
The earthing network is generally designed and implemented by the facility builder to have an impedance as low as possible in order to divert the power fault currents as well the HF currents without passing through the electronic apparatus or systems. Different earthing network layouts exist and may give satisfaction to their users. But some of these earthing network layouts require observing specific conditions to be effective. For example, a central administration or large organization with appropriate structures may design and maintain every aspect of an earthing system from soil resistivity measurement to the final control. In particular, some installation practices such as a "Star Network" or "Isolated Bonding Network" for earthing are based on different approaches to EMC that have been found satisfactory for specific installations ***when correctly applied and the topology maintained by competent specialists.***

These specific conditions are generally not fulfilled by the typical user of an installation. Therefore, the guidance given in this technical report is intended for this typical user, rather than the organizations with established and successful approaches.

The concept of independent, dedicated earth electrodes (presumably in accordance with definition 3.14, illustrated by figure 3), each serving a separate earthing network, is a misconception that not only will not promote EMC, but is a serious safety hazard. In some countries, national codes prohibit such practice. The use of a separate “clean” electronic earthing network and a “dirty” power earthing network is not recommended to achieve EMC, even with the use of a single earth electrode (figure 4). Although not universally accepted, IEC 61024-1 subclause 3.1.2b) requires bonding *“at vertical intervals not exceeding 20 m for structures of more than 20 m in height. Bonding bars shall be connected to the horizontal ring conductors which bond the down-conductors”*. This arrangement is shown schematically in figure 5.

It is recognized that some of the recommendations of this technical report might be difficult to implement in an old building. Nevertheless, some improvements of the earthing network are possible. Examples include a raised floor with meshed earthing network underneath, or the interconnection of all the chassis of the apparatus exchanging signals (figure 6). Other installation mitigation methods can also complement these.

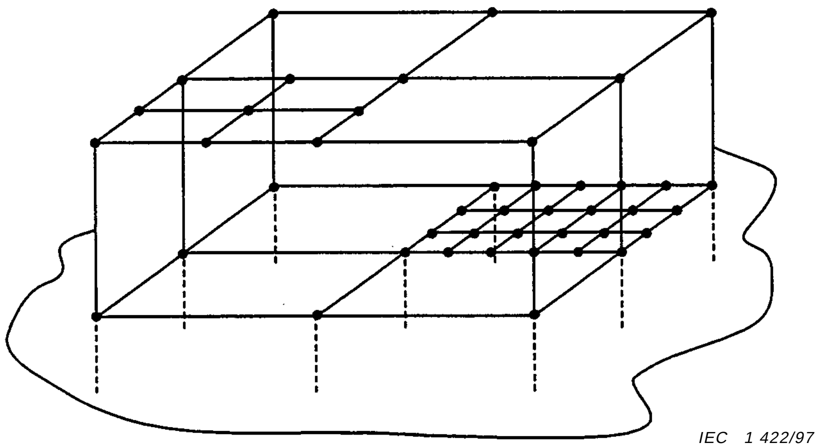
One often-cited objection to a meshed earthing network is that this approach results in earth loops, a situation viewed as undesirable because of noise problems. In fact, the noise problems can be reduced by the methods described in clause 7. In any event, a perceived need for separating earthing networks because of noise problems should never lead to adopting unsafe practices.



NOTE – In (a), a loop is formed that involves the signal cable shield, an undesirable situation. In (b), the loop between the two chassis mitigates the involvement of the signal cable.

Figure 6 – Loops involving signal cables and earthing network

As a typical installation may have many floors, each floor should have its own earthing network (generally implemented as a mesh, see figure 7), and all these networks should be connected to one another and to the earth electrode. A minimum of two connections are required (redundancy should be built-in) to be sure, in case one of the conductors breaks, that no part of the earthing network becomes isolated. Practically, more than two connections are used to have a better symmetry for current circulation, to minimize voltages differences, and to decrease the global impedance between two floor levels.



NOTE – Each floor has its mesh grid, the grids are interconnected at several points between floors, and some floor grids are reinforced as needed in some areas.

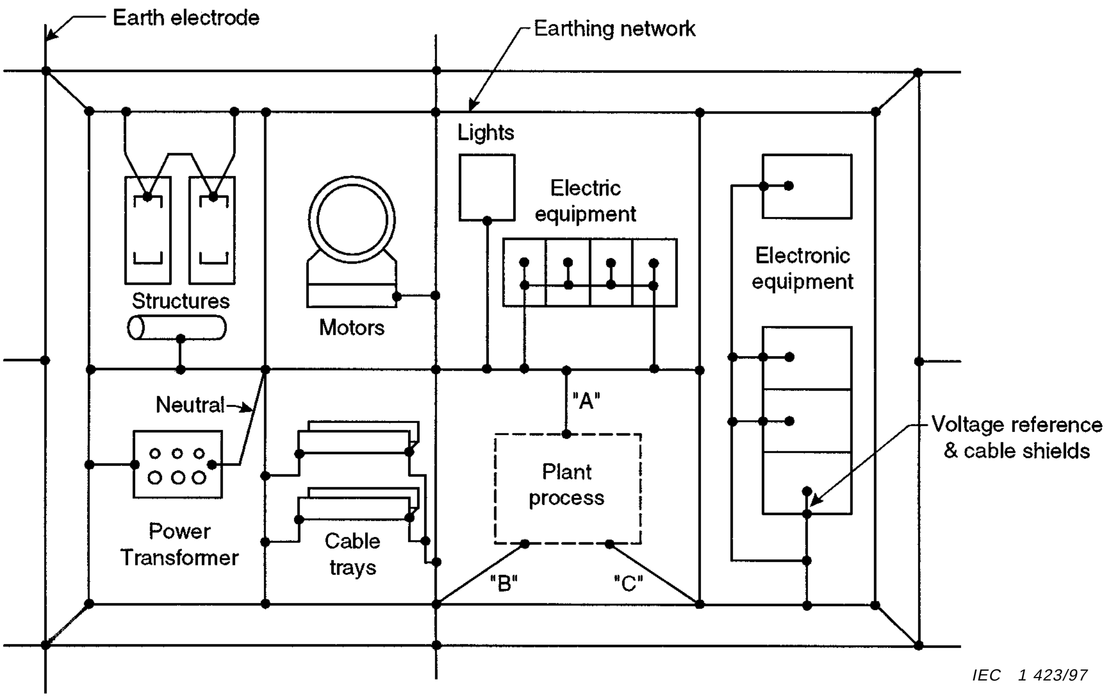
Figure 7 – A three-dimensional schematic of the recommended approach for the earthing network

These multiple and parallel paths have different resonance frequencies. So, if there is for a given frequency a path with a high impedance, this path is certainly shunted by another which has not the same resonance frequency. Globally, over a large frequency spectrum (d.c. to tens of megahertz), a multitude of paths gives a low impedance system.

Each room of the building should have earthing network conductors to allow bonding of apparatus or systems, cable trays, structures: slab reinforcement of buildings, water pipes, gutters, supports, frames etc. In particular cases, such as control or computer rooms with raised floor, an earth reference plane or earthing straps in the area of electronic systems can be used to improve the earthing of sensitive equipment and to protect the interconnecting cables.

The arrangement of sensitive or high-power apparatus or system to be installed in the building may require local reinforcement of the earthing network, for example: in control or computer rooms, near a power transformer, etc. A way to decrease coupling between electromagnetic interference (EMI) sources and a sensitive device is distance. This principle should be also applied to the earthing network. Different zones should be created, for example: electronic zone, machine zone, etc. These zones are interconnected by the earthing network, but layout of the installation should be such that distance should be as large as possible between sources and sensitive apparatus or systems as shown in figure 8.

A motor with a potentially large fault current should not be bonded on the same earthing conductor as sensitive electronics (common impedance coupling should be carefully avoided). It is recommended to connect the various apparatus at the nodes of the earthing network in order to improve the EMC performance of the installation.



NOTE – The topology of connections "B" and "C" provides better EMC performance than the topology "A". Details of connections may vary with specific cases.

Figure 8 – General principles for bonding of various apparatus or systems to the earthing network

Some organizations, where central engineering has made tight control of the design and implementation possible, have successfully applied an approach where each floor has its own isolated meshed earthing network, the so-called "Hybrid-Earth" [4] (see figure A.1). A main feature is the strict cable routing concept which demands that all cables enter the specific system at one interface, similar to the example of figure A.2 (which is topologically equivalent). This approach offers the advantage of minimizing noise problems sometimes associated with an integral meshed network, but it requires carefully maintaining the isolation between the specific isolated meshed network and extraneous conductive parts.

The main physical difference between the earth electrode and the earthing network concerns their implementation. There is little risk of corrosion inside buildings (generally) so that it is possible to use stranded cables for conductors and mechanical tightening for the connection of conductors.

5.3.3 Lightning rod down-conductors

These conductors, which are part of the earthing network, are specific for many reasons. The amplitude and the equivalent frequencies of the lightning currents require that more than one down conductor be used for each lightning rod:

– to decrease the impedance of the path;

– to limit the current in one conductor;

– to avoid the risk of a lightning rod becoming disconnected from the down conductor.

From the EMC point of view, these multiple conductors present the advantage of limiting the inductive effects inside the building if the layout of the installation is such that these conductors are not too close to sensitive electronic apparatus or systems (there is generally poor attenuation from building walls for electric and magnetic fields).

Generally installed outside the building, solid conductors are used to better resist corrosion. Normally, for buildings with a small number of floors, the earth electrode is the only connection between the lightning conductors and the earthing network inside the building (distance principle). This arrangement may be difficult to obtain for industrial buildings with metallic structures or buildings with a large number of floors, so for these specific cases a preferred solution, with regards to EMC, is to have lightning conductors not insulated from structures and have them connected to the earthing network on each floor, or at least every few floors (see figure 5).

In this last configuration, considering that lightning current is a transient current, the major part of the initial lightning current will stay on the external conductors as a result of the electromagnetic field interaction. Only the small currents strictly necessary for "potential equalization" will flow inside the building, thus avoiding the hazard of a side flash between the lightning down-conductors and earthed apparatus inside the building. The latter concern is more a safety issue than an EMC issue, but an unsafe situation can be created by misguided EMC-inspired attempts to keep lightning currents ***completely*** out of the building.

Furthermore, it should be kept in mind that, for most commercial and industrial buildings, many earthed objects (lighting, air-conditioning, ventilation, communications antennae, etc.) are located at the top of the building and can unwittingly act as lightning rods, involving their communications, power, or protective earth conductors rather than the lightning-rod down-conductors intended for that purpose.

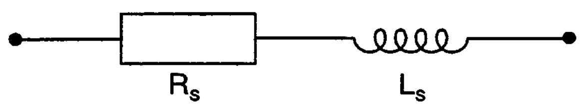
Electromagnetic interaction between the fields established by the lightning currents flowing in several down conductors distributed around the building ensures that most of the initial current will flow on the outside conductors, the intended down-conductors, building steel or rebars, rather than the inside conductors that see very little of the front of the lightning current impulse (Schnetzer and Fischer, 1992 [5]).

6 Bonding

Bonding all exposed metallic parts of an installation and connecting them to the earthing network is a way for meeting safety requirements (touch and step voltages). Figure 8, discussed above, shows a schematic diagram of various apparatus or systems connected to the earthing network in an industrial installation. This connection can be implemented in a manner that will not only satisfy safety requirements, but also enhance the EMC performance of the installation.

6.1 General

The straps between apparatus or systems and the earthing network may be represented by the equivalent circuit of figure 9. R_S and L_S are representative of the bonding conductor itself. Nevertheless, parasitic elements such capacitances of the apparatus or systems versus earthing network, C_P, or strap contact impedances, Z_c, modify this simple situation (figure 10).



IEC 1 424/97

Figure 9 – Simplified representation of a bonding strap

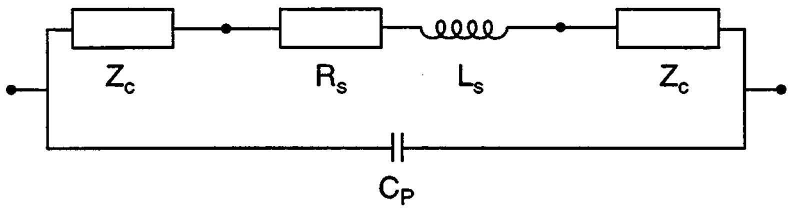


Figure 10 – A more realistic representation of an installed bonding strap

For a low bonding impedance, R_S and L_S, which are a direct function of the length and shape of the strap, should be minimum. In practice this implies that apparatus or systems should always be connected to the nearest earthing network conductor, which should be sufficiently close to the equipment (a point to keep in mind when designing the installation layout).

The impedance Z_C should be as low as possible. This impedance involves not only the earthing network, but also the apparatus or systems to be connected, and the way of implementing bonding.

Dissimilar materials for earthing network, bonding straps and apparatus or systems to be bonded can cause problems due to electrochemical effects, and should be monitored if this is unavoidable.

Equipment is concerned, since the connecting point is often part of the apparatus or systems structures. Unfortunately, as part of the structure, this point may be initially covered by paint or electroplating treatment which gives poor contact impedances. Special care should be exercised on this point.

The method of bonding has direct influence on the Z_C value and on the stability of this value with time (corrosion). Several methods have been used:

– welded connection;
– soldered connection;
– screwed or bolted connection;
– riveted connection;
– crimped connection;
– clamped connection;
– etc.

6.2 Bonding straps

For bonding straps, suitable conductors include metal strips, metal mesh straps or round cables. For these high frequency systems, metal strips or braided straps are better (skin effect). A typical dimensional length/width ratio for these straps should be less than five. Figure 11 shows examples of implementation.

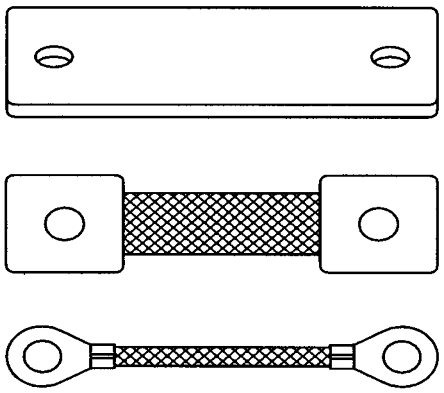


Figure 11 – Typical bonding straps

From the EMC point of view, round cables are not effective for bonding straps in systems where frequencies above 10 MHz are generated or processed, or in systems which may be affected by such frequencies. A round conductor has, at high frequency, a higher impedance than a flat conductor with the same material cross-section (figure 12). Note, however, that the effect of using a flat strap rather than a round cable is sometimes over-emphasized. A still lower impedance can be achieved by multiple bonds (figure 13).

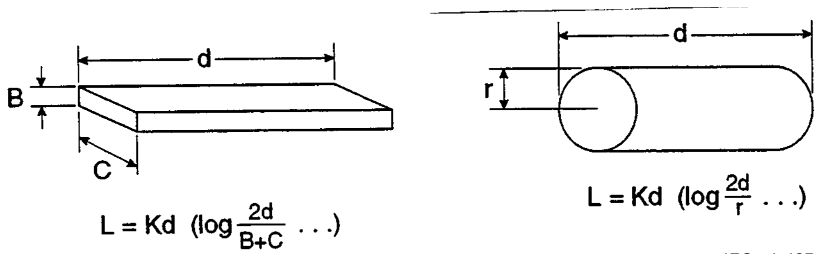


Figure 12 - Relative inductance of flat and round conductors

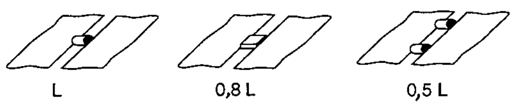


Figure 13 – Relative inductance of round, flat and double bonding straps of same total cross-section

6.3 Connections

6.3.1 Permanent connections

Permanent connections made by welding or soldering present the advantage of having the lowest value for contact impedance, and this with a good stability in time. Rivets and crimped connections may provide the necessary contact pressure to obtain reliable and durable connections. Nevertheless, these methods require clean metal surfaces and due precautions to avoid corrosion.

6.3.2 Removable connections

Clean metal surfaces ensure good conduction and durable connections if they are pressed together at high pressure (this arrangement requires periodic maintenance in industrial installations), so the result is equivalent to welding with the added possibility of disconnecting if necessary.

For connections where clean metal surfaces cannot be obtained, washers can be used that penetrate the non-conducting layers. However, it is a palliative solution. If aluminum conductors are used, appropriate joint compounds must be applied.

6.3.3 Surface treatment

Earthing connections require the contact of clean metal surfaces. Paint or other non-conducting protective layers should be removed from the contact areas. The clean area should be larger than the contact area. After the connection of contact surfaces, a protective coating, such as paint or grease, must be applied to prevent corrosion of the cleaned surface outside the contact area, which is exposed to the various environmental conditions which have to be considered (figure 14).

