APPLICATION GUIDE

Radio frequency interference in HVAC applications

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This paper is devoted to explaining the best practices in selecting and installing variable frequency drives for heating, ventilation and air-conditioning systems, when considering compliance with electromagnetic compatibility standards for high frequency electromagnetic disturbances.

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Glossary

BDM	Basic drive module
CDM	Complete drive module
CISPR	International Special Committee on Radio Interference
EEA	European Economic Area
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
FCC	Federal Communications Commission of the USA
HFI	High frequency interference
HVAC	Heating, ventilation and air conditioning
IEC	International Electronical Commission
IEEE	Institute of Electrical and Electronics Engineers
PDS	Power drive system
RFI	Radio frequency interference
VFD	Variable frequency drive

Introduction

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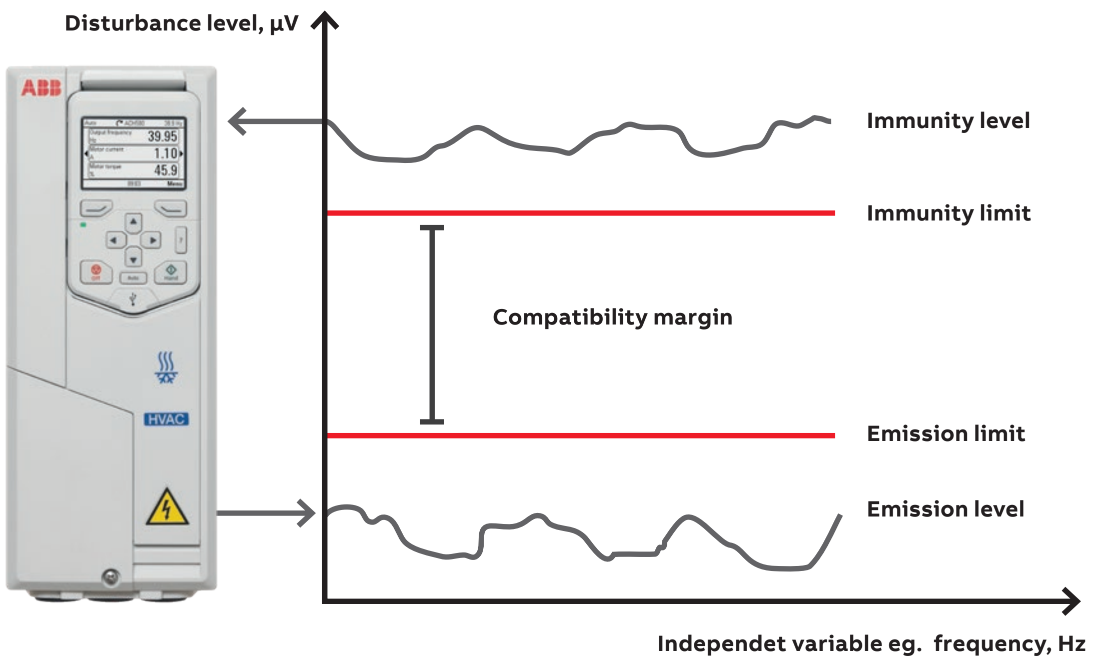
01 Fig. Immunity and emission compatibility.

A heating, ventilation and air conditioning system is an integral part of almost every building or facility regardless of its function. HVAC systems can be trivial, but they can also be highly sophisticated with numerous additional functions besides air supply and exhaust. The more sophisticated the building systems are, the more electrical and electronic components they have, and, therefore, the more attention should be paid to the aspects of electromagnetic (EM) compatibility.

As defined in International Electronical Commission directives, electromagnetic compatibility is the ability of electrical or electronic equipment to operate without problems within an electromagnetic environment: the equipment must not disturb or interfere with any other products or systems within its locality. At the same time, the electrical equipment should be immune or tolerant to specific levels of electromagnetic disturbances.

This is a legal requirement for all the equipment taken into service within the European Economic Area. The aim of EMC standards is to ensure the reliability and safety of all types of systems wherever they are used and exposed to electromagnetic environments.

Since variable frequency drives are potential sources of electromagnetic interference, it is natural that they are part of the EMC compliance. The terms used to define electromagnetic compatibility are shown in Fig. 01.



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02 Fig. Typical frequency bands for different types of electromagnetic disturbances.
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01 Ref. IEC/EN 61800-3:2004 "Adjustable speed electrical power drive systems - Part 3: EMC requirements and specific test methods".
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02 Ref. Note: In IEC/EN 61800-3:2004 standard, the limit between low frequency and high frequency is 9 kHz according to common practice in IEC. This terminology does not refer to broadcasting bands.
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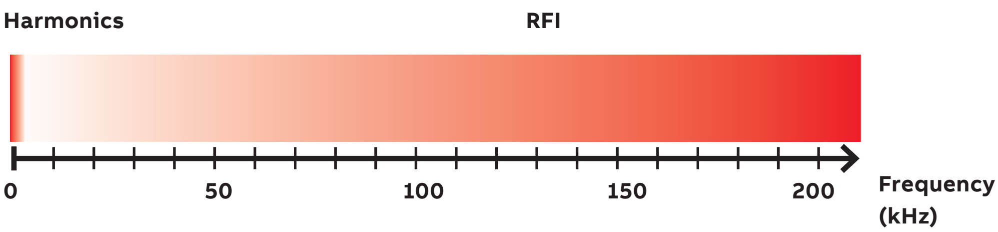
03 Ref. Radio frequency is any of the electromagnetic wave frequencies that lie in the range 20 kHz to 300 GHz.

It should be clarified that EMC standards refer to electromagnetic disturbances of different types and nature. According to International Electrotechnical Commission, they are classified into the following groups:

- Conducted low frequency (LF) disturbances including harmonics, voltage fluctuations, voltage dips and interruptions, voltage unbalance, power frequency variations, induced low frequency voltages
- Radiated low frequency disturbances including continuous and transient magnetic fields, electric fields
- Conducted high frequency (HF) disturbances including directly coupled or induced voltages or currents, transients
- Radiated high frequency disturbances including magnetic fields, electric fields and electromagnetic fields

Frequency is the key characteristic of electromagnetic disturbances. Product standards for VFDs typically cover the frequency band from 0 Hz to 1 GHz. International Electrotechnical Commission standard for power drive systems IEC 61800-3:2004 [01 Ref.] sets 9 kHz as the boundary between low frequency and high frequency disturbances [02 Ref.]. Since the standard regulates high frequency electromagnetic disturbances in the range 150 kHz to 1 GHz, it is common to refer to radio frequency interference when considering high frequency electromagnetic disturbances [03 Ref.].

This paper is devoted to high frequency electromagnetic disturbances that might be caused by VFDs in HVAC. For information on low frequency disturbances, please see the ABB Harmonics application guide, document number 3AUA0000224344.



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High frequency electromagnetic disturbances

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03 Fig. High frequency distortion in the voltage waveform.

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01 Ref. IEC/EN 61800-3:2004 "Adjustable speed electrical power drive systems - Part 3: EMC requirements and specific test methods".

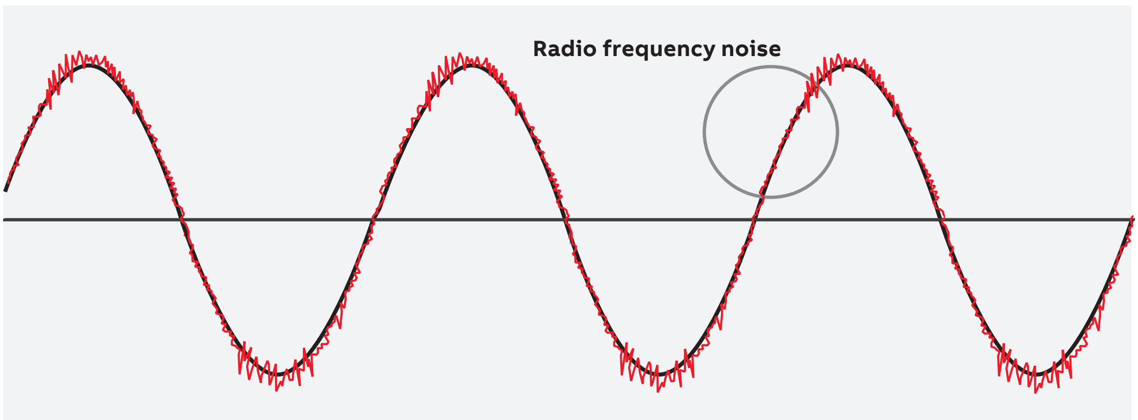
The load on power networks has significantly increased for the last years due to wide use of electrical and electronic, mainly office, equipment (computers, displays, printers, communication devices, etc). This trend is also common for building services such as elevators, lighting, information and communication lines, fire protection, security systems, energy and water supply, plumbing and HVAC. In particular, there is an increasing use of variable frequency drives in HVAC. As a result, it has led to increasing electromagnetic and, especially, high frequency emissions.

