Electromagnetic compatibility : part 5, installation and mitigation guidelines, section 3, cabling and wiring

tu/e
Research Report
ISSN 0167-9708
Coden: TEUEDE

Eindhoven
University of Technology
Netherlands

Faculty of Electrical Engineering

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by
A.P.J. van Deursen

EUT Report 93-E-275
ISBN 90-6144-275-3
July 1993

Eindhoven University of Technology Research Reports

EINDHOVEN UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering
Eindhoven, The Netherlands

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CIP-DATA KONINKLIJKE BIBLIOTHEEK, DEN HAAG

Deursen, A.P.J. van
Electromagnetic compatibility : part 5, installation and mitigation guidelines, section 3, cabling and wiring / by A.P.J. van Deursen. - Eindhoven : Eindhoven University of Technology, Faculty of Electrical Engineering. - Fig. -
(EUT report, ISSN 0167-9708 ; 93-E-275)
With ref.
ISBN 90-6144-275-3
NUGI 832
Subject headings: electromagnetic compatibility / electrical installation.

Electromagnetic Compatibility.
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Prologue

Electromagnetic Compatibility guidelines are presented for the installation of cables and wires between electrical equipment. With these guidelines, an installation can be designed to operate correctly even in an environment with intense electromagnetic disturbances, such as in high voltage substations or in case of lightning protection. Similarly, cables and wires can be protected when high reliability is required, such as e.g. industrial installations, airplanes or hospitals. Appropriate measures can also be established for situations with less intense disturbances.

This report is under discussion in the IEC Technical Committee 77, Electromagnetic Compatibility, WG 2. It has been circulated once for comments by the national committees of the countries which are member of the IEC. The comments received are included in the text. Two other documents written by other members of TC77/WG2, which deal with general EMC aspects of installations (IEC-1000-5-1) and with earthing and bonding (IEC-1000-5-2) were circulated simultanuously.

The author acknowledges the contribution of members of the group EHC, prof. P.C.T. van der Laan, M.A. van Houten and M.J.A.M. van Helvoort and of F. Martzloff, National Institute of Standards (USA) and P. Guillery, Electricité de France.

Keywords: electrical installation, EMC, cabling, protection, grounding.

- Deursen, A.P.J. van
Electromagnetic Compatibility. Part 5, Installation and Mitigation Guidelines. Section 3, Cabling and Wiring.
Faculty of Electrical Engineering, Eindhoven University of Technology,
The Netherlands, 1993, EUT Report 93-E-275.

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ELECTROMAGNETIC COMPATIBILITY (EMC)

Part 5: Installation and mitigation guidelines

Section 3: Cabling and Wiring

1 Scope

This section of IEC 1000-5 is concerned with the selection, installation, and connection practices for cables used in industrial, commercial, and residential installations. These cables are those 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. Cables serving outward telecommunications, or power cables on the utility side of the point of common connection are not included in the scope, as they are dealt with by the appropriate authority.

The recommendations presented in this section address the concerns of electromagnetic compatibility (EMC) 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. As each installation is unique, it is the responsibility of the designer and the installer to select the relevant recommendations most appropriate to a particular installation.

This document does not contain prescriptions for the type of cable to be used in a particular application. It rather presents a line of thought by which a cable can be selected. In addition, this section provides general considerations on the coupling between the differential mode and the common mode circuits. Subsequent clauses provide a set of EMC rules for cabling and wiring methods aimed at mitigation of interference, routing and bundling of cables, and connections to the ports of equipment. Some test methods are mentioned. These rules do not seek to preclude existing installation practices, when they have shown to perform satisfactorily, but aim rather to complement them. The rationale for the approach, more detailed considerations such as the coupling with external electric and magnetic fields, a special cabinet in which all recipes of this document are applied, and a bibliography are provided as informative annexes.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this section of IEC 1000-5. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this section of IEC 1000-5 are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

[Editor's note, not part of the standard: For the information of reviewers and placing the present document in its ultimate context, the following list contains documents currently under development; some of them may be published simultaneously with the present document while other may follow shortly thereafter. The IEC Central Office will be consulted at the time of final editing on the appropriate procedure for listing these references.]

IEC 50(161) International Electrotechnical Vocabulary - Chapter 161: Electromagnetic Compatibility

IEC 1000-2-x [List of appropriate environment documents will be added]

IEC 1000-5-1 General introduction to EMC of installations

IEC 1000-5-2 Earthing and bonding

IEC 1000-5-4 Shielding

IEC 1000-5-5 Filtering

IEC 1000-5-6 Protective devices

IEC 1000-5-7 Protection against ESD

Note that other documents are cited in brackets as B[identification, year] and are listed in the Bibliography of Informative Annex A4 includes documents that were used in developing the present text, documents cited in support of a recommendation, and documents suggested as reference for complementary information.

3 Definitions

The terms used in this document follow the definitions provided in IEC 50, International electrotechnical vocabulary (IEV), in particular Chapter 161, Electromagnetic compatibility. Terms frequently used in this document and listed in IEV 161, or new terms, are defined as follows:

apparatus (new)
A finished combination of devices (or equipment),with an intrinsic function intended for final user and intended to be placed on the market as a single commercial unit.

common mode (CM) circuit (new)
The full current loop or closed circuit for the CM current, including the cable, the apparatus, and the nearby parts of the earthing system.
Note: A part of this current loop is well known, and consists of the apparatus and interconnecting cables. The rest of the CM current loop may be less well determined, as it consists of the nearby earthing system, local parasitic capacitances etc.

161-04-09 **common mode voltage**
asymmetrical voltage
The mean of the phasor voltages appearing between each conductor and a specified reference, usually earth or frame.
Note: For the purpose of this document only the value of the CM voltage is important when measured over an interruption of the CM current loop. Sometimes the ambiguous term longitudinal voltage is used also.

differential mode (DM) circuit (new)
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. Instead of differential mode, the terms normal mode and serial mode are used sometimes.

161-04-08 **differential mode voltage**
symmetrical voltage
The voltage between any two of a specified set of active conductors.

Note: For the purposes of this document, only the value of the DM voltage is important when measured between the two terminals at a port of an apparatus.

earthed conductor, parallel to a cable (ECP) (new)
A conductor parallel to a cable, connected at both ends to the local earth, frame or reference.

port (new)
A place of access to a device or network where energy may be supplied or withdrawn, or where the device or network variables may be observed or measured.

Notes
1. At each place of access, a separate port is assigned to each significant independent mode of propagation.
2. In any particular case, the ports are determined by the way the device is used and not by its structure alone.
3. A terminal pair is a special case of port.
4. The housing of an apparatus is the enclosure port.

transfer impedance Z_t (new)
A parameter which describes the coupling between the CM current and the DM circuit; different localised contributions stem from the cable proper and from the apparatus.

4 General considerations

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 (EM) 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 the apparatus without observing recommended procedures. The ports of the apparatus 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 EM environment, by means of a carefully selected cable, properly routed, and properly connected to the apparatus. This approach can be used to optimize EMC but will require observance of EMC principles such as those defined in this document.

Actually, EMC can be obtained in a number of different ways. It is not possible to present a unique, single solution. Therefore, this section of IEC 1000-5 provides guidelines and a broad range of general recommendations. Conformity with these general guidelines and recommendations will enhance the EMC performance of the installation.

4.1 Basic considerations

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:

- which may be concentrated in certain frequency bands or (quasi-) continuous wave (CW) signals; power delivered as d.c., a.c. 50 or 60 Hz is considered as equivalent to a signal. Furthermore, one has signals in the audio frequency band, which may also be extended to a few MHz as e.g. for high-speed telephony (ISDN); video signals and high-frequency (h.f.).
- 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, e.g. thermocouple signals (μV range), computer outputs (< = 24 V range); a.c. power e.g. between 110 and 250 V.

b) the type of disturbances to be expected

- CW, burst, pulse, lightning and lightning-induced, power faults; the type and severity depend on the application and the installations in the environment;

c) the type of apparatus to be connected

- the characteristics of the ports: impedance for differential mode (DM) and for common mode (CM); termination of h.f. 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, CW and pulse.

The requirements for the acceptable disturbance level at both ends of the cable must be established. The cable or wiring should not degrade the intended operation.

It is stressed that only a statistical confidence level can be obtained. The total installation determines what amount of disturbances is acceptable. In critical installations (e.g. 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 is 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 preferred to have a technically competent person or a legal body with sufficient authority responsible for the EMC-design at all times, to ensure the maintenance of the selected EMC-approach.

4.2 Differential and common mode circuit, transfer impedance Z_t

A simple model, which will be used throughout the document, 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 youngsters, may not be familiar with the material. More information on the subject is presented in annex A1 and in the bibliographic references (annex A4).