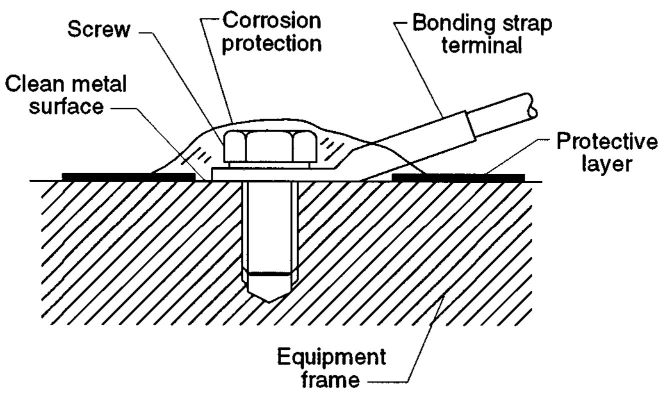


Figure 14 – Example of protected removable connection of a bonding strap

6.4 Bonding of specific equipment

6.4.1 Cubicles

For cubicles, one bonding strap is generally enough. But if electromagnetic interference sources are such that the highest frequencies they produce have wavelengths shorter than the greatest dimension of the cubicle, then multiple bonding straps should be used. In such a case, a typical distance between every bonding strap is one-tenth of the shortest wavelength of interest, with a minimum of 0,3 m for the distance. Insignificant improvements would be obtained for shorter distances. For a given cubicle, cables penetrations and the bonding strap should be close together (on the same side of the cubicle) to avoid current circulation on or in the cubicle enclosure.

6.4.2 Shielded cables

Shields of cables are bonded to the earthing network at one or two extremities depending on the signals being transmitted and on possible electromagnetic interference sources. But in all cases the best solution for bonding is to have a 360-degree connection around the shield. This may be implemented by a suitable metal gland or welding at the entrance of enclosures (figure 15). See 7.6 for more details.

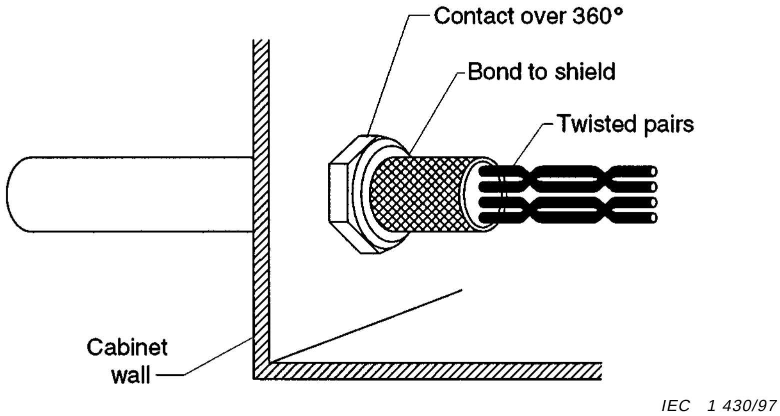


Figure 15 – Example of optimal bonding of a shielded cable to the enclosure by a compression fitting providing a 360-degree bond

6.5 Procedures for users

Because the earthing system is installed first in a building or a plant (before apparatus or systems needed for the final purpose of the installation) and is often part of the structure of the building, it is very difficult for the users to verify or modify this system once the installation is active. For this reason, users should ensure appropriate design and implementation of this system at the design stage (for example: how to maintain the earthing system during the life of the installation) and initial wiring.

With respect to EMC, a good earthing system is not expensive if the general guidance defined in the present document is taken into consideration at the design stage. In the case of older buildings, or new buildings that were not designed with EMC in mind, the cost can be greater, but still necessary when sensitive electronic equipment is involved.

For verification, only the screwed or bolted connections (earthing network and bonding) can be verified during the active life of an installation. This verification may be performed visually or by systematic tightening of each connection, or by d.c. measurement across the joint.

In case of EMC problems (following or not a modification of the installation) it may be necessary to provide local improvement of the earthing network. This operation is often expensive and difficult to manage due to the presence of apparatus or systems, machines, etc. The operation may be facilitated by the use of raised floors with earthing network conductors underneath. Another approach is to interconnect all chassis with bonding strips, and to route signal cables next to these strips, as schematically represented in figure 16 (see clause 7 for more details).

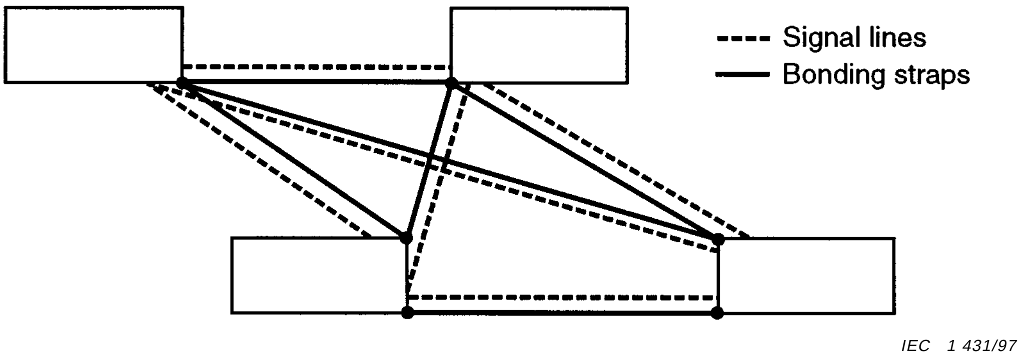


Figure 16 – Schematic of interconnected chassis with bonding strips and signal cables

7 Cables and wires

7.1 General

To ensure optimum electromagnetic compatibility, the choice of a cable, its connection to the apparatus ports, its routing from one apparatus enclosure to another, the grouping into bundles of different cables, and the installation in general, should be based on a consistent approach to EMC. In a harsh electromagnetic environment, two approaches may be taken for the configuration of cabling of the installation.

– Large signals may be transported by means of cables of a type selected arbitrarily, routed without particular care, and connected to equipment without observing recommended procedures. The ports of the equipment should then be capable of accepting the large signal and separating it from the disturbances induced by the cabling.

– Small signals can be carried through the same harsh electromagnetic environment, by means of a carefully selected cable, properly routed, and properly connected to the equipment. This approach can be used to optimize EMC but will require observance of EMC principles such as those defined in this technical report.

Actually, EMC can be obtained in a number of different ways. It is not possible to present a unique, single solution. Therefore, this technical report provides guidelines and a broad range of general recommendations. Conformity with these general guidelines and recommendations will enhance the EMC performance of the installation.

In the selection of a cable, its connection at both ends, and its routing, a number of items should be considered.

a) *The signals to be transported*

– They may be concentrated in certain frequency bands or (quasi-) continuous wave (CW) signals; power delivered as d.c., a.c. 50 Hz or 60 Hz is considered as equivalent to a signal. Furthermore, there are signals in the audio frequency band, which may also be extended to a few megahertz, as for instance high-speed telephony, video and high-frequency signals.

– Pulsed signals: duration, repetition rate, burst rate, rise and fall time, upper and lower limit of frequency range of interest.

– The signal level: measurement and control at low level, such as thermocouple signals (microvolt range), computer outputs (24 V range); a.c. power (1 000 V).

b) *The type of disturbances to be expected*

Continuous wave, burst, pulse, lightning and lightning-induced, power faults; the type and severity depend on the application and the installation in the environment.

c) *The type of apparatus to be connected*

Characteristics of the ports: impedance for differential mode (DM) and for common mode (CM); termination of HF signals into characteristic impedance; distinction between disturbances inside the frequency band for intended signal and outside this band; the non-linear behaviour of the ports, the overload characteristics for DM and CM, continuous wave and pulse.

The requirements for an acceptable disturbance level at both ends of the cable must be established. Neither the cable nor the wiring should degrade the intended operation. It is stressed that only a statistical confidence level can be obtained. The total installation determines what amount of disturbance is acceptable. In critical installations (nuclear power, chemical process plant), no interruption of functioning is allowed. In less critical installations, a short interruption can be acceptable, as long as normal or safe operation after the interruption is guaranteed, either automatically, or by human action.

Once an EMC approach has been selected, with proper design, cable, connections, and routing, it should be strictly adhered to. Future additions or alterations must be compatible with the approach chosen. It is preferable to have a technically competent person with sufficient authority responsible for the EMC design at all times, to ensure the maintenance of the selected EMC approach.

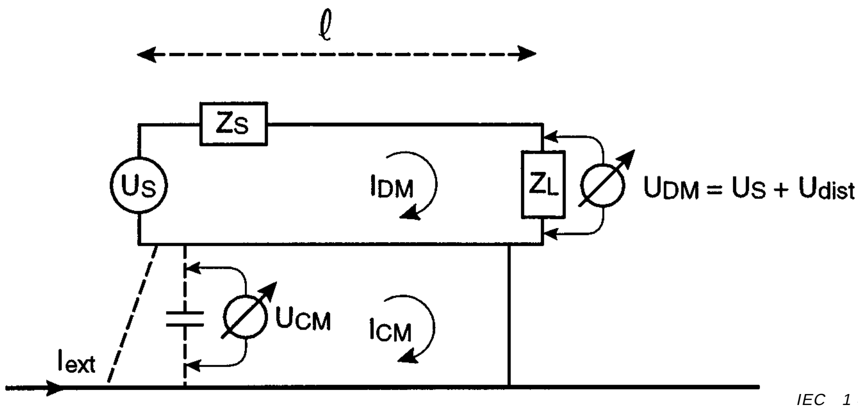
7.2 Differential and common mode circuit, transfer impedance Z_t

A simple model, which will be used throughout this report, is presented for the coupling of disturbances along a cable and to electronic apparatus. Several textbooks also deal with this matter; the essential points are repeated here, because many engineers, experienced as well as newcomers, may not be familiar with the material. More information on the subject is presented in annex B and in the bibliography (annex D).

Strictly speaking, the model is only valid at low frequencies, where the wavelength is much larger than the cable length. At higher frequencies, precise calculations become more involved. However, the mitigation measures presented remain valid, or become even more necessary.

7.2.1 The two circuits

A signal source (output impedance Z_S) is connected to a load (impedance Z_L) by a cable of length ℓ (figure 17). Any signal connection involves at least two leads, signal and return, between equipment. A coaxial cable or a bifilar cable are common examples. The source, load and the two leads form the *differential mode* (DM) circuit. This circuit is now properly defined as a closed current loop.



NOTE – Two leads interconnect a signal source (signal voltage U_S, with output impedance Z_S) and a load with impedance Z_L. The leads, source and load make up the differential mode (DM) circuit. For the sake of simplicity, it is assumed that Z_L is much larger than Z_S. The DM voltage over the load U_{DM} is important; U_{DM} consists of some fraction of the signal source output U_S and an added disturbance term U_{dist} due to the coupling with the CM circuit via the transfer impedance Z_t.

The CM circuit may be closed conductively. Without conductive closure (shown at the source end of the cable), the CM loop closes at HF through capacitances, deliberately put there or parasitic; some voltage U_{CM} may appear over these capacitances. The CM current proper can be driven by an external current I_{ext} which flows through the earth (heavy line) and/or by an external magnetic flux through the CM loop.

Figure 17 – Differential mode circuit and common mode circuit for an unbalanced signal transmission system

In addition, the two leads always form a second circuit which closes somewhere, even if not included in the immediate vicinity of the circuit. This *common mode* (CM) circuit consists of one or both leads, the apparatus and the nearby earth. The earthing system discussed in clause 5 forms a part of the CM circuit. Even without any conductive continuity, the CM circuit is present and closes through local capacitances (parasitic or placed there intentionally) between the cable, the apparatus and earth (see figure 22). The current I_{CM} stems from sources such as:

– voltage drop over the relevant part of the earthing system due to I_{ext};

– a magnetic flux through the earth (CM) loop caused by a current in the earthing system I_{ext} (such as lightning and power faults) or external sources such as transformers, transmitters or other disturbance-generating equipment.

The distribution of I_{CM} over the two leads depends on:

– the type of cable, such as two parallel leads or a coaxial cable;

– the electrical connection at both ends, unbalanced or balanced, and both DM and CM impedance.

In some apparatus the actual electric or electronic parts might be insulated with respect to the enclosure. In figure 17 it was assumed that this held for the electronics of the signal source. In such a case the CM loop closes for instance through the capacitance between the electronics and the enclosure, taken for the moment to be metallic. If the enclosure proper is connected to earth, the idea of figure 17 can still be applied. The CM current loop remains relevant; the corresponding CM voltage is found between the low voltage side of the electronics and the enclosure. Considering a single I_{ext} might be too simple when the earthing system becomes more complex. See B.2 for further information.

7.2.2 Coupling between the circuits

Coupling between the CM and DM circuit causes disturbances in the DM circuit. The coupling is described by two parameters: the transfer impedance Z_t and the transfer admittance Y_t. Separate contributions to Z_t stem from:

a) the cable or leads, distributed over the entire length;

b) the terminal connections at each apparatus.

In the LF approximation, the disturbance contribution to the total DM voltage U_{dist} at the load due to the current in the CM circuit I_{CM} is computed according to the following equation (1).

$$Z_t = U_{dist} / I_{CM} \qquad (1)$$

when Z_L is much larger than Z_S; when Z_L and Z_S are of the same magnitude, the voltage U_{DM} and consequently U_{dist} are lowered by a factor $Z_L / (Z_L + Z_S)$. See B.3 for a detailed example.

The transfer impedance of a cable is often specified per unit length, Z'_t. At low frequency, the total Z_t becomes $Z'_{t} \cdot \ell$ with ℓ the length of the cable. At high frequency, when the wavelength becomes comparable to the length ℓ, the coupling is calculated at each infinitesimal part of the cable; the final value of U_{dist} is obtained by integration over the length of the cable, taking delay times into account (see for instance Vance, 1976 [6]). The transfer impedances at source and load are often determined by the connectors, and their mounting on an earthed frame.

The CM circuit can be large. In low-impedance earthing systems, an intense CM current over a broad frequency range has to be reckoned with. The coupling of I_{CM} through Z_t is often more important than direct induction by the magnetic fields in the small DM loop. Some ports discussed in clause 4 are unintentional ports, and may form a part of the CM loop. The enclosure port is an example.

Another type of coupling occurs via a transfer admittance Y_t; most often Y_t is a parasitic capacitance, $Y_t = \omega \cdot C_t$. The coupling via Z_t is often more important. For instance, for a coaxial cable with a solid outer conductor Y_t is zero at all frequencies, while Z_t approaches the resistance of the outer conductor at lower frequency. In many cases a low Z_t implies a low Y_t. For different types of cables both Z_t and Y_t vary over a wide range. In particular Z_t behaves differently as function of frequency. For shielded cables Z_t is mainly determined by the construction of the shield. The transfer admittance Y_t also depends on the parameters of the CM and the external circuit.

The important notion is the identification of ***two*** circuits. The two generalized transfer parameters are coined for the coupling between the CM and the DM circuit. This coupling occurs locally, at each position along the circuits. The main advantage of this description is that the effect of local mitigation measures against interference becomes apparent. In order to obtain the final disturbance level at both ends of a cable, it is necessary to sum or to integrate the local contributions.

The two transfer parameters also describe the disturbance coupling in the other direction, DM to CM; that is, they are reciprocal. Similar parameters represent the coupling between two adjacent DM circuits, for instance between signal and power, between various data lines, or between input and output.

A low coupling of disturbances can be obtained in two ways, a reduction of I_{CM}, or a low Z_t. The reduction of the overall Z_t is treated throughout this report. The current I_{CM} through the signal cable proper can be reduced by rerouting this current via a parallel conductor (see 7.5). Alternatively, the impedance of the CM loop can be made high by a local impedance or even by an interruption (electrical separation at d.c.). The position of this local high impedance, and its capability to withstand a high voltage should be carefully considered. Typical devices to obtain such separation are isolation transformers, optocouplers, or optical fibres; their discussion is deferred to clause 8.

Cables also interact with electromagnetic fields. The EMC guidelines presented in this report aim at obtaining a low value for Z_t with respect to currents in nearby earthed conductors. A low Z_t value implies a low interaction with electromagnetic fields.

7.3 Set of EMC rules for cable and wire installation

The guidelines presented in this report are derived from the following set of EMC principles. Conformity with the principles will decrease susceptibility and will increase immunity for disturbances simultaneously. While this technical report, as discussed in clause 4, cannot present mandatory rules, the principles presented here should be regarded as desirable goals and, therefore, are worded as objective rules.

a) *Consider complete and closed current loops, for both the DM circuit and the CM circuit, and also for relevant nearby external circuits.*

– As mentioned in 7.1 c), any connection between ports of different apparatus is always considered as a two-terminal port: a signal or power entrance only in combination with its return which has to be positioned in the immediate vicinity. The DM current and voltage at the port are important. First they comprise the intended signal or power. In addition, disturbances are present which stem from the coupling between the DM and the CM circuit via Z_t and Y_t.

– Cables are often large and effective antennae, carrying CM currents to the apparatus. These currents may cause interference not only at the input and output circuits directly connected to the leads, but also at circuits deeper inside the apparatus.

– Other circuits of concern are formed by conductors such as water pipes, tubes belonging to a central heating or air-conditioning system. As discussed in 4.7 of IEC 61000-5-1, even a short stub may act as a HF antenna, and carry a CM current to the apparatus.

b) *Make all DM circuits compact, and thereby immune to local electric and magnetic fields.*

– This rule implies for each DM circuit an individual balanced pair cable, preferentially twisted; the DM circuit may be balanced or unbalanced. For a coaxial cable, the DM current through the inner conductor returns through the outer conductor; this cable is compact by its nature provided that the outer conductor is connected at both ends.

