Functional Bonding and Shielding of PROFIBUS and PROFINET

Guideline

for PROFIBUS and PROFINET

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Management Summary

This document deals with the shielding of PROFIBUS/PROFINET networks and with equipotential bonding in the corresponding plants in non-hazardous areas. The document describes an optimized structure for process automation systems intended to reduce the effects of electromagnetic interference (EMI) and disturbances by using equipotential bonding systems. In a tiered approach, the readers are first made familiar with the technical basics of electromagnetic compatibility (EMC), equipotential bonding and shielding. In chapter 4, six recommendations for action are developed by using a plant example.

The recommendations for action are listed in the following table.

R1	Provide both protective equipotential bonding and functional equipotential bonding through a common bonding network (CBN).
R2	Preferably use a 230/400 V power supply using a TN-S system.
R3	Use a common bonding network (CBN). Mesh equipotential bonding systems as finely as possible (MESH-BN).
R4	Provide a connection of the PROFIBUS/PROFINET cable shields through the housings of the connectors and through the housings of the devices and thus to the common bonding network (CBN) at each cable end with big contact surfaces (low impedance).
R5	• Use shielded motor cables in accordance with the manufacturer specifications and provide for large-surface connection of the shield at each end to the common bonding network (CBN) with low impedance. • Connect the motor to the common bonding network (CBN). • If not excluded by the manufacturer of the frequency converter, preferably use symmetrical shielded three-wire motor cables with separate protective conductor.
R6	• Multiple connections of 24-V-Supply-Circuits to the common bonding network (CBN) have to be avoided. • In order to keep the cables between the power supply unit and the consumer as short as possible, it is recommended to use several smaller power supplies rather than a single big one.

Content

List of figures

List of tables

1 Introduction

This document deals with functional bonding and shielding of PROFIBUS/PROFINET networks and with equipotential bonding in plants in non-hazardous areas. The aim is to provide users and designers with a standardized procedure in order to achieve a disturbance-free structure for automation systems. In addition to the procedures described in this document, the applicable standards and guidelines for electrical safety must be observed. The illustrations and symbols used in this document may differ from those in the relevant standards and guidelines.

1.1 Introduction to the subject/problem

An analysis conducted by the “Field Service Excellence” work group (WG) of the PROFIBUS User Organization in the years 2009 to 2014 has revealed the error causes that were most frequently identified during PROFIBUS and PROFINET service operations. It should be mentioned in this context that the service assignments of the WG are mainly troubleshooting activities that go far beyond the usual range of requirements on electrically skilled service and maintenance personnel.

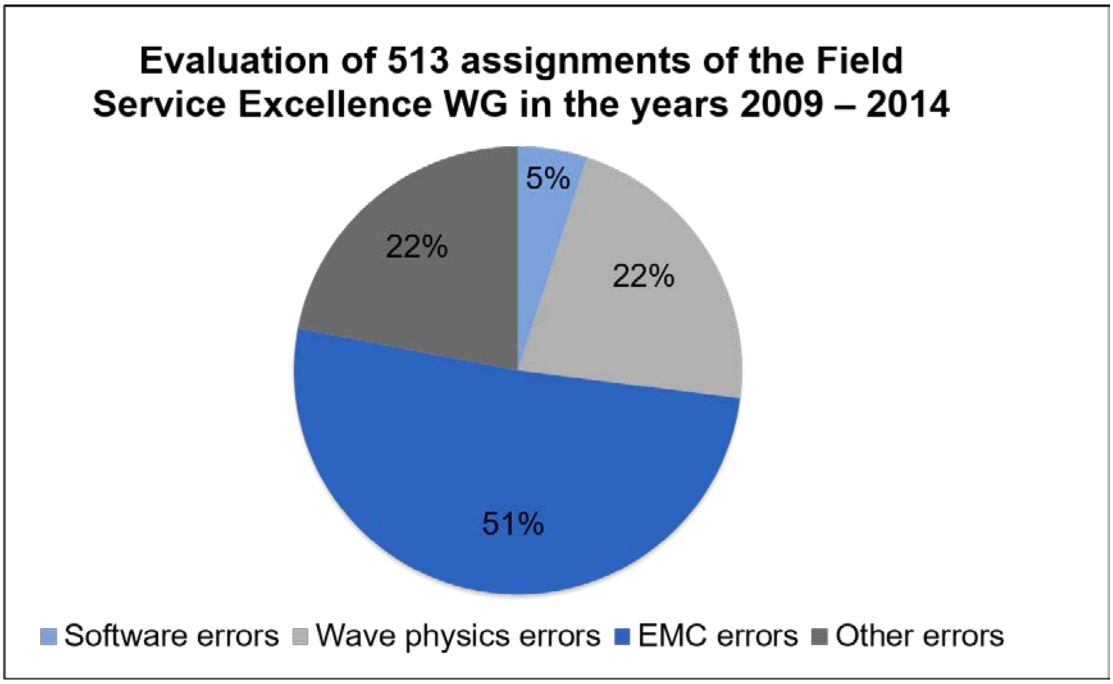


Figure 1: Evaluation of the assignments of the Field Service Excellence WG from 2009 to 20014 [GÖH2015]

Figure 1 clearly shows that EMC errors resulting from electromagnetic incompatibility have caused more than half of the service assignments of the companies joining the Field Service Excellence work group. These EMC errors are mainly problems that manifest themselves through impermissibly high shield currents, inductances without interference suppression and loads of the equipotential bonding systems.

1.2 Aim of this document

The aim of this document is to provide a basis for the functional bonding and shielding of PROFIBUS and PROFINET bus systems. The focus is not on the design of PROFIBUS/PROFINET devices, but on their correct connection and on the cabling of plants in order to prevent field-based disturbances and disturbances through the equipotential bonding system.

In a tiered approach, the readers are first made familiar with the technical basics of electromagnetic compatibility. Then the document imparts the fundamentals of functional bonding and shielding in process automation systems. In the next step, six recommendations for actions allowing to implement PROFIBUS and PROFINET networks with only little disturbance are given. A list of acceptance criteria completes this document.

2 EMI fundamentals

Electromagnetic interference (EMI) is a phenomenon where devices are affected by electric and magnetic fields. All electrical devices generate magnetic and electric fields, which may disturb the function of other devices. For example, EMI causes potential problems and data loss in communication lines. The counterpart of EMI is electromagnetic compatibility (EMC). A device's EMC must ensure that no field-conducted or line-conducted influences may disturb the device.

As can been seen in Figure 2, electrical devices may be affected by fields which have an effect on the PROFIBUS/PROFINET lines, power supply lines, signal/control lines or the functional earthing of the device.

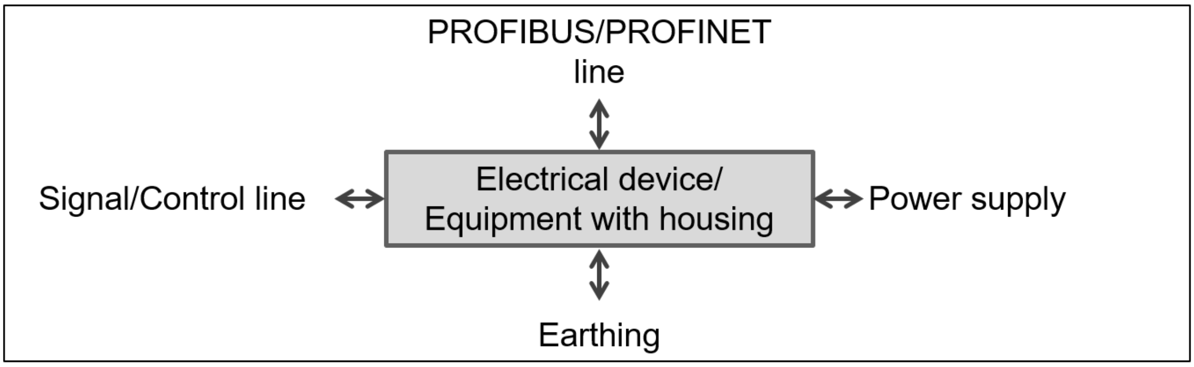


Figure 2: EMC interfaces of a device according to [RUD2011]

Besides the line-conducted disturbances shown in Figure 2, electric, magnetic and/or electromagnetic fields may additionally affect a device. However, these are not further considered here.

The conductive housings of automation system components are usually earthed due to reasons of electrical safety. Therefore, a potential equalization system in a plant is usually earthed as well. For this reason, this document does not differentiate between the connection to an earthing system and the connection to a potential equalization / equipotential bonding system. For technical reasons in many cases, the connection to a potential equalization system without earthing might be sufficient to fulfill the EMC requirements. This document will recommend in section 4.1.3 the use of a common bonding network (CBN) that serves the purpose of potential equalization, functional earthing and protective earthing. The expression CBN will be used in this document.

2.1 Couplings

A source of disturbance is only capable of disturbing another device if there are coupling lines. The coupling lines connect the source to the susceptible device (see Figure 3). In this context, the term "susceptible device" refers to electrical equipment such as PROFIBUS lines or a PROFIBUS device that may be affected by electromagnetic interference (EMI).

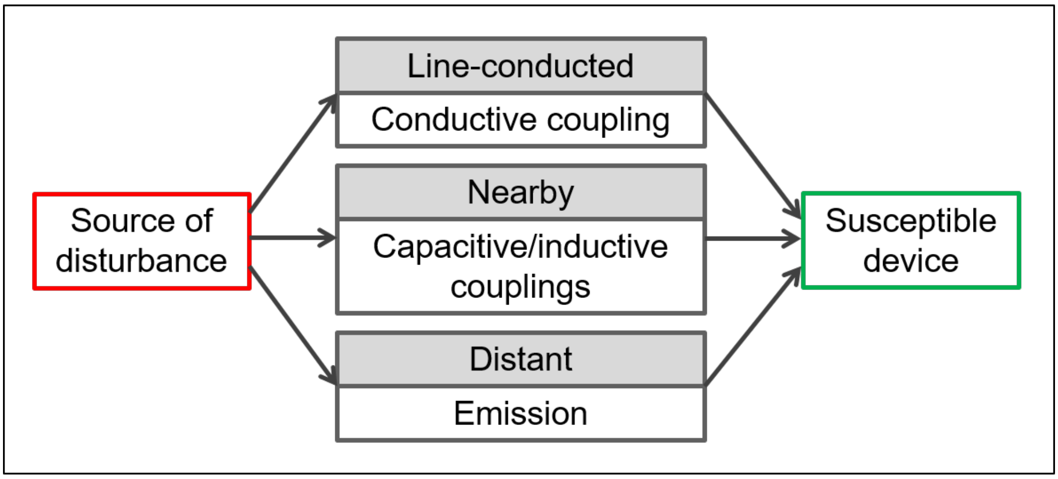


Figure 3: Coupling lines

The coupling lines shown in Figure 3 can be assigned to three different groups:

1. Line-conducted disturbances are caused by conductive connections between devices.
2. Nearby disturbances are produced by magnetic or electric fields causing inductive or capacitive coupling.
3. Emission lets disturbances in the form of electromagnetic waves propagate over long distances and couple into other devices (susceptible devices). This form of coupling is outside the scope of this document.