Strictly spoken, the model is only valid at low frequencies, for which 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 rather become even more necessary.

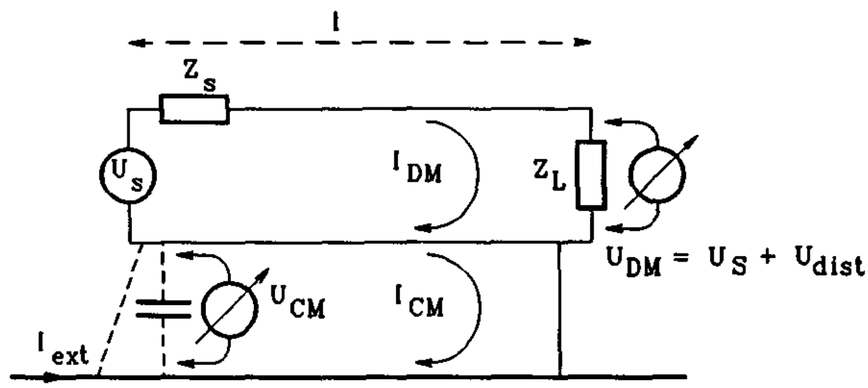


Fig. 1: Two leads interconnect a signal source (signal voltage U_S, output impedance Z_S) and a load with impedance Z_L. The leads, source and load make up the differential mode (DM) circuit. For sake of simplicity, it is assumed that Z_L is much larger than Z_S. The DM voltage over the load U_{DM} is important; U_{DM} consists of some fraction of the generator output U_G and an 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 h.f. through capacitances, deliberately put there or parasitic; some voltage U_{CM} may appear over this capacitance. The CM current proper can be driven by an external current I_{ext} or by an external magnetic flux through the CM loop.

The two circuits

A signal source (output impedance Z_S) is connected to a load (impedance Z_L) by a cable of length ℓ (Fig. 1). Any signal connection involves at least two leads, signal and return between apparatus; 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.

In addition, the two leads always form a second circuit which closes in the outside world. This *common mode* (CM) circuit consists of one or both leads, the apparatus and the nearby earth. The earthing system discussed in document IEC 1000-5-2 forms a part of the CM circuit. Even without any conductive continuity, the CM circuit is present and closes through local capacitances (placed there purposely, or parasitic) between the cable, the apparatus and earth (see Fig. 1). The current I_{CM} stems from sources such as:

- resistive 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} (e.g. lightning and power faults) or external sources as transformers, transmitters or other disturbances generating apparatus.

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

- the type of cable, e.g. two parallel leads or a coaxial cable,
- the electrical connection at both ends, unbalanced or balanced, and both impedances for DM and CM.

See annex A1.1 for more information.

The coupling between the circuits

The coupling between the CM and DM circuit causes disturbances in the DM circuit. The coupling is described by two parameters, transfer impedance Z_t and transfer admittance Y_t. Separate contributions to Z_t stem from a) the cable or leads, distributed over the entire length, and b) the terminal connections at each apparatus.

In the l.f. approximation, the disturbance contribution to the total DM voltage U_{dist} at the load due to the current in the CM circuit I_{CM} reads:

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

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 $Z_L/(Z_L+Z_S)$.

The transfer impedance of a cable is often specified per unit length, Z'_t. At low frequency, the total Z_t becomes $Z'_t.\ell$ 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 e.g. B[Vance, 1976].

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, one has to reckon with intense CM current over a broad frequency range. 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 the Introduction document IEC 1000-5-1 are unintentional ports, and may form a part of the CM loop as well. 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, $Y_t=\omega C_t$. The Y_t is described in some more detail in Annex 1.4. The coupling via Z_t is often more important. For instance, for a coaxial cable with a solid outer conductor (OC) Y_t is zero at all frequencies, whilst Z_t approaches the resistance of the OC 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 generalised 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, one has to sum or to integrate the local contributions.

The two transfer parameters also describe the disturbance coupling in the other direction, DM to CM; i.e. they are reciprocal. Similar parameters represent the coupling between two adjacent DM circuits, e.g. 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 document. The current I_{CM} through the signal cable proper can be reduced by rerouting this current via a parallel conductor (clause 7). 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 13.

Cables also interact with EM-fields; the guidelines in this document aim at a low Z_t with respect to currents in nearby earthed conductors. A low Z_t implies a low interaction with EM fields (see also annex A1.4).

5 Set of EMC rules

The guidelines of this document are derived from the following set of EMC rules. Conformity with the rules will decrease susceptibility and will increase immunity for disturbances simultaneously. While this section of 1000-5 cannot be presented as a mandatory standard, as discussed in clause 4, the rules presented here should be regarded as desirable goals and, therefore, are worded as such.

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 clause 4.1 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 stems from the coupling between the DM and the CM circuit via Z_t and Y_t.
>
> Cables are often large and effective antennas, 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 airconditioning system. As discussed in "Earthing and bonding" document 1000-5-2, even a short stub may act as a h.f. 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 bifilar 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 (i.e. high Z_t) connector ruins an otherwise good cable. The lay-out of the connection and the lay-out in the apparatus has large influence on the overall Z_t and on the EMC quality. Shields are preferentially *circumferentially* connected to well conducting surfaces, e.g. cabinet walls, at the point where the cable enter. Pigtail connections (see also clause 12.2) there are certainly not recommended.

c) Keep DM circuits close to earthed elements.

> Actually, for EMC one requires a low transfer impedance of the current through the earthed element 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 document.

d) Earth loops are allowed.

Earth loops are effective mitigation measures against interference caused by currents and EM fields from e.g. external sources. A CM current through an earth loop consisting of a parallel earth conductor is perfectly acceptable, provided that the transfer impedance of that loop with respect to nearby DM circuits is low. More details on earthing systems are presented in section IEC 1000-5-2.

e) A conductor, earthed at least at both ends, should be installed parallel to the cables between apparatus.

This earthed parallel conductor (ECP) should carry the main part of disturbance current I_{CM} and divert this current from the 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 (clause 7 and annex A2).

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 clause 9.4 and 10. 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 ns-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 B[Goedbloed,1990; Benda,1991] is a flat cable for communication between printer and a computer. 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 l.f. power input can be strongly filtered at the point of entrance into the apparatus.

Here the EMC performance should be optimised 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.

6 Types of cables and their use with regard to EMC

For l.f. signal and control, bifilar cables are frequently used. The two leads should be used for the signal and the return.

In case of single or three phase power, the earth lead must be connected to earth at both ends, for safety and for EMC.

In multi-lead cables, each signal conductor should have its proper return (rule 5b) nearby; preferentially the two conductors are 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 ECP. 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 ECP, which should be earthed at both ends. Inner shields or earth leads may also be earthed at one or both ends (see also clause 8).

Signals at h.f. 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 (OC) are used when a low Z_t is required. The OC's may be laid directly over each other, or be insulated with respect to each other. Mu-metal or ferrite between the OC's further reduces the Z_t (superscreen cables). Most often all OC's are interconnected at both ends of the cable, and earthed. In some application the outmost conductor is used as ECP, whilst the OC's 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 nearby proper return. Such cables are preferentially shielded, with the shield properly earthed to the apparatus at both ends.

7 Types of earthed parallel conductor (ECP)

For EMC it is preferred to route a cable along a ECP which is connected at both sides to the local earth of the apparatus. Some examples are mentioned in clause 5 sub e. The ECP should form a continuous, well conducting metallic structure over its full length.

A properly chosen ECP diverts the CM-current from the DM circuit, a cable or its shield. Effectively this reduces the Z_t of the combination ECP and shield. The shape of the ECP strongly influences the h.f. Z_t. In order of decreasing h.f. Z_t are listed: a wire, a plate, a U-shaped conduit, and a shield or a solid tube. Typical values for the h.f. part of Z_t are presented in Fig. 2. At high frequency, the two latter structures provide an electromagnetic separation of the outside and the inside because of the skin-effect.

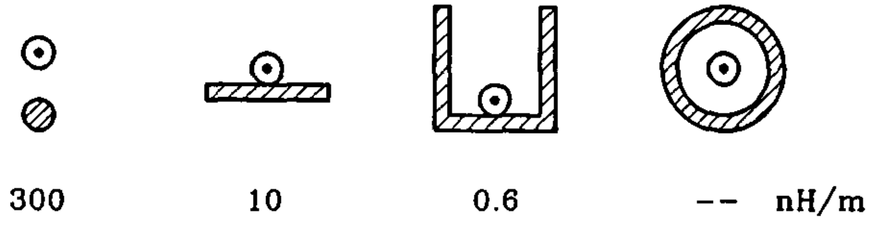


Fig. 2: Several shapes of a earthed conductor parallel to a coaxial cable. Typical values for the Z_t at h.f. are given as mutual inductance M in nH/m. The values of the h.f. Z_t depend on the shape rather than on the total cross-section of the ECP.