– Connectors at the ends of a cable are an integral part of the DM circuit; a poor connector (high Z_t) ruins an otherwise good cable. The layout of the connection and the layout in the apparatus has large influence on the overall Z_t and on the EMC quality. Shields are for preference *circumferentially* connected to well-conducting surfaces such as cabinet walls, at the point where the cables enter. Pigtail connections are certainly not recommended at that point (see also 7.9).

c) *Keep DM circuits close to earthed elements.*

Actually, for EMC a low transfer impedance of the current through the earthed element is required with respect to the DM circuit. The transfer impedance also depends on the cross-section of the earthed element, and on the position of the cable on the earthed element. Further elaboration follows under e) and in the rest of this report.

d) *Earth loops are allowed.*

In meshed earthing systems, earth loops are effective mitigation measures against interference caused by currents and EM fields from external sources. A CM current through an earth loop consisting of a parallel earthing conductor is perfectly acceptable, provided that the transfer impedance of that loop with respect to nearby DM circuits is low. See clause 5 for more details on earthing systems.

e) *In meshed earthing systems, a conductor, earthed at least at both ends, should be installed parallel to the cables between apparatus.*

In meshed earthing systems, this parallel-earthing-conductor (PEC) should carry the main part of disturbance current I_{CM} and divert this current from the installation cables proper. Examples are an earth lead in a power cable, a shield of a cable, a conduit in which cables are placed, etc. The total area of the cross-section is governed by the amplitude of the quasi-continuous current expected through the earth conductor. The ohmic heating must be kept acceptably low. The shape of the conductor is dictated by EMC requirements (see 7.5 and annex C).

f) *Separate high-power and low-power or signal DM circuits electromagnetically.*

A number of mitigation methods for cross-talk exists; details are presented in 7.7 and 7.8. Electromagnetic separation may involve a physical separation.

g) *Consider the full frequency range for which disturbances can be conducted along a cable (DM and CM) rather than the often more restricted band of the intended signals.*

When switches open or close, a breakdown (start of arcing) causes nanosecond fast transients, even in d.c. power lines.

h) *Limit the frequency range for the DM signals to the bare minimum; limit the sensitivity of the ports to the absolutely necessary frequency range by filters or other means.*

– A typical example is a flat cable for communication between printer and a computer (Goedbloed, 1990 [7]; Benda, 1994 [8]). The data transfer is rather slow; no faster pulses than necessary for a good communication should be used. As a second example, a d.c. or LF power input can be strongly filtered at the point of entrance into the apparatus.

– Here the EMC performance should be optimized with respect to economics and reliability. Filters at the ports of an apparatus can be an economic solution, especially when only out-of-band disturbances are expected. Extensive EMC measures at the cables also reduce this interference. An optimum solution balances both approaches.

7.4 Types of cables and their use with regard to EMC

For LF signal and control, bifilar cables (two parallel leads, twisted or not twisted) are frequently used. The two leads should be used for the signal and the return.

In multi-lead cables, each signal conductor should have its proper return nearby (see 7.3 b)); the two conductors should be twisted. In any case, the signal and return lead should be in the same cable. In shielded bifilar or multi-lead cables, the shield should be regarded as a PEC. The shield is earthed at both ends in principle, thus providing a path for I_{CM}. When more than one shield is present, the outer shield is the PEC, which should be earthed at both ends. Inner shields or earth leads may also be earthed at one or both ends (see also 7.6).

Signals at high frequency are commonly transported through coaxial cables. At both ends of the cable, the outer conductor should be connected to the apparatus, thus closing the DM circuit. When the low-voltage side of the apparatus port is connected to the local earth, this rule implies that the outer conductor (shield) is earthed there.

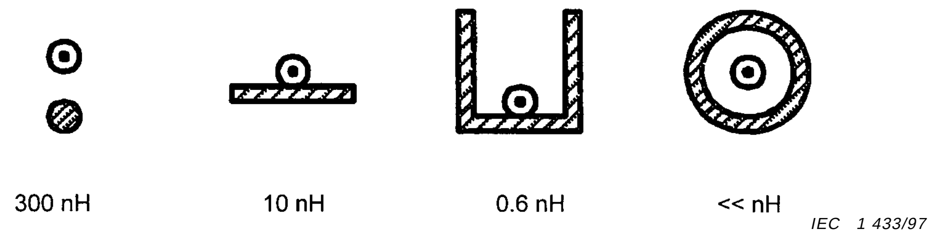
Coaxial cables with multiple outer conductors are used when a low Z_t is required. The outer conductors may be laid directly over each other, or be insulated with respect to each other. Mu-metal or ferrite between the outer conductors further reduces the Z_t (superscreen cables). Most often all outer conductors are interconnected at both ends of the cable, and earthed. In some application the outermost conductor is used as a PEC, and the outer conductors inside are connected to the (perhaps floating) DM circuit only.

Flat ribbon cables are frequently used for transport of slow digital data. Each signal conductor should have its proper return nearby. Such cables are preferably shielded, with the shield properly earthed to the apparatus at both ends.

7.5 Types of parallel-earthing conductor (PEC)

For EMC it is preferred to route a cable along a PEC which is connected at both sides to the local earth of the apparatus. Some examples are mentioned in 7.3 e). The PEC should form a continuous, well-conducting metallic structure over its full length.

A well-chosen PEC diverts the CM current from the DM circuit, a cable or its shield. Effectively this reduces the Z_t of the combination PEC and shield. The shape of the PEC strongly influences the HF Z_t. In order of decreasing HF Z_t are listed: a wire, a plate, a U-shaped conduit, a shield or a solid tube. Typical values for the HF part of Z_t are presented in figure 18. At high frequency, the two latter structures provide an electromagnetic separation between the outside and the inside because of the skin effect.



NOTE – Typical values for the Z_t at HF are given as mutual inductance M in nH/m. The values of the HF Z_t depend on the shape rather than on the total cross-section of the PEC.

Figure 18 – Effect of the configuration of a parallel-earthing conductor on the transfer impedance for coaxial cables

More information on the value of Z_t, in particular on the Z_t of conduits, is given in C.2. The final DM disturbance voltage is calculated according to C.1. Between the PEC and the cable shield an earth loop is formed as an intermediate circuit. The impedance of the loop can be made high, for instance by CM chokes placed around the cable shield (see clause 9). The high impedance reduces the current I_{IM} in that intermediate circuit, and thereby the final DM disturbance voltage at the end of the cable.

Once a particular shape for a PEC is chosen as minimally required, it should be continued throughout, over its full length. For example, when a U-shaped conduit is required, this conduit should be connected over the full cross-section to the cabinet at the ends. A short single lead as connection provides a local high Z_t (particularly at high frequency) and degrades the overall EMC performance for all cables in the conduit. Note that the term conduit includes cable trays where relevant.

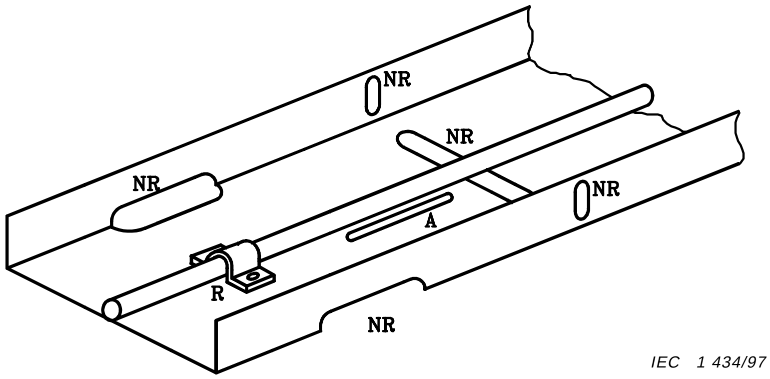
Shields of (multi-lead) cables serve very well as PEC. The coaxial cable is a special case; the outer conductor serves as a path for the DM signal and the CM current. More information about coupling of disturbances into coaxial cables is given in B.3.

7.5.1 Conduits and cable trays as parallel earthed conductors

A conduit or cable tray as PEC should form a continuous metallic structure. When a conduit is made of several shorter parts, care should be taken to ensure this continuity by correct bonding between different parts. Preferably, the parts are welded over their full perimeter. Riveted joints or screwed joints are allowed, provided that the contacting surfaces are good conductors (no paint), and are safeguarded against corrosion.

All shields and perhaps other earthed conductors that enter a conduit should be properly connected to the conduit at the point of entrance. This allows an exchange of the common mode currents between these cables and the conduit. Because the arriving CM current flows in a circuit closing outside the conduit, this current also tends to flow at the outside rather than to enter into the conduit.

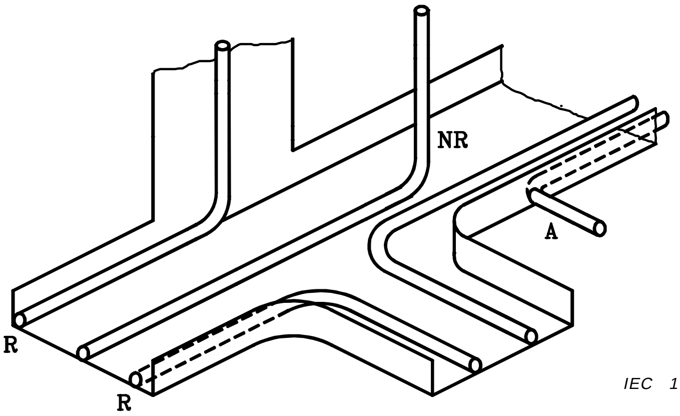
Conduits often have slits for easy attachment of cables. The least harmful of these are small holes (figure 19), filled by bolts. A less desirable position of the slits is parallel to the conduit, at some distance from the cables. Long parallel slits perturb the CM current pattern slightly, and produce some coupling, albeit small. Slits should not be positioned at the corners of a conduit because the disturbance current tends to concentrate there. Slits perpendicular to the conduit axis force the disturbance current through the conduit to make a large detour and thereby produce a strong coupling; these slits are not recommended.



NOTE – Slits in a conduit or cable tray are not recommended at positions and orientation indicated by NR. If, because of some non-EMC requirements, slits are an absolute necessity, the least harmful position is parallel to the axis (A), if possible at some distance from the cables and the corners of the tray. It is recommended to secure cables by clamps (R) over the cable, screwed to the conduit. The primary EMC goal of these clamps is to electrically connect the cable shield, or other PEC of the cable proper, to the conduit.

Figure 19 – Slits in conduits and cable trays

Conduits may have branches (figure 20), or other intermediate points where cables enter. Branches are preferred, and should keep the separation of inside and outside intact. Cables enter along a plate connected to a side wall of a conduit. As a second option, the shield of a cable is properly connected, from the EMC point of view, at the point of entrance into the conduit. Certainly no cable should enter a conduit directly, without a proper path for the disturbance current to feed onto the conduit. An insulating protective sheathing must be interrupted there, in order to allow the desired contact.



NOTE – A cable leaving the conduit should have the shield circumferentially connected to the conduit at the point of departure (A, acceptable). No cable should leave the conduit (NR) without provision of a well-conducting path for its CM current (see figure 22 a) ; compare with R in figure 19. A shallow cable tray is shown in this figure for the sake of clarity. It is recognized that this is a highly desirable arrangement that may not be easy to implement and not always necessary, but it can be useful for installations immersed in harsh environments.

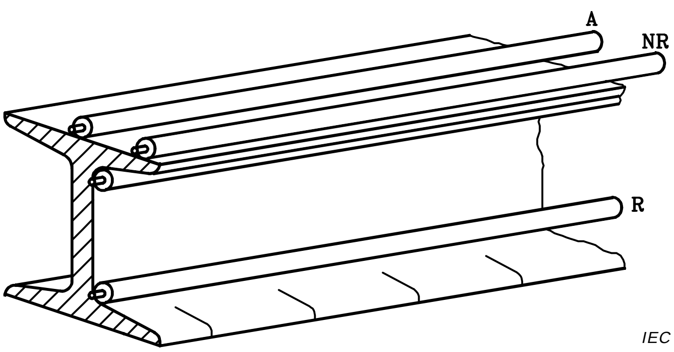
Figure 20 – Recommended configuration for cable trays with branches

A shielded cable inside a conduit can be described in a similar way as a shielded cable with two outer conductors. The shield connected at the conduit at both ends, can be described similarly as a double shielded coaxial cable, with the two shields interconnected (see also B.3).

Detailed calculations of the Z_t as a function of the shape of a conduit (material, width, depth, and wall thickness) are presented in C.2. A preferred type of conduit is made of at least 1 mm steel; the depth over width ratio should be about 1 or larger. A cover closing a conduit also reduces Z_t. It is preferred to electrically connect the cover to the conduit over its full length. However, an insulated cover can also be effective at high frequency, as discussed in C.2.3.

7.5.2 Construction elements as parallel earthed conductors

Metallic construction elements of buildings can serve EMC objectives very well. Steel beams of L-, U-, T- or H-shape often form a continuous earthed structure that offers large cross-sections and large surfaces with many intermediate connections to earth. Because the material is many millimeters thick, such beams already provide a low Z_t at powerline frequencies. Cables are preferably laid against such beams. Inside corners are preferred over the outside surfaces (figure 21).



NOTE – Less preferred than R, but still acceptable for EMC, the position A is likely to be objectionable from a safety point of view. The position NR is not recommended from the EMC point of view, and is objectionable from the safety point of view.

Figure 21 – Recommended cable positions parallel to an H-shaped beam from the EMC point of view

7.6 Connecting and earthing of cables and parallel earthed conductors

The DM circuit must be compact. At both ends of the cable, the signal and the return lead must be connected to the apparatus. If the ports of both apparatus have their return or low voltage side earthed, this rule also implies that the return lead is earthed at both ends of the cable.

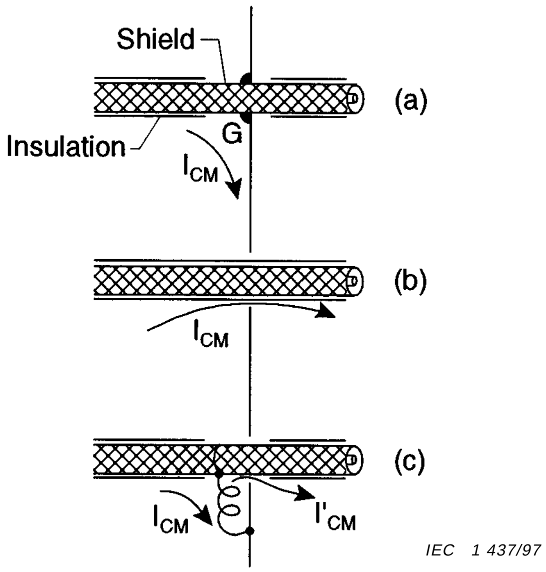
In some cases, one of the ports has the low-voltage side floating, or connected to the local earth via a high impedance; a large CM voltage should be expected over this interruption of the CM circuit. The equipment should then be designed to cope with this CM voltage, over the full spectrum and amplitudes to be expected.

If a PEC is present, it should always be connected to the local earth (preferably a large metal wall of the apparatus cabinet) at both ends, in such a way that the local Z_t is low:

– a single lead as PEC is earthed via a short connection;
– a plate or conduit as PEC is earthed over a large cross-section, preferably the full cross-section;
– a shield or tube as PEC is earthed over the full perimeter, by appropriate glands or other means;
– a pigtail connection (figures 22 and 26) at either end of the cable should not be used.

The main goal of the PEC is to carry the major part of the I_{CM}. When a PEC, such as a conduit or shield, is installed correctly, the EMC requirements for the DM circuits inside become less stringent.

Example: A (quasi d.c.) thermocouple signal is transported over a two-lead cable inside a shield; the shield is connected to earth at both ends. The thermocouple is also earthed. The input amplifier of the receiver can have its low-voltage side floating (for LF); the CM voltage between the low-voltage side and the local earth is limited by the PEC.



NOTE – When a shielded cable runs through a metallic wall of an apparatus enclosure or a cabinet, the shield should be connected over its full perimeter to the wall (a), preferably by an appropriate gland (G). A shield should never run through a wall without electrical contact (b). A pigtail connection (c) is not recommended, not even as a short straight wire because of the high local Z_t; some part of the I_{CM} will pass though the wall due to the pigtail connection.

Figure 22 – Penetration of a shielded cable through an enclosure wall

For very long distances, additional connections of the PEC to the earthing system are recommended at (perhaps irregular) intervals between the apparatus. These extra connections provide an early return path for the disturbance current through the PEC. For U-shaped conduits, shields and tubes, the additional earthing connections should be made on the outside, preserving the separation from the inside.

It should be reckoned that large CM current might flow through the PEC in heavy industry, or in high voltage substations, or in the case of power faults, or when the PEC also makes up a part of the lightning protection system. Two approaches are available. First the PEC proper can be designed to withstand the large CM current and to provide sufficient protection for the signal circuits inside by a low transfer impedance. Generally a cable shield as PEC might not be able to cope with these large currents. The alternative approach is then to choose the routing of the cable properly, and to lead the cable along metallic construction elements or conduits, which then act as another PEC for the cable shield.