2.1.1 Conductive coupling

Conductive coupling requires an electrically conductive connection between two current circuits. This connection is also called coupling impedance. The common current flow of the two current circuits causes a voltage drop across the coupling impedance. This voltage drop produces a potential shift at both consumers (loads). Due to this potential shift, the voltage of the consumers/loads may fall below or exceed their rated voltage. [SCH2008]

Conductive coupling is hence a frequent cause of the emergence of potential differences in equipotential bonding systems. The drawings below illustrate the causes of potential differences in equipotential bonding systems.

Figure 4 shows a single current circuit in which the negative pole of the voltage source (U_1) has a connection to the common bonding system (CBN). Additionally, the line impedances (Z_L) and a consumer or load impedance (Z_C) are shown. The current I_1 flows from the voltage source across a line impedance to the consumer or load and returns via the second line impedance to the voltage source. No current flows through connector to the CBN, which only has to fulfill a safety function. As a result, conductive coupling into non-system current circuits is impossible.

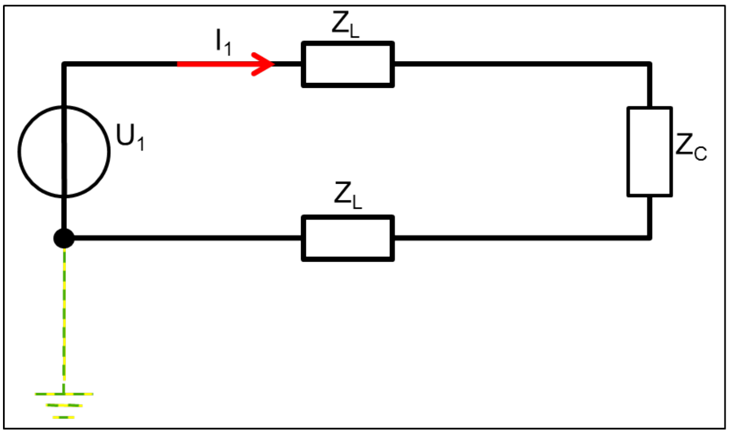


Figure 4: Conductive coupling in equipotential bonding system 1

In Figure 5, you can see another connector to the CBN at consumer/load Z_C. Due to this second connection, a parallel current circuit is formed (see Figure 6) through the equipotential bonding system. The parallel current circuit is represented in the illustration by series-connected equipotential bonding system impedances (Z_E).

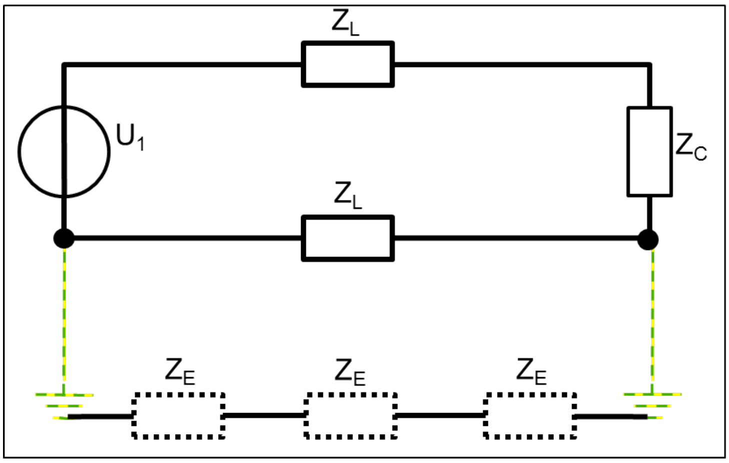


Figure 5: Conductive coupling in equipotential bonding system 2

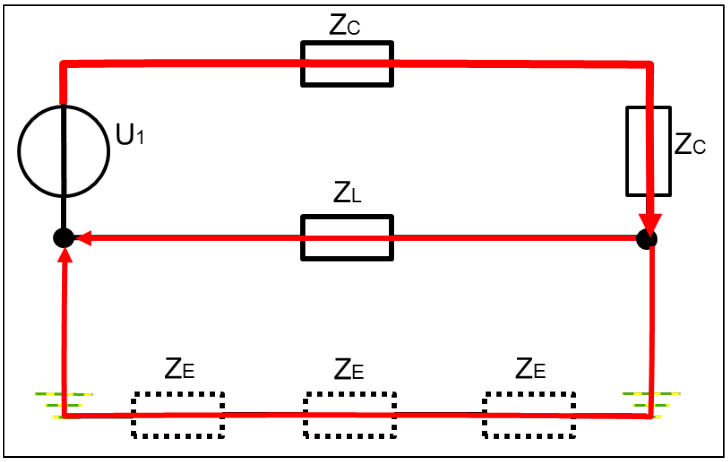


Figure 6: Conductive coupling in equipotential bonding system 3

In Figure 7, a measuring instrument is connected to the equipotential bonding system. The measuring instrument indicates a potential difference between two points of the equipotential bonding system emerging due to the current flow through the equipotential bonding system.

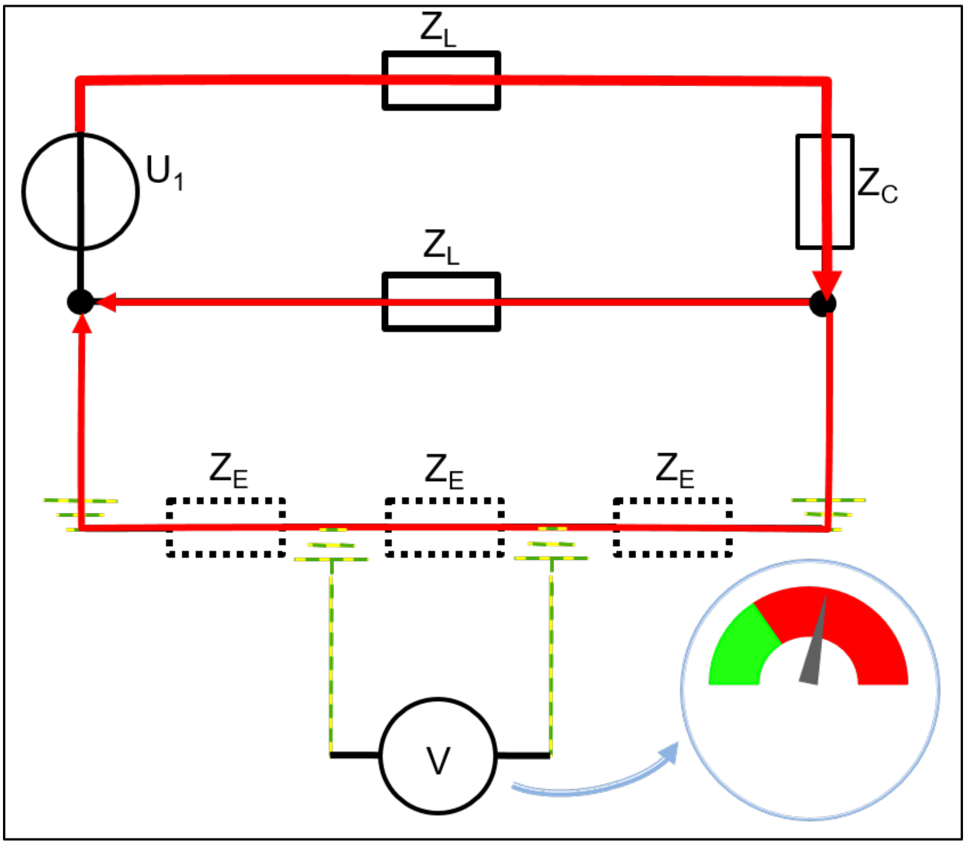


Figure 7: Conductive coupling in equipotential bonding system 4

If current circuits are connected to the common bonding system (CBN) several times, be it intentionally or unintentionally, a part of the current may flow through the equipotential bonding system. As a result, potential differences occur in the equipotential bonding system, despite its low inductance. These potential differences affect, amongst other things, shielded cables that have multiple connections to the equipotential bonding system. As cable shields are connected to the housing of the device, and thus with the common bonding network (CBN) each cable end, currents from the equipotential bonding system may flow through the cable shield of a data line and hence couple disturbances into it.

2.1.2 Capacitive coupling

Capacitive coupling emerges between two conductors that have at least a conductive connection and a potential difference. Figure 8 shows two voltage sources (U_1, U_2) with different voltages or shifted phases. Moreover, they are connected to the same equipotential bonding system. This connection and the different voltages produce an electric field between the cables. In the equivalent circuit diagram, the electric field is represented by a stray capacitance ($C_{1/2}$) [SCH2008].

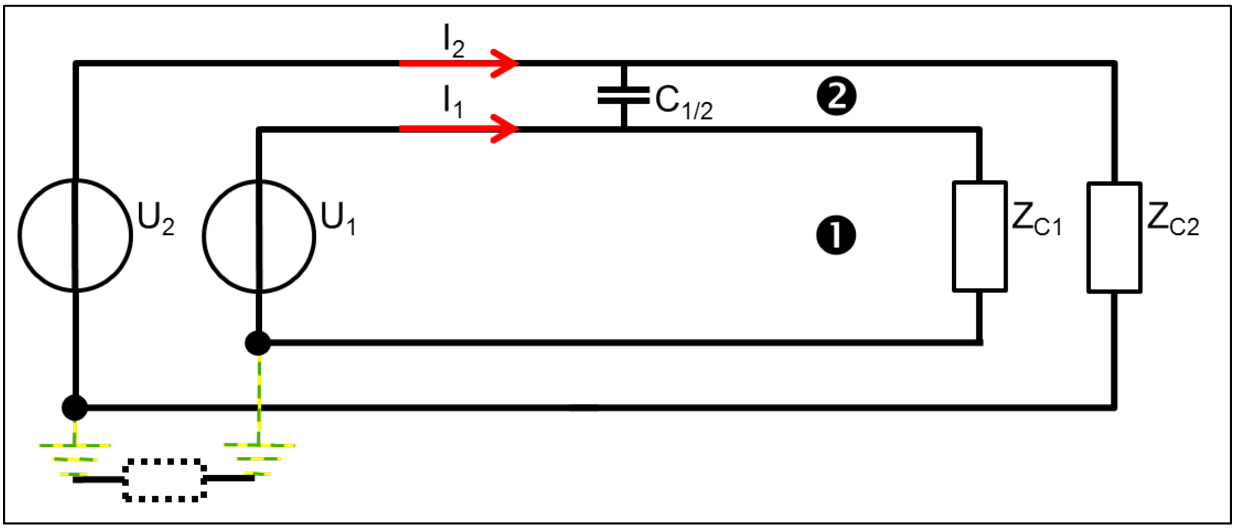


Figure 8: Capacitive coupling

The potential difference between two signal cables that have the same reference to the common bonding network (CBN) is a simple example of capacitive coupling. Due to the potential difference between the two cables, an electric field emerges which may cause mutual interference.