More information on the Z_t, in particular on the Z_t of conduits, is given in annex A2.1.3. The final DM disturbance voltage is calculated according to Annex 2.1. Between the ECP and the cable shield an earth loop is formed as an intermediate circuit. The impedance of the loop can be made high by e.g. CM chokes around the cable shield (see also clause 13). 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 ECP 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.

Shields of (multi-lead) cables serve very well as ECP. The coaxial cable is a special case; the outer conductor serves as path for the DM signal and the CM current. More information about coupling of disturbances into coaxial cables is given in annex A1.2.

Note: The term conduit also includes cable trays and trunking where relevant.

7.1 Conduits as ECP

A conduit as ECP 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. Preferentially, the parts are welded over their full perimeter. Riveted joints or screwed joints are allowed, provided that the contacting surfaces are well conducting (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.

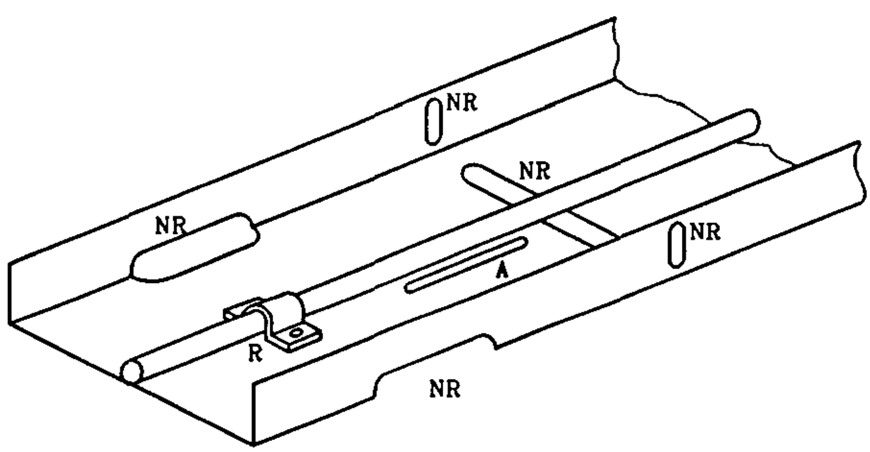


Fig. 3: Slits in a conduit are not recommended at positions and orientation indicated by NR. If, because of some non-EMC requirements, slits are an absolute necessity, the least harmful position is parallel to the axis (A) at some distance of the corners. It is recommended to secure cables by clamps (R) over the cable, screwed to the conduit. The primary EMC goal of these clamps is to electrically connect the cable shield, or other ECP of the cable proper, to the conduit.

Conduits often have slits for easy attachment of cables. The least harmful are small holes (Fig. 3), filled by bolts. A less desirable position of the slits is parallel to the conduit, at some distance of the cables. Long parallel slits perturb the CM current pattern slightly, and produce some but small coupling. 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.

Conduits may have branches (Fig. 4), 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 EMC properly connected at the point of entrance into the conduit. Certainly no cable should enter a conduit directly, without 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.

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 Annex A2.1.1).

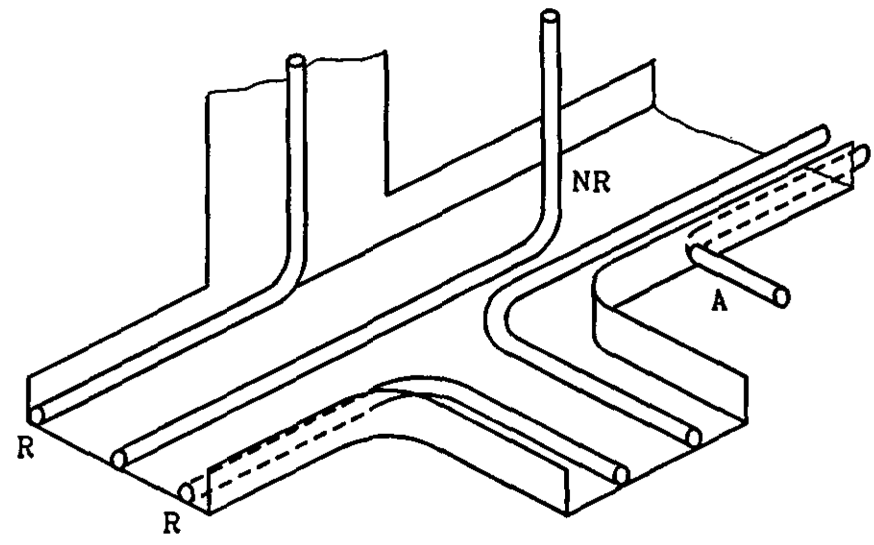


Fig. 4: Recommended conduit with branches, or with a plate leaving the conduit wall. A cable leaving the conduit should have the shield circumferentially connected to the conduit at the point of departure (A, acceptable). No cable should leave the conduit without a well conducting path for its CM currents (NR); compare R in Fig. 3. A shallow conduit is shown for sake of clarity.

Detailed calculations of the Z_t as function of the shape of a conduit (material, width, depth, and wall thickness) are presented in annex A2.1.3. 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 may also be effective at high frequency, as discussed in annex A2.1.3.

7.2 Construction elements as ECP

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 millimetres thick, such beams provide a low Z_t already at powerline frequencies. Cables are preferentially laid against such beams. Inside corners are preferred over the outside surfaces (Fig. 5).

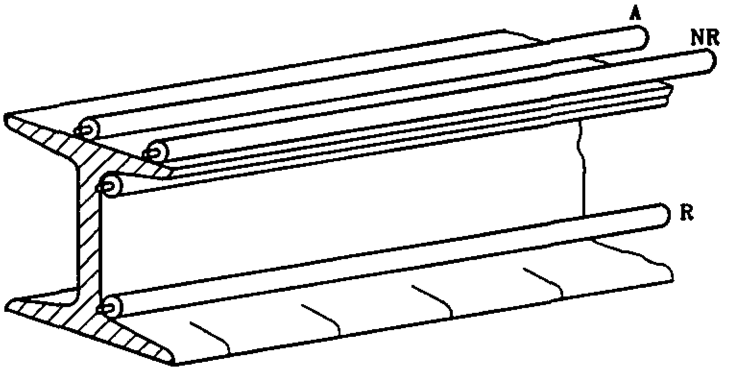


Fig. 5: Recommended cable positions (R) parallel to an H-shaped beam. Less preferred, but still acceptable (A) position, and position not recommended (NR).

8 Connecting and earthing of cables and ECP's

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 an ECP is present, it should always be connected to the local earth (preferentially 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 ECP is earthed via a short connection,
- a plate or conduit as ECP is earthed over the large cross section, their full cross-section preferentially,
- a shield or tube as ECP is earthed over the full perimeter, by appropriate glands or other means.

A pigtail connection (Fig. 6 and 10) at either end of the cable should not be used.

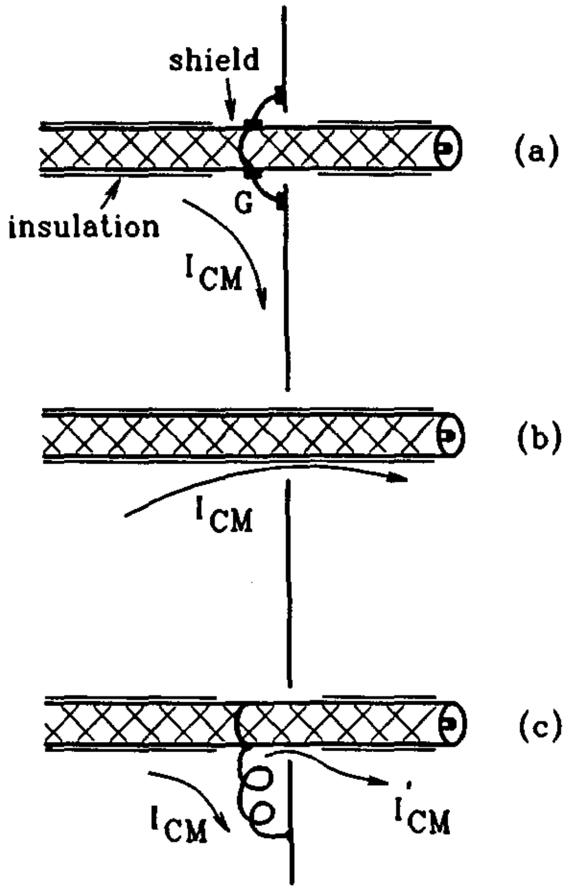


Fig. 6: A shielded cable runs through a metallic wall of an apparatus enclosure or a cabinet. The shield should be connected over its full perimeter to the wall (a) by an appropriate gland (G). A shield should never run through a wall without electrical contact (b). A pigtail connection (c) is not recommended, 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

The main goal of the ECP is to carry the major part of the I_{CM}. When a ECP like 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 l.f.); the CM voltage between the low voltage side and the local earth is limited by the ECP.