The two aspects affecting VFD's EMC performance most are the design of the VFD and the installation practices. Poorly designed or installed VFDs can produce significant high frequency disturbances which are able to affect operation of other electronic equipment. High frequency disturbances are quite harmful within an electrical system and can cause serious problems for both end users and building owners.

Types of high frequency disturbances
High frequency disturbances can be differentiated by methods of transfer and duration. As mentioned earlier, high frequency electromagnetic disturbances can have both a conductive and radiative nature. The lower the frequency, the more likely disturbances will propagate through cabling, grounding and the metal frame of an enclosure via conduction. This is due to the fact that the size of an antenna structure should be bigger to transfer low frequency disturbances via radiation, and the physical size of most devices is simply not sufficient for that. International Electrotechnical Commission standard for power drive systems 61800-3:2004 [01 Ref.]) regulates conducted high frequency disturbances in the range from 150 kHz to 30 MHz.

The radiated range is set from 30 MHz to 1 GHz [01 Ref.]. If electrical energy conducted through the cable contains frequencies above 30 MHz, it can radiate out and interfere with proper operation of nearby equipment. In this case, cables act like antennas: the longer the cable, the longer the antenna and the more HF noise is emitted to surroundings.

Source of high frequency disturbances
The main source of continuous high frequency electromagnetic disturbances caused by VFDs is fast switching of electronic components, such as transistors. A small wave of electromagnetic energy is emitted whenever electrical current in a transistor is switched on or off. The energy from switching action generates high frequency noise. As an example, high frequency distortion of voltage waveform caused by a VFD connected to the same input power source is shown in Fig. 03.



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04 Fig. Mechanisms of EM disturbances transfer.

The electromagnetic noise is usually stronger at positive and negative peaks of the sine wave where line voltage reaches the highest value.

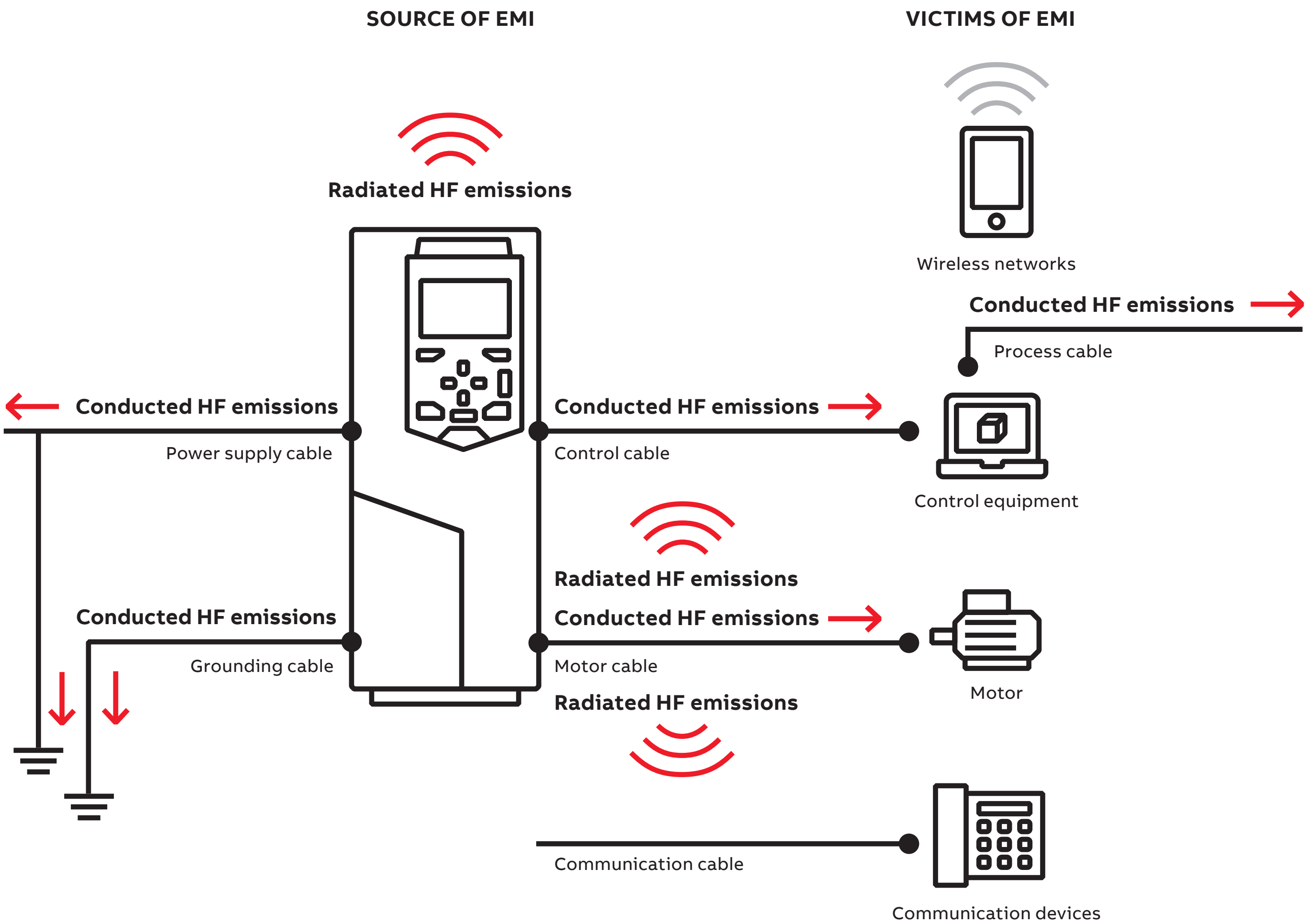
Electromagnetic interference
Electromagnetic interference is interference with equipment normal operation caused by abnormal electromagnetic energy entering the equipment either by conduction through wiring connections or by reception of radiated waves. Conducted EMI is also called high frequency line noise. Radiated EMI is also called radio frequency interference.

EMI can be caused by both natural and man-made sources such as the sun, weather events and other magnetosphere occurrences, as well as electric, magnetic and wireless devices and larger systems such as industrial power equipment and power transmission lines.

Nearly all electrical and communication equipment generates electromagnetic emissions and can be susceptible to them as well. Variable frequency drives are potential sources of EMI and are rarely victims that can be explained by high immunity levels set by standards for VFDs.

Technically, the process of EMI may by expressed by induction of unwanted currents in the equipment circuits that leads to improper functioning or even damage of the equipment.

Even weak unintended electromagnetic waves may cause loss of reception, noise in sound or intermittent video when radiating out and interfering with the radio waves used for broadcasting or communication.



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Consequences for end users and property owners

Depending on the type of building, its electromagnetic environment can be formed by different kinds of loads and therefore, by electromagnetic disturbances of different type and nature. Typical loads in residential and commercial buildings are lighting, heating, ventilation and air conditioning systems, elevators, safety systems, information and communication lines including wireless networks as well as office and domestic appliances. Diverse and numerous loads significantly increase electromagnetic and, in particular, high frequency disturbances in the building. High frequency disturbances in a power supply system and surrounding environment lead to equipment malfunctioning as a result of such disturbances and significant problems for end users and property owners.

As already mentioned, high frequency electromagnetic disturbances may have conductive nature and, in case of poorly designed or installed VFDs, propagate to the power network through the input power cable. Noise-sensitive devices sharing the same busbar with an active source of EMI may suffer from serious interference. Practically, it results in eg. flickering lights and screens, incorrect operation or failure of IT equipment, including memory losses and shutdowns.

If electrical energy conducted through the cable contains frequencies above 30 MHz, it can radiate out and interfere with proper operation of nearby equipment or with data running on communication cabling and cause increased errors, higher network traffic due to data retransmissions and network overload as a result. End users may occasionally experience noisy phone lines and dropped connections.

Therefore, high frequency electromagnetic disturbances may be quite harmful within a power network and may lead to serious consequences for property owners. Usually, the consequences are not easily quantified and not associated with the problem of exceeding HF emissions. These are costs associated with reduced equipment life-time, additional system maintenance, and lost productivity.

Property owners invest a lot in energy efficiency of a building. This is the reason for increased application of variable frequency drives in HVAC: VFDs control HVAC systems and therefore adjust energy consumption to actual needs of a building. But there is a risk that the investments building owners made in motors, drives and other power equipment will not be paid off if drives do not function properly and cause significant problems for power network and environment.

Furthermore, malfunctioning of elevators, lighting, safety systems (security, fire, smoke, gas and water control) and professional equipment due to electromagnetic disturbances can put people's security at risk especially in critical facilities such as hospitals, airports, or high-rise buildings.

As VFDs are potential sources of high frequency electromagnetic emissions, it is critically important to choose a drive that meets emission limits for a particular EMC environment and install it in accordance with manufacturer's recommendations to make the whole installation EMC-compliant. If aspects of EMC are not taken into account when choosing and installing variable frequency drives, property owners and end users are more likely to encounter the problems listed above.

EMC standards

EU Council Directives
In the European Economic Community, the EU Council Directives set standards for various products. Many of these standards are derived from standards written by the International Electrotechnical Commission.