2.1.3 Inductive coupling

Inductive coupling results from magnetic fields between two current circuits (① and ②). The alternating current (I_2) generates a magnetic field, which causes a magnetic flux. The magnetic flux crosses the mesh of the current circuit ① and induces a voltage in it. The induced voltage generates a current in current circuit ① which overlays the wanted signal and may impair the function of the current circuit [SCH2008].

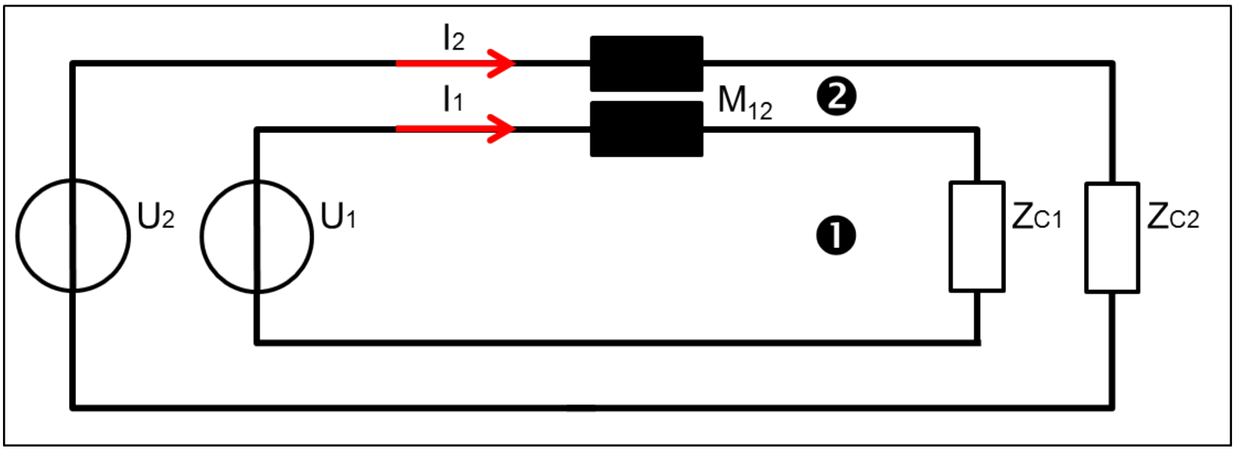


Figure 9: Inductive coupling

Inductive coupling is a phenomenon that frequently occurs in practice because it only requires current circuits in which the current changes over the time, such as alternating currents or transient currents in switching actions (on or off) that are located in the vicinity of other current circuits. No conductive connection between the two current circuits is needed. Physical proximity suffices to produce a significant common coupling inductance M_{12}.

2.1.4 Radiated coupling

In industrial cables of usually up to 100 m of length, radiated coupling between high-energy disturbers and signal current circuits only occurs at high frequencies (approx. 30 MHz and higher). This type of coupling is caused by the electromagnetic field [SCH2008]. PROFIBUS and PROFINET cables are relatively well protected against radiated coupling by their high signal level, twisted wires and shielding. Usually, radiated coupling impairs the electronics of the connected devices, for example due to insufficiently shielded device housings or electronics with insufficient EMI shielding. As the design of PROFIBUS/PROFINET devices are beyond the scope of this document and only their cabling is covered here, radiated coupling is not considered any further.

2.2 Electrostatic discharge

Electrostatic charges emerge from major potential differences caused by friction or separation of different materials. Friction of different materials leads to the transfer of electrons (charge separation) between the two materials. Due to the electron transfer, one material collects a positive charge and one material a negative charge. Typical examples of electrostatic charges emerging in an industrial environment are charges produced by plastic containers on a conveyor. Filling bulk material or liquids from one vessel into another is also likely to produce electrostatic charges. The electrostatic charges are discharged as soon as there is a conductive connection between two materials with a sufficiently high potential difference or a spark is produced because the dielectric strength of the air gap is exceeded. The resulting high current flow may disturb sensors and the related data communication [KLE2016].

2.3 Typical sources of disturbance in automation systems

In industrial environments, there are many potential sources of disturbance that are likely to jeopardize the reliable and safe operation of automation systems. Most of the disturbances are caused by the types of coupling described in section 2.1. This is why disturbing equipment often features high performance and higher frequencies or short switching times. Typical potential sources of disturbance are, for example, frequency converters, welding systems, solenoid valves and switching operations. Table 1 shows the frequency spectrum of these potential sources of disturbance.

Table 1: Frequency spectrum of potential sources of disturbance from [SCH2008]

Type of equipment	Frequency spectrum
Motor	10 Hz to 50 MHz
Frequency converter	1 Hz to 10 MHz
Switching operations	1 kHz to 200 MHz
Rectifier systems	50 Hz to 5 MHz
Power electronics	100 Hz to 100 MHz

Various types of shielding measures and the functional bonding of equipment are used to protect automation systems against typical frequency-dependent sources of disturbance. The following section details the fundamentals of functional bonding and shielding.

3 Fundamentals of equipotential bonding and shielding

This section deals with protective measures against functional disturbances used in automation systems. The first subsection focuses on cable shielding and the second subsection considers equipotential bonding.

3.1 Cable shielding

Cable shields use two different principles to suppress the individual types of disturbance. These principles are called “active shielding” and “passive shielding”. They are explained in more detail in the following two subsections. Besides these two shielding measures, there are other protective measures such as the twisting of data wires in order to ensure undisturbed data communication via PROFINET and PROFIBUS cables.

3.1.1 Passive shielding

A shielding effect solely achieved by using shielding material of sufficient thickness is referred to as “passive” shielding. The minimum material thickness required for the shielding effect depends on two factors: firstly, the frequency of the disturbance and, secondly, the magnetic permeability of the material in the presence of magnetic fields. If the shield has a material thickness greater than the minimum required material thickness, eddy currents can occur inside the shield. The eddy currents generate a field that is oriented oppositely to the disturbing field. This nearly eliminates the disturbing effect. However, this shielding effect is normally provided by cable shields, as their material thickness is insufficient and instead is usually achieved by metal-type cable ducts with separators and covers or steel tubes.

3.1.2 Active shielding

Due to the low material thickness of cable shields, the active shielding effect is used. However, for active shielding to work, it is necessary to connect the cable shield to the common bonding network (CBN) at several points in order to establish a current circuit [WOL2008].

It the cable shield is connected to the common bonding network (CBN) at one point, only, capacitive coupling will occur if there is a potential difference between a cable and the shield. Figure 10 shows a schematic structure of capacitive coupling between two current circuits. This schematic structure can also be applied to active shielding against electric fields (Figure 11).

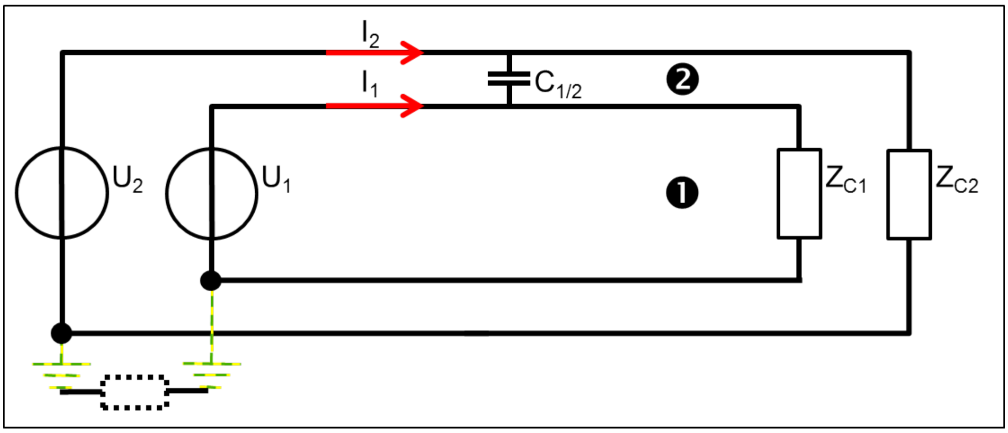


Figure 10: Repetition of capacitive coupling

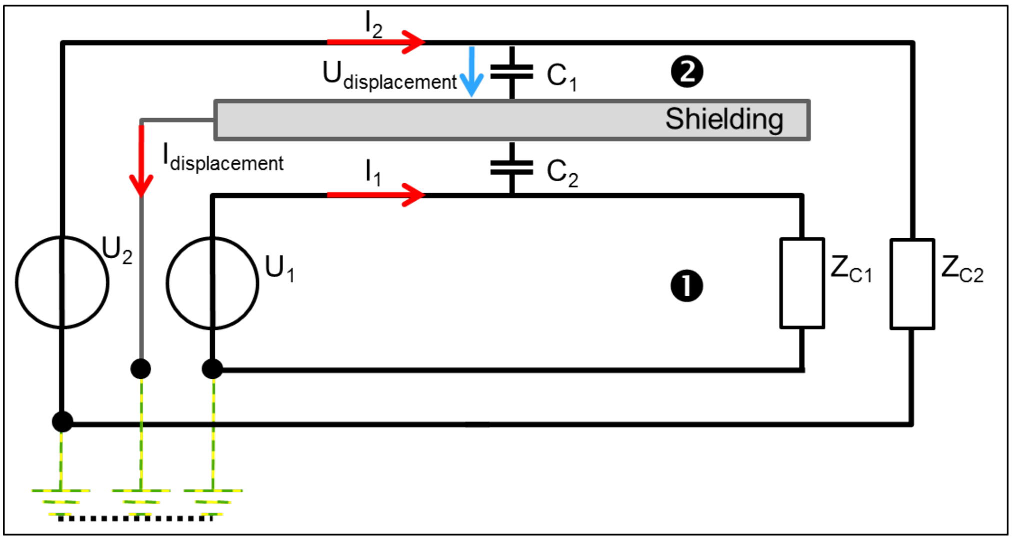


Figure 11: Active shielding with one-sided connection to the common bonding network (CBN)

Due to one-sided connection of the cable shield (shown in gray color in Figure 11) to the common bonding network, the two stray capacitances C_1 and C_2 are produced between the current circuits (① and ②) and the cable shield. These stray capacitances emerge because the cable shield has a 0 V potential resulting from its connection to the common bonding network (CBN). Coupling disturbances from current circuit ② into current circuit ① is hence prevented, because the displacement currents ($I_{displacement}$) coupled into the circuit can directly return to the voltage source U_2.

If the cable shield has two or more connections to the common bonding network (CBN), there is an additional shielding effect against magnetic fields called “active shielding”. When exposed to magnetic fields, a voltage is induced due to multiple connections of the cable shield to the common bonding network (CBN), and the induced voltage allows a current ($I_{induced}$) to flow in the cable shield (②), as shown in Figure 12.