An alternative solution can be adopted for the protection against power faults because the disturbance current has a known and low frequency. A capacitor, earthing the shield at one end (capacitive earth), blocks the power frequency current in the CM loop, and may still provide a path for HF disturbance currents. Such a solution requires a good quality capacitor of low inductance, mounted in such a way that the local Z_t is low. In addition, the input of the apparatus connected has to withstand the (large) CM voltage at power frequency, and the remaining part of the CM voltage at higher frequencies as well. This capacitor should not be inserted in the shield, as this practice would produce a high local Z_t.

7.7 General routing of cables

The routing of a cable should be carefully designed. EMC requirements dictate the path followed, and the design of earthed conductors parallel to the cables (PECs), their presence, their connection to the earthing structure, their cross-section and shape. In any case, the EMC requirements prevail over practical considerations, convenience of mounting, and aesthetic aspects. This does not exclude the possibility that these secondary considerations and the EMC requirements can be met simultaneously.

For the intended signal, the shortest distance allowed in a particular installation would be chosen because of damping, copper cross-section etc. EMC requirements alter this choice into the shortest distance properly protected.

7.7.1 Routing between apparatus in a cabinet

The preferred type of cabinet has at least one continuous metal wall that is well bonded to earth (see also clauses 5 and 6). Cables are preferably placed against that wall, and are routed via the shortest distance between the connections of the apparatus.

Not recommended are cabinets for which the walls do not form a continuous metallic conductor, such as those painted before mounting, or mounted with only few screws. In such cabinets however, vertical or horizontal beams can be used as PEC if the beams are properly earthed.

The shortest connection between two equipments is allowed provided that a PEC is present which offers sufficiently low Z_t. An exception to this rule may be a cable serving apparatus for which the CM immunity (current and/or voltage) is sufficiently high for all disturbances likely to occur within the environment of that application.

7.7.2 Routing between cabinets

A cable in combination with a PEC is recommended. As is apparent from figure 18, such a PEC may be the protective earth lead in a cable; a shield acting as PEC offers a better EMC performance. Conduits may run parallel to the cable shields. Both shields and conduit should be properly connected to the cabinet wall: shields over the full perimeter by appropriate glands, conduits over the full cross-section.

7.7.3 Routing between installations or between buildings

For larger distances between installations, some appropriate form of a PEC is desirable. As discussed in 7.6, additional earthing connections to the PEC reduce the disturbance current over the length of the PEC.

Cables are often bundled and carried by metal trays. The metal trays should be (inter)connected to maximize their EMC benefits as well, and treated as a PEC. As a minimum, the trays are connected at both ends to earth and to the apparatus served by the cables in it. Non-conducting trays are not recommended, but can be used when other PECs are provided. Many forms of tray are possible: a metal tray of ladder type has a limited EMC quality. A plate, a U-shaped conduit, and a solid wall or continuously welded pipe give a better performance.

A ladder has two side beams with rungs in between. For EMC, the side beams of a ladder are more important, because they form the path for disturbance current parallel to the cables. As far as Z_t is concerned, the beams can be regarded as two parallel wires as in 7.5.

7.7.4 Distance between conduits

Different cable trays or conduits may run parallel over an appreciable distance. The DM-to-DM cross-talk between the cables they contain may become important. The recommended mutual distance between the cables in the trays depends on two parameters, first on their quality as PEC, which means the low Z_t, second on the DM-to-DM cross-talk, which may require shielding against the (magnetic) fields caused by the DM currents proper. A deep conduit or tube, of sufficient wall thickness can provide both simultaneously; they can often be laid next to each other.

A special case is the DM-to-DM cross-talk between cables carrying high current at power line frequency and low-level signal cables. There are several possibilities.

– ***Shielding against the magnetic field*** – A single shield may surround the single-phase or three-phase leads and the neutral. A braided shield seldom provides sufficient shielding at power line frequencies against the local magnetic fields. Additional shielding by the PEC may be needed, either by the PEC belonging to the power line cables, or by the PEC belonging to the signal cables. This reduction of cross-talk requires separate tubes or deep conduits, with a sufficient wall thickness of at least 2 mm of steel (see shielding in B.5 as well as 7.5).

– ***Reduction of the magnetic field by layout*** – The power lead may be equipped with its own shield, which should be connected at both ends of the cable to the apparatus. Magnetic induction causes a current flow in each shield, opposite to the current through the lead inside. The magnetic field outside the shield is reduced. This reduction is due to the strategic position of each shield, rather than due to an actual shielding. Sufficient reduction may already be obtained by a less radical solution, when the power line cables are placed parallel and close to each other, and are mounted directly against a PEC of sufficient thickness. This mounting diminishes the size of the CM circuit. In addition, in the PEC the mirror image circuit is formed, which reduces magnetic fields at some distance from the power leads. A conduit or tray with a partition (figure 23) provides further reduction, when compared to a simple conduit.

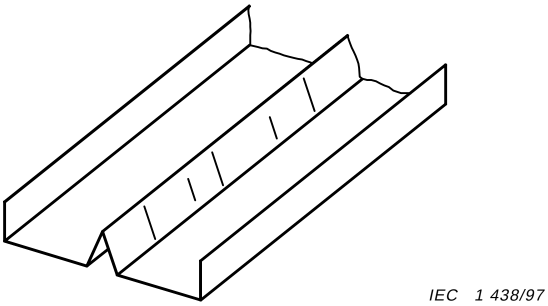
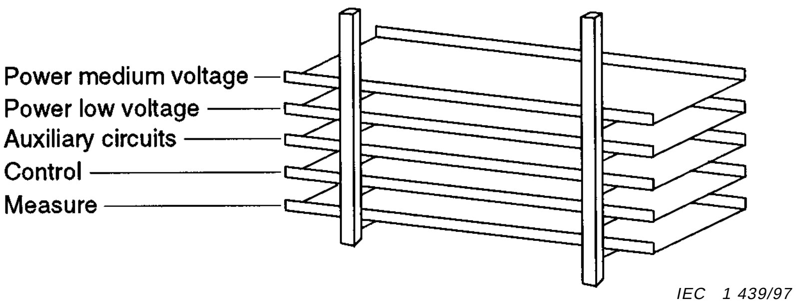


Figure 23 – Tray with partition

– ***Reduction of the magnetic field by distance*** – A third option is to keep some distance between (shallow) conduits for the different types of cable. Experience suggests a stacking order as shown in figure 24. Distances between the different conduits should be larger than 0,15 m, in vertical or horizontal direction. The conduit containing the sensitive measuring cables should preferably be covered when it is at a distance of less than 1 m from the high-current power cables.



NOTE – In the case of stacked conduits or cable trays containing different types of cables, a minimum distance between the trays of 0,15 m is advised. The trays should be electrically connected at the vertical supports. The conduit for the low-level measuring signals should be covered.

Figure 24 – Example of stacking for conduits or trays

7.8 Cable bundles

The DM-to-DM cross-talk between different cables deserves attention. Cables transporting similar signals can often be bundled together. With cables transporting different signals differences may be made (Goedbloed, 1990 [7]) between cables that are:

- very sensitive: cable that carries low-voltage or low-current signals such as those coming from sensors;
- sensitive: signalling cable at ≤ 24 V, flat cable for parallel data transfer;
- indifferent: a.c. power between 100 V and 250 V, depending on the EMC properties of the apparatus connected;
- noisy: a.c. and d.c. relay feed-line without protection (filters or diodes for instance)
- very noisy: leads to d.c. motor with brushes, switched power lines, cables and earth wires in high-voltage switchyard, etc.

Cables of different categories should not be in the same bundle. Different bundles should be separated electromagnetically from each other, either by shields as PEC, or by placing the cables in different conduits. The quality of the PEC determines the distance to be kept between the bundles (and their PECs). Suggestions are given in 7.5. Without any PEC, a sufficient distance should be kept; experience suggests a distance of 10 times the largest lead diameter.

In effect, two sometimes opposing requirements have to be balanced: first, compact circuits for CM mitigation, which ask for a small distance between the bundles, and second, low DM to DM cross-talk which requires some distance. A solution is to place the different bundles in individual shields or conduits. The shield should be of sufficient thickness (see also B.5). Braided shields seldom provide any shielding at powerline frequencies. A single conduit may be divided by a partition (one or more, figure 23) to form a set of connected, but electromagnetically separated, conduits.

Examples:

- The input and output lines of a filter should not be in the same bundle. The disturbance currents will pass around the filter via other cables in the bundle.

  A two-lead cable feeds a relay without protective elements such as filters for a.c. and diodes for d.c. This cable should not be in the same bundle with cables for digital signals.

DM-to-DM coupling occurs also when cable bundles cross at an angle, or perpendicularly. Without any PEC a minimum distance between the bundles is advised of about 10 times the bundle diameter. Shorter distances are allowed for bundles in good shields or conduits.

7.9 Cables serving power ports

7.9.1 Connection to the ports of apparatus

Cables of appropriate insulation and copper cross-section connect the power source and the apparatus. The contacts are bolted or pressed on bare metal surfaces. The contact metals should be matched to prevent electrochemical corrosion even in dry atmosphere. Soldered copper wires are not allowed under a bolt. Fully soldered connections can be used for low-power applications.

All connections of the power leads should be placed close together (compact DM-circuit) inside an apparatus or cabinet. This applies for d.c. power, a.c. single-phase, and a.c. three-phase connections. In a three-phase star system the neutral (N) conductor should be treated like a phase conductor, and kept close to the phase conductors.

NOTE – In three-phase systems several arrangements exist for the neutral and protective earth (PE) conductor. From the EMC point of view, the TN-S system is preferred; the separate N-conductor together with the three phase-leads provide a set of clearly defined DM circuits. The additional PE, either a shield or a lead, provides an extra separate path for the disturbance currents.

An earth lead in a cable should be connected to the metallic structure of an apparatus or cabinet as close as possible to the point of entrance of the cable. The earth lead of a cable may continue after that connection inside the cabinet to different apparatus (see 7.3 e)).

When several cables are connected to a cabinet, for instance containing a power supply, all earth leads are often connected to an earthing rail for convenience of mounting. For EMC purposes, the correct position of this rail is on the outside of the cabinet, or on the outside of the compartment of the cabinet which contains sensitive electronics. The rail should be bolted or welded at many places over its full length to the metallic structure of the cabinet. An insulated rail, bonded by a single lead to the cabinet, should not be used for earthing. Inside an apparatus the earth lead should be connected to the metallic housing via the shortest length possible.

A shield of a cable should be connected to the metallic walls of the cabinet at the point of entrance of the cable. A circumferential connection is preferred; it should be ensured by an appropriate gland. A single-wire connection (pigtail, see figure 22) between the shield and the cabinet wall should not be used. The shield may continue through the gland and be connected to local earth deeper inside the cabinet.

Earth leads in a shielded cable are treated as described above for earth leads proper.

NOTE – Shields consisting of steel wires around power cables are mainly designed for mechanical protection rather than for EMC purposes. The transfer impedance of such a shield is seldom well known, but it may be low, certainly when compared to the transfer impedance of a single earth wire. Even if such a shield is coarsely woven, it is also recommended to connect this type of shield by glands as described above.

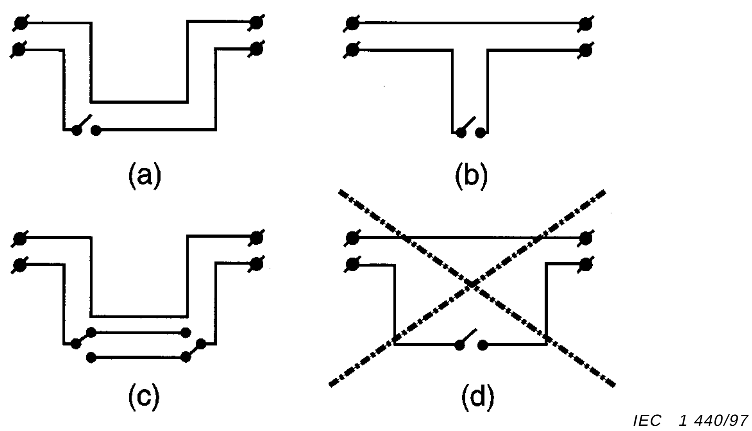
7.9.2 Power switches between apparatus

Mechanical switches may be placed in a cable, for instance lighting fixtures circuits. In all applications the DM circuit consists of the power lead and its return; the DM circuit should be maintained as compact as possible. The compact design avoids a local coupling of DM disturbances, which may cause interference of apparatus at other places connected to the same power line. An additional earth lead or shield should provide a continuous current path at the switch. When the switch is contained in a fully closed metal box, it should be treated as an apparatus proper, with routing and connection of the power lead and its return, and of perhaps the earth lead and shield as described above.

Two types of switches are available, a single-pole or a double-pole design. A double-pole switch, for d.c. or single-phase a.c., acts on both leads, power and return; the two leads should be kept close together. For single contact switches, a compact DM circuit should be ensured. Preferentially the switched and non-switched leads follow the same physical path (figures 25a and 25c). When the switch is at some distance of the original position of the cable, the switched lead goes to and returns from the switch along a single path (figure 25b).

7.10 Cables serving signal and control ports

First the reader is referred to the set of EMC rules in 7.3. From the EMC point of view, the installation of cables and the connections for signal and control ports have many items in common, also with those for the power ports.



NOTE – There are several solutions (a, b, c) to keep the DM circuit compact when switches are installed. The lead position indicated in (d) should not be used.

Figure 25 – Topology of circuits containing switches

It is not possible to give an exhaustive classification for signal and control levels. Not every application can be covered. For LF signals, some are mentioned here in order of increasing level:

– thermocouple and microphone (µV up to mV);
– thermistor sensors (mV up to V);
– position indicators as electronic rulers or switches;
– digital controls and similar signals between 1 and 24 V;
– signalling voltages in high power installations, often 42 V or 110 V;
– high-impedance current loops (4 mA – 20 mA), often used to transmit LF analogue signals.

Parallel data transport between digital equipment such as computer and printers are a case of intermediate speed. High-frequency signals include:

– video-signals, internal closed television circuits using HF carriers;

– fast serial data communication using coaxial cables.

Cables serving the antennae for mobile communication can in principle also be installed according to the guidelines of this technical report.

7.10.1 Signal cable selection

The choice of the cable, the connection and routing is based on the required signal to disturbance ratio at both ends of the cable, and on the DM and CM immunity of the apparatus ports. A tentative list of cables comprises:

Unbalanced: coaxial, bifilar, multi-lead flat cable.

Balanced: bifilar without shield, shielded two-lead cable, flat cable, multi-twisted pair bundle with and without shield.

Bifilar cables are mainly used for LF signals or power. More recently, it is intended to employ bifilar leads for higher frequency digital system signals. Coaxial cables are used for LF and HF signals; the available bandwidth is mainly determined by the damping due to the skin effect in the conductors, and also depends on the length of cable; short coaxial cables can be used up to many gigahertz. The transfer impedance is most important for evaluation of the EMC characteristic for the cable, and should be specified by the manufacturers. Coaxial cables or multi-lead cables with more than one shield may offer a lower transfer impedance than cables with a single shield. There is the option to interconnect all shields at both ends, or at one end only. In the latter case, a HF current path is always formed by the capacitances between the shields. A more detailed discussion is presented in B.2.

For low-frequency signals, balanced and unbalanced transport should be compared. Especially at LF, low transfer parameters can be obtained with balanced signal transport. Over the length of the cable the CM current is equally divided over the two leads. The apparatus should provide a low Z_t path for the CM current by an appropriate filter at the port. In addition, the balance of the port should be maintained over the frequency range of interest for disturbances. This requires a good common mode rejection ratio of the port. This is difficult to realize at frequencies out of the band of the intended signals. Therefore, balanced signal transport is often limited to LF or audio frequencies.

Preferably, each DM signal circuit is given its own return lead in a multi-lead cable (compact DM circuits). This avoids DM-to-DM coupling between the circuits via a mutual resistance at d.c. and at low frequencies. Bifilar cables and pairs of leads in multi-lead cables should be twisted to prevent inductive and capacitive DM-to-DM crosstalk at higher frequencies. The transition between lower and higher frequencies here may already occur at a few kilohertz, or even at power frequency.

NOTE – Other standards and documents dealing with customer premises wiring have been published or are in preparation. See for instance ISO/IEC 11801:1995, *Information technology – Generic cabling for customer premises.*

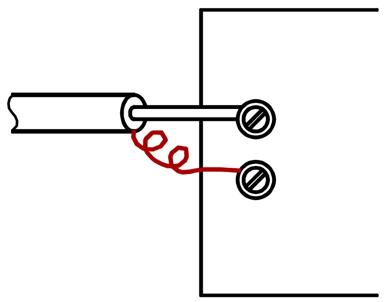
7.10.2 Connectors

Terminals for signal and return should be in close proximity (compact DM circuits). Contacts should be corrosion resistant; for example, gold surfaces are preferred over silver. Corroded contacts may show non-linear current-voltage characteristics; distortion of the intended signal and (audio) rectification of HF disturbances may result. The variable resistance of corroded contacts may cause unpredictable cross-talk between different DM circuits. Worst of all, a corroded connector may result in a high and non-linear Z_t.

Both contact materials should be matched in order to prevent thermocouple effects at the connector, especially in the case of low-amplitude d.c. signals, such as from thermocouple temperature sensors. The connector should match the type of cable. The matching concerns the signal, voltage and current level; at high frequency the characteristic impedance is also important. For EMC purposes the matching also concerns the transfer parameters, Z_t and Y_t, over the full frequency range where disturbances can be expected, and over which range the electronics are sensitive.