For very long distances, additional connections of the ECP 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 ECP. For U-shaped conduits, shields and tubes, the additional earth connections should be made at the outside, preserving the separation with respect to the inside.

The ECP must be designed to withstand large currents when it is used as lightning protection. Also, in heavy industry and high voltage substations, large currents may flow through the ECP in case of power fault. When a cable shield as ECP is not designed to cope with these large currents, the first approach is to route the cable via metallic construction elements, or conduits, which then act as another ECP for the total cable.

An alternative solution can be adopted for the protection against power faults; 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 h.f. 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 an unacceptably high local Z_t.

9 General routing of cables

The routing of a cable should be based on a careful consideration. EMC requirements dictate the path followed, and the design of earthed conductors (ECP's) parallel to the cables, their presence, their connection to the earthing structure, their cross-section and shape. In any case the EMC requirements prevail over practical considerations, or convenience of mounting, or aesthetic aspects. This does not exclude the possibility that those secondary considerations and the EMC requirements are met simultaneously.

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

9.1 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 "Earthing and bonding", IEC 1000-5-2). Cables are preferentially 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, e.g. painted before mounting, or mounted with only few screws. In such cabinets however, vertical or horizontal beams can be used as ECP if the beams are properly earthed.

A shortest connection between two apparatus is allowed provided that a ECP 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 possible in the proper application.

9.2 Routing between cabinets

A cable in combination with a ECP is recommended. As is apparent from Fig. 2, such a ECP may be the protective earth lead in a cable; a shield as ECP offers a better EMC performance. Conduits may run parallel to the cable shields. Both shields and conduit should be connected properly to the cabinet wall: shields over the full perimeter by appropriate glands, conduits over the full cross-section.

9.3 Routing between installations or between buildings

For larger distances between installations, some appropriate form of a ECP is desirable. As discussed is clause 8, additional earth connections to the ECP reduce the disturbance current over the length of the ECP.

Cables are often bundled and carried by metal trays. The metal trays should be (inter)connected to maximise their EMC benefits as well, and treated as a ECP. The trays are connected at least 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 ECP's 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 pipe show a better performance.

Note: 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 for the Z_t, the beams can be regarded as two parallel wires as in clause 7.

9.4 Distance between conduits

Different cable trays or conduits may run parallel over an appreciable distance. The DM to DM cross-talk may become important. The recommended mutual distance between the trays now depends on two parameters, first on their quality as ECP, 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 meet both requirements 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. One has several possibilities:

- **Shielding against the magnetic field.**
  A single shield may surround the one or three phase leads and the neutral. A braided shield seldom provide sufficient shielding at power line frequencies against the local magnetic fields. Additional shielding by the ECP may now be needed, either by the ECP belonging to the power line cables, or by the ECP 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 annex A1.3, see also clause 7).

- **Reduction of the magnetic field by lay-out.**
  The power lead may be equipped with its proper shield, which is 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 strategic position of each shield, rather than due to an actual shielding. Sufficient reduction may already be obtained by a less drastic solution, when the power line cables are placed parallel and close to each other, and are mounted directly against a ECP of sufficient thickness. This mounting diminishes the size of the CM circuit. In addition, in the ECP the mirror image circuit is formed, which reduces magnetic fields at some distance of the power leads. A conduit with a septum (Fig. 7) provides further reduction, when compared to a single conduit.

- **Reduction of the magnetic field by distance.**
  An third option is to keep some distance between (shallow) conduits for the different types of cable. Experience suggests the stacking order as in Fig. 8. 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 preferentially be covered when it is at a distance of less than 1 m from the high-current power cables.

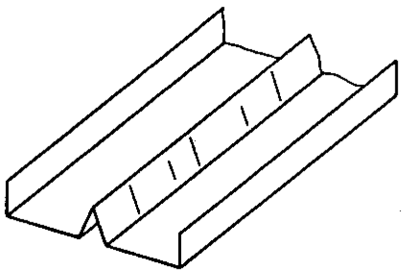


Fig. 7: Conduit with septum.

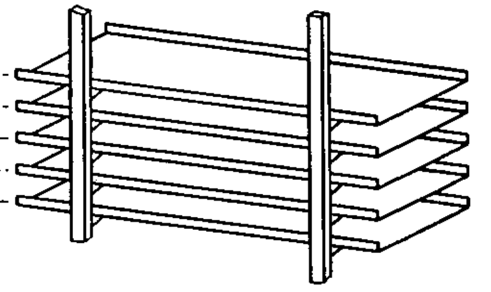


Fig. 8: Example of stacking for conduits or trays containing different types of cable. A minimum distance between the trays is advised of 0.15 m. The trays should be electrically connected at the vertical supports. The conduit for the low-level measuring signals should be covered.

10 Cable bundles

The DM-DM cross-talk between different cables deserves attention. Cables transporting similar signals can often be bundled together. With cables transporting different signals one may differentiate B[Goedbloed, 1990] between cables that are:

very sensitive:	cable that carries low-voltage or low-current signals as from sensors
sensitive	e.g. signalling cable at < = 24 V, flat cable for parallel data transfer
indifferent	a.c. power, e.g. between 110 V and 250 V, depending on the EMC properties of the apparatus connected
noisy	a.c. and d.c. relay feed line without protection measures as filters or diodes
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 never be in the same bundle. Different bundles should be separated electromagnetically from each other, either by shields as ECP, or by placing the cables in different conduits. The quality of the ECP, determines the distance between the bundles (and their ECP's) one should be kept. Suggestions are given in clause 7. Without any ECP one should keep a sufficient distance; experience suggests a distance of 10 times the largest lead cross-section.

In fact one has to balance two sometimes opposing requirements, firstly compact circuits also for CM, which ask for a small distance between the bundles, and secondly 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 thick enough (see also annex A1.3). Braided shields seldom provide any shielding at powerline frequencies. A single conduit may be divided by a septum (one or more, Fig. 7) to form a set of connected, but electromagnetically separated conduits.

Examples:

The input and output line of a filter should never be in the same bundle. The disturbance currents will pass around the filter via other cables in the bundle. For correct mounting of filter see the appropriate IEC 1000-5-5 document.

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-DM coupling occurs also when cable bundles cross at an angle, or perpendicularly. Without any ECP 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.

11 Cables serving power ports

11.1 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 non humid atmosphere. Soldered copper wires are nor allowed under a bolt. Fully soldered connections can be used for low-power/voltage (e.g. < 220 V) applications.

All connections of the power leads should be placed at small relative distance (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 exits for the N- 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 provides 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.

A 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 clause 5 sub e).

When several cables are connected to a cabinet (e.g. containing a power supply), all earth leads are often connected to a earthing rail for convenience of mounting. For EMC purposes, the correct position of this rail is at the outside of the cabinet, or at 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 again.

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 Fig. 6) 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 shielded cable are treated as described before 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 recommended to also connect this type of shield by glands as described above.

11.2 Power switches between apparatuses

Mechanical switches may be placed in a cable, e.g. for lighting fixtures. 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 or a two-contact design. A two-contact switch, for d.c. or single phase a.c., acts on both leads, power and return; the two leads should always be kept close together.

Single contact switches

A compact DM circuit should always be ensured. Preferentially the switched and non-switched lead follow the same physical path (Fig. 9a and c). 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 (Fig. 9b).

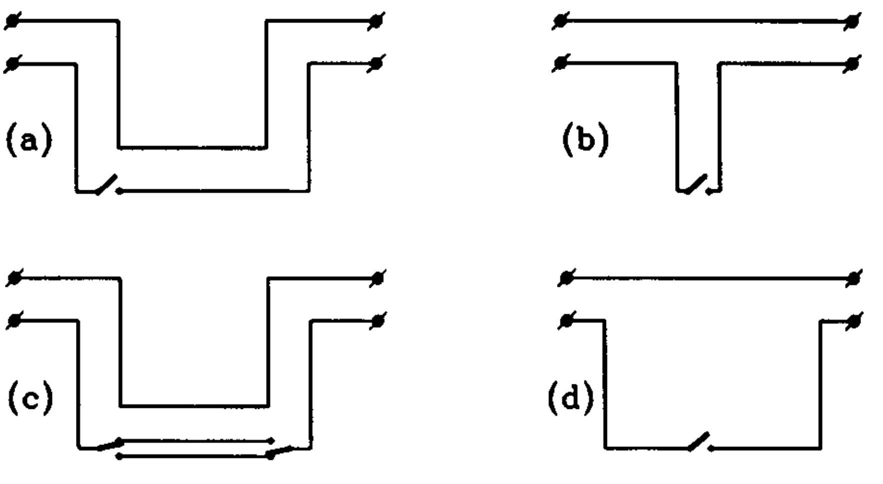


Fig. 9: Several solutions (a,b,c) to keep the DM circuit compact when switches are installed. The lead position indicated in (d) should not be used.