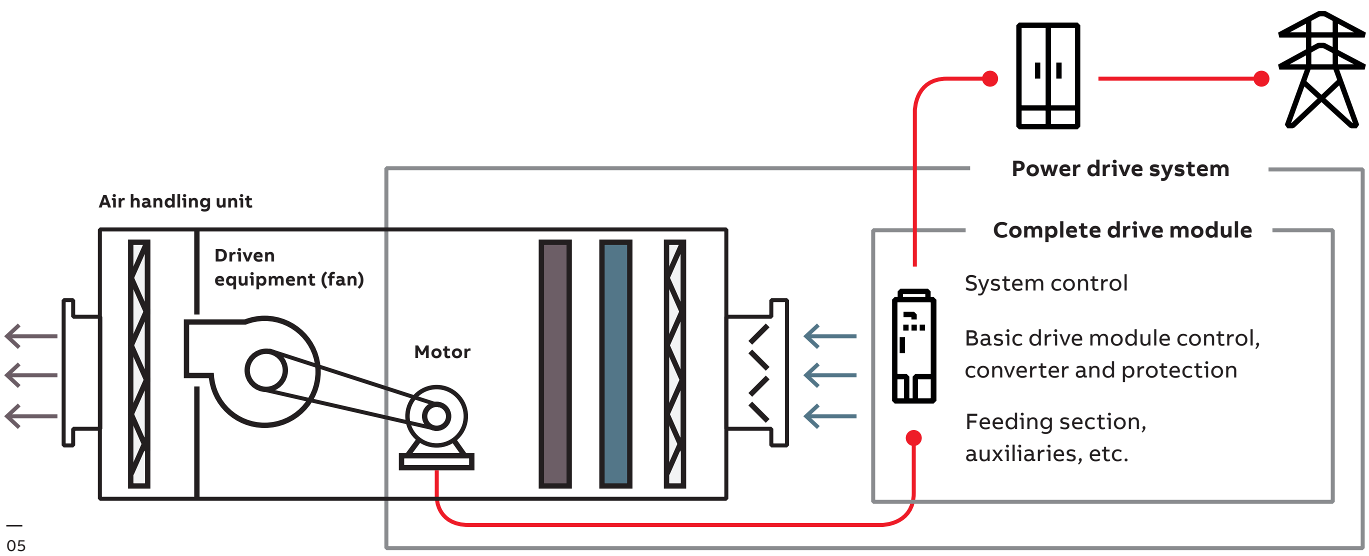
The generic European standard for EMC valid nowadays is IEC/EN 55011:2016 “Industrial, scientific and medical equipment – Radio frequency disturbance characteristics – Limits and methods of measurement” (analogous to international standard CISPR 11:2015). It applies to industrial, scientific and medical electrical equipment operating in the frequency range of 0 Hz to 400 GHz and defines the limits of electromagnetic disturbances, measurement requirements and special provisions for test site measurements. It also outlines the radiation measurements in the frequency range of 1 GHz to 18 GHz, safety precautions that should be taken, and the assessment of equipment conformity.

The IEC/EN 55011:2016 standard separates all the equipment in two groups – Group 1 and Group 2. Each group is further subdivided into two classes – class A and Class B.

- **Group 1** covers all the equipment in the scope of this standard that is not covered by Group 2 equipment.
- **Group 2** covers all industrial, scientific and medical RF equipment that intentionally generates and uses or only uses radio frequency energy in the range 9 kHz to 400 GHz in the form of electromagnetic radiation, inductive and/or capacitive coupling, for material treatment, for inspection/analysis purposes, or for transfer of electromagnetic energy.
- **Class A** covers equipment suitable for use in all locations other than those allocated in residential environments and those directly connected to a low voltage power supply network which supplies buildings used for domestic purposes.
- **Class B** covers equipment suitable for use in locations in residential environments and in establishments directly connected to a low voltage power supply network which supplies buildings used for domestic purposes.

IEC/EN 55011:2016 standard should only be applied when there is no specific product standard available. Since there is a product category specific standard for drives IEC/EN 61800-3:2004/A1:2011 “Adjustable speed electrical power drive systems - Part 3: EMC requirements and specific test methods”, IEC/EN 55011 should never be applied to variable frequency drives.

The IEC/EN 61800-3:2004/A1:2011 standard specifies electromagnetic compatibility requirements for power drive systems with converter input and/or output voltages up to 35 kV AC RMS in the frequency bands 150 kHz to 30 MHz for mains terminal disturbance voltage



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05 Fig. Definition of a power drive system (PDS) and its components.

(power ports) and in the frequency band 30 MHz to 1,000 MHz for electromagnetic radiation disturbance (enclosure port). In the frequency range from 2 kHz to 150 kHz EMC requirements are not specified.

For EMC requirements within frequency range up to 2 kHz, product specific standard IEC/EN 61800-3:2004/A1:2011 refers to product family standards IEC/EN 61000-3-2:2014 and IEC/EN 61000-3-12:2011. These standards specify limits for harmonic currents produced by equipment connected to public low voltage systems with input current up to 75 A per phase for frequencies up to 40th harmonic (2,000 Hz for 50 Hz net or 2,400 Hz for 60 Hz net). For equipment which draws more than 75 A per phase no limits are specified by these standards.

It should be noted that standards apply to a complete power drive system. PDS incorporates a complete drive module and a motor. A complete drive module consists of a variable frequency drive, motor cabling and control system interfacing (see Fig. 05 on p. 11), i.e. the complete system and not just a VFD, as in earlier standards. When one or more power drive systems are included in the equipment, the standards apply to the complete equipment, not the PDS alone.

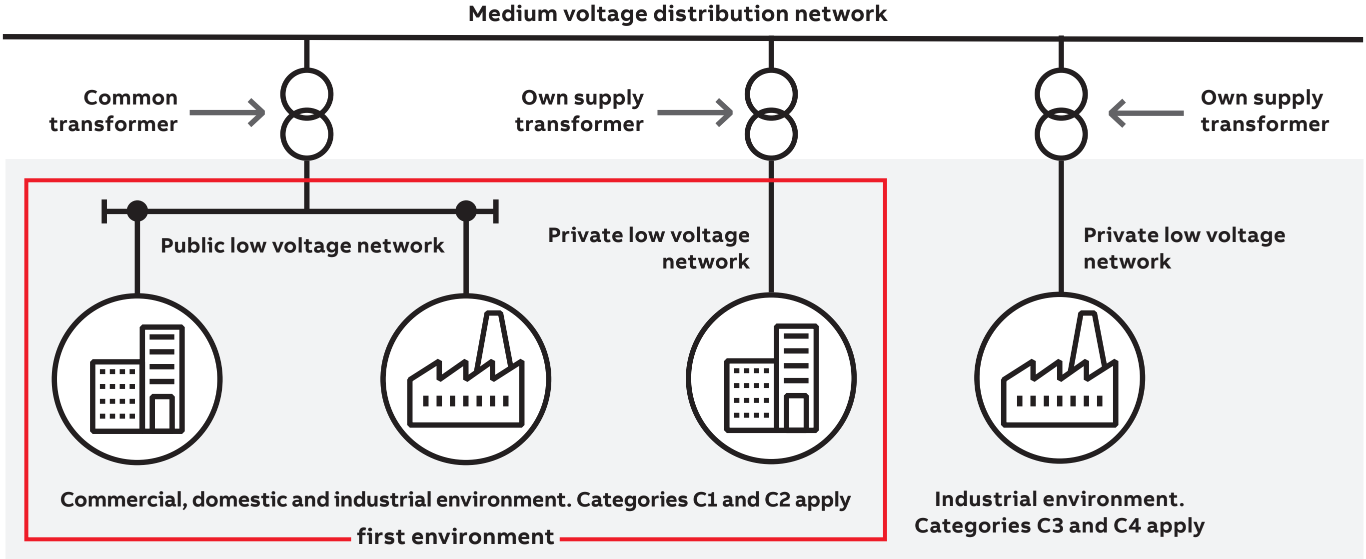
In Europe, the product specific standard IEC/EN 61800-3:2004/A1:2011 followed by new IEC/EN 61800-3:2017 takes precedence over all generic or product family EMC standards previously applicable.

According to IEC/EN 61800-3:2004 standard, there are two environments where equipment is used:
- **First environment** – environment that includes residential premises and establishments directly connected without intermediate transformers to a low voltage power supply network which supplies buildings used for residential purposes. Houses, apartments, commercial premises or offices in a residential building are examples of first environment locations. Equipment connected to a public low voltage network, i.e. shared between many buildings and users, is covered by this environment.
- **Second environment** – environment that includes all establishments other than those directly connected to a low voltage power supply network which supplies buildings used for residential purposes. Industrial areas or technical areas of any building fed from a dedicated transformer are examples of second environment locations. The fundamental difference to first environment is the private nature of the entire low voltage network, including the supply transformer.

When it comes to a power drive system designed to run heating, ventilation and air conditioning, usually it refers to first environment and residential or commercial application (see Fig. 06).

In most cases, hospitals, airports, clean- rooms and other sensitive facilities as well as many residential and commercial facilities with high power demand have their own low voltage supply transformers that, according to the classification, makes them second environment. However, they may need to meet the emission limits for the first environment.