Coaxial cables should be fitted with connectors that preserve the coaxial symmetry throughout. The outer conductor of a coaxial cable must always be connected to the DM circuit at both ends of the cable. For unbalanced ports, this may involve earthing of the outer conductor at both ends.

Balanced pair cables with shields should use connectors that allow a circumferential contact for the shield. Pigtails at the end of any shield (figure 26) should be avoided. If for some non-EMC reason a pigtail connection is necessary, the CM current should be given a path circumventing the pigtail. The best way is an circumferential connection of the cable shield to a wall at some point of the cable before the pigtail.



NOTE – A pigtail connection at the end of a coaxial cable results in a high local value of Z_t. Such a pigtail should be avoided as termination for the shield of any cable, even if it is a short straight wire instead of the coiled wire shown in the figure.

IEC 1 441/97

Figure 26 – Undesirable connection of a coaxial cable

7.10.3 Routing of signal and control cables

The routing of these cables should be as described in 7.7 and 7.8. Some additional remarks are given below:

– Coaxial cables carrying HF signals can be bundled. The Z_t of the cables should be low enough to avoid unwanted DM-to-DM cross-talk. An additional shield installed around a bundle of coaxial cables reduces coupling to the environment. The shield provides a good path for an overall CM current, provided that it is properly connected in a manner to ensure EMC.

– Twisted-pair leads are often used for low-frequency signal and control. They can be bundled; each pair should preferably be twisted separately. Here again, an additional shield is helpful, as described above.

– Coaxial cables, carrying HF signals, and twisted pairs connected to LF apparatus should not be bundled together. Cross-talk of HF signals into LF signal circuits may result in additional interference due to the non-linear characteristics of the low-frequency circuits. Demodulation of the HF simulates a d.c. signal, or a low-frequency signal, when the HF signals are amplitude-modulated.

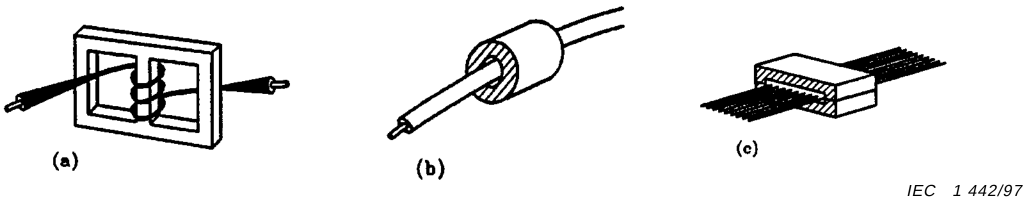
– A flat cable is often used for parallel data transport between digital equipment. Each data line and return line should be at alternate positions, next to each other. A single return for several data lines is not recommended. The flat cable can be shielded. Two flat shields at both sides are recommended; the shields should be connected at both ends over their full width to the local earth (plate) by appropriate connectors.

8 Additional interference mitigation methods

In addition to the preventive measures of proper earthing, bonding, and cable routing, additional mitigation methods include filtering, shielding, and installation of surge-protective devices. This clause provides a brief description of additional mitigation methods related to cabling methods and alternatives to signal transmission by metallic means.

8.1 Common-mode ferrite choke

Filters can be applied at the ports of apparatus. The filters should establish a proper path for the CM current, of sufficiently low Z_t. A common mode choke provides a local increase of the impedance of the CM (or IM, see annex C) circuit, and thereby reduces the CM current (figure 27). The CM circuit proper remains present. Whether an effective reduction is obtained, depends on the original impedance of the CM circuit. Ferrite cores or beads around a cable are in effect a single turn self inductance in the CM circuit. Several cores or beads may be used in series. Neither transformer nor ferrite affect the DM signal. A special form of the CM choke is the so-called “neutralizing” transformer, which is sometimes applied in high-voltage substations.



(a): CM choke with a coaxial cable; the self inductance provided by the CM choke adds to the CM circuit, but not to the DM circuit. (b): ferrite bead around a coax (c): ferrite yoke around a flat cable. All these schemes have the same purpose.

Figure 27 – Typical implementations of common-mode ferrite chokes

The additional self inductance provided by the CM choke or ferrite competes with the impedance of the rest of the CM circuit $Z_{CM,rest}$. The reduction of the CM current is largest when $Z_{CM,rest}$ is already low. This is the case when a earthed conductor (PEC) is in parallel to the cable. Examples are:

– a CM choke or ferrite core around a cable in a conduit;

– a ferrite between two shields of a double-shielded cable forces the CM current to flow through the outer shield;

– a ferrite around a cable with a separate earth lead nearby;

– ferrites cores around a coaxial cable at irregular distances, with the cable shield connected to the earth conductor between the cores.

Special coaxial cables with ferrite between two shields are commercially available. The CM choke has several or many turns of the DM cable around a core of magnetic material or air; capacitance between the windings and core losses limit its use to lower frequencies.

8.1.2 Properties of ferrite

Ferrites are magnetic materials, with a permeability μ_r varying over a wide range, between 10 and 10 000. Some conductivity is present; most materials also have a substantial dielectric constant. At low frequencies, ferrite provides inductance. At higher frequencies the induced currents and other mechanisms make the inductance become lossy. The transition between the two frequency regions depends on the composition and fabrication process.

8.1.3 Some considerations on the application of ferrites

With ferrites around a cable, resonances or standing waves may occur in the CM circuit. The resonance frequencies are substantially lower than expected from multiples of half wavelength on the length of cable, due to both the μ_r and the ε_r of the ferrite. For EMC, the losses are welcome as they tend to dampen resonances.

Ferrites may also be used around cables without parallel conductors. The cores or beads should then be mounted close to the point where the cables are connected to the apparatus. The reduction of the I_{CM} results in a lower emission of radiation. It depends on the impedance of the full I_{CM} loop whether ferrites decrease the overall susceptibility for interference.

For large CM currents, the ferrite may saturate, and become ineffective. This may be caused by power faults and lightning. Hysteresis may prevent normal operation of the ferrite after saturation. Rings of sufficient size can also be used around power cables. Even for higher DM currents, saturation hardly occurs.

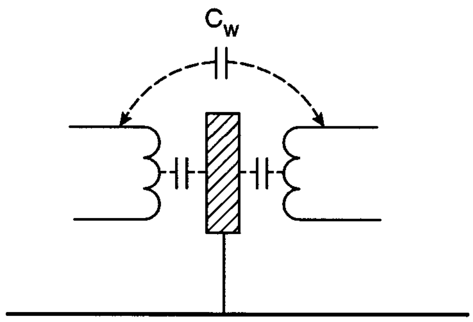
In any application, manufacturer data should be consulted in the selection of the ferrite for EMC.

8.2 Electrical separation

Electrical separation is often employed to increase the impedance of the CM circuit. This separation may be effective at d.c. and low frequencies, but deteriorates at higher frequencies because of parallel parasitic capacitances. Typically an isolation transformer, optical fibres, or optocouplers are employed. Provided that some care is taken in their application, these devices can be used for EMC.

8.2.1 Isolation transformers

The CM loop is interrupted by the electrical separation between the primary and secondary windings. The CM voltage withstand capability between the windings should be high enough for all disturbances that are expected. Unwanted coupling between primary and secondary, both CM-CM and CM-DM, occurs via the parasitic capacitance C_w. Electrostatic shields, which are placed between the windings and which should be properly earthed, reduce the capacitance between the windings, and provide well defined and separated paths for the CM currents through the cables connected to the different windings. The cables or wires connected to the transformer should be separated in such a way that the transformer is not bypassed via parasitic capacitance elsewhere. Again, the full spectrum of possible disturbances should be considered.



NOTE – An isolation transformer interrupts the CM loop for low frequencies. At higher frequencies the parasitic capacitances between the primary and secondary winding C_w and a similar capacitance between the wiring of the transformer form a possible CM current path. For the sake of clarity, the capacitor C_w is only drawn between the upper wires. In fact, this capacitor is distributed between both windings and all connecting wires.

IEC 1 443/97

Figure 28 – Limitations in the effectiveness of an isolation transformer

8.2.2 Optical fibres

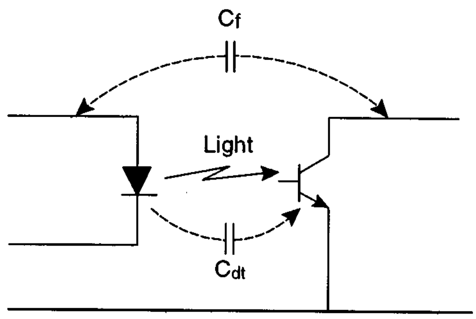
The DM signal is converted into a modulated light signal, which is sent through the fibre. Large bandwidth and low attenuation for the light signal is available when the fibres are properly chosen. For EMC the following remarks are important:

– the EMC of the send and receive apparatus should be sufficient, with respect to the CM currents arriving via the signal leads and power supplies;

– the fibre proper should be free of metal. This rule concerns metal added for mechanical protection of the fibre, or power supply leads parallel to the fibre, but also the possible metal cladding of a fibre for protection against moisture ingress. Any metal will form a CM current loop which passes through a very sensitive port. Most likely, this loop will be very unexpected, and therefore a source of interference.

8.2.3 Optocouplers

Optocouplers serve a similar goal as isolation transformers. For EMC the parasitic capacitance C_{dt} between the light emitting diode and the phototransistor is important. A high-frequency CM current through this capacitance flows through the transistor, and may cause erroneous switching of this transistor. The leads to the optocoupler can form a bypass for HF disturbances through the parasitic capacitance C_f.



NOTE – An optocoupler consisting of a light-emitting diode and a phototransistor interrupts the CM current loop at low frequencies. At higher frequencies the capacitance between the leads C_f, and the capacitance between the diode and transistor C_{dt} by-pass the optocoupler. Furthermore, the CM current through C_{dt} may erroneously turn on the phototransistor, even without any light from the diode.

Figure 29 – Parasitic coupling at high frequencies

9 Measuring and testing methods

9.1 Earthing and bonding

There are no general, recognized, or standardized methods for high-frequency measurements nor precise criterion for the impedance between two points of an earthing system. Nevertheless, the fundamental objective is to reduce this impedance to the lowest possible value. From this point of view, the following procedure gives some guidance to users for the design of a new earthing system.

a) Define the needs:

– know the systems to be installed and protected;

– have documentation and use it.

b) Implement a good earth electrode (safety considerations):

– know the soil;

- geological aspects;
- other existing earthing system(s);

– improve the soil if necessary.

c) Implement a good earthing network (EMC considerations):

– select optimal layout;

– a single meshed network is the recommended practice, unless the application dictates another well-proven approach;

– reinforce mesh (tighter cells) in critical areas.

d) Maintain the earthing system:

– check bonding connection resistance;

– clean connections (corrosion);

– maintain protective coatings;

– keep screwed and bolted connections tight.

9.2 Cables and installation

A number of tests are proposed in related EMC documents, such as the IEC 61000-4 series or the Bersier current injection method. All tests couple a current (CM or DM) into the cable, either capacitively or inductively. The current itself is not always measured; rather, the effect on the apparatus is detected. It should be established whether the prescribed test is a reasonable representation of the actual disturbances; however, it must be understood that no test specification can pretend to emulate all possible disturbances. The prescribed test can be basis for a commercial or legal agreement between parties, with the expectation that meeting the test requirements enhances the likelihood of satisfactory performance of the installation under real-world conditions.

The objective for all guidelines is to obtain a low DM disturbance voltage at the ports of the apparatus. When the CM impedance of the port is large, it is necessary to also verify that the CM voltage is within the limits of the apparatus. The measuring equipment should be carefully designed, in order not to introduce interference by its presence. The EMC quality of the measuring equipment proper should also be sufficient. The bandwidth of the measuring set-up should be adapted to the disturbances. Especially when breakdown and arcing occurs nearby, nanosecond-fast equipment is preferred.

Interference of the normal operation of the apparatus may occur, or unacceptably high voltages may be found. First the CM currents along the cables are determined at the position where they are connected to the apparatus. Secondly, the CM currents at locations farther away are measured. This technical report provides a number of solutions to reroute the CM currents, and thereby reduce the disturbances.

Annex A
(informative)

Examples of earthing systems and cable implementation

The earthing system described in clause 5, a meshed configuration, is the recommended approach for the general case of a new installation, in particular when the building is to be occupied by organizations that do not have well-established EMC maintenance practices. It has been emphasized in this technical report that other approaches are recognized as being effective, as demonstrated by their successful application, in particular by organizations that have the means and the authority to apply consistent EMC maintenance practices. The following figures illustrate examples of the variety of practices that have been successfully applied.

– Figure A.1 shows the arrangement of a telecommunication facility according to the directive K.27 of the former CCITT.

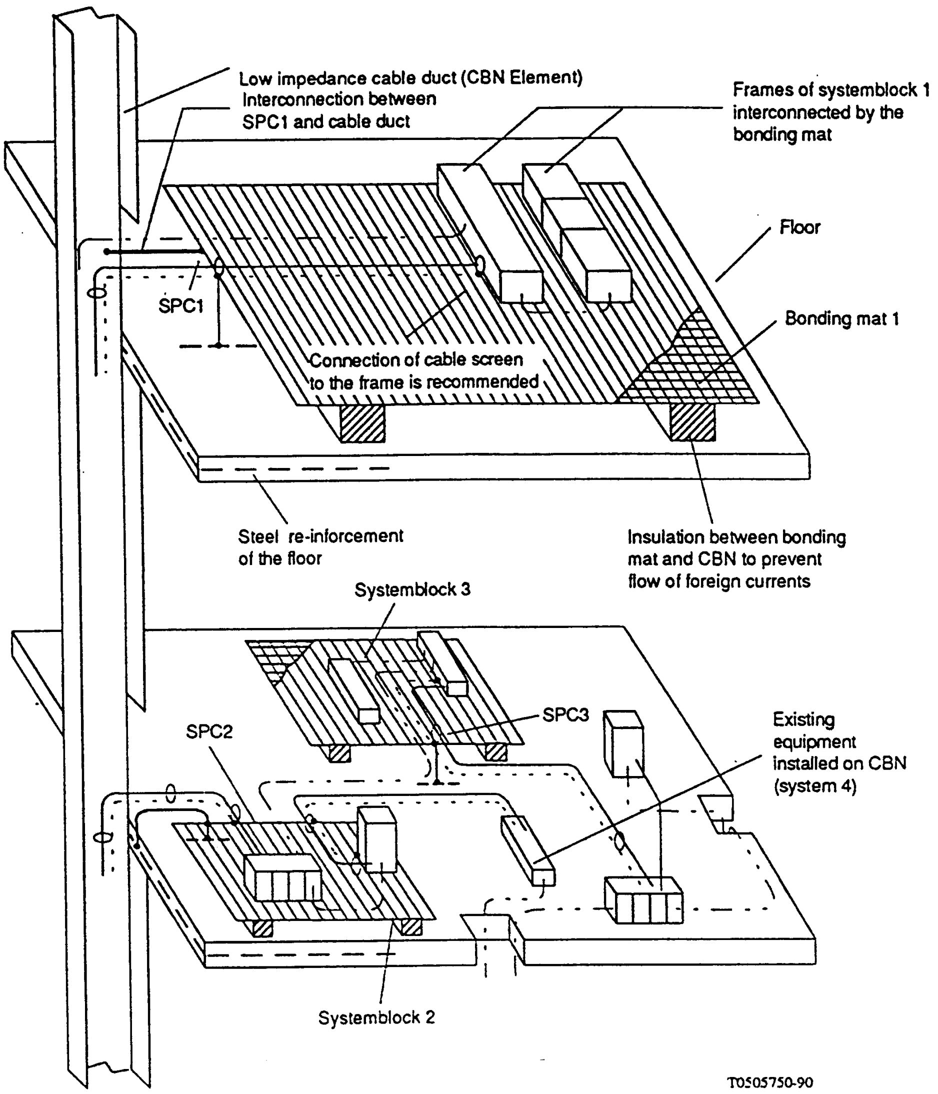
– Figure A.2 shows the topology of a cabinet limited to five sides only, providing EMC in a harsh environment.

– Figures A.3 and A.4 show examples of earthing systems for high-power electronics.

– Figures A.5 and A.6 show a case history of improvements in wiring practice for EMC.

A.1 Hybrid bonding arrangement

This arrangement is an example of practices applicable where the operator/owner of the facility has complete control over the new installation. It has been successfully applied for many years, especially within existing buildings when new equipment needs to be installed in combination with existing equipment. It provides clear-cut interfaces for EMC acceptance tests and demarcation of responsibilities for different system suppliers and users. (Montandon, 1992 [4].) Figure A.1 illustrates a schematic of such an approach as described in CCITT (now UIT-T) directives.



SPC Single point connection

——— Equipotential bonding conductor

— — — Steel re-inforcement

— · · — Unshielded intra-or inter-system cabling

· · 0 · · Shielded intra-or inter-system cabling

Dots (-•-•-•-) along the edge at a bonding mat denote its SPC.

Inter-system cabling entering the systemblock must enter close to the SPC.