11.3 Routing of power cables

As described in the general routing and bundling clauses 9 and 10.

12 Cables serving signal and control ports

First the reader is referred to the set of EMC rules in clause 5. 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.

It is not possible to give an exhaustive classification for signal and control levels. Not every application can be covered. For l.f. signal, 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 (X.21 and similar signals between 1 and 24 V). Signalling voltages in high power installations are often 42 V or 110 V. High-impedance current loops (4 - 20 mA) are often used to transmit l.f. analog signals.

Parallel data transport between digital equipment (e.g. computer and printers) are a case of intermediate speed. As h.f. signals one has:

> video-signals, internal closed television circuits using h.f. carriers, fast serial data communication using coaxial cables. Cables serving the antennas for mobile communication can in principle also be installed according to the guidelines of this document.

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

Coaxial or multi-lead cables with more than one shield offer a lower transfer impedance. One has the option to interconnect all shields at both ends, or at one end only. A more detailed discussion is presented in annex A2.

Balanced signal transport should be compared to unbalanced transport. Especially at low frequencies, 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, also at frequencies out of the band of the intended signals.

Each signal DM circuit should be given its own return lead (compact DM circuits). This avoids DM-DM coupling between the circuits via a mutual resistance at d.c. and l.f.. Bifilar cables should be twisted in order to prevent inductive and capacitive DM-DM crosstalk at higher frequencies. The transition between lower and higher frequencies here may already occur at a few kHz, or even at power frequency.

12.2 Connectors

Terminals for signal and return should always be in close proximity (compact DM circuits). Contacts should be corrosion resistant; for example, gold surfaces are preferred over silver. Corroded contacts may show highly non-linear current voltage characteristics; distortion of the intended signal and (audio) rectification of h.f. disturbance 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 case of low-amplitude d.c. signals, such as from thermocouple temperature sensors. The connector should match the type of cable. The matching regards the signal, voltage and current level, at high frequency the characteristic impedance is important also. For EMC purposes the matching also regards the transfer parameters, Z_t and Y_t, over the full frequency range where disturbances can be expected, and over which range the electronics is 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.

Bifilar cables with shields should use connectors that allow a circumferential contact for the shield. Pigtails at the end of any shield (Fig. 10) should be avoided in general. 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.

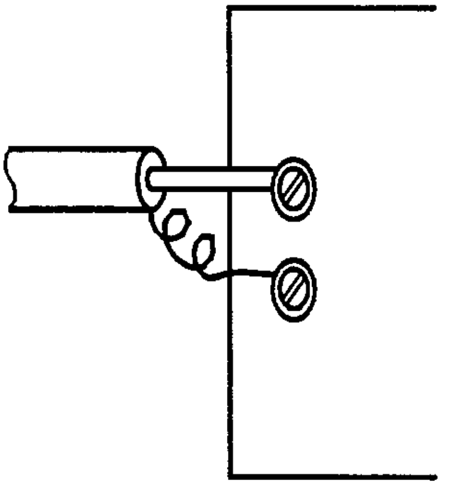


Fig. 10 A pigtail connection at the end of a coaxial cable results in a high local Z_t. Such a pigtail should be avoided as termination of the shield of any of cable, even when it is a short straight wire instead of the coil as shown.

12.3 Routing of signal and control cables

As described in the clauses 5 and 9. Some additional remarks:

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

Twisted-pair leads are often used for l.f. signal and control. They can be bundled; each pair should preferentially be twisted separately. An additional shield again is helpful as described above.

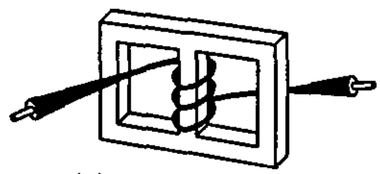
Coaxial cables, carrying h.f. signals, and twisted pairs connected to l.f. apparatus, should not be bundled together. Cross-talk of h.f. signals into l.f. signals may result in additional interference due to non-linear characteristics of the l.f. circuits; h.f. demodulation simulates a d.c. signal, or a l.f. signal when the h.f. signal is 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; 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.

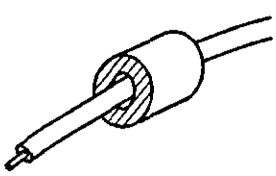
13 Additional interference mitigation methods

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. More information is supplied in the appropriate IEC document 1000-5-5.

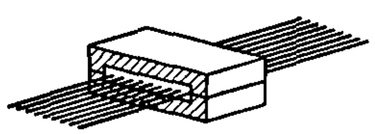
A common mode choke provides a local increase of the impedance of the CM (or IM, see annex A2) circuit, and thereby reduces the CM current (Fig. 11). The CM circuit proper remains present. Whether an effective reduction is obtained, depends on the original impedance of the CM circuit. Ferrite cores or 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. Both transformer and ferrite do not affect the DM signal. A special form of the CM choke is the 'neutralising' transformer, which is sometimes applied in high-voltage substations.



(a)



(b)



(c)

Fig. 11: 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. A ferrite bead around a coax, or a ferrite yoke around a flat cable serve the same purpose.

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 $Z_{CM,rest}$ was already low. This is the case when a earthed conductor (ECP) is in parallel to the cable. Examples are:

- a CM choke or ferrite core around a cable in a conduit;
- ferrite between two shields of a double shielded cable forces the CM current to flow through the outer shield;
- 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.

13.1 Properties of ferrite

Ferrites are magnetic materials, with a permeability μ_r varying over a wide range, between 10 and 10^4. Some conductivity is present; most materials also have a substantial dielectric constant. At low frequencies ferrite provide inductivity; 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.

13.2 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. Such 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 will hardly occur.

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

13.3 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 one employs an isolation transformer, optical fibres, or optocouplers. Provided that some care is taken in their application, these devices can be used for EMC indeed.

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 to be expected. Electrostatic shields between the windings may 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 the parasitic capacitance elsewhere. Again, the full spectrum of possible disturbances should be considered.

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 regards metal 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 highly unexpected, and thereby a source of interference.

Optocouplers

Optocouplers serve the similar goal as isolation transformers. For EMC the parasitic capacitances between the light emitting diode and the phototransistor are important. A h.f. CM current through this capacitance flows through the transistor, and may cause inadvertent switching of this transistor. The leads to the optocoupler may also form a bypass for h.f. disturbances.

14 Measuring and testing methods

The criterion for all guidelines is a low DM disturbance voltage at the ports of the apparatus. When the CM impedance of the port is large, one should 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. One determines first the CM currents along the cables at the position where they are connected to the apparatus. Secondly, the CM currents at locations farther away are measured. This document provides a number of solutions to reroute the CM currents, and thereby reduce the disturbances.

14.1 Testing methods

A number of test are proposed in related EMC documents, such as the 801 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 faithful reproduction of the actual disturbances. Alternatively, the prescribed test can be basis for a commercial or legal agreement between parties.

Informative Annex A1: General behaviour of Z_t for different types of cable

Throughout this section of IEC 1000-5 a generalised 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 behaviour 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 h.f. cables the reader is referred to other documents such as those by IEC TC46.

A1.1 Two parallel leads

Unbalanced DM circuit

In Fig. A1 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 Fig. 1 (see clause 4.2) the connection to earth is made explicitly; other possibilities are discussed in clause 4.1. For this unbalanced signal circuit, one naturally chooses all I_{CM} to flow through the earthed lead. The receiver (with high input impedance Z_L) at the end of the cable sees 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}.

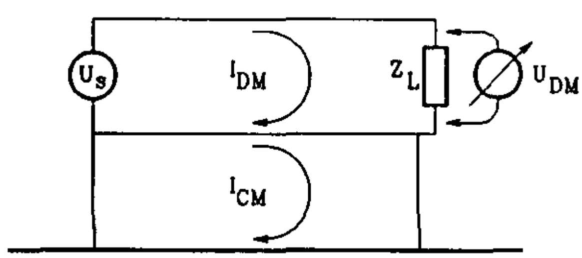


Fig. A1 Unbalanced transport of signals. The DM voltage U_{DM} at the receiving end consists of the intended signal U_S plus an disturbance term U_{dist} caused by I_{CM}, coupled into the DM circuit via Z_t.