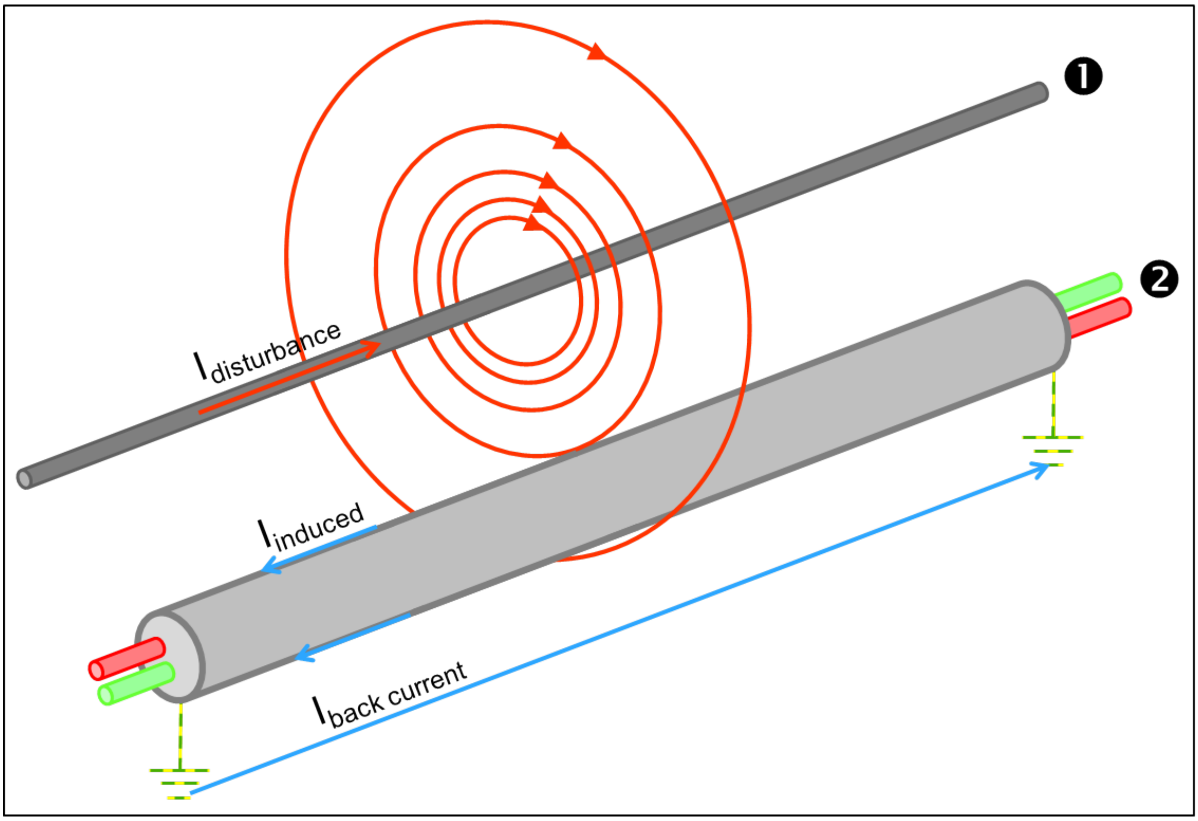


Figure 12: Induction in the cable shield

The induced current flow produces a counter-induction with a 180° phase shift to the initial induction of the magnetic field. Inside the cable, the magnetic field of the disturbance and the magnetic field of counter-induction overlay each other. This overlay produces an area that is nearly free from any fields in the middle of the cable② [WOL2008].

For this reason, cable shields should be connected to the common bonding network (CBN) at least at both ends in order to achieve a sufficient shielding effect against magnetic fields and alternating electromagnetic fields.

3.2 Equipotential bonding

Earthing points can be found everywhere in a plant or on plant equipment. A distinction is made between protective earthing (PE) and functional equipotential bonding. Protective earthing is intended to ensure the safety of humans and to prevent hazardous touch voltages on housings and other conductive parts. Functional equipotential bonding, in contrast, serves the equipotential bonding of devices that is not safety relevant.

3.2.1 Protective earth conductor (PE)

The protective earth conductor ensures protection of electrical active devices with the protective measure “protective earthing” in the event of a fault. It facilitates the protection of persons against electrical shock by indirect contact.

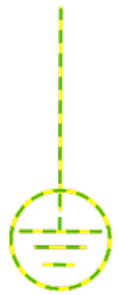
Indirect contact is caused by an electrically conductive, usually metallic, object of electrical active devices, which may build up an electrical voltage to earth in the event of a fault. Such a fault scenario could be a 230 V cable, which has accidentally come loose and come in to contact with a metal part of the device. Therefore, every electrical device with an operating voltage above 50 VDC or 120 VAC must have a PE-terminal for the protective earth conductor.

3.2.2 Protective equipotential bonding

A different setting applies for electrically passive, but touchable, conductive parts of the plant, e.g. a handrail, a protective fence or a roller conveyor. Here no PE terminal is present. However, it is recommended to connect those parts of the plant to the protective equipotential bonding system. If a handrail is connected to the protective equipotential bonding system, then - in the case of an error (phase connected to the handrail due to failure of basic and additional insulation) - a fault current can trigger a protective device like a fuse or an RCD and switch off the circuit.

As the handrail is connected to the protective equipotential bonding conductor, a fault current of sufficient intensity is produced and triggers a safety device (fuse, fault current circuit breaker) to disconnect the current circuit from mains. If, however, the handrail were not connected to the protective equipotential bonding conductor, a voltage of 230 V would be present between the handrail and earth, presenting a danger to the life of humans and (farm) animals that might come into contact with it. It is therefore recommended to connect all passive, electrically conductive objects such as pipes, protective fences, ladders, handrails, metal cable ducts or other structural components to the protective equipotential bonding in order to prevent impermissible touch voltages.

In this document, the connection of electrical equipment to a protective conductor or protective equipotential bonding is marked by the following symbol:



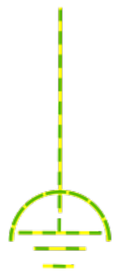
3.2.3 Functional equipotential bonding (FE)

"The purpose of functional equipotential bonding is the reduction of:

- *the effects of an insulation fault that may affect operation of a machine;*
- *the effects of electrical disturbances on sensitive electrical equipment that may affect operation of a machine."* [DIN-EN 60204-1]

This means that functional equipotential bonding does not serve the safety of humans and (farm) animals, but the functional reliability of a plant. Among the objects that are usually connected to the functional equipotential bonding are, for example, motor shields, data cable shields and functional bonding conductors of sensitive component parts.

In this document, the connection of electrical equipment to a functional equipotential bonding is marked by the following symbol:



4 Recommendations for the design of PROFIBUS and PROFINET networks with little disturbance

These recommendations provide instructions on how to design systems with only little disturbance. The individual recommendations deal with the following:

- Combination of protective and functional equipotential bonding systems to form a common network
- Implementation of 230/400 V power supply differentiation between the individual types of earthing for network systems (TN-S, TN-C, TN-C-S, TT and IT)
- Minimum distances between power cables and PROFIBUS/PROFINET cables
- Setup of the equipotential bonding system
- Connection of PROFIBUS/PROFINET cable shields
- Peculiarities of motor cables
- Connection of the negative pole in a 24 V power supply circuit to the common bonding network (CBN)

The following subsections provide general explanations and problem descriptions for all seven topics on the basis of standards and specialist literature. Additionally, a recommendation for the functional bonding and shielding of PROFIBUS/PROFINET networks is derived from the standards. The recommendations are applicable for both the manufacturing industry and the process industry. The only exception is the application in hazardous areas where this subject is not covered by these recommendations, as additional regulations are valid and must be observed for the functional bonding and shielding of cables in hazardous areas. For bus lines that either leave the building envelope or are laid outdoors the applicable lightning protection directives must also be observed in addition to this document. It is recommended to preferably use fiber optic cables as bus lines that leave buildings or are supplied from different main distributors.

Figure 13 shows a plant example from the process industry.

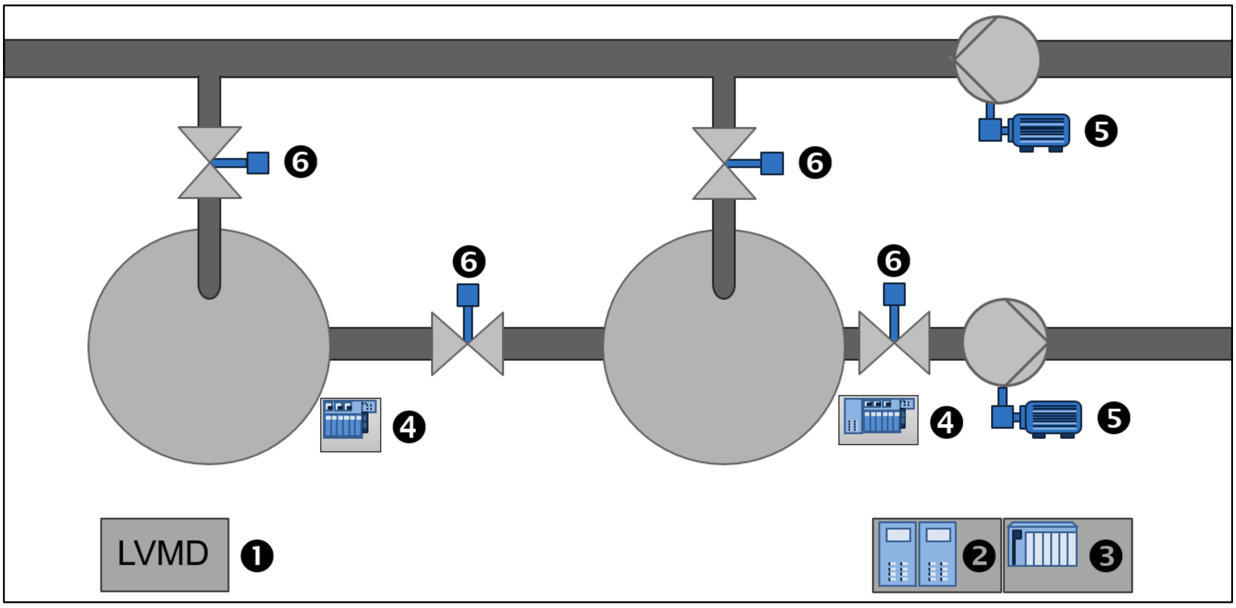


Figure 13: Plant example from the process industry

The plant shown in Figure 13 has two vessels that are filled and emptied by pumps ⑤ and valves ⑥. A low voltage main distributor ① (LVMD) is used for power supply to the plant. It supplies the cabinet that accommodates the frequency converter ② and the programmable logical controller ③ (PLC). Additionally, the plant comprises two decentralized remote I/O units ④ controlling the sensors and actuators. In this plant example, you can see an exemplary presentation of the following problems: Control of drives/actuators, wide-spread plants and automation equipment distributed in the field.