Note 1 – Systemblocks 1, 2 and 3 are new installations conforming to the mesh-IBN method. They may be connected to existing installations (system 4) that use any method of bonding.

Note 2 – The SPC is the only metallic interface between the mesh-IBN and the CBN. It must be directly connected to the reinforcement of the floor. All cables leading to the system enter here. All conductors that are bonded to the mesh-IBN must be connected to the SPC (e.g. cable screens, battery return, etc.).

FIGURE B-2/K.27

Mesh-IBN with bonding-mat

IEC 1 445/97

NOTE – This topology is based on a zoning concept. System blocks 1, 2, and 3 are new installations strictly respecting the hybrid-bonding principle. They may be connected to existing systems (system 4) that need not be changed. See the source cited above for details of implementation.

Figure A.1 – Example of topology for a hybrid earthing system

A.2 EMC cabinet

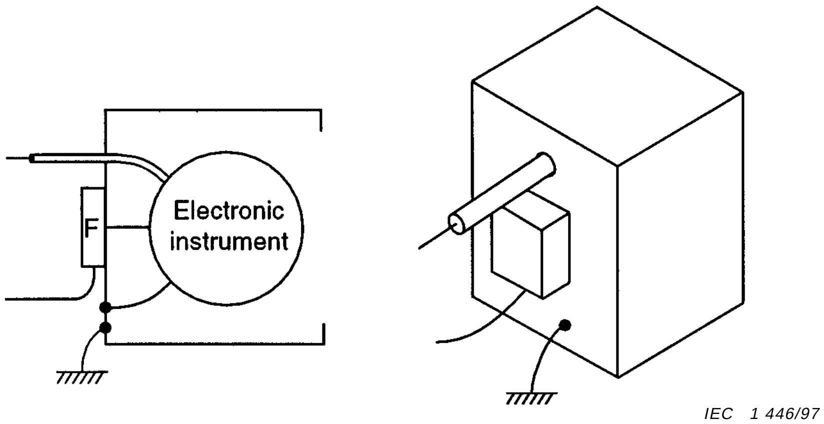
In this example, an EMC cabinet is described, which has been proved to result in a very good protection of electronic equipment even in harsh EM circumstances, such as directly under the HV bushing in a 380 kV open-air high voltage substations (van Houten, 1990 [9]). This EMC cabinet is presented here as the ultimate protection that can be obtained by a reduction of the transfer impedance Z_t and a rerouting of the common-mode currents. A careful layout, according to the guidelines of this report, for the cables installed inside the cabinet further enhances the performance.

In an environment with less disturbances than HV substations, simplified and reduced versions of the EMC cabinet are possible, retaining the principles. As an example, the backplane only may be used, or even the size be reduced of that single plane, as long as a clear path for the common-mode currents around the electronics can be maintained.

The cabinet has continuous metallic walls on five sides; the front is left open, which might appear a deviation from conventional wisdom that a shielded enclosure should be closed on all sides. When compared to the previous example of hybrid bonding, it becomes apparent that this EMC cabinet and the "systemblocks" of figure A.1 are topologically equivalent: the systemblocks and their cable terminations are equivalent to the configuration of the EMC cabinet if its back and four sides were unfolded into a single plane, similar to the raised floor of the systemblock of figure A.1.

All cables, signal and power, enter the cabinet through the backplane of the cabinet. The shields or outer conductors of the signal cables are circumferentially connected to the backplane. The a.c. power enters the cabinet through a filter (F), well bonded to the backplane; an additional safety earth lead is also connected nearby the filter.

All CM currents arriving at the cabinet through the cables and the safety earth lead flow via the backpanel; this results in a very low transfer impedance between the CM currents outside the cabinet and the electronic instruments inside. It turns out that in many applications this low Z_t is much more important than the possible shielding provided by the cabinet, even if closed to form a Faraday cage.



NOTE – All external CM currents are routed via the backplane, thereby providing a minimal Z_t between the currents outside the cabinet and the electronics inside.

Figure A.2 – EMC cabinet for the protection of sensitive electronics

A.3 Earthing arrangements in industrial electronic installations

The principles of earthing arrangements discussed in this technical report have been used successfully in industrial installations that include utilities and electronic controls (Benda, 1994 [8]). Figures A.3 and A.4 illustrate in schematic form the practical implementation of these principles.

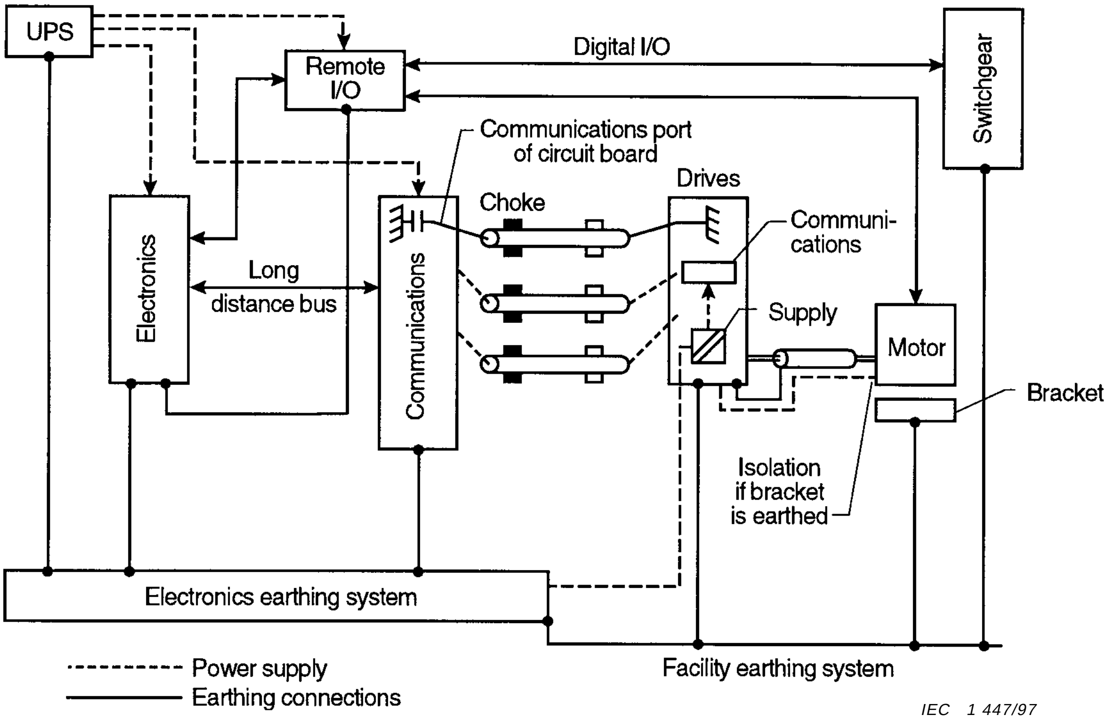


Figure A.3 – Earthing system for a drive with converter and associated electronics

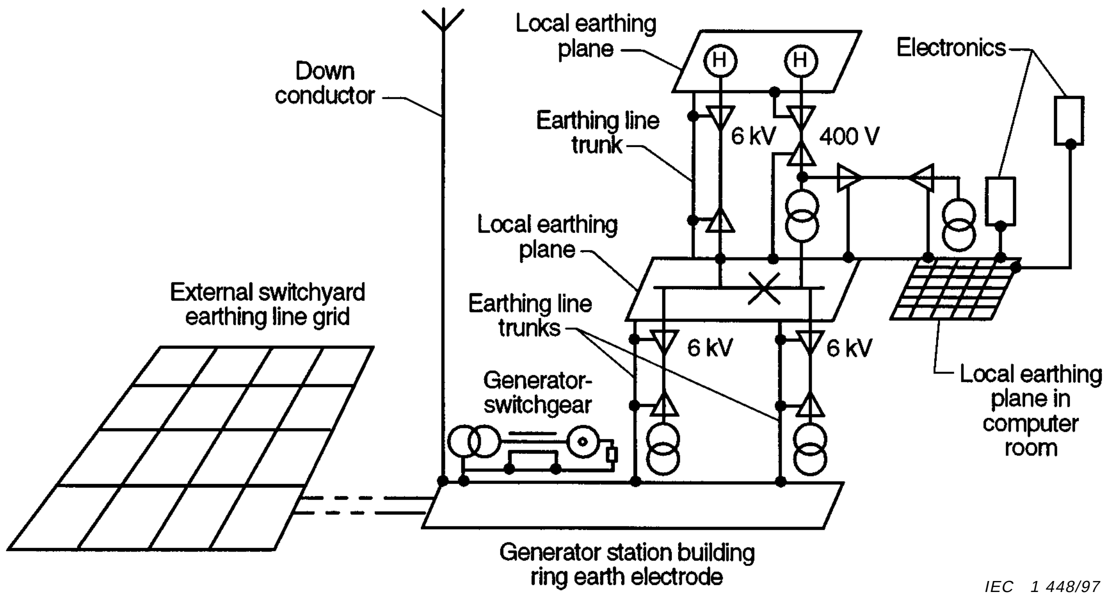
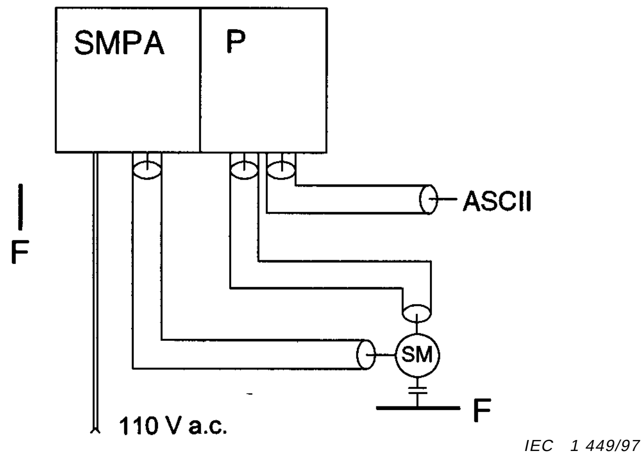


Figure A.4 – Earthing configuration for a power supply system with associated electronic control and supervisory systems

A.4 Example of shield bonding

In this case history, a servo motor (SM) was powered by a switched-mode power amplifier (SMPA) which was controlled by an on-board microprocessor P (figure A.5). Feedback signals from SM to the SMPA processor concerned the position via a digital encoder, and the torque. The input to the processor was ASCII coded RS232 digital information in the sequence “address of the SMPA” and “data”. A single SMPA-SM unit connected to the mains and a computer commanding the SMPA processor functioned properly. Serious problems occurred when several units were installed in a large processing machine, in which a single main computer controlled the process, a single power supply fed all SMPAs (110 V a.c.), and all ASCII data lines were interconnected in series.



NOTE – The servo motor (SM) is powered by a switched-mode power amplifier (SMPA) which is controlled by a microprocessor (P) and fed from 110 V a.c. Feedback signals from the motor to the processor include position and/or torque.

Figure A.5 – Initial arrangement of the power and control cables

An EMC engineer was asked to assist in solving this problem. The SMPA-SM units had been supplied by a third party. No schematic diagrams had been given to the builder of the processing machine. From the layout of the SMPA boards it became clear that no or little filtering was present in the output stage of the SMPA or in its supply lines.

The CM currents were measured over all cables connected to the SMPA. When the motor was driven to its maximum torque, CM currents of about 1 A with submicrosecond rise times were found at the cable between the SMPA and the SM. The large CM current loop comprised the cable, the parasitic capacitance between the motor windings and chassis, the frame (F in figure A.5) of the machine, and the power supply which was also connected to the frame. Significant couplings with other nearby loops were certainly possible.

Accordingly, large CM currents flowed through the cable from the power supply as well as through the cable between the control computer and the SMPA processor.

The problem was solved by the following analysis: since a single SM-SMPA unit was not perturbed, the CM currents of each unit did not disturb its proper operation. The most likely cause for the problems was a mutilation of the ASCII messages between the main computer and other processors.

Because there was only a short time available for solving the problem, as is usual when EMC problems are suspected in processing equipment, a certain path towards EMC had to be found. The costs were less important, which is also not unusual under these circumstances.

First, the SMPA was equipped with a brass front plate, which was a more reliable conductor than the anodized original (figure A.6). Second, the shield of the cable already present between SM and SMPA was connected to that plate at the SMPA, and to the chassis at the SM. Originally, the shield was only earthed at the SMPA. The same action was taken for the shield of the position and torque data cables between SM and SMPA.

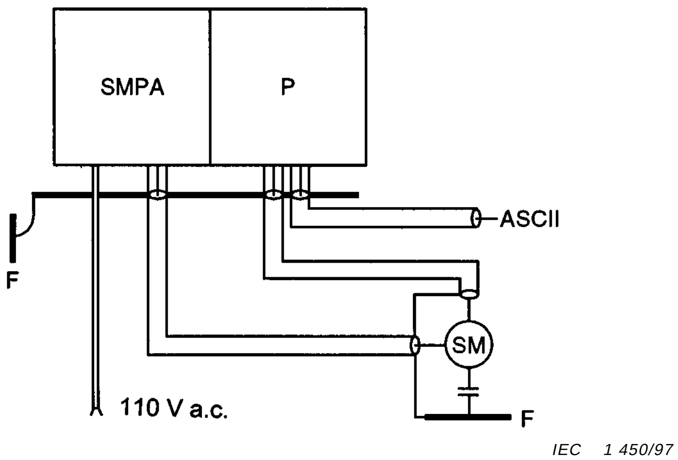
Shield and brass plate provided a compact path for the CM current over the SM power cable. The total CM current through shield and cable was reduced by a factor of about 20.

Third, the shield of the ASCII data cable was connected to the brass plate, as well as to the local earth at the other end of the cable. A simple R-C low pass filter was mounted in the ASCII data lines entering and leaving each processor unit. The roll-off frequency was adapted to the baud rate of the communication.

It took about two days to realize and install the modifications. After that, up to seven SM-SMPA units worked in harmony.

Some remarks are in order:

– Of course, a CM filter at the output of the SMPA was also tried. It turned out that the electronics became unstable with a large variety of filter types.
– A filter in the a.c. power supply was envisaged, but turned out unnecessary.
– The main reason for discussing this problem here is that although the EMC engineer was unfamiliar with the details of operation of the electronics, a careful look at the CM interference currents, and appropriate measures to improve the CM current paths, completely solved the problem.



NOTE – In the improved design, a brass front plate carefully connected to the machine frame F replaced the anodized original at the SMPA. All shields of cables were connected to that brass plate, and to the local earth at the other end.

Figure A.6 – Improved design with appropriate shield connections

Annex B
(informative)

Applying cable theory to enhance EMC: Behaviour of Z_t for different types of cable

B.1 General

Throughout this technical report, a generalized transfer impedance Z_t is used, not only the Z_t for coaxial cables, but also for other types of cable, and for the ports of an apparatus. Here a short description of the transfer impedance Z_t is presented for different cables, in connection with the termination at both ends of the cable.

For unbalanced signal transport, two types of cable can be considered as extremes:

a) a two-lead cable,

b) a coaxial cable with a solid outer conductor.

Other types, such as cables with a braided outer conductor, show a behavior of Z_t intermediate between these two extremes; their Z_t can be understood starting from these two. For a detailed description of measuring methods and for a general overview of Z_t for HF cables the reader is referred to other documents such as those by IEC TC 46.

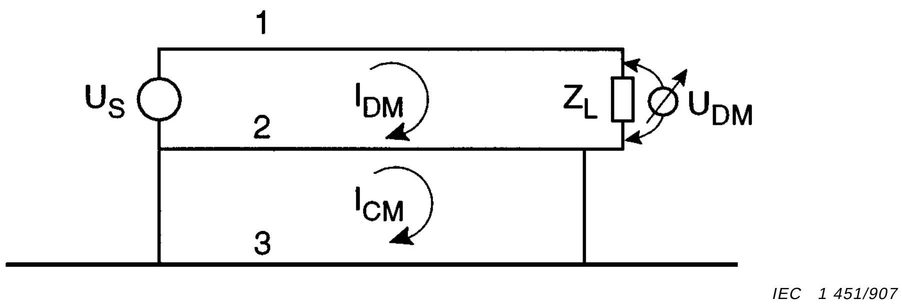
B.2 Two parallel leads

B.2.1 Unbalanced DM circuit

In figure B.1 a DM signal is transported in an *unbalanced* circuit, through a cable connected to the local earth at both ends. In this simplified version of figure 17 (see 7.2) the connection to earth is made explicitly; other possibilities are discussed in 7.2. For this unbalanced signal circuit, naturally, all I_{CM} are chosen to flow through the earthed lead. The receiver (with high input impedance Z_L) at the end of the cable has a DM voltage U_{DM} which consists of the intended signal U_S, and an additional disturbance voltage U_{dist} due to:

a) the resistance of the return lead;

b) the magnetic flux in the DM circuit caused by I_{CM}.