Here it is assumed that the apparatus at both ends 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 ℓ of the cable, one may write:

$$\frac{U_{int}}{I_{CM} \cdot l} = Z_t' = R' + j\omega M' \tag{A1}$$

where R' is the resistance of the earthed lead, perhaps increased by the skin effect. The mutual inductance part can be approximated by $(\mu_0/2\pi)\cdot\log(d/r)$ 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 Fig. A2, 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.

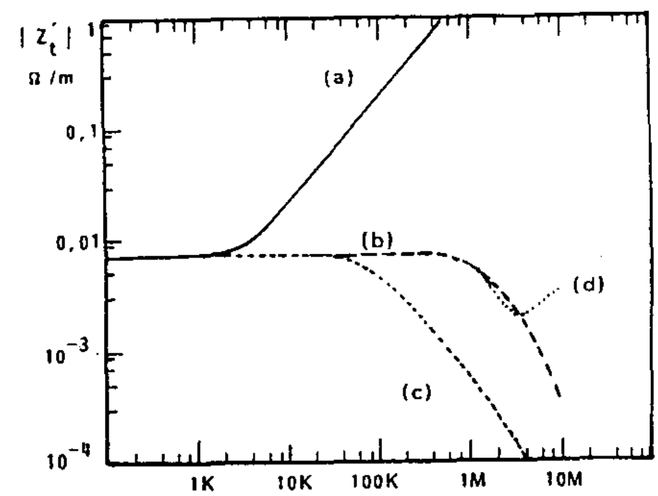


Fig. A2 Sketch of the behaviour of Z'_t as function of frequency for
(a) a two wire transmission line (2.5 mm^2 Cu),
(b) a coaxial cable with solid outer conductor with an assumed radius r = 3 mm and thickness d = 0.13 mm, 2.5 mm^2 Cu,
(c) the OC of (b) split into two OC's at the distance of 1 mm, r = 3 mm and 4 mm respectively, d = 0.056 mm, total 2.5 mm^2 Cu,
(d) the behaviour of the cable in (b) when openings in the OC result in an assumed M' of 50 pH/m.

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, l.f. approximation I_{int} is given by

$$I_{int} = Z_t' \cdot I_{CM} \cdot l / Z_{DM} \tag{A2}$$

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 one observes the fraction

$$U_{int} = Z_t' \cdot I_{CM} \cdot l \cdot \frac{Z_L}{Z_{DM}} \tag{A3}$$

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

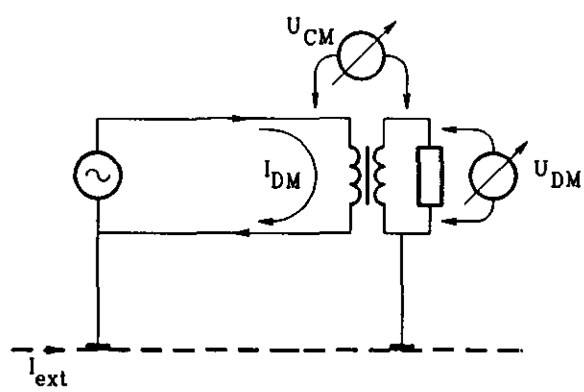


Fig. A3 An unbalanced transmission system, earthed at one end; over the interruption of the CM circuit (represented here by the transformer) a CM voltage develops due to the flux in the earth loop.

As discussed in clause 8 the CM circuit may sometimes be interrupted. Over this interruption a CM voltage develops. It depends on the apparatus (such as the transformer in Fig. A3) 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.

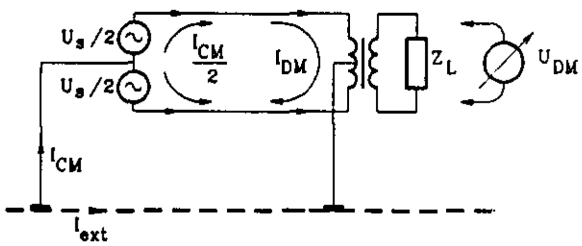


Fig. A4 The balanced system allows a well defined path for the CM current, certainly for low frequencies. Proper care should be taken for the symmetry, along the line, and at both ends of the line, in order to avoid conversion of CM disturbances into DM signal.

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 (Fig. A4). 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 even be used without the need for a ECP.

A1.2 Coaxial cable

A coaxial cable with a *solid* outer conductor (OC) is sketched in Fig. A5. The Z'_t for a thin OC (wall thickness d) is given by B[Kaden, 1956; Schelkunoff 1934]:

$$Z'_t = R'_{dc} \cdot \frac{kd}{\sinh(kd)} \tag{A4}$$

where R'_{dc} is the dc resistance per meter of the OC, $k = (1+j)/\delta$, with $\delta = \sqrt{2\rho/\mu_0\mu_r\omega}$ the skin depth in the OC. The behaviour of this Z'_t is also depicted in Fig. A2.

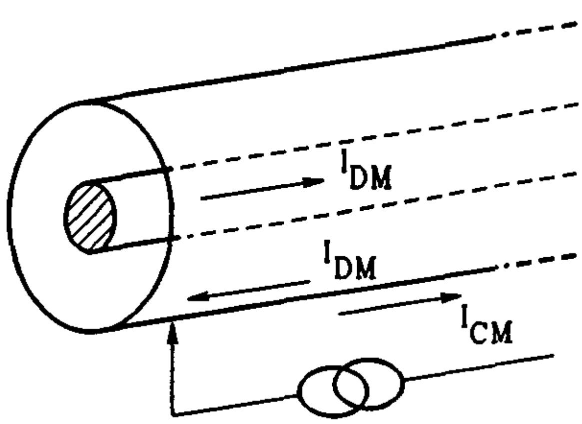


Fig. A5 A coaxial cable. The DM current through the inner lead returns through the outer conductor; the CM current flows through the outer conductor.

The contrasting behaviour, with respect to the two-lead cable, is the *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 OC, the CM current flows mainly at the outside of the OC. The magnetic field caused by I_{CM} is outside the solid OC. Consequently there is no M'-part in Z'_t.

More often an outer conductor is *braided*. The magnetic field due to I_{CM} which was originally outside the OC, now penetrates through the openings, slits, holes, etc., as depicted in Fig. A6. Now a M'-part is present in Z'_t, however generally many orders of magnitude smaller than the one for a two lead cable, down to the 1 nH/m or 1 pH/m level, depending of the type of cable and its OC.

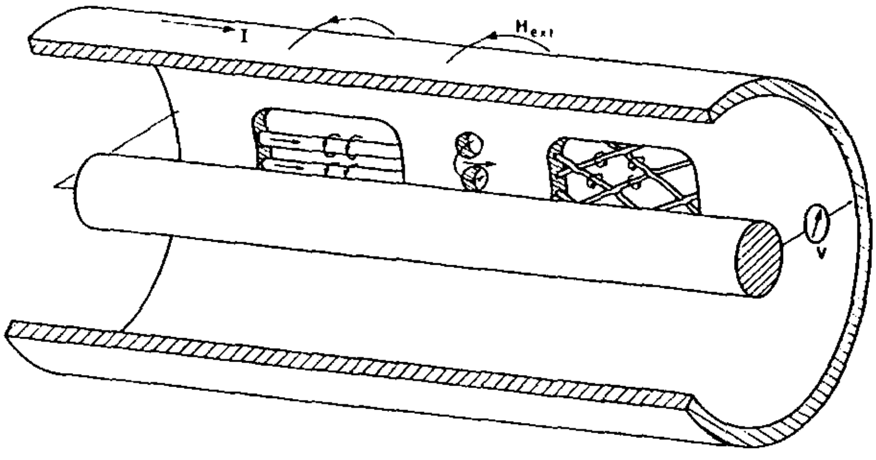


Fig. A6 The magnetic field H_{ext} due to the CM current in the wall of a coaxial system penetrates for some part through the openings in the wall. When a net flux appears in the DM circuit, a DM voltage is generated which can be measured at the end of the cable.

Note that the different behaviour of Z'_t for the unbalanced two lead system and the coaxial system is solely caused by the lay-out of the metal and does not depend on the number of mm^2 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.

A1.3 Shielding against E-fields and B-fields by an outer conductor of a coaxial cable

The outer conductor (OC) has three functions. First, it serves as a return path for the DM current; consequently the OC should always be connected at both ends to the DM circuit. Second, it forms a part of the CM circuit as indicated in clause A1.2. 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.