Figure 14 shows a manufacturing plant. In this plant, robots ⑥ transport various components between conveyors ⑦ and processing tables ⑧.

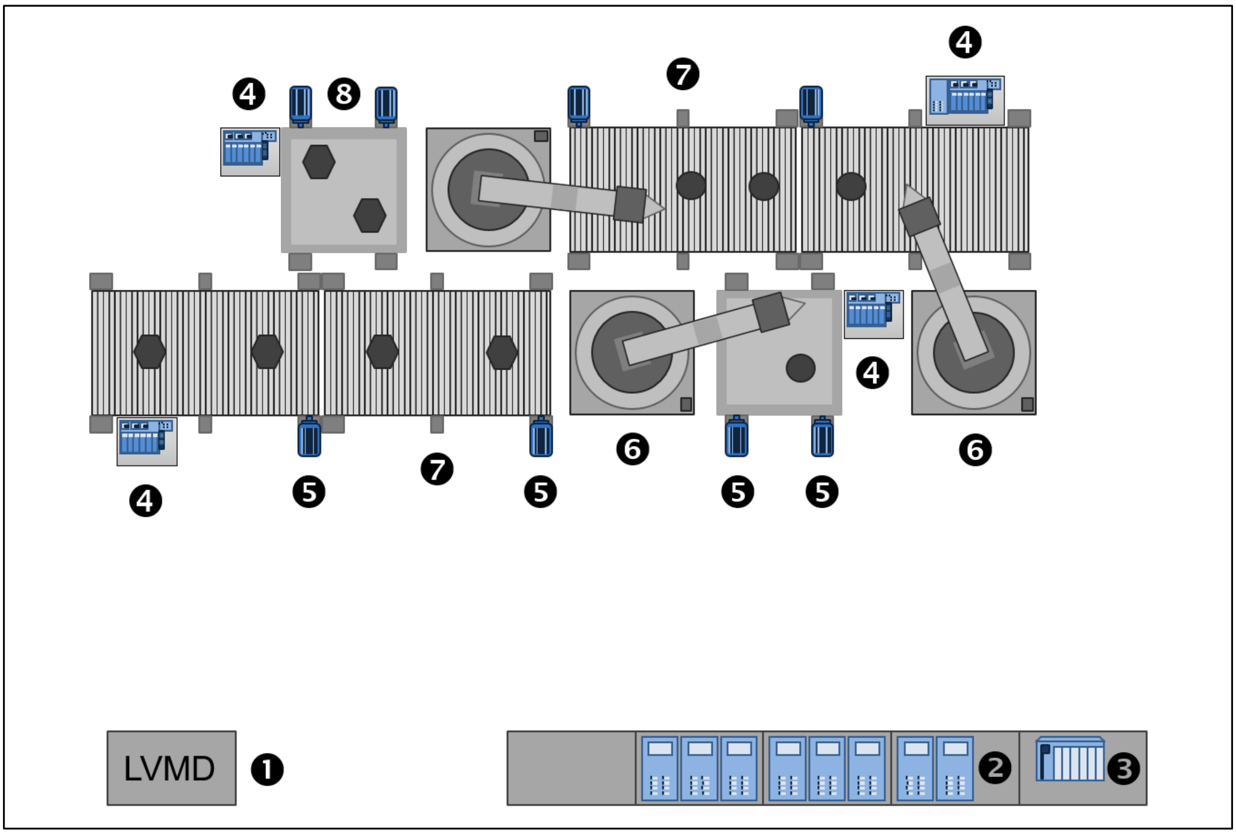


Figure 14: Plant example from the manufacturing industry

Like in the plant example from the process industry described above, the manufacturing plant in this example is supplied via the low voltage main distributor ① (LVMD); the cabinet accommodates the programmable logical controller ③ and several frequency converters ② for operating the motors ⑤. Some decentralized remote I/O units ④ are located in the field of the plant. In this plant example, you can see an exemplary presentation of the following problems: Control of drives/actuators, wide-spread plants with conveyors and connection of robots.

4.1 Combination of protective and functional equipotential bonding systems

In the manufacturing industry and in the process industry both separate and common protective and functional equipotential bonding systems are used. Separating the two systems is reasonable under the assumption that in this case no currents flowing in the protective equipotential bonding system can couple into the functional equipotential bonding system, causing disturbances. Protective equipotential bonding serves the safety of humans and (farm) animals. Functional equipotential bonding serves to ensure full plant functionality, for example by eliminating disturbances caused by electromagnetic fields. Both equipotential bonding systems are laid out in a star or tree topology distributed over the entire plant area, and they are interconnected at a just one point. Usually, the central protective earth connector (Main Earth Terminal) of the plant is used as the connection point for the protective and the functional equipotential bonding systems.

4.1.1 Problem description

Nowadays, having completely separated functional equipotential bonding and protective equipotential bonding systems in a plant is no longer practical as there are always several points in a plant where unwanted connections are likely to occur.

For example, the usage of PROFIBUS and PROFINET may result in a connection between the functional and the protective equipotential bonding system. In order to ensure full functionality of PROFIBUS/PROFINET lines, you have to connect each line end to the functional equipotential bonding system (see section 3.1.2).

To achieve this, the cable shield has to be connected to a large contact surface on a PROFIBUS/PROFINET connector housing, a separate equipotential bonding bar or a suitable shield connector at the device. This measure already satisfies the requirement to connect the functional and the protective equipotential bonding systems to each other.

4.1.2 Solutions from standards and specialist literature

No standard requires a strict separation of the functional and protective equipotential bonding systems. In the standard [DIN-EN 60204-1] you will find an explanation on how to achieve functional equipotential bonding by means of a connection to the protective equipotential bonding system. If, however, the protective equipotential bonding system is heavily loaded by currents, providing a separate functional equipotential bonding system may become necessary.

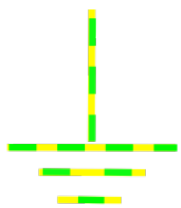
Hence, when using a common equipotential bonding system it must be ensured that the currents flowing through it are as low as possible.

Additionally, the standard [IEC 60364-5-54] requires that common protective and functional equipotential bonding conductors always have to meet the requirements on protective conductors. With this, the minimum cross-sectional areas, line impedances, minimum ampacity and protection against self-loosening of equipotential bonding conductors are clearly defined.

4.1.3 Recommendations for PROFIBUS and PROFINET

As already stated, a strict separation of functional and protective equipotential bonding systems is not feasible in practice, as unintended connections between the two bonding systems frequently occur. Moreover, attempts to separate the two systems can incur high costs. Common equipotential bonding is therefore recommended. A common equipotential bonding system of this kind is referred to as Common Bonding Network (CBN). It combines both the protective functions required for triggering circuit breakers in case of a fault and the functional equipotential bonding functions for avoiding electromagnetic interference.

In this document, the following symbol is used for marking a CBN connection:



Please note that this symbol is just used for the purpose of this document. In the relevant standards on this subject you can find different symbols for this.

From this section of the document, the first recommendation R1 is derived:

Provide both protective equipotential bonding and functional equipotential bonding through a common bonding network (CBN)

4.2 Implementation of 230/400V mains supply

This section deals with the reduction of disturbances and loads of the equipotential bonding system by using the appropriate mains supply network systems. The standard [DIN-VDE 0100-100] specifies several mains supply network systems. They are called TN-S, TN-C, TT and IT systems and are shown in Figure 15.

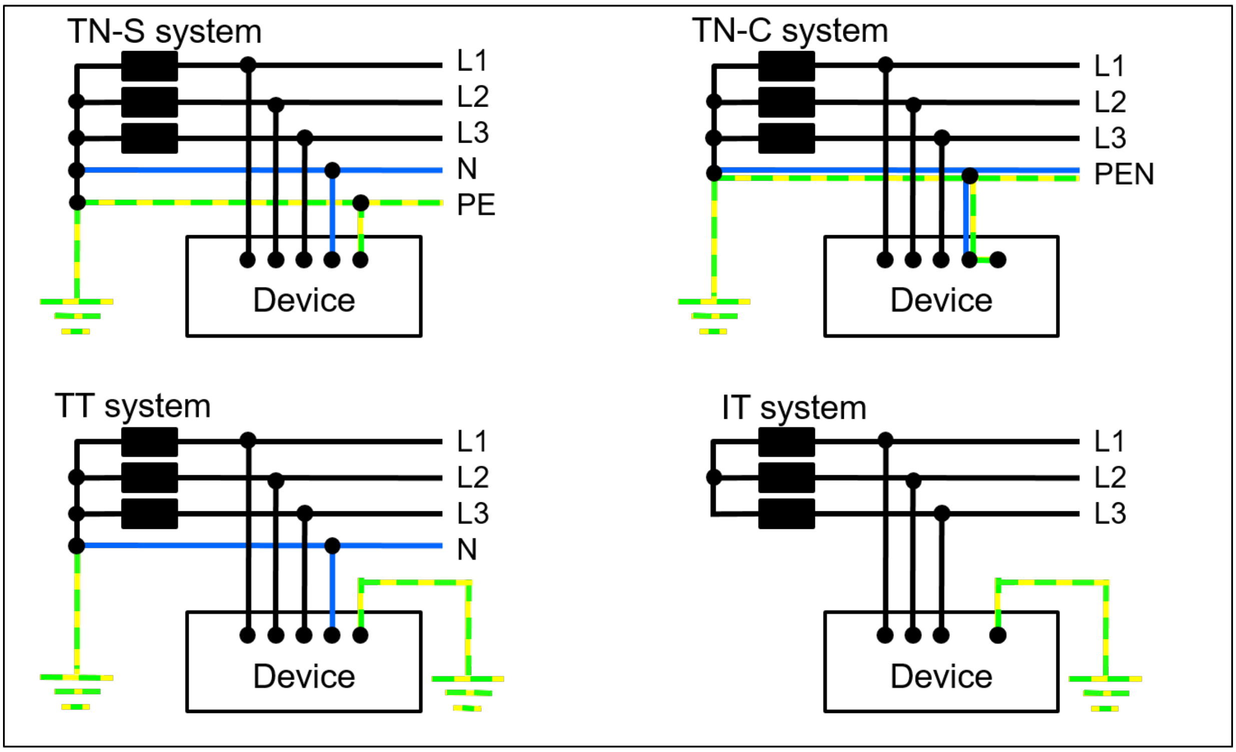


Figure 15: Network systems

In the TN-S, TN-C and TT systems shown in Figure 15, the neutral point of the feeding transformer is connected to protective earth. The neutral point in an IT system is not earthed and a neutral conductor may or may not exist in an IT system.

In TN and TT systems, the star point of the transformer is earthed. In TN-S networks the protective earthing of the device takes place via the protective earth conductor, that is grounded at the star point of the transformer. In TN-C networks the protective earthing of the device is performed via the combined Protective / Neutral conductor (PEN). The protective conductor and the neutral conductor in a TN-C system are parts of a common conductor line. In a TN-S system, on the contrary, the protective conductor and the neutral conductor are laid separately.