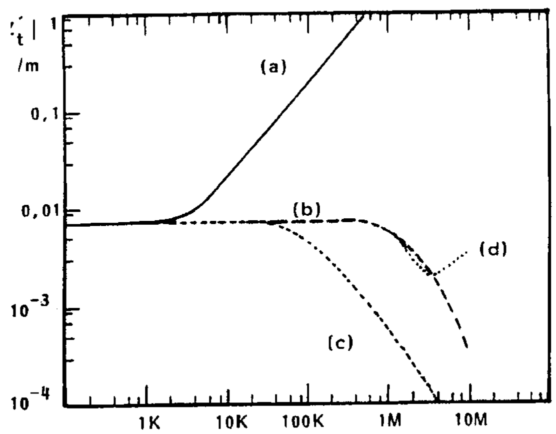
NOTE – The DM voltage U_{DM} at the receiving end consists of the intended signal U_S plus a disturbance term U_{dist} caused by I_{CM}, coupled into the DM circuit via the transfer impedance Z_t. The numbers 1, 2 and 3 are referred to in B.4.

Figure B.1 – Unbalanced transport of signals

Here it is assumed that the apparatus at both ends of the cable do not contribute to the total transfer impedance. The voltage U_{dist} is then proportional to the length of the line. At frequencies for which the wavelength is larger than the length of the cable may be written according to equation (B.1):

$$U_{int} / (I_{CM} \cdot \ell) = Z'_t = R' + j\omega \cdot M' \qquad (B.1)$$

where R' is the resistance of the earthed lead, perhaps increased by the skin effect. The mutual inductance part can be approximated by $[(\mu_0/2\pi) \log (d/r)]$, where d is the distance between the two leads of the DM circuit and r the radius of the earthed lead. For a standard power cord with 2,5 mm^2 leads R' is about 20 mΩ/m, M' about 0,3 µH/m. The behaviour of Z'_t is depicted in figure B.2, together with the Z_t for other types of cable to be discussed later on. The M' causes a *rise* in Z'_t at frequencies above 4 kHz. This Z'_t is not influenced by twisting the leads.



(a) A two-wire transmission line (2,5 mm^2 copper)

(b) A coaxial cable with solid outer conductor with an assumed radius r = 3 mm and thickness d = 0,13 mm, 2,5 mm^2 copper

(c) The outer conductor of (b) split into two conductors at the distance of 1 mm, r = 3 and 4 mm respectively, d = 0,056 mm, total 2,5 mm^2 copper

(d) The behaviour of the cable in (b) when openings in the outer conductor result in an assumed M' of 50 pH/m.

IEC 1 452/97

Figure B.2 – Behaviour of Z'_t as function of frequency for several coaxial cable configurations (a), (b), (c) and (d)

When source and receiver both have a low impedance, a current I_{int} flows in the DM circuit, generated by the I_{CM} through the Z_t. In a short cable, LF approximation I_{int} is given by equation (B.2):

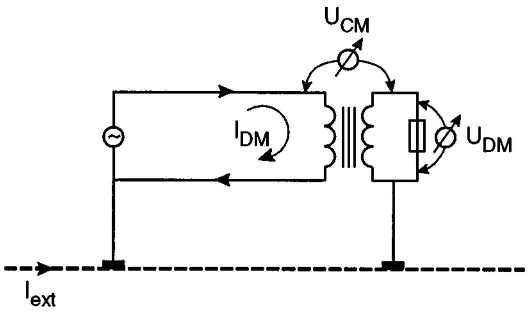
$$I_{int} = Z'_t \cdot I_{CM} \cdot \ell / Z_{DM} \qquad (B.2)$$

where Z_{DM} is the total impedance of the DM loop: source, cable and receiver. The disturbance voltage is now shared by the different impedances in the DM loop; over Z_L the fraction given by equation is observed (B.3):

$$U_{int} = Z'_t \cdot I_{CM} \cdot \ell \cdot ZL / Z_{DM} \qquad (B.3)$$

The current I_{CM} is always correctly measured by a current probe around the cable.

As discussed in 7.6, the CM circuit may sometimes be interrupted. During this interruption a CM voltage develops. It depends on the apparatus (such as the transformer in figure B.3) whether this CM voltage presents a danger to the apparatus. In the extreme case spark-over may occur causing uncontrollable interference or even destruction. No interruption is perfect; the local parasitic capacitance of the transformer will always allow a CM current to flow. This parasitic capacitance has a lower impedance at higher frequencies, thus aggravating the interference problem.

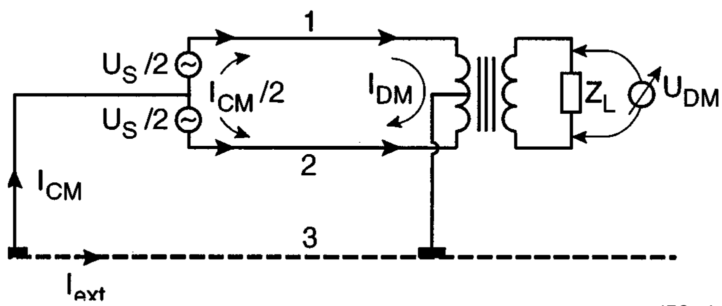


NOTE – A CM voltage develops due to the flux in the earth loop, across the interruption of the CM circuit (represented here by the transformer)

Figure B.3 – Unbalanced transmission system connected to earth at one end

B.2.2 Balanced DM circuit

When the DM circuit is *balanced*, a natural choice divides I_{CM} equally over both leads. For a perfectly balanced DM circuit Z'_t is zero (figure B.4). There is no magnetic induction in the DM loop from the equal halves of I_{CM} through both leads; also the DM voltage caused by the resistance of the wires does appear in U_{DM}. The actual reduction with respect to the unbalanced cable depends on the symmetry along the cable and on the symmetry at the send and receive apparatus; –40 dB can be obtained with some care at low frequencies. Maintaining the balance over the full frequency spectrum or amplitudes of the disturbances (I_{CM}) is difficult. Again, twisting the leads does not reduce the disturbances stemming from the residual unbalance. In special apparatus, designed to accept the CM current along the DM leads over the full spectrum of disturbances, a balanced signal transport may be used without the need for a PEC.



NOTE – The balanced system allows a well-defined path for the CM current, certainly for low frequencies. Proper care should be taken for symmetry, along the line, and at both ends of the line, in order to avoid conversion of CM disturbances into DM signal. The numbers 1, 2 and 3 are referred to in clause B.4.

Figure B.4 – Balanced transmission system

The system shown in figure B.4 has two explicit conductive connections to earth at both ends of the cable. Either of these conductive connections may be absent; even both in a *balanced floating* configuration, as is often the case in professional audio systems for instance. However, it is necessary to always be aware that local parasitic capacitances still provide a path for high-frequency CM currents.

B.3 Coaxial cable

A coaxial cable with a *solid* outer conductor is sketched in figure B.5. The Z'_t for a thin outer conductor (wall thickness d) is given by (Kaden, 1956 [10]; Schelkunoff, 1934 [11]):

$$Z'_t = R'_{dc} \cdot k \cdot d / \sinh (k \cdot d) \qquad \text{(B.4)}$$

where R'_{dc} is the d.c. resistance per metre of the outer conductor,

$k = (1 + j) / \delta$, with the skin depth of the outer conductor $\delta = (2\rho / \mu_0 \cdot \mu_r \cdot \omega)^{1/2}$.

The other symbols have the usual meaning:

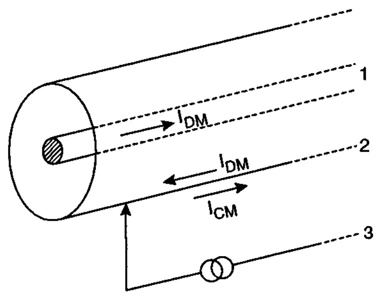
ρ = resistivity of the wall material;

μ_0 = magnetic permeability of vacuum;

μ_r = relative permeability of the wall material;

ω = angular frequency.

The behaviour of this Z'_t is also depicted in figure B.2.



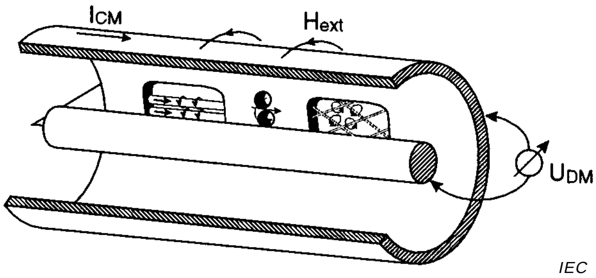
NOTE – The DM current through the inner lead returns through the outer conductor; the CM current flows through the outer conductor. The particular choice of the DM and CM currents, which is the same as in figure B.1, is explained in clause B.4.

Figure B.5 – Current paths in a coaxial cable

The contrasting behaviour, with respect to the two-lead cable, is a *decrease* in Z'_t. The skin effect brings an effective separation of the DM and CM circuits: the DM current returns mainly at the inside skin of the outer conductor, the CM current flows mainly at the outside of the outer conductor. The magnetic field caused by I_{CM} is outside the solid outer conductor. Consequently there is no M' part in Z'_t.

Most often an outer conductor is *braided*. The magnetic field due to I_{CM}, which was originally outside the outer conductor, penetrates through the openings, slits, holes, etc., as depicted in figure B.6. Now an M' part is present in Z'_t; however, it is generally many orders of magnitude smaller than the one for a two-lead cable, at nH/m or pH/m levels, depending of the type of cable and its outer conductor.

Note that the different behaviour of Z'_t for the unbalanced two-lead system and the coaxial system is solely caused by the layout of the metal and does not depend on the cross-section of the return conductor. The return for the DM signal is chosen either as a lead parallel to the signal lead or a conductor surrounding the signal lead.



NOTE – The magnetic field H_{ext} due to the CM current in the wall of a coaxial system penetrates for some part through the openings in the wall. When a net flux appears in the DM circuit, a DM voltage is generated which can be measured at the end of the cable.

Figure B.6 – Differential-mode voltage induced by a magnetic field in a cable with braided shield

B.4 Circuits for differential mode and for common mode

Clauses B.2 and B.3 deal with an unbalanced signal transport through a bifilar or a coaxial cable. The circuit for the intended signal is formed by the conductors 1 and 2 in figures B.1 and B.5, carrying a current I_1 and I_2 in the same direction respectively. In the unbalanced configuration conductor 2 is connected to the local earth at both ends of the cable. The CM current is generally taken to be equal to $I_1 + I_2$. This CM current returns via earth, shown as conductor 3 in figures B.1 and B.5. For the calculations it may be assumed that the full CM current flows through the earthed conductor 2. The DM current loop is chosen to be the aforementioned signal circuit, conductors 1 and 2, the signal source and the load. The choice for the CM and DM circuits implies $I_1 = I_{DM}$ and $I_2 = I_{CM} - I_{DM}$. Consider, for instance, a shielded cable: the preferred return path for a signal current through the inner lead is the shield. When the shield is solid and a good conductor, the currents I_{CM} and I_{DM} represent the proper electromagnetic transmission modes; the I_{DM} flows at the inside wall and the I_{CM} flows at the outside wall of the shield, due to the skin effect. The CM circuit is also in accordance with the definition and measurement methods for the transfer impedance Z_t.

In figure B.1 the voltage over the high impedance input of the receiver is the DM voltage U_{DM}, in accordance with the definition given in 3.5. The contribution due to the CM current is equal to $[Z_t \cdot I_{MC} \cdot \ell]$, where ℓ is the length of the cable. When the impedance Z_{DM} of the full DM loop, including the input impedance of the receiver, is low, some DM current I_{DM} flows due to the voltage $[Z_t \cdot I_{MC} \cdot \ell]$ over Z_{DM}. This does not directly affect the value of I_{CM} or Z_t.

Balanced signal transport through a two-wire cable requires balanced terminations at both ends and a symmetrical position of both wires 1 and 2 with regard to 3, the earth or return wire. A reasonable choice for the combination of I_{CM} and I_{DM}, which leads to a simple description, is $I_{CM} = I_1 + I_2$ and $I_{DM} = (I_1 - I_2)/_2$, or inversely $I_1 = I_{CM}/2 + I_{DM}$ and $I_2 = I_{CM}/2 - I_{DM}$. The chosen I_{CM} and I_{DM} correspond to the electromagnetic transmission modes for a symmetrical cable. The choice for I_{CM} is analogous to the definition given in 3.4.

Generally the true currents I_1 and I_2 can be represented by differently chosen sets of I_{DM} and I_{CM} currents; the linear transformation matrix will be different for each choice. This freedom should be used to achieve easier or more convenient calculations and a description in agreement with the behaviour at high frequencies. Both choices proposed above can easily be adapted to multi-shield or multi-lead cables by the additional definition of the most appropriate currents and their loops. The loops should then close inside the cable; only the CM loop closes via the outside of the cable. Such an approach is followed in the subsequent C.2.1 and C.2.2.

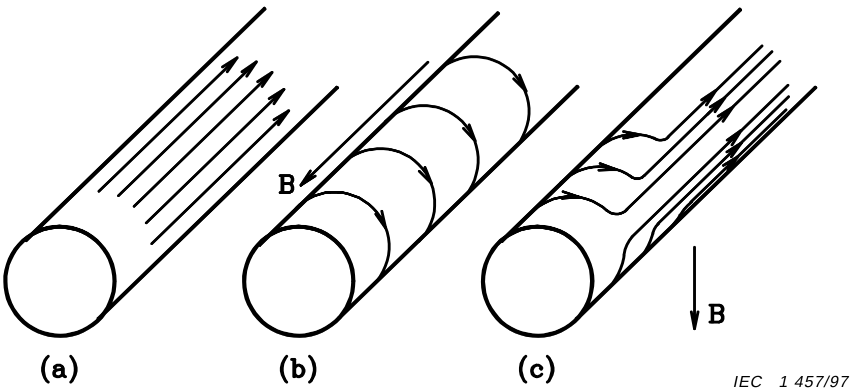
As described above, in both balanced or unbalanced cases, a current probe around the cable correctly measures the CM current. Of course, the Z_t may be very different for cables in the two systems.

B.5 Shielding against E-fields and B-fields by the outer conductor of a coaxial cable

The outer conductor has three functions. First, it serves as a return path for the DM current; consequently the outer conductor should always be connected at both ends to the DM circuit. Second, it forms a part of the CM circuit as indicated in B.3. Third, it may shield the interior of the cable against external E-fields and B-fields, whence it is often named: shield. The question is whether such shielding is effective, and also whether it is needed.

B.5.1 Shielding against E-fields

A solid metal outer conductor is a very good shield for E-fields at all frequencies. As a source of the E-field, some other lead at some distance of the cable may be thought of, at some voltage with respect to the outer conductor. By connecting the outer conductor at least at one end to the earth or CM circuit, a return path for the capacitively coupled (displacement) current is created. Large CM voltages at both ends are then avoided. The induced current pattern is shown in figure B.7.



(a) Longitudinal currents from earthed end to earthed end (outer conductor as DM and CM circuit element), or arriving at the outer conductor as displacement current, as a result of an external E-field (outer conductor as shield); this latter circuit can be closed by earthing the outer conductor at one end.

(b) Circulating currents on the outer conductor, induced by a longitudinal B-field (outer conductor as shield).

(c) Current pattern induced by a B-field perpendicular to the axis of the cable (outer conductor as shield).

Figure B.7 – Currents in the outer conductor of a coaxial cable

Openings in the outer conductor allow E-field lines to penetrate into the DM circuit. The current induced in the signal lead can be described by a transfer admittance, Y_t. This admittance is most often a capacitance between an external lead or earth and the inner lead of the coaxial system. For a solid metal outer conductor, Y_t is zero.

B.5.2 Shielding against B-fields

Two different orientations of the external B-field can be distinguished: perpendicular and parallel to the axis of the cable. The currents induced in the outer conductor are shown in figures B.7(b) and B.7(c). There is no net current induced in the shield. The external fields penetrates a solid outer conductor at frequencies such that $r \cdot d < \delta^2$, with r the radius of the outer conductor, and d and δ as given in B.3. For a braided outer conductor, the current pattern is more complex; it results in less shielding. For most commonly used cables with a braided outer conductor and a small product [$r \times d$], an external B-field penetrates into the interior of the cable. However, this does not induce a DM voltage in the cable when the central conductor is on the axis of the cable.

A local B-field at the cable does **not** induce a CM current. For this current the total flux through the CM circuit should be considered, as well as the total impedance of the CM current loop.

B.5.3 Shielding against EM-waves

Generally, a coaxial cable is laid close to large metal surfaces in installations. Impinging EM-waves are strongly modified by reflections. The outer conductor of the cable is just one of the earthed conductors. Current is induced in the outer conductor; coupling to the DM circuit is described by Z_t. Electric field lines end on the outer conductor of the cable predominantly perpendicularly; some E-field lines may pass through the holes in the outer conductor and induce a DM current. Again, the coupling via Z_t is often predominant.

B.5.4 Emission of EM-waves

The emission by a coaxial cable is described accurately by a two-step process: first the DM circuit couples via Z_t to the CM circuit, here the outer conductor. The CM circuit or outer conductor then acts as an antenna. Unwanted emission can be prevented by either reduction of the two transfer parameters, or by increasing the impedance for the CM current, for instance by ferrite beads around the cable. As an alternative, the layout of the CM circuit can be changed in such a way that circuit becomes a poor antenna. Proper application of metal in the vicinity of the cable also helps.

B.6 Coupling to two-lead cable without shield

B.6.1 E-fields

E-field lines ending on a two-lead cable cause (displacement) current through both leads. Figure B.8 shows an equivalent circuit diagram. For a symmetrical position of the leads with respect to nearby earth, the currents I_{int} in both wires are equal. Twisting the leads also helps to distribute the currents more evenly over both leads.