Shielding against E-fields
A solid metal OC is a very good shield for E-fields at all frequencies. As a source of the E-field one may think of some other lead at some distance of the cable, at some voltage with respect to the OC. By connecting the OC at least at one end to e.g. 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 Fig. A7.

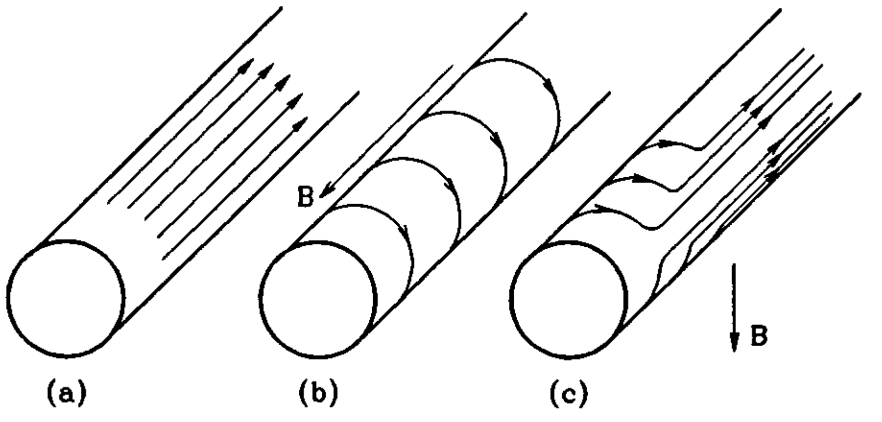


Fig. A7 Currents in the OC of a coaxial cable
(a) Longitudinal currents from earthed end to earthed end (OC as DM and CM circuit element), or arriving at the OC as displacement current, as a result of an external E-field (OC as shield); this latter circuit can be closed by earthing the OC at one end.
(b) Circulating currents on the OC, induced by a longitudinal B-field (OC as shield).
(c) Current pattern induced by a B-field perpendicular to the axis of the cable (OC as shield).

Openings in the OC 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 OC Y_t is zero.

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 OC are shown in Fig. A7b and c. There is no net current induced in the shield. The external fields penetrates a solid OC at frequencies such that $rd < \delta^2$, with r the radius of the OC, and d and δ as given in annex A1.2. For a braided OC, the current pattern is more complex; it results in less shielding. For most commonly used cables with a braided OC and a small product r.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.

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

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 OC. The CM circuit or OC then acts as antenna. Unwanted emission can be prevented by either reduction of the two transfer parameters, or by increasing the impedance for the CM current e.g. by ferrite beads around the cable. As an alternative, the lay-out 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.

A1.4 Coupling to two-lead cable without shield

E-fields

E-field lines ending on a two-lead cable cause (displacement) current through both leads. Figure A8 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 and c) whether the circuit is balanced or not.

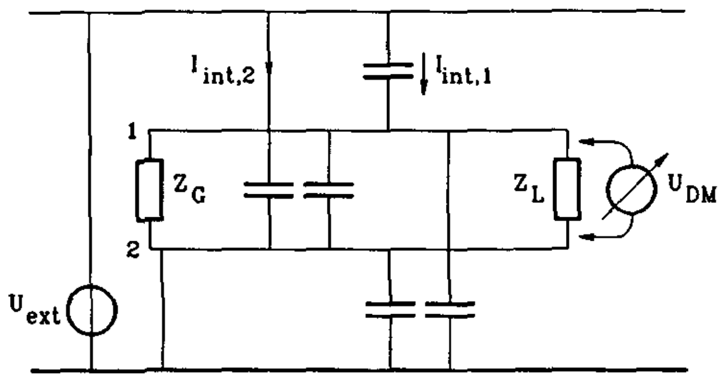


Fig. A8 A two leads cable perturbed by a nearby lead at the voltage U_{ext}.

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

$$U_{DM,int} = U_{ext} \cdot Y_t' \cdot l \cdot Z_{par} \tag{A5}$$

with Z_{par} the impedance of the source and the load in parallel (see also Fig. 2). In addition, the current I_{int} through the earthed lead may induce a second order DM voltage through the Z_t.

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 extremal 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.

Coupling with EM-waves

The balanced two-lead cable is a poor antenna with respect to I_{DM}, even up to frequencies higher than 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 annex A1.3.

Informative Annex A2: Benefits of additional conductors parallel to a cable

The parallel earthed conductor (ECP) has already been proposed in clause 5 and 7. The goal of the ECP is to reduce the CM current through the leads that also carry the DM signal (see Fig. A9). In fact we now have two circuits outside the DM circuit. One is the intermediate circuit between the ECP and the cable proper. The second one is the large CM circuit outside the ECP.

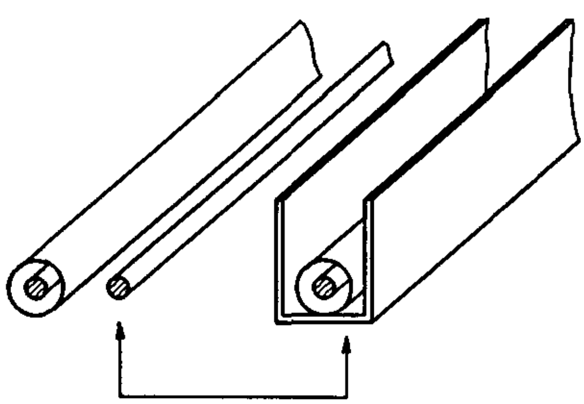


Fig. A9 (left) A coaxial cable with a parallel copper lead in order to divert some disturbance current from the cable proper. When the OC of the cable and the parallel lead are of comparable size, and are connected to each other at both ends, a h.f. disturbance current is shared by the OC and the parallel lead in about equal amounts.
(right) Coaxial system in conduit. The major part of the CM current flows through the conduit.

For a description, we proceed along the same line as in annex A1. Two circuits are present outside the DM (see Fig. A10). The intermediate IM circuit is now well defined. The external circuit is the large (CM) circuit originally present, but now modified by the ECP. The coupling between the IM circuit and the CM circuit is given by the Z'_t of the ECP. The current in the cable shield I_{IM} becomes:

$$I_{IM} = I_{CM} \cdot Z'_{t,ECP} \cdot l / Z_{IM} \qquad \text{(A6)}$$

with $Z'_{t,ECP}$ the transfer impedance of the ECP, and Z_{IM} the impedance of the IM loop. In a good approximation the overall transfer impedance Z_t' is given by

$$Z'_t = \frac{Z'_{t,ECP} \cdot Z_{t,IM}}{Z_{IM}} \qquad \text{(A7)}$$

with $Z_{t,IM}$ the transfer impedance between the IM and the DM circuit. The impedance Z_{IM} of the IM loop can be selected at will by proper application of air spacing, ferrite, iron, or μ-metal; it will vary with the application (see also clause 13.

The ECP is always connected to the local earth at both ends. The ECP may be, in order of decreasing transfer impedance: a parallel wire, a flat plate, a conduit, a (second) braid, a solid wall tube (see also clause 7). The parallel lead and the solid wall tube are the equivalent of the DM circuits described in annex A1.1 and A1.2, where the signal lead is replaced by a cable.

Equivalent expressions for the overall transfer admittance are given by B[Vance,1976].

A2.1 Examples of additional conductors

A2.1.1 Coaxial cable with two OC's

We consider a coaxial cable with two solid OC's at some distance around each other with air separation (Fig. A10). The two OC's are interconnected at both ends of the cable. The total transfer impedance is to a good approximation given by Eq. A6. The impedance Z_{CM} may now be written as $R_1 + R_2 + j\omega L$; here R_1 (R_2) are the resistances of the two conductors and ωL describes the magnetic flux between the inner and outer OC, all three parameters as seen by the inside CM current loop. A calculated example is shown in Fig. A2. Both resistances and inductance may be enhanced by ferrite or mu-metal placed in the CM loop as mentioned in clause 13. Such cables are commercially available as 'low EMI' or 'superscreen' cables. Note that already at low frequencies (several kHz) inductance rather than the resistance determines the current flow even with an air spacing. Coaxial cables with three OC's can be discussed along the same line of reasoning.