Standard IEC/EN 61800-3:2004 divides PDSs and their component parts into four categories depending on the intended use:
- **Category C1:** PDSs of rated voltage less than 1,000 V, intended for use in the first environment.
- **Category C2:** PDSs of rated voltage less than 1,000 V, which is neither a plug in device nor



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— 06 Fig. Installation environments in accordance with EN 61800-3.

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01 Ref. For more information see FCC 02-157.
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02 Ref. See FCC DA 03-3848.

a movable device and, when used in the first environment, is intended to be installed and commissioned only by a professional – a person or an organization having necessary skills in installing and/or commissioning power drive systems including their EMC aspects.
- **Category C3:** PDSs of rated voltage less than 1,000 V, intended for use in the second environment and not intended for use in the first environment.
- **Category C4:** PDSs of rated voltage equal to or above 1,000 V, or rated current equal to or above 400 A, or intended for use in complex systems in the second environment.

The information on electromagnetic emission limits for each category according to IEC/EN 61800-3:2004 is given in Tab. 1 to 4 and Fig. 12 (see the attachment).

Codes and Standards in the USA
In the USA, there are no codes and standards that specifically and completely cover electromagnetic compatibility of VFDs.

Part 15 of the United States Federal Communications Commission rules and regulations covers unlicensed equipment that emits radio frequency energy. Part 15 applies to any VFD as an "incidental radiator." The operation of any equipment covered by Part 15 is subjected to the general conditions of operation listed under paragraph 15.5. The essential requirements of 15.5 are that the equipment must not interfere with any licensed broadcast, navigation or safety services and must accept any interference caused by other equipment. Under Part 15.13, the manufacturer of an incidental radiator "shall employ good engineering practices to minimize the risk of harmful interference."

Microprocessor controlled VFDs are also covered by FCC Part 15 as digital devices. As commercial or industrial equipment, VFDs are "exempted devices … subjected only to the general conditions of operation in 15.5". However, the FCC strongly recommends that the manufacturer of an exempted device endeavor to have the device meet the specific technical standards of Part 15. Part 15 lists limits for radio frequency voltage conducted to the public utility power lines by digital devices. The range of frequencies covered is 150 kHz to 30 MHz. Part 15 also lists limits for the field strength of radiated emissions from digital devices. The range of frequencies covered is 30 MHz and above. At frequencies lower than the radio frequencies regulated by the FCC, voltages conducted to the power lines would be considered to be harmonic distortion voltages. Harmonic distortion issues are covered by IEEE Standard 519. If evaluating a drive as an FCC Part 15 "digital device", a drive's microprocessor is not likely to be a significant source of EMI. The most significant potential source of EMI in a drive is the power switching circuitry, that is largely unrelated to the design of the microprocessor or other type of control circuitry. EMI is generated in a drive by switching the output terminals back and forth between the positive and negative sides of the DC bus to generate an AC output waveform. Each time the output transistor switches operate, the terminal voltage jumps, eg. in a 480 V drive from 650 volts of one polarity to 650 volts of the opposite polarity. This nearly instantaneous voltage change has the potential to generate a significant amount of radio frequency energy.

Therefore, evaluating the drive as a micro-processor controlled "digital device" does not correctly target the most significant source of EMI.

Since the applicable requirements are not very specific or restrictive, almost any drive could be said to meet the requirements of FCC Part 15 without actually providing a significant level of electromagnetic filtration.

A drive could be required to meet the conducted and radiated emission limits listed in FCC Part 15 for a Class A or Class B digital device, but Part 15 does not contain or specify a testing procedure that is designed for use with drives. Without specifying a suitable testing procedure, any declaration that a drive meets the specified limits might be suspect.

The conducted emission limits listed in Part 15 of FCC were revised in 2002 to "harmonize the domestic requirements with the international standards developed by the International Electrotechnical Commission, International Special Committee on Radio Interference" [Ref 01]. The CISPR 11 standard provides a suitable test procedure for testing drives to verify conformance with these limits.

The radiated emission limits specified by CISPR 22 are lower than the limits listed in Part 15. Accordingly, in 2003, Part 15 was revised to include the paragraph 15.109(g): "As an alternative to the radiated emission limits shown in paragraphs (a) and (b) of this section, digital devices may be shown to comply with… Pub. 22 (CISPR 1997)". [Ref. 02]

CISPR 22 covers digital devices while CISPR 11 covers industrial scientific and medical equipment. The U.S. Food and Drug Administration encourages manufacturers of electromedical equipment to use CISPR 11.

EMC categories in the HVAC industry

Power drive systems intended for use in the first environment which is relevant mainly for commercial and residential HVAC systems, fall under category C1 if they comply with emission limits, both conducted and radiated, for C1 category.

Drive manufacturers often position their products as compatible with C1 requirements without specifying that products only comply with C1 conducted emission limits or considering only a basic drive module while applying standards for power drive systems.

At the same time, C1 category's requirements are not applicable to, and excessive for most of those power systems present on the market today, which are not plug-in or movable.

Power drive systems intended for use in the first environment, which is relevant mainly for commercial and residential HVAC systems, fall under Category C2 if they comply with emission limits, both conducted and radiated, for C2 category and are neither plug-in nor movable devices.

In fact, it means that IEC/EN 61800-3:2004 does not require compliance of PDSs present on the market today with C1 emission levels meaning that compliance with C2 for drives installed in the first environment is fully sufficient unless otherwise stated in specific project requirements.

C2 emission levels were set to avoid interfering with other equipment in the first environment. Therefore, providing equipment which meets C1 emission levels is excessive and does not bring much value to customers in most cases.

Most modern HVAC drives comply with C2 requirements for electromagnetic emission levels through the use of standard internal filters or external filters.

Power drive systems intended for use in the second environment that is relevant typically for industrial facilities with their own supply transformers on site, fall under category C3.

Most modern HVAC drives produced nowadays comply with C2 requirements for electromagnetic emission levels. However, for HVAC drives installed in the second environment, it is sufficient to comply with only C3.

Power drive systems intended for use in the second environment and falling under Category C4, have no practical relevance to HVAC segment and therefore are not reviewed further.

VFD manufacturers generally claim that only qualified electricians should perform the drive installation since installation practices significantly influence the end result of power drive system compliance with EMC requirements.

For manufacturers of variable frequency drives for HVAC industry it is challenging and furthermore unnecessary to claim compliance with C1 category for both conducted and radiated emissions. Compliance with C1 conducted emission limits can

be achieved by using filters and implementing proper installation of power drive systems. But, in order to comply with C1 radiated emission limits, all parts of a power drive system should form a Faraday cage against radiated emissions. This is why drive manufacturers should be careful when claiming C1 compliance whereas, in fact, providing compliance with C1 conducted emission limits only.

It is also common on the market to refer to the generic EMC standard EN 55011 that does not require a motor to be connected to a drive when verifying EMC compliance. This standard should not be considered for drives since the product specific standard IEC/EN 61800 overrides the generic one.

Furthermore, it is important to remember that EMC performance of a certain drive depends on the length and type of motor cable. Thus, a drive fitted with an internal or external filter that complies with EMC requirements at a certain cable length, may not comply with requirements at longer lengths. Similarly, use of non-recommended cable types in installation can lead to non-compliance with the standard.

Another important aspect to take into account is that standards for electromagnetic compatibility listed above apply to power drive systems. On its own, a basic or complete drive module is a component only and as such has no functional value to a user. In order to function, a drive always needs its motor, coupled mechanically to the driven load and electrically (through a cable) to the drive. Only then it becomes a PDS (containing also feeders, protection and communication components, etc.) that obviously has higher electromagnetic emissions than a CDM. Thus, a BDM/CDM that complies with C1 category by itself, may not comply when considering a PDS.

Cabling and grounding practices

One of the most important aspects that significantly affects system EMC performance is installation practices and, in particular, cabling, wiring and grounding. The RFI filter cannot solve a problem of system EMC compliance by itself. If the installation isn't done properly and manufacturer instructions are neglected, the PDS may not be EMC compliant even when having a necessary RFI filter.