The neutral point in an IT system is not earthed.

In a TT system, the neutral point of the transformer is earthed. There is no protective conductor connection between the neutral point of the transformer and the connected devices. These are earthed locally. [SCH2008]

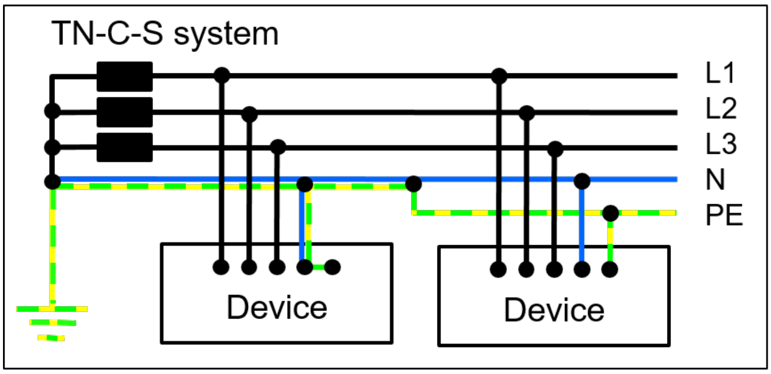


Figure 16: TN-C-S system as network system

A TN-C system and a TN-S system can be combined to form a TN-C-S system. Figure 16 shows a TN-C-S system. In this TN-C-S system, Device 1 is connected to the TN-C system, whereas Device 2 is connected to the TN-S system. The connection of the systems between the two devices is achieved by separating the previously used PEN conductor into a protective conductor and a neutral conductor. It is important not to recombine the separated N conductor and PE conductor to form a common PEN conductor again.

The type of mains supply is defined when deploying the energy supply system. It determines whether using a TT system, TN system or IT system is possible or not. Normally, power is supplied via a TN-C system; therefore, the recommendation at the end of this section is based on this system type.

4.2.1 Problem descriptions

4.2.1.1 Mains supply network as TN-C system

In Figure 17, a cabinet powered via a low voltage main distributor (LVMD) and a TN-C system is shown. In addition to the three active conductor lines (L1, L2, L3), the LVMD comprises the PEN conductor. This is a typical conductor in a TN-C system and it combines the protective conductor and the neutral conductor. In order to simplify the illustration, no fuses, terminals, meters etc. are shown. Nevertheless, they will have to be considered later on in the planning phase of the system. Additionally, an exemplary representation of the central earthing point can be seen in the LVMD. The central earthing point connects the foundation earth electrode to the PEN conductor at one point.

The low voltage main distributor is powered via a transformer. Figure 17 only shows the secondary circuit of the transformer.

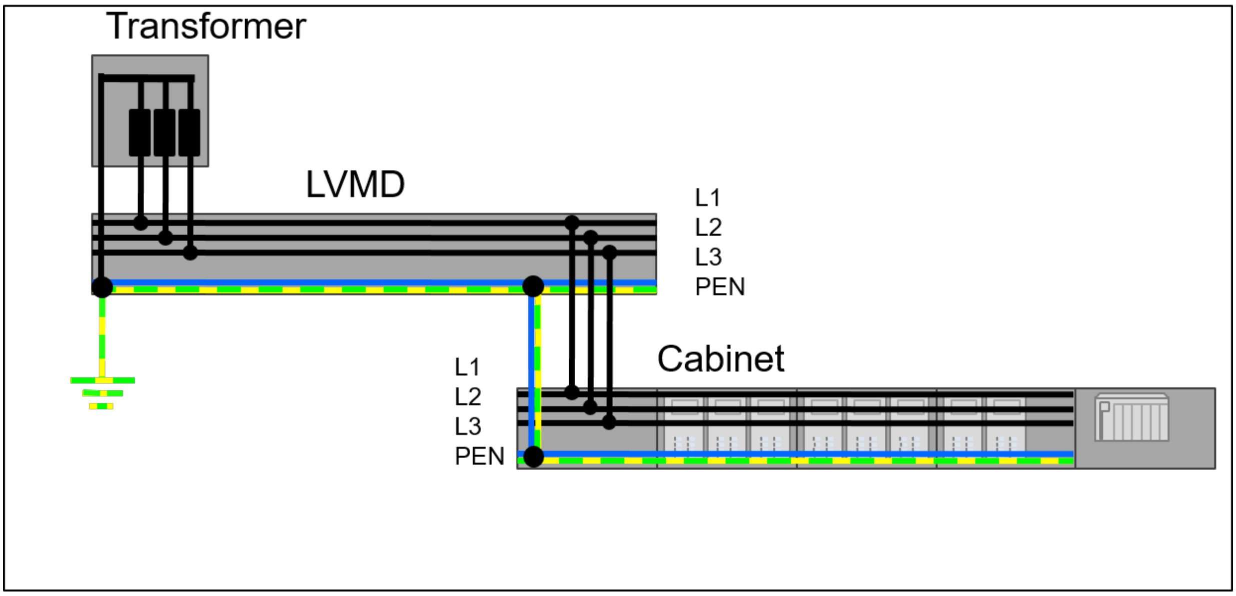


Figure 17: TN-C system

In the following step, the current flow is considered. For this reason, in Figure 18 a single-phase motor is connected into the circuit between L1 and PEN as a load.

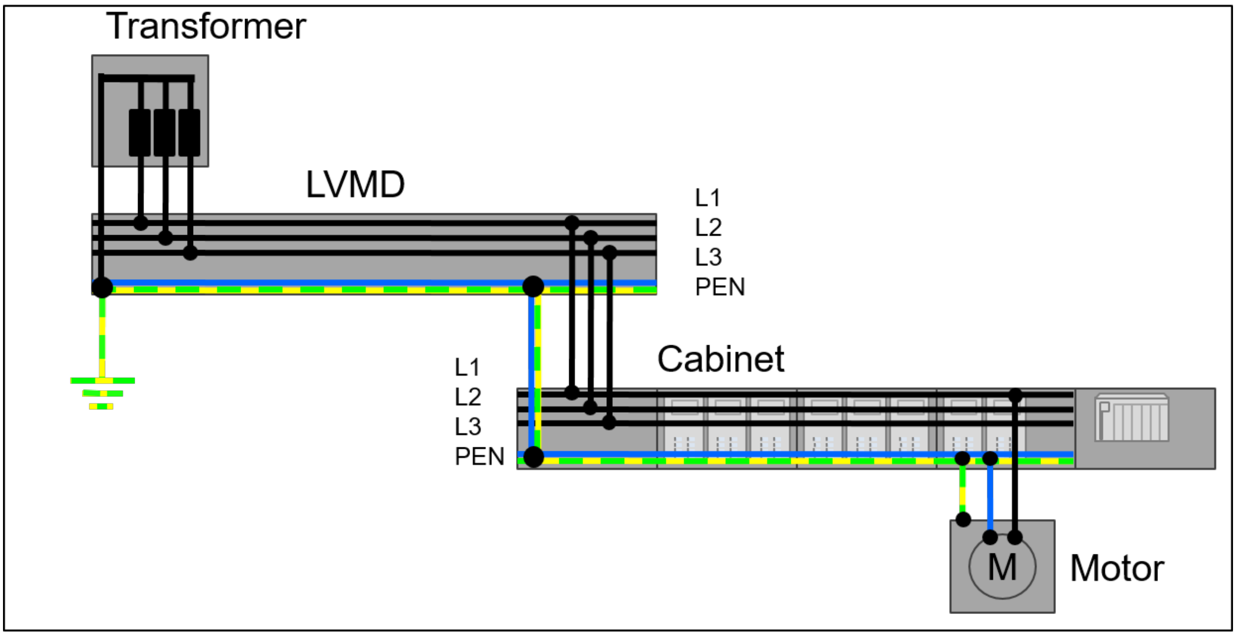


Figure 18: TN-C system with load

Figure 19 illustrates the current flow generated by the motor that has been connected into the circuit. The current flows from the transformer via L1 to the motor. It returns from the motor via its neutral conductor to the distribution panel in the cabinet and from there via the PEN conductor to the transformer.

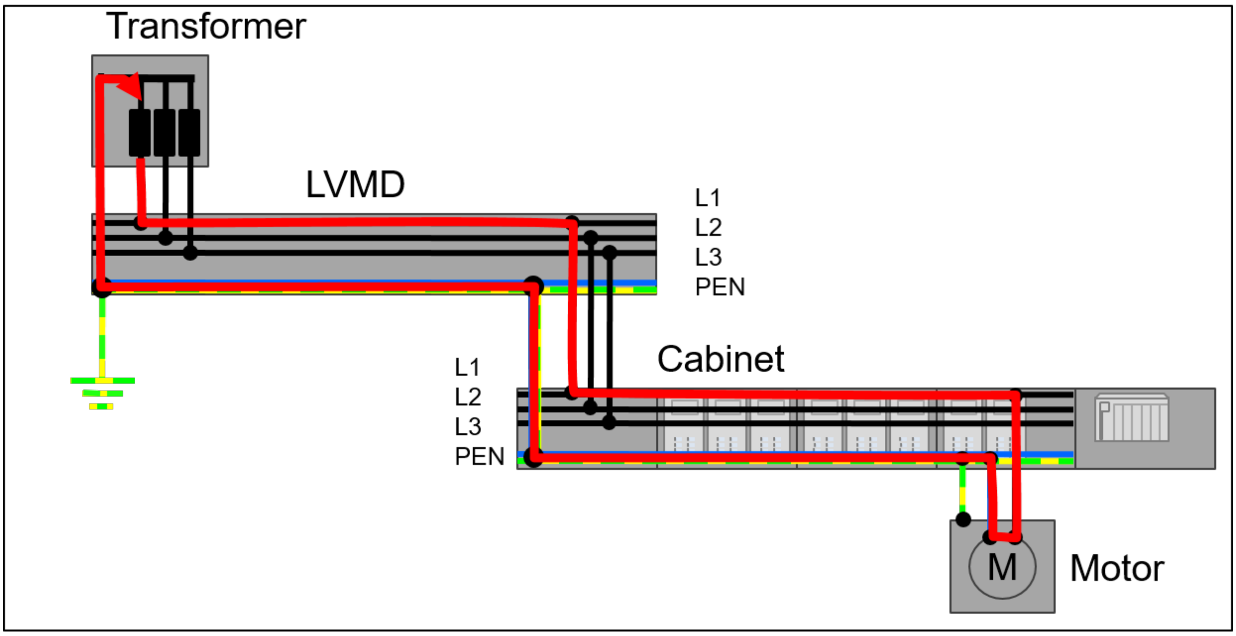


Figure 19: TN-C system with load and current flow

Problems will occur in the TN-C system as soon as the PEN conductor is connected intendedly or unintendedly to the equipotential bonding system. Such an additional connection may occur at the motor shaft or the motor fastening point to a metal support, owing to the construction. In Figure 20, the connection of the motor to the equipotential bonding system is shown under ① as an example.