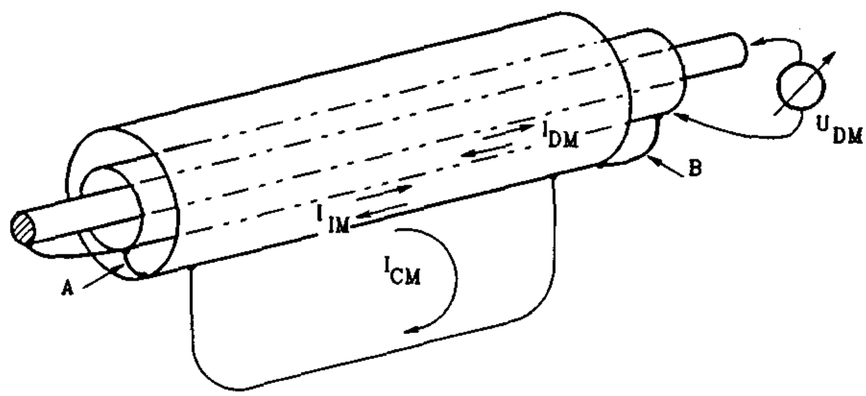


Fig. A10 A coaxial cable with two OC's. Currents in the three circuits (DM, IM and CM) are indicated.

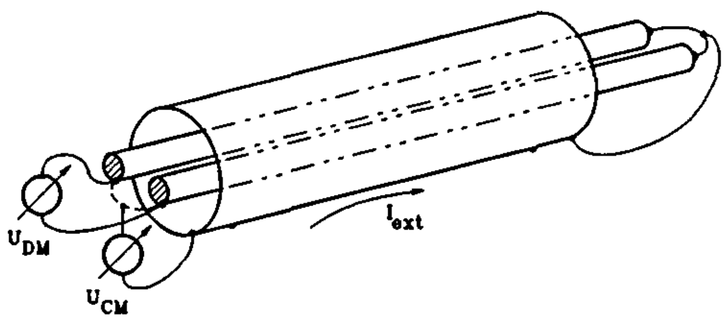
A2.1.2 Balanced two lead cable in an OC

A l.f. example is a balanced microphone cable (see Fig. A11). The two important voltages are U_{DM} between the two leads, and U_{CM} between both leads and the OC. Consequently there also are two transfer impedances, describing the coupling between the current through the OC, I_{ext}:

$Z_{t,DM}$ describing the disturbance term in U_{DM} caused by I_{ext} and
$Z_{t,CM}$ for the corresponding disturbance term in U_{CM}.

The behaviour of both Z_t's is sketched in Fig. A11. The $Z_{t,CM}$ behaves similarly as the Z_t for a single lead in an OC, see e.g. curve d in Fig. A2. The $Z_{t,DM}$ lacks a resistive part; the inductive part is substantially lower than that for $Z_{t,CM}$; with some care in the construction -40 dB can be obtained. Actual values for $Z_{t,DM}$ depend strongly on the construction of the cable and on its history, way of mounting etc. Therefore, no absolute scales are given in Fig. A11.

For a floating DM circuit, i.e. not earthed at either end as e.g. used in some audio circuits, the voltage U_{CM} is shared by the interruption at both ends.



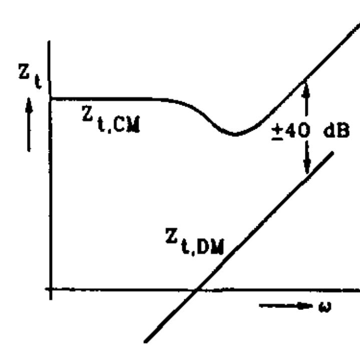


Fig. A11 (left) A balanced two-lead cable in a shield. (right) The transfer impedance with respect to DM and CM.

A2.1.3 Conduits as ECP

The calculated Z_t for a general conduit is shown in Fig. A12 B[van der Laan, 1993]. The dimensions of this aluminum conduit are: height h equal to width 2w, equal to 9 cm (see also Fig. A13); 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 $|Z_t|$ drops already 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, both for the IM currents inside the conduit, and for the external currents outside. Steel conduits are the preferred type.

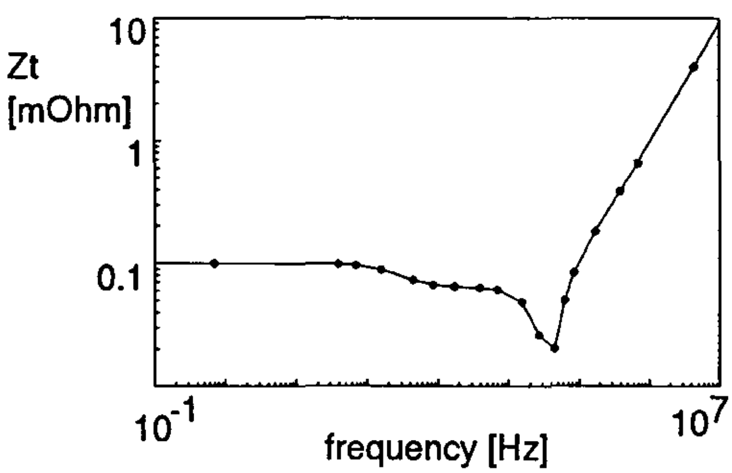


Fig. A12 The $|Z_t|$ per meter, for a 1 mm thick aluminium conduit of h = 2w = 90 mm, with a measuring lead at 0.75 mm above the midst of the bottom. The dots are the caculated values; the line is a guide to the eye. Below 100 Hz the Z_t is equal to the d.c. resistance. Above 100 Hz the current concentrates 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.

For conduits the M'-part depends barely on the material, but strongly on the shape. In Fig. A13 B[van Houten, 1990] 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 2h + 2w 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 Fig. A13; the M'-part of Z_t decreases accordingly.

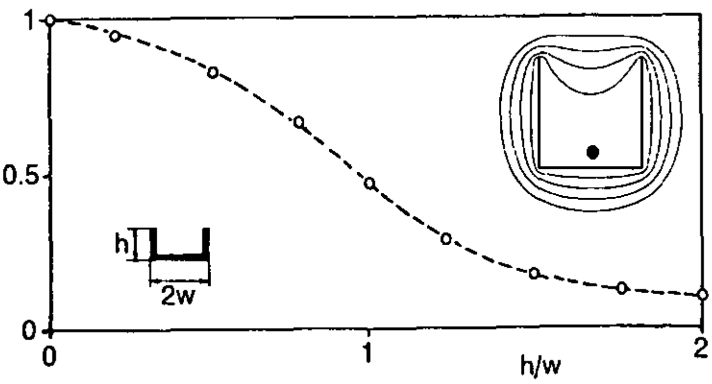


Fig. A13 The mutual inductance M for a conduit, with respect to that for the plate of the same 2h+2w. The inset shows several magnetic field lines for a conduit with h=2w.

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 (e.g. by metal springs) over the full length is preferred.

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

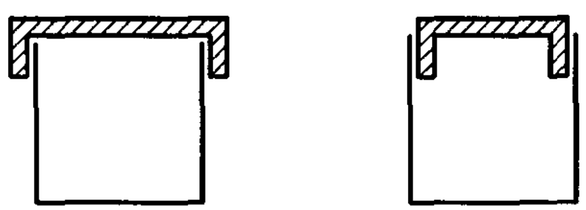


Fig. A14 Insulated covers over a conduit; inside covers are preferred.

A2.1.4 Resonances in the CM loop

With a ECP, 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 ECP.

Informative Annex A3: EMC-cabinet

An EMC-cabinet is described, which has been proven 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 B[van Houten, 1990].

The cabinet has continuous metallic walls at five sides; the front is left open. All cables, signal and power, enter the cabinet through the backplane. 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 ground lead is also connected nearby the filter.

All CM currents arriving at the cabinet through the cables and the safety ground 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's cage.

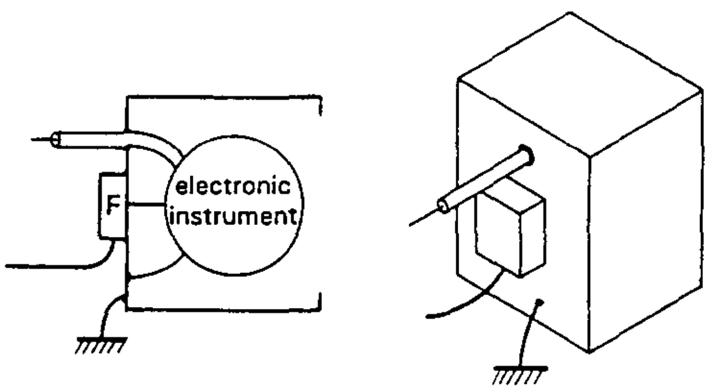


Fig. A15 An EMC cabinet for the protection of sensitive electronics. All external CM currents are routed via the backplane, thereby providing a minimal Z_t between the currents outside the cabinet and the electronics inside.

This EMC-cabinet is presented here as the ultimate protection that can be obtained by a reduction of Z_t and a rerouting the CM currents. A careful lay-out, according to the guidelines of this document, for the cables 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, one may use the backplane only, or even reduce the size of that single plane, as long as a clear path for the I_{CM} around the electronics can be maintained.

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