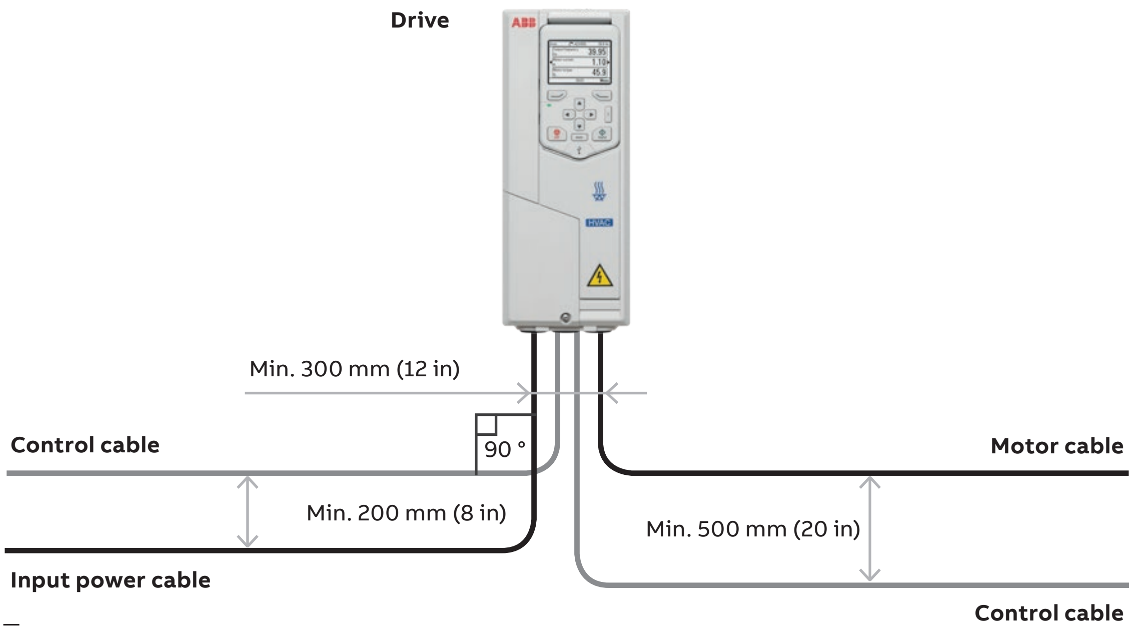
Cabling practices
Fulfilment of general requirements for drive cabling and wiring constitutes part of EMC compliance. These requirements include routing the motor cable away from other cable routes. Motor cables of several drives installed next to each other can be run in parallel only if each motor's cable is individually shielded. In North American practices, motor cables from several drives are not allowed to run in the same conduit.

Crossing of different cable types should be avoided. Where this is not possible, different cable types, eg. power and control cables, should cross at an angle as near to 90 degrees as possible. Running of extra cables through the drive is not permitted due to possible noise induction from motor cables, which essentially short circuits the RFI filters.

The motor cable, input power cable and control cables should be installed on separate trays (see Fig. 08 on next page).

Cable tray design and material might contribute to the EMC performance of installation as well. Thus, non-metal cable trays can be used mostly in environments with low electromagnetic emission levels and for cables with low electromagnetic emission levels respectively. In most other cases, metal cable trays should be used. Metal cable trays with solid bottom and cover are preferred over open ones due to minimizing the possibility of EMC issues.

Cable types to be used with VFDs
The EMC product standard IEC/EN 61800-3 applies to a complete power drive system, which means that cables contribute to system EMC performance as well. To secure compliance with the EMC requirements, it is necessary to use one of the approved cable types. of the approved cable types. The table 1 on the next page shows the generic approved cable types.



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07 Fig. Cable routing general requirements.

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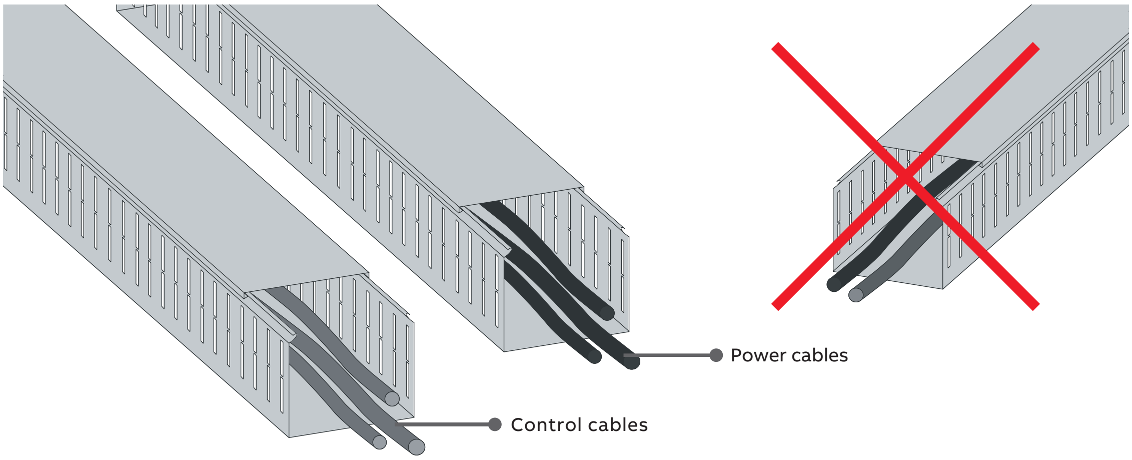
08 Fig. Running different cable types in cable trays.



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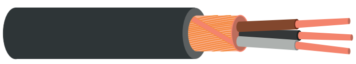
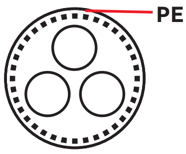
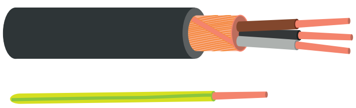
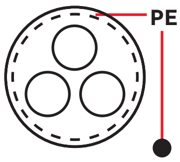
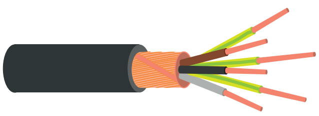
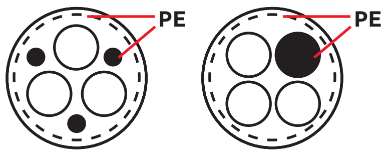
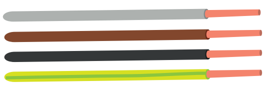
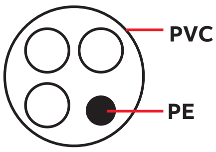
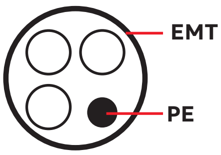
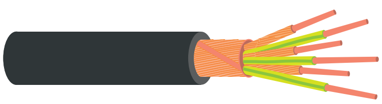
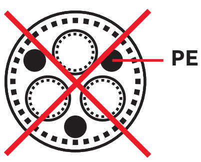
Tab. 1. Cable types overview

Recommended cable types		
		Symmetrical shielded cable with 3-phase conductors and a concentric copper or aluminum PE conductor as shield. Cable shield must meet IEC 61 439-1 requirements.
		Symmetrical shielded cable with 3-phase conductors and a concentric steel or galvanized iron PE conductor as shield. A separate PE conductor is required if cable shield does not meet IEC 61 439-1 requirements.
		Symmetrical shielded cable with 3-phase conductors, 1 or 3 symmetrically constructed PE conductors and shield. PE conductor must meet IEC 61 439-1 requirements.
Cable types for limited use		
		A 4-conductor system (3-phase conductors and protective conductor on a cable tray) is allowed for input cabling only and not allowed for motor cabling. Not allowed for usage in IT (ungrounded) networks.
		A 4-conductor system (3-phase conductors and PE conductor in a PVC conduit) is allowed for input cabling with phase conductor cross-section less than 10 mm^2 (8 AWG) or motors < 30 kW (40 hp). Not allowed in the USA.
		Corrugated cable or electrical metallic tubing EMT with 3-phase conductors and a protective conductor are allowed for motor cabling with phase conductor cross-section less than 10 mm^2 (8 AWG) or motors < 30 kW (40 hp).
Not allowed cable types		
		Symmetrical shielded cable with individual shields for each phase conductor is not allowed on any cable size for input or motor cabling.

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09 Fig. Motor cable shielding.

As a general rule, it is important to have a manufacturer's confirmation that a specific cable is suitable for the application, as the shield material and construction of the shield impact the protection against electromagnetic radiation.

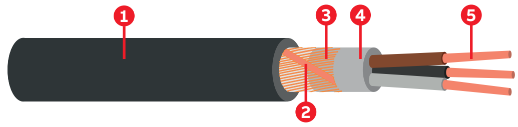
Shield is a layer of insulation containing electrical energy that is wrapped around an electrical cable to prevent the cable from emitting or absorbing electromagnetic disturbances. There are different types of cable shielding including foil, spiral, braided shielding as well as their combinations.

Braided shielding is the most traditional form of shielding. Its mechanical strength and flexibility offers greater versatility than eg. foil shielding. However, braided shielding does not work at all electromagnetic frequencies due to limited braid coverage over the cable (typically 70 to 95%): it performs best at low frequencies up to 15 kHz and deteriorates around 100 MHz.

Foil shielding encases a cable via a thin layer of copper or aluminum with a polyester sheath that increases mechanical strength. It works in tandem with a copper drain wire to ground the shield. Foil shielding provides 100% coverage making it superior at high frequencies, starting around 10 MHz and going up to 20 GHz in some designs, but has poor flexibility.

Spiral shielding is usually formed from copper strands wrapped around the conductor. It is more flexible than braid shielding and provides easy grounding. Although spiral shielding obtains coverage of 95% and higher, it is effective only at frequencies in audio range that is below 20 kHz.

As an optimal solution, often a braid shield is supplemented by a foil shield to provide the mechanical strength and maximum shielding efficiency across a wider frequency spectrum.