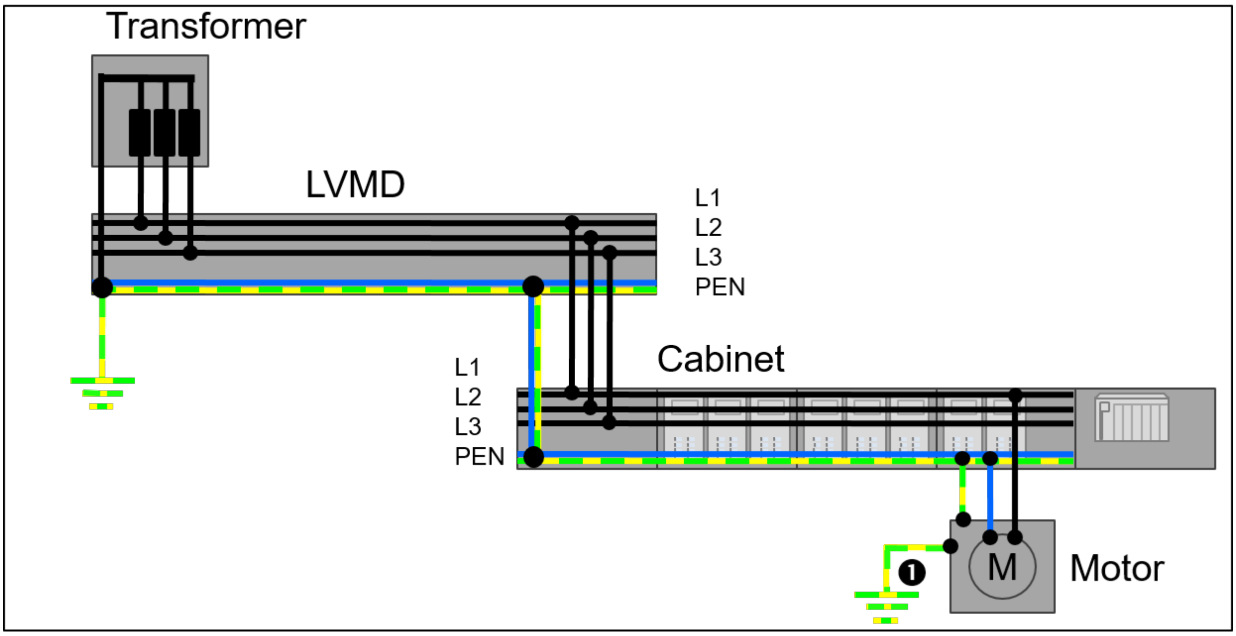


Figure 20: TN-C system with several connections to the equipotential bonding system

Figure 21 shows another possible current flow than Figure 19, taking into account the potential current flows at the motor and the existing connection to the equipotential bonding system. In this case, the current flows from the motor via the N conductor back to the PEN conductor of the cabinet. The major part of the current will flow via the PEN conductor to the LVMD and to the transformer. A partial current, however, will also flow through the PE conductors to the motor housing and return from there through the equipotential bonding system to the LVMD earthing point and to the transformer.

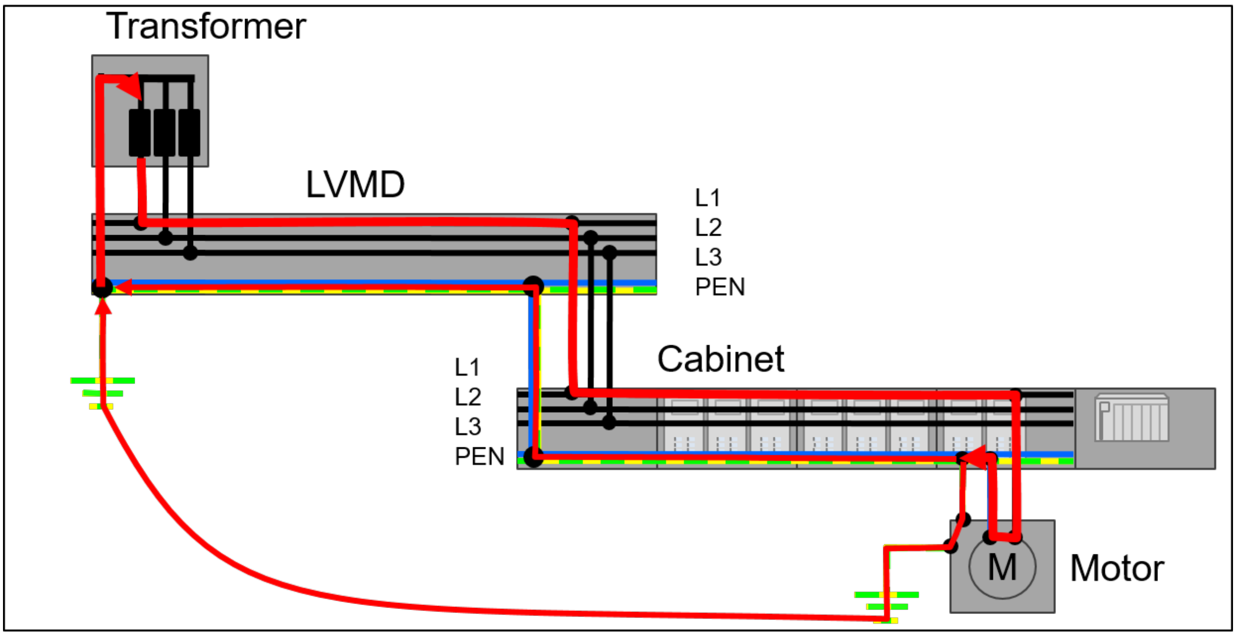


Figure 21: TN-C system with multiple earthing, load and current flow

A potential difference between the two earthing points emerges due to the current in the equipotential bonding system and to the voltage drop caused by the current flow. This potential difference may be bridged by the cable shields of the motor and data lines, as the cable shields are connected to the equipotential bonding system at several points. However, the cable shields are not designed for carrying operating currents and may be damaged due to excessive current load.

4.2.1.2 Mains supply network as TN-C-S system

The new TN-S system has been developed from the TN-C system, which is rather outdated seen from the vantage point of the present. In this case, the neutral conductor and the protective conductor are implemented separately. It is, however, also possible to combine both systems. The combination, called TN-C-S system, is shown in Figure 22. The system in the LVMD is still a classical TN-C system with a PEN conductor. In the cabinet, the protective conductor and the neutral conductor are separated from each other, making the system a TN-S system. The only connection between these two conductors is a PEN bridge.

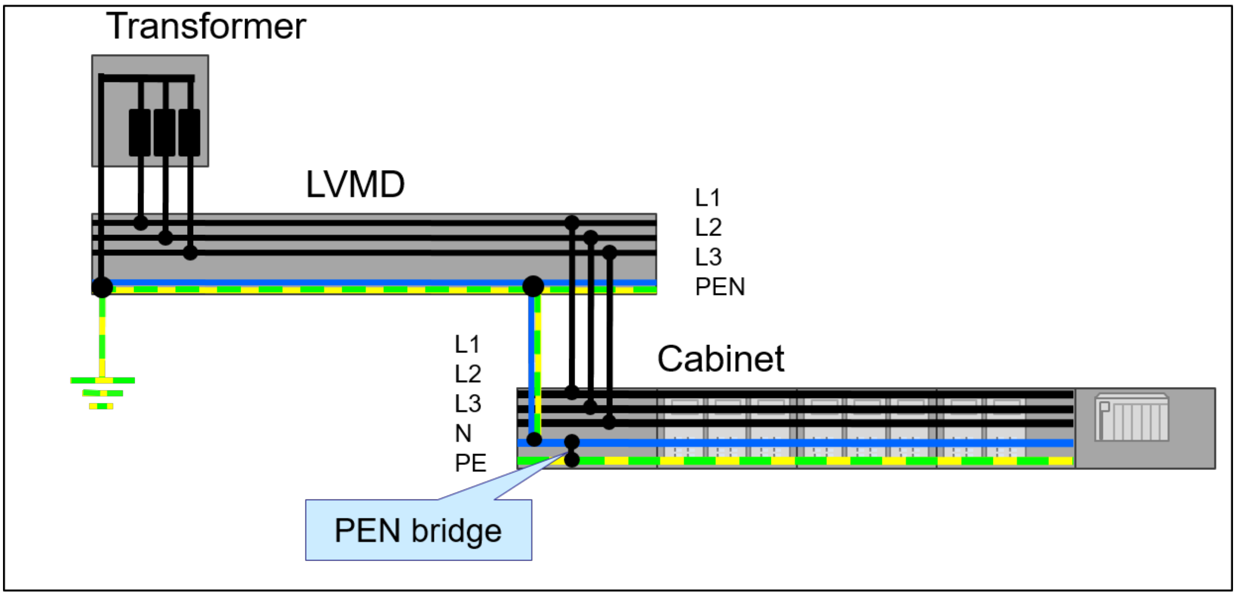


Figure 22: TN-C-S system

The current flow through the motor connected into the circuit in Figure 22 as an exemplary load is shown in Figure 23 in red. The current flows from the transformer via the conductor line L1 through the LVMD and the cabinet to the motor. From the motor, it flows via the neutral conductor to the cabinet and returns from there via the PEN conductor in the LVMD to the transformer.