The CM and DM disturbance voltages at both ends of the cable depend on:

a) the impedances at both ends of the cable;

b) the capacitance between the leads;

c) whether the circuit is balanced or not.

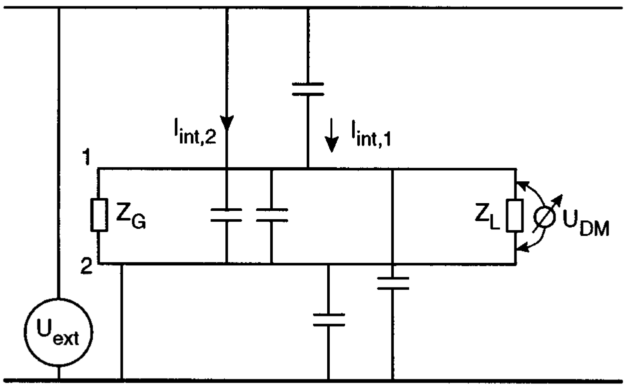


Figure B.8 – A two-lead cable perturbed by a nearby lead at the voltage U_{ext}

The DM disturbance voltage $U_{DM,dist}$ is zero for a perfectly balanced termination. As mentioned before, such a balance is nearly impossible to obtain over a broad frequency range. For an unbalanced termination with one lead earthed, $U_{DM,int}$ is given by the following equation (B.5):

$$U_{DM,int} = U_{ext} \cdot Y'_t \cdot \ell \cdot Z_{par} \tag{B.5}$$

with Z_{par} the impedance of the source, and the load in parallel (see also figure 18). In addition, the current I_{int} through the earthed lead may induce a second order DM voltage through the Z_t.

B.6.2 B-fields

B-fields perpendicular to the plane of the leads result in a magnetic flux between the leads. Twisting both leads forms a series of small areas with opposite flux in the DM circuit loop; the total flux in the DM circuit is reduced.

The two leads may be unevenly twisted; in the extreme case one lead spirals around the other straight lead. A flux-capturing area is then formed for B-fields parallel to the line; this causes a DM induction voltage not present for the untwisted or evenly twisted cable.

B.6.3 Coupling with EM-waves

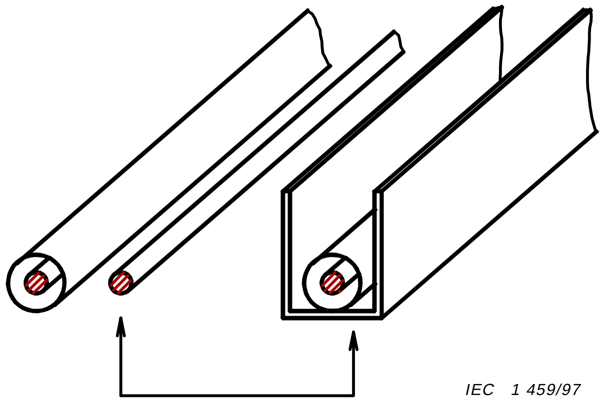
The balanced two-lead cable is a poor antenna with respect to I_{DM}, even up to frequencies above 100 MHz. Unbalance may occur over the length of the cable or at both ends of the cable; this unbalance causes a conversion of DM signals to CM, and vice versa. For I_{CM} the cable is often an effective antenna, regarding both emission and reception. This antenna can be made less effective by nearby metal, as discussed for the coaxial cable in B.3.

Annex C
(informative)

Benefits of additional conductors parallel to a cable

C.1 General

The parallel-earthing conductor (PEC) has already been proposed in 7.3 and 7.5. The purpose of the PEC is to reduce the CM current through the leads that also carry the DM signal (see figure C.1). In fact we now have two circuits outside the DM circuit. One is the intermediate circuit between the PEC and the cable proper. The second one is the large CM circuit outside the PEC.



Left: A coaxial cable with a parallel lead in order to divert some disturbance current from the cable proper. When the outer conductor of the cable and the parallel lead are of comparable size, and are connected to each other at both ends, a HF disturbance current is shared by the outer conductor and the parallel lead in about equal amounts.

Right: Coaxial system in conduit. The CM current flows through the conduit, as described according to figure C.2.

Figure C.1 – Coaxial cables with parallel-earthing conductors

The PEC is always connected to the local earth at both ends. The PEC may be, in order of decreasing transfer impedance: a parallel wire, a flat plate, a conduit, a (second) braid, a solid wall tube (see figure 18). The parallel lead and the solid wall tube are the equivalent of the DM circuits described in B.2.1 and B.2.2, where the signal lead is replaced by a cable. Equivalent expressions for the overall transfer admittance are given by (Vance, 1976 [6]).

C.2 Examples of additional conductors

C.2.1 Coaxial cable with two outer conductors

We consider a coaxial cable with two solid outer conductors at some distance around each other with air separation (figure C.2). The two outer conductors are interconnected at both ends of the cable.

For a description, we proceed along the same lines as in B.1. Two circuits are present outside the DM. The intermediate IM circuit is now well defined. The external circuit is the large (CM) circuit originally present, but now modified by the PEC. The coupling between the IM circuit and the CM circuit is given by the Z'_t of the PEC. The CM current flows through the conduit. Some disturbance current IIM flows through the cable outer conductor, in the intermediate loop formed by that outer conductor and the conduit. The current I_{IM} in the cable shield becomes, according to (C.1).

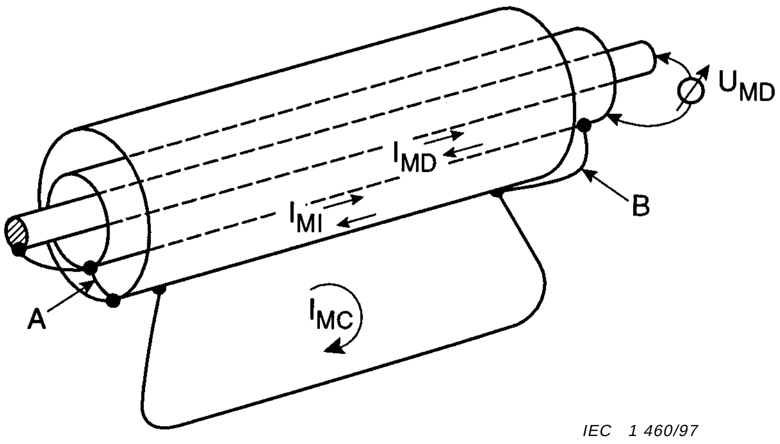
$$I_{IM} = I_{CM} \cdot Z'_{t,PEC} \cdot \ell / Z_{IM} \quad \text{(C.1)}$$

with $Z'_{t,PEC}$ the transfer impedance of the PEC, and Z_{IM} the impedance of the IM loop. In a good approximation the overall transfer impedance Z'_t is given by equation (C.2):

$$Z'_t = Z'_{t,PEC} \cdot Z_{t,IM} / Z_{IM} \quad \text{(C.2)}$$

with $Z_{t,IM}$ the transfer impedance between the IM and the DM circuit. The current I_{IM} is smaller than I_{CM} when the transfer impedance of the conduit ($Z'_{t,PEC}$) is smaller than the impedance of the IM loop (Z_{IM}). This condition can easily be satisfied for usual conduit shapes and cable positions. The impedance Z_{IM} of the IM loop can be selected at will by proper application of air spacing, ferrite, iron, or mu-metal; it will vary with the application (see Vance, 1976 [6]).

The total transfer impedance is to a good approximation given by equation (C.1). The impedance Z_{CM} may now be written as $R_1 + R_2 + j\omega \cdot L$, where R_1 and R_2 are the resistances of the two conductors and L describes the magnetic flux between the inner and outer conductor, all three parameters as seen by the inside CM current loop. A calculated example is shown in figure B.2. Both resistances and inductance may be enhanced by ferrite or mu-metal placed in the CM loop as mentioned in clause 8. Such cables are commercially available as “low EMI” or “superscreen” cables. Note that already at low frequencies (several kilohertz) inductance rather than the resistance determines the current flow even with an air spacing. Coaxial cables with three outer conductors can be discussed following the same line of reasoning.



NOTE – In a coaxial cable with two outer conductors, there are currents in the three circuits (DM, IM and CM), as indicated. The two outer conductors are connected at the ends A and B.

Figure C.2 – Coaxial cable with two outer conductors

C.2.2 Balanced two-lead cable in an outer conductor

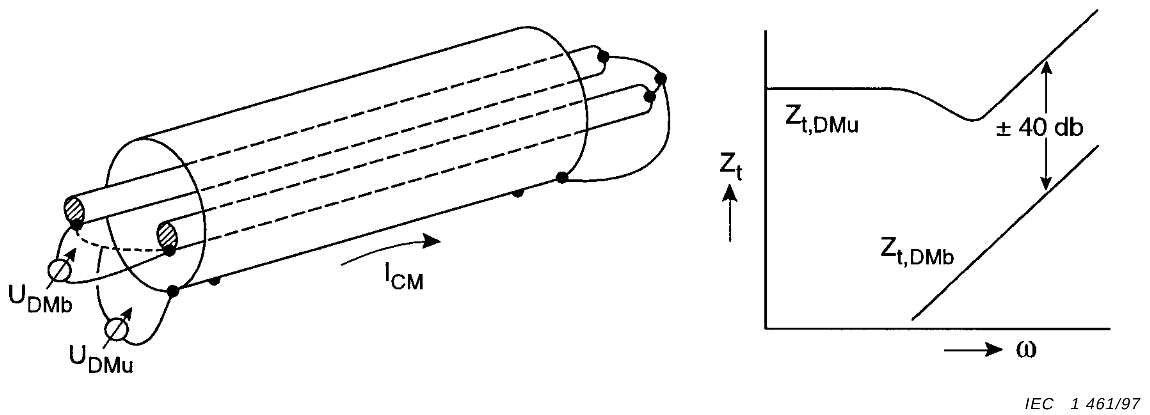
A low-frequency example is a balanced microphone cable (see figure C.3). Inside the shield two differential modes exist, a balanced mode (DMb) between the two leads and an unbalanced mode (DMu) of both leads in parallel with the shield as return. The two important voltages are U_{DMb} between the two leads, and U_{DMu} between both leads and the outer conductor. Consequently there also are two transfer impedances, describing the coupling between the CM current through the outer conductor, I_{CM}:

$Z_{t,DMb}$ describing the disturbance term in U_{DMb} caused by I_{CM} and

$Z_{t,DMu}$ for the corresponding disturbance term in U_{DMu}.

The behaviour of both Z_t is sketched in figure C.3. The $Z_{t,DMu}$ behaves similarly as the Z_t for a single lead in an outer conductor, see curve d in figure B.2. The $Z_{t,DM}$b lacks a resistive part; the inductive part is substantially lower than that for $Z_{t,DMu}$, with some care in the construction –40 dB can be obtained. Actual values for $Z_{t,DMu}$ depend strongly on the construction of the cable and on its history, way of mounting etc. Therefore, no absolute scales are given in figure C.3.

For a floating DM circuit, that is, not earthed at either end, as used for instance in some audio circuits, the voltage U_{DMu} is shared by the interruptions at both ends.



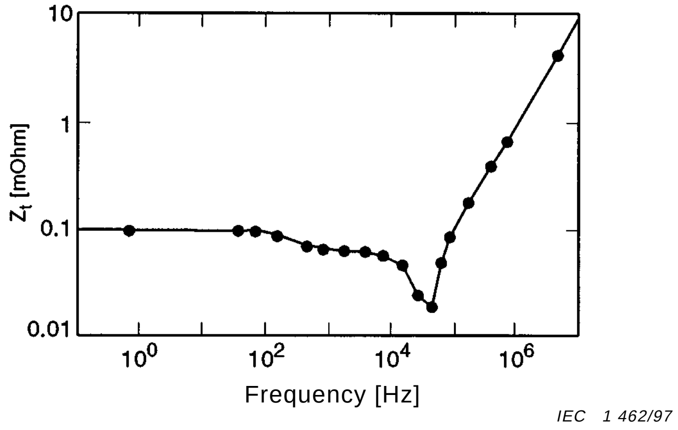
Left: A balanced two-lead cable in a shield

Right: The transfer impedance with respect to both differential modes

Figure C.3 – Transfer impedances in a shielded balanced pair

C.2.3 Conduits as parallel earthed conductors

The calculated Z_t for a general conduit is shown in figure C.4 (van der Laan, 1993 [12]). The dimensions of this aluminum conduit are: height h equal to twice the width, that is, 9 cm (see also figure C.5). The wall thickness is 1 mm. The measuring lead is at 0,75 mm above the midpoint of the bottom of this conduit. A copper conduit has a slightly lower d.c. resistance. A steel conduit of the same size has a higher d.c. resistance, but its $|Z_t|$ already drops at a lower frequency than for an aluminum or copper conduit when the steel has a high μ_r. In addition, steel provides a damping due to the skin effect for the IM currents inside the conduit and for external currents. Steel conduits are the preferred type.

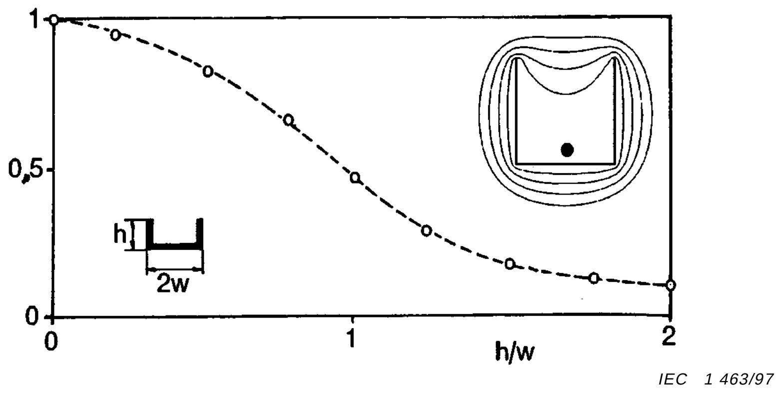


NOTE – The Z_t per metre, for a 1 mm thick aluminum conduit with height h = twice the width, that is, 90 mm, with a measuring lead at 0,75 mm above the middle of the bottom. The dots are the calculated values. The line is a guide to the eye. Below 100 Hz the Z_t is equal to the d.c. resistance. Above 100 Hz the current concentrates at the edges of the conduit, and Z_t is reduced. At about 7 kHz the skin effect becomes important; above 40 kHz Z_t is dominated by a M' = 150 pH/m for this conduit and cable position.

Figure C.4 – Example of transfer impedance for an aluminum conduit as a function of frequency

For conduits the M' part barely depends on the material, but strongly on the shape. In figure C.5 (van Houten, 1990 [9]) the variation of M' as function of width over height ratio is given. The factor *g* represents the ratio between the M' part of Z_t for a conduit and the M' part for a flat reference plate. In this comparison each conduit with its proper (2 × h + 2 × w) is made by folding a flat plate of same material thickness and constant total width. The current I_{CM} is also kept constant. Deep conduits are preferred because of their low M'.

At a fixed height, the M' part also depends on the position of the cable on the bottom. Near the corners the magnetic fields decreases, as is shown in the inset in figure C.5; the M' part of Z_t decreases accordingly.



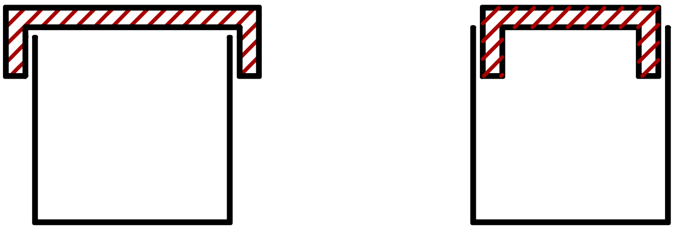
NOTE – The curve shows the mutual inductance M for a conduit, normalized with respect to that for an unfolded plate of the same dimension [2 × h + 2 × w]. The inset shows several magnetic field lines for a conduit with dimensions h = 2 × w.

Figure C.5 – Mutual inductance and magnetic field for a conduit or cable tray

C.2.4 Covers on a conduit

A good cover meets the same requirements as the conduit proper: a contiguous structure, connected in a well conducting way to the conduit at least at both ends. A cover with many contacts, such as by metal springs over the full length, is preferred.

When an easy access to the cable is also required, an insulated cover may also be employed, at the cost of an increased transfer impedance. The overlap between cover and conduit is important. An inside cover is preferred, as it results in a factor 2 lower M' of the conduit and cover (van Houten, 1990 [9]).



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NOTE – For EMC, inside covers are preferred because of the lower value of the mutual inductance component M'.

Figure C.6 – Insulated covers over a conduit

C.2.5 Resonances in the common mode loop

With a PEC, the IM circuit is made compact. Resonances in the transmission line thus formed may enhance the IM current in case of harmonic interference, and thereby increase the effective coupling of the cable into the DM circuits. A first remedy would be to short circuit the IM circuit at short irregular intervals. This increases the resonance frequencies, but lowers the Q-factors because of damping by the skin effect. The irregular structure also inhibits travelling waves in the IM circuits. A second remedy is to provide damping by resistors, or by providing absorbing ferrite around the cable in the PEC.

Annex D
(informative)

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