1 Sheath
2 Helix of copper tape or copper wire
3 Copper wire shield
4 Filling
5 Cable conductors

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09

If the motor cable shield is used as the sole protective earth conductor of the motor, the conductivity of the shield should be sufficient.

To effectively suppress radiated and conducted radio frequency emissions, the cable shield conductivity must be at least 1/10 of the phase conductor conductivity. The requirements are easily met with a copper or aluminum shield. The minimum requirement of the motor cable shield is shown in Fig. 09. It consists of a concentric layer of copper wires with an open helix of copper tape or copper wire. The better and tighter the shield, the lower the emission level and bearing currents.

Additional US requirement prescribes to use Type MC (metal clad) continuous corrugated aluminum armor cable with symmetrical grounds or shielded power cable for motor cables if metallic conduit is not used.

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Tab. 2. Grounding systems characteristics including EMC performance

Distribution system type	Main application	Human safety	Property safety	EMC performance
TT	Domestic installations and similar, small industries with low voltage power supply	Good Residual current circuit breakers required	Good Medium fault current 10 -10 0 A	Good Risk of overvoltages Equipotential problems Need to manage devices with high leakage currents
TN-S	Industries and big installations with medium voltage power supply	Good Continuity of the PE conductor must be ensured	Poor High fault current similar to single-phase fault current	Very good Few equipotential problems Need to manage devices with high leakage currents High fault currents (transients)
TN-C				Poor (should never be used) Circulation of disturbed currents in exposed conductive parts (high radiated emissions) High fault currents (transients)
IT	Chemical and petrochemical industries, i.e. plants for which service continuity is fundamental	Good Continuity of the PE conductor must be ensured	Good Low current for the 1^{st} fault (µA-2 A) and high current (values typical for TN or TT systems) for the 2^{nd} fault	Poor (should be avoided) Risk of overvoltages Common-mode filters must handle phase-to-phase voltages Residual current circuit breakers subject to tripping if common mode capacitors are present

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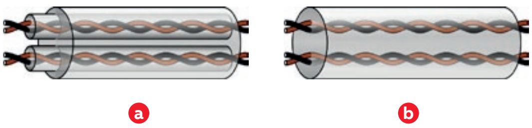
10 Fig. Control cable shielding.

Another important aspect to consider is control cable types. In general, all control cables are recommended to be shielded (see Fig. 10). Analog and digital signals should be run in separate, shielded cables.



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For analog signals a double-shielded twisted pair cable should be used – one individually shielded pair for each signal. It is not permitted to use common return for different analog signals. Analog voltage signals, such as 0 - 10 V, should be shielded because of the high impedance of the control circuit. Analog current signals, such as 0/4 - 20 mA, generally do not require shielding because of the low impedance of the control circuit.

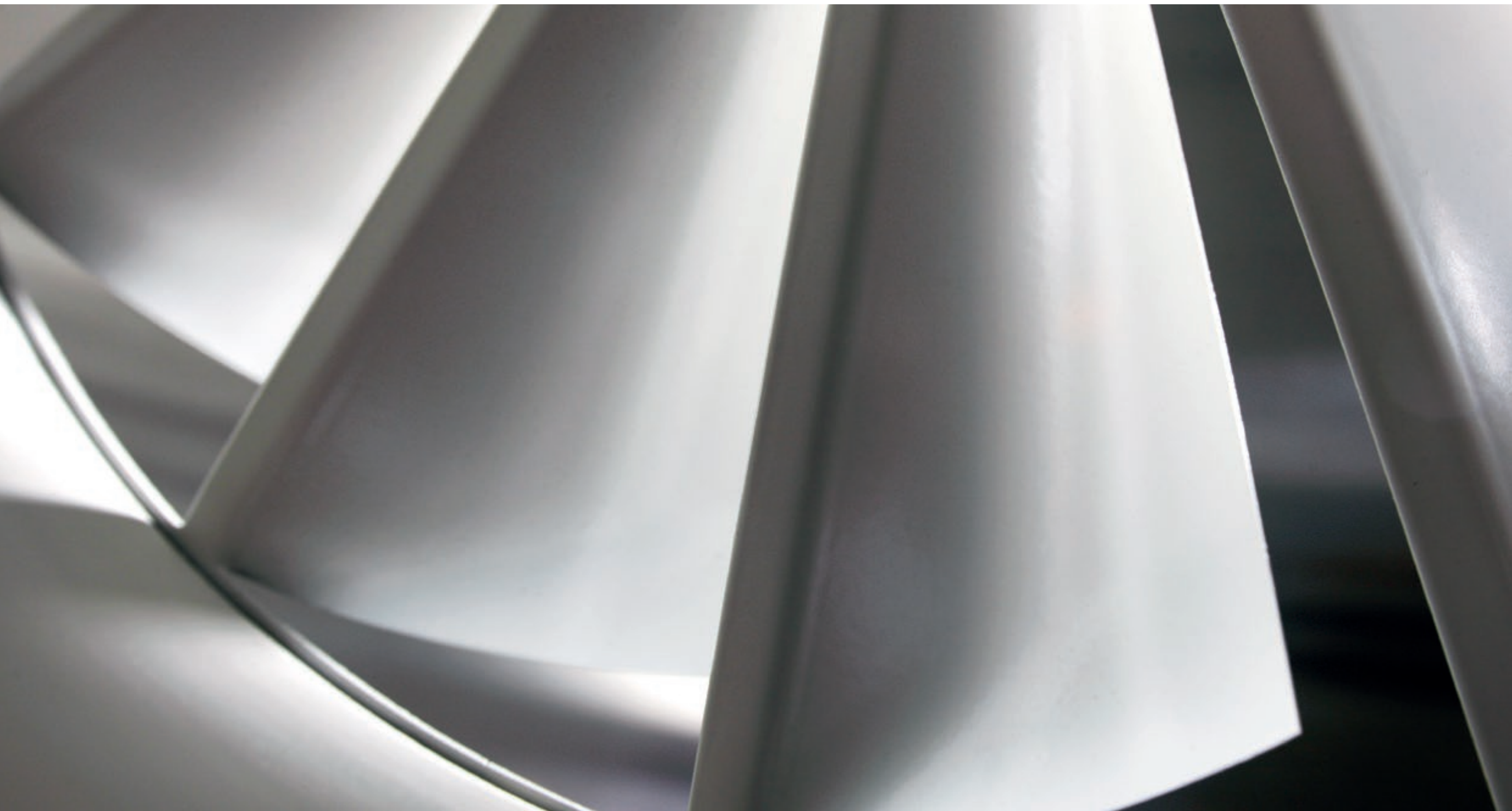
Digital signals, such as the commands being given to the drive digital inputs, do not require shielding in the vast majority of cases. Serial communications cables should be shielded due to their high frequencies and low voltages. Relay-controlled signals with voltage not exceeding 48 V can be run in the same cables as digital input/output signals.

Grounding practices
Conducted disturbances can propagate from the drive to other equipment via all conductive paths, including grounding.

The system grounding should ensure not only safety of life and property, but EMC compliance as well. European standards EN 50174-2:2009/A1:2011 "Information technology - Cabling installation - Part 2: Installation planning and practices inside buildings" and EN 50310:2016 "Telecommunications bonding networks for buildings and other structures" recommend the TN-S system, which causes the least EMC issues for IT and telecommunication equipment.

Grounding systems help to achieve EMC compliance by maintaining the same ground potential throughout the building. If a grounding system is not equipotential, high frequency stray currents start flowing between different parts of the building electrical system throughout the ground. This may disturb sensitive equipment connected to the system. In such cases it is very difficult to determine the root cause of electromagnetic disturbances since the source may be in an entirely different part of the building.

This is why it’s critical to have building grounding systems interconnected to help ensure a constant ground potential throughout the building. If the entire grounding system of a building is equipotential, the difference in potential between devices is low and a large number of EMC issues disappears.



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11 Fig. VFD grounding and wiring practices.

Equipment grounding is an important aspect when considering system EMC performance. Grounding of a VFD as a potential source of EMI requires attention in particular.

Motor and power supply cables should be grounded 360 degrees. EMC cable glands are the optimal solution, but metal cable clamps with full cable shield contact are also sufficient (Fig. 11, a). The shield wires must be twisted together into a bundle (pigtail) not longer than five times its width and connected to the grounding terminals of the drive (Fig. 11, b). The motor cable shield should be grounded at the motor end as well. As a general rule, the unshielded cable parts should be kept as short as possible.

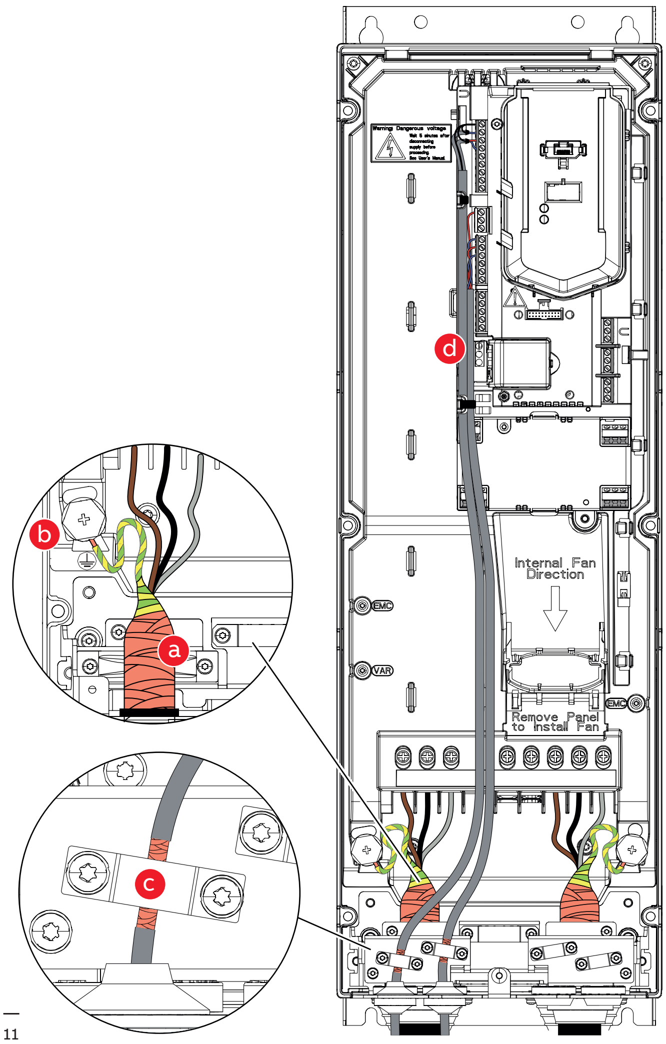
In North American practices, separate parts of cable conduits must be coupled together, the joints should be bridged with a ground conductor bonded to the conduit on each side of the joint. The conduits should be bonded also to the drive enclosure and motor frame. For input power, motor, brake resistor, and control wiring separate conduits should be used. When conduit is employed, type MC (metal-clad) continuous corrugated aluminum armor cable or shielded cable is not required. A dedicated ground cable is always required.

To minimize electromagnetic emission levels when safety switches, contactors, junction boxes or similar equipment is installed on the motor cable between the drive and the motor, the equipment must be installed in a metal enclosure with 360 degree grounding for the shields of both the incoming and outgoing cable, otherwise shields of the cables must be connected together. In North American practices, the equipment must be installed in a metal enclosure in a way that the conduit or motor cable shielding runs consistently without breaks from the drive to the motor.

The cable trays must have good electrical bonding to each other and to the grounding electrodes. Metal cable trays or conduits can be used to improve local equalizing of potential.

Drive control cables should be properly terminated and grounded to reduce noise on the control network. The outer shield of the control cable should be 360 degrees grounded via the grounding clamp (Fig. 11, c). Also, the control cable shields and grounding wires should be connected to a grounding terminal at the drive side. The cables should be kept unstripped as close to the terminals of the control board as possible (Fig. 11, d). Any signal wire pairs should be kept twisted as close to the terminals as possible. Twisting the wire with its return wire reduces disturbances caused by inductive coupling.

A control cable shield left unconnected (ungrounded) at both ends does not suppress disturbances. Grounding a control cable shield at one end only suppresses the electromagnetic field and inductive disturbances enough in most cases. Grounding a control cable shield at both ends improves disturbance suppression above a certain frequency, but forms also a loop where low frequency current flows if the ends of the cable shield are at different potentials. Therefore, if high frequency grounding is needed, the other end of the shield should be grounded via a capacitor. In some equipment the capacitor is incorporated.



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11

Real world cases

In this chapter, examples from real life are intended to highlight some of the effects of improper installation on system EMC performance.

Case 1
ACH580 drives were installed in the basement of an apartment house while the air handler was at the rooftop, six stories above. As this was a retrofit case, the cables to the old motors were used with the new motors, and they were unshielded cables. While installing the automation, some new sensors (eg. outdoor temperature sensor) were installed on the rooftop and their analogue control cables were run with the motor cables in the same cable channel. The analogue cables were unshielded as well.

The drives were malfunctioning. The root cause was identified to be from the non-shielded motor cables disturbing the analog input signals to the drives. The outdoor temperature was used to trigger various functions of the drive such as running the motor at a low speed for freeze protection when the outdoor temperature is low and running the motor at a controlled speed when the outdoor temperature is higher. As there were no other problems identified in the apartment building, the immediate solution was to add filtering in a form of analog input filter time and ferrites to filter out common mode noise from the analogue cable.

ABB's recommended solution was to replace the motor and analogue cables with shielded cable types and to reroute the analogue signal via a separate cable channel.

Case 2
In a recently retrofitted office building there was a problem with the fluorescent lights occasionally flickering. This seemed to mostly happen when the drives were running near full speed and load. The investigation showed that the root cause was the new wiring to the drives. The cables used for the motors and for the input power to the drives were both unshielded and were run in the same cable tray, which allowed the RFI from the motor cables to couple to the building's power grid. In addition, the cross-sectional area of the drives' ground wires was too small to ensure proper grounding.

The solution was to replace the existing motor cables with shielded ones and run an extra PE cable to meet the minimum cross section for grounding.

ABB's recommendation is always to follow the minimum grounding wire cross section requirements and use only recommended cable types for the motor connection. In addition, motor and supply cables should never be run right next to each other in the same cable tray.

Case 3
A problem of tripping ventilation occurred at an industrial site. This happened occasionally when the drive was getting a very low speed reference signal from the automation system. After investigating the problem, it was determined that the root cause was a ground loop current between the drive and the automation system that was controlling it.

The automation system was giving the drive both a digital signal to run and an analogue reference. These signals were transmitted through a single unshielded control cable. The noise from the environment and the differences in ground potential between the automation controller and the drive were interfering with the analog speed reference signal and preventing its correct interpretation.

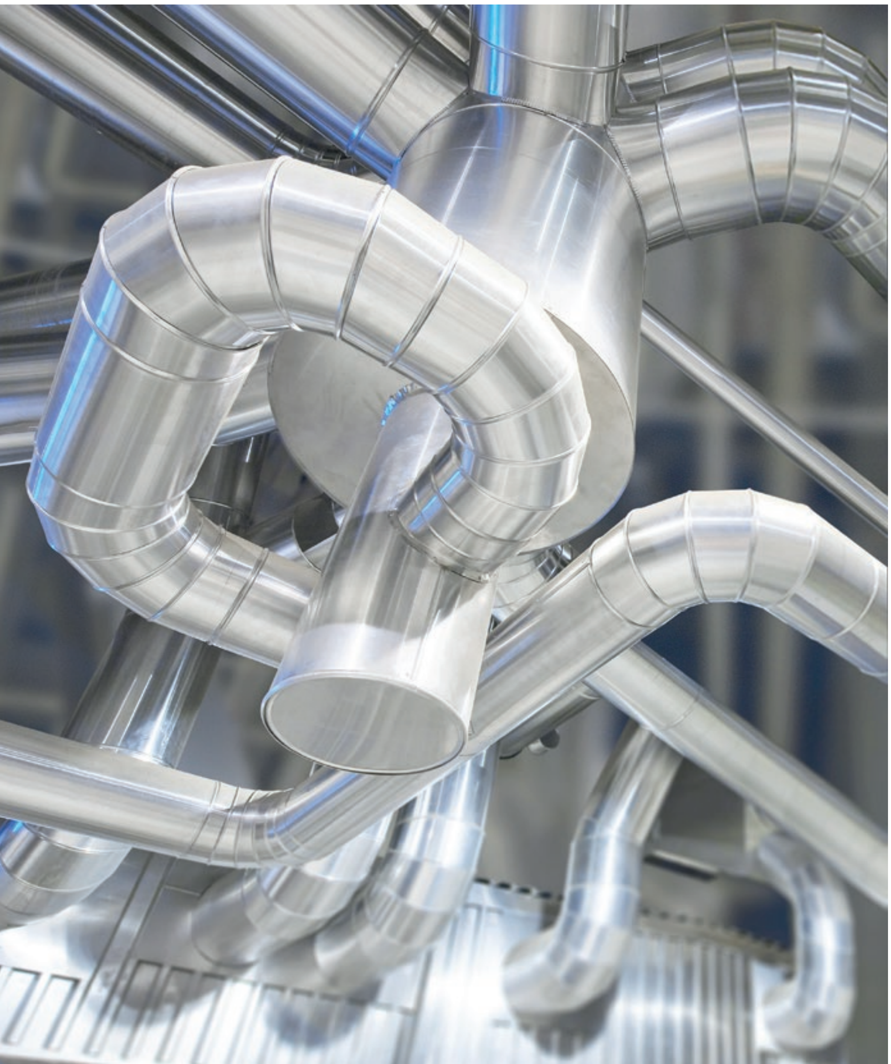
The problem was solved by replacing the unshielded control cable with a new shielded cable. This shielded cable was grounded only at the controller side. The shield was left open at the drive side and was taped off so that it would not come in contact with anything. In addition, the cable had twisted pair conductors for the analog speed reference and it is common. This type of connection helped by disconnecting the ground loop and by shielding the analog input cable from environmental noise.

ABB's recommendation is to use shielded cables for digital signals and double shielded cables for analog signals. It is also recommended not to combine them in the same cable. To prevent noise issues, analog reference ground and digital common on the control unit need to be wired separately to the drive.

Recommended practices

In practice, when referring to EU EMC standards, there is no difference between C1 and C2 categories in HVAC application in terms of environment. Compliance to C1 category over C2 should not be advocated by drive manufacturers as, in most cases, VFDs meet C1 conducted emission limits only over quite short distances and do not meet C1 radiated emission limits without being installed in a Faraday cage.

At the same time, C1 emission limits are set for plug-in/ movable devices and, therefore, excessive for power drive systems with fixed installation. C2 emission limits are set for power drive systems in accordance to immunity levels of neighboring equipment that could possibly be installed in the first environment. Therefore, compliance of PDSs to C2 emission limits is absolutely sufficient and exceeding of C2 requirements does not bring most customers value, but only added installation cost.



For certain cases eg. critical facilities, installation of RFI filters to comply with C1 conducted emission limits can make sense, but, before making C1 a requirement, there should be an evaluation of the immunity levels of the equipment installed in the facility.

In most cases, C1 levels for conducted emissions can be achieved by VFD manufacturers, while the limits for radiated emissions are very challenging to comply with. The ABB drives for HVAC applications have been tested for meeting conducted emissions limits within category C1 with optional filters. However, as this is not the only requirement of the C1 category, ABB does not advocate C1 compliance.

Another important aspect to consider is installation practices that may significantly affect equipment compliance with EMC requirements. In most cases, a VFD with C2 RFI filter installed in accordance with manufacturer's requirements will perform better, from an EMC point of view, than an improperly installed VFD with a C1 filter.

In order to avoid potential EMC issues and associated undesired effects on surrounding equipment for our customers, ABB Drives' policy is to refer drives that partially meet C1 standard to category C2 which, in addition to total compliance with C2 emission levels, implies installation and commissioning through a competent, professional channel.

It is a top priority for ABB to create added value for our customers, not only through improving the efficiency and effectiveness of HVAC systems with ABB’s dedicated HVAC drives, but also by providing a secure building environment in terms of power quality and network robustness.

Attachments

Limits for mains terminal disturbance voltage (power ports) in the frequency band 150 kHz to 30 MHz and limits for electromagnetic radiation disturbance (enclosure port) in the frequency band 30 MHz to 1,000 MHz for first and second environments according to IEC/EN 61800-3:2004 followed by IEC/EN 61800-3:2017.

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Tab. 3. Limits for mains terminal disturbance voltage in the frequency band 150 kHz to 30 MHz.
PDS in the first environment – PDS of category C1 and C2

	Category C1		Category C2	
Frequency band MHz	Quasi peak dB(μV)	Average dB(μV)	Quasi peak dB(μV)	Average dB(μV)
0.15 ≤ f < 0.50	66 Decreases with log of frequency down to 56	56 Decreases with log of frequency down to 46	79	66
0.5 ≤ f ≤ 5.0	56	46	73	60
5.0 < f < 30.0	60	50	73	60

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Tab. 4. Limits for electromagnetic radiation disturbance in the frequency band 30 MHz to 1,000 MHz.
PDS in the first environment – PDS of category C1 and C2

	Category C1	Category C2
Frequency band MHz	Electric field strength component Quasi-peak dB(μV/m)	Electric field strength component Quasi-peak dB(μV/m)
30 ≤ f ≤ 230	30	40
230 < f < 1,000	37	47

NOTE: Measurement distance 10 m.

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Tab. 5. Limits for mains terminal disturbance voltage in the frequency band 150 kHz to 30 MHz.
PDS in the second environment – PDS of category C3

Size of PDS	Frequency band MHz	Quasi peak dB(μV)	Average dB(μV)
I ≤ 100 A	0.15 ≤ f < 0.50 0.5 ≤ f < 5.0 5.0 ≤ f < 30.0	100 86 90 Decreases with log of frequency down to 70	90 76 80 Decreases with log of frequency down to 60
100 A < I	0.15 ≤ f < 0.50 0.5 ≤ f < 5.0 5.0 ≤ f < 30.0	130 125 115	120 115 105

NOTE: These limits do not apply to power ports operating above 1,000 V.

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Tab. 6. Limits for electromagnetic radiation disturbance in the frequency band 30 MHz to 1,000 MHz.
PDS in the second environment – PDS of category C3

Frequency band MHz	Quasi peak dB(μV)
30 ≤ f ≤ 230 230 < f ≤ 1,000	50 60

NOTE: Measuring distance 10 m.

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Tab. 7. Comparison of standards EN 55011:2009 and EN 61800-3:2004

	EN 55011: 2016	EN 61800-3: 2004
Emission limits	Class B (Residential area) Group 1+2	Environment 1 (Residential area) Category C1
	Class A (Industrial area) Group 1 (Internal filter)	Environment 1 or 2 (depending on the decision of the user) Category C2
	Class A Group 2 (External filter, not applicable to drives)	Environment 2 (Industrial area) Category C3
		Category C4 (Exceeds the Class A2 limits 1,000 V or 400 A)

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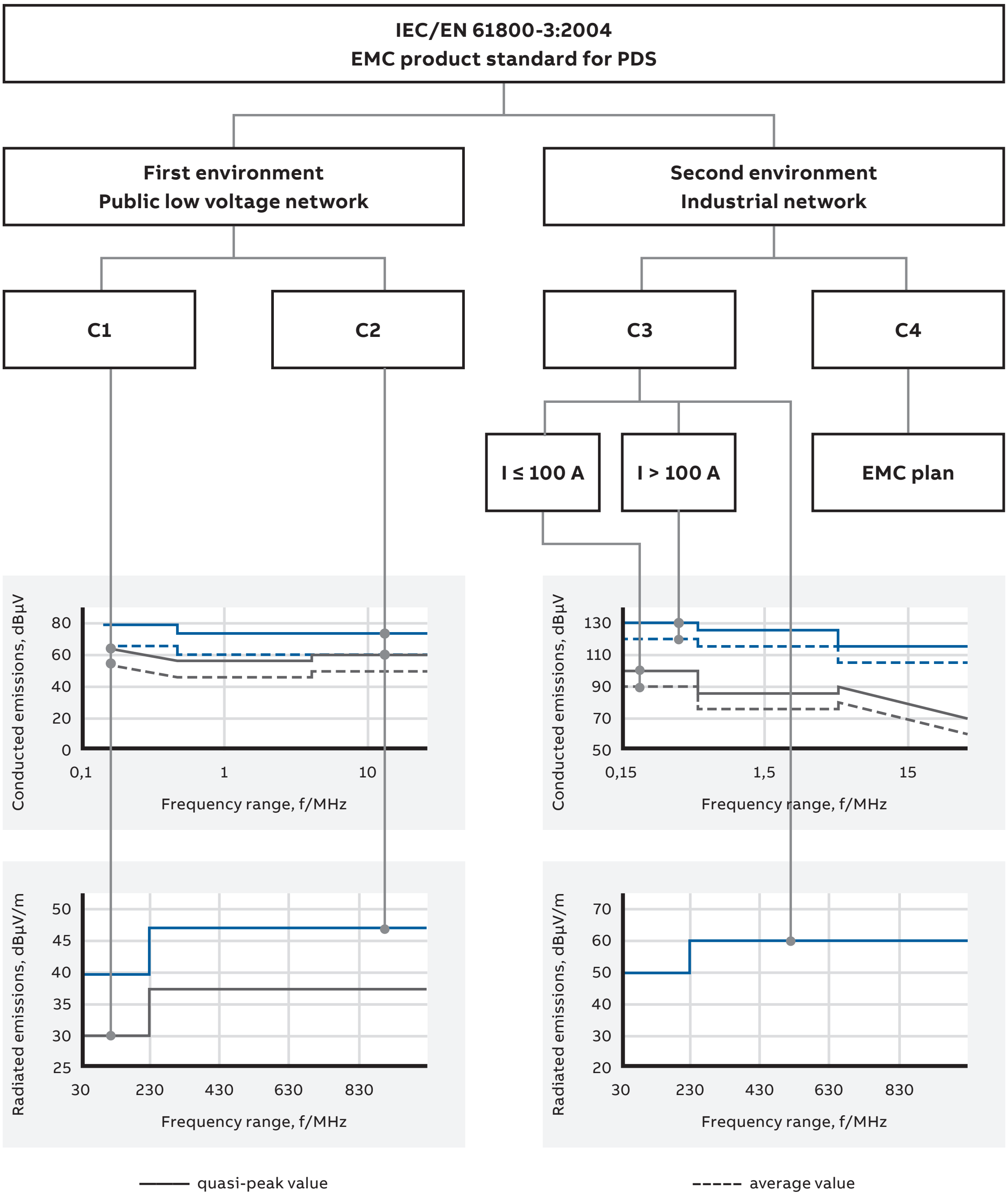
12 Fig. Emission limits for PDS.



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Notes

Notes

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