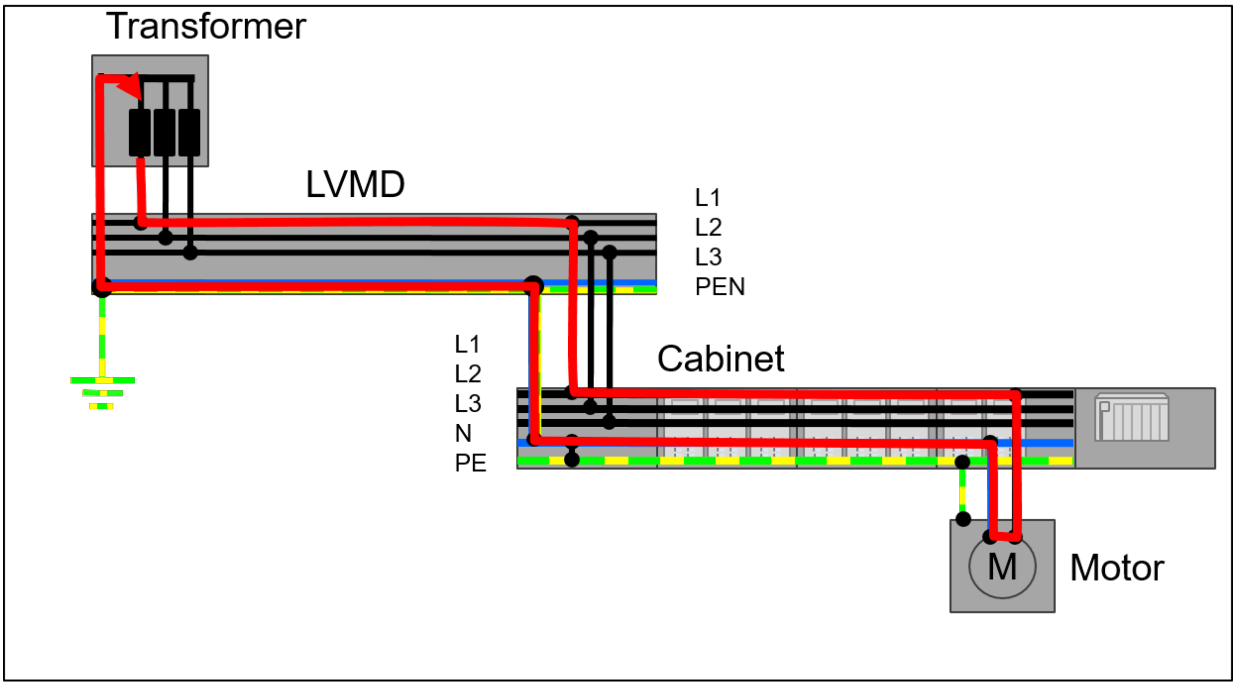


Figure 23: Current flow in a TN-C-S system

As the motor may have several intended or unintended conductive connections to the equipotential bonding system, the current flow shown in Figure 24 is also possible. In this example, the current does not only return from the cabinet to the LVMD via the PEN conductor, but also - as a partial current - via the protective conductor of the motor and the equipotential bonding system.

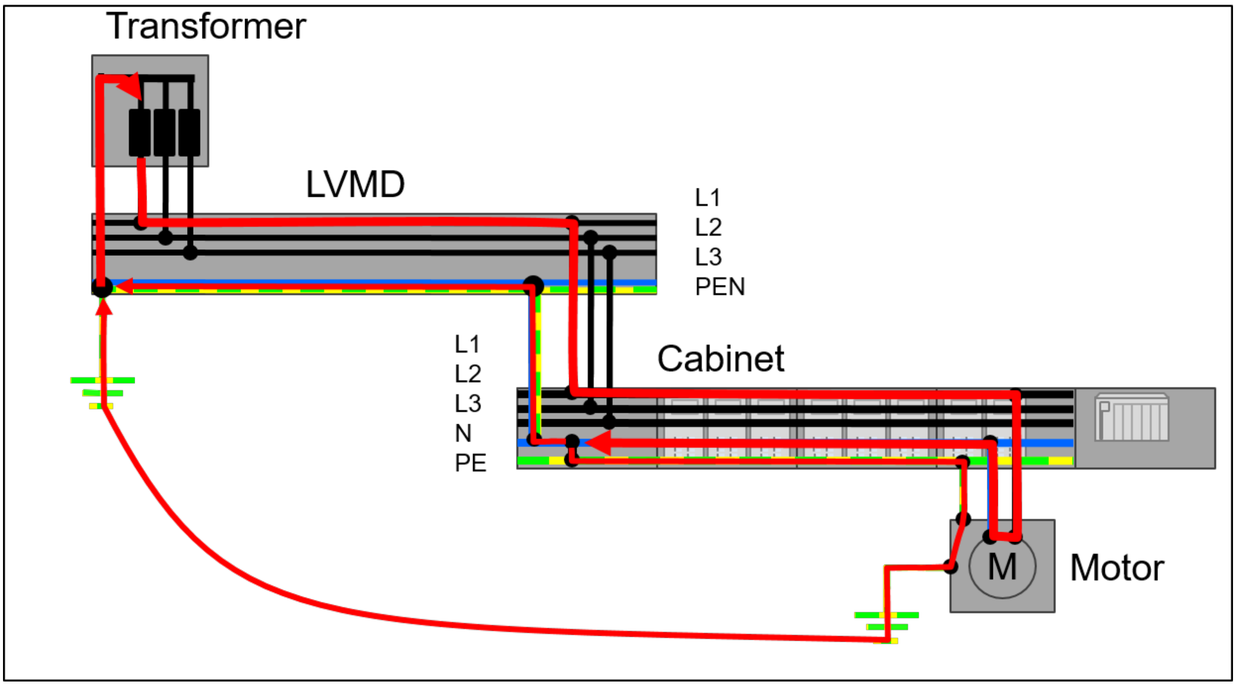


Figure 24: Current flow in a TN-C-S system with multiple earthing

As this current flow may not only cause damage to the equipotential bonding system, but could also affect other components such as motor bearings or gears, it is recommended to intentionally implement a second connection between the equipotential bonding system and the protective conductor of the TN-S system in the cabinet. Such a connection is shown in Figure 25. Earthing considerably reduces the current flow through the protective conductor to the motor.

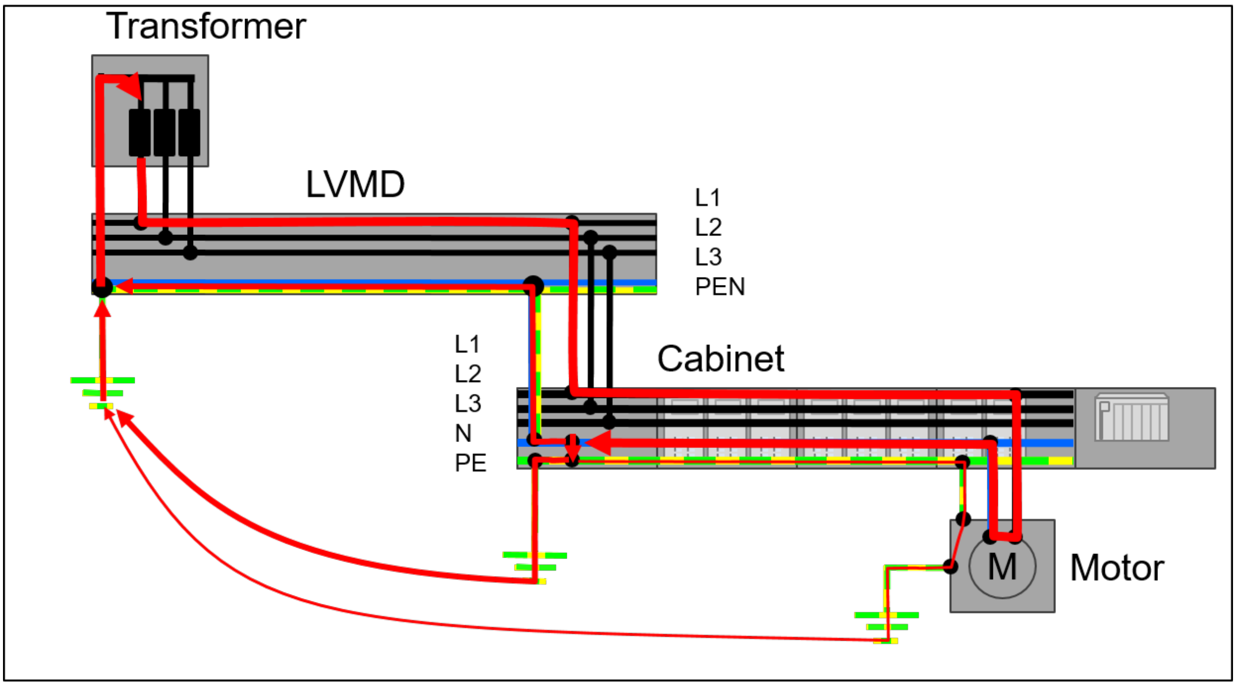


Figure 25: Current flow in a TN-C-S system with targeted multiple earthing

The taken measure, i.e. the connection of the protective conductor to the equipotential bonding system when implementing the TN-S system in the cabinet protects the connected loads against operating currents through the protective conductor. However, the current flow through the equipotential bonding system is not prevented. The residual current flow is still capable of damaging the cable shields of data lines.

4.2.1.3 Mains supply network as TN-S system

Seen from the vantage point of the present, it is better to have pure TN-S systems or to separate the individual components of the plant's PEN conductor early. The separation is made in the LVMD, as shown in Figure 26.

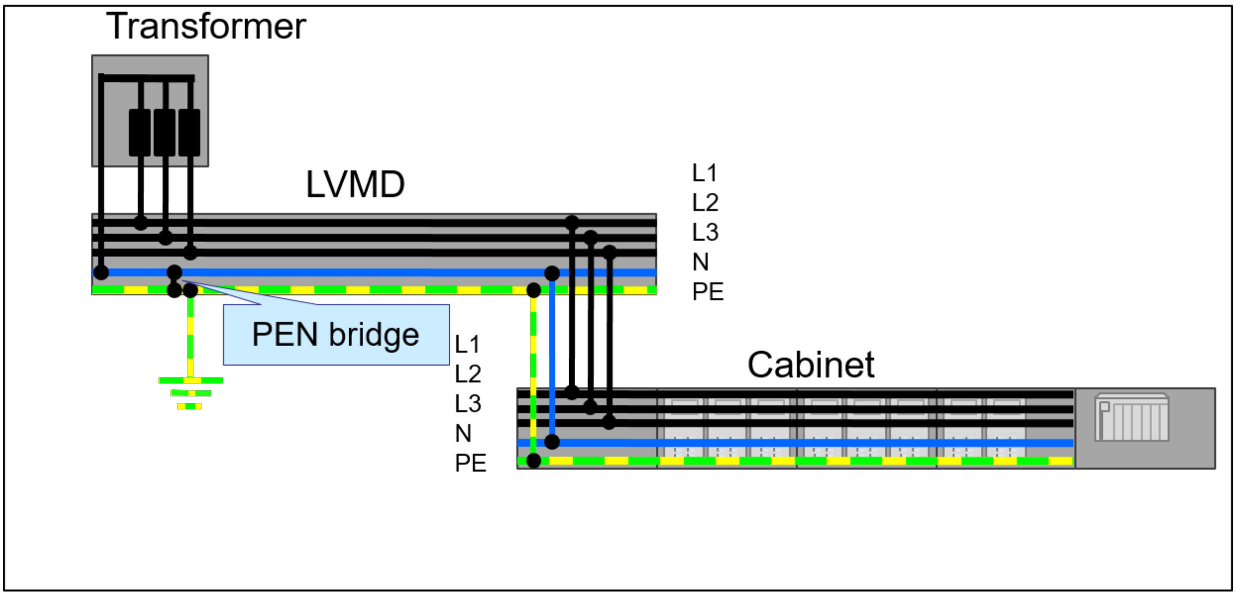


Figure 26: TN-S system

In Figure 26, the central earthing point of the equipotential bonding system in the LVMD is only connected to the protective conductor. Additionally, a PEN bridge is provided at the central earthing point (CEP) in the LVMD.

For the purpose of demonstrating the current flow in the TN-S system in Figure 27, a motor is connected into the circuit next to the cabinet as an additional load. Both the cabinet and the motor have other connections to the equipotential bonding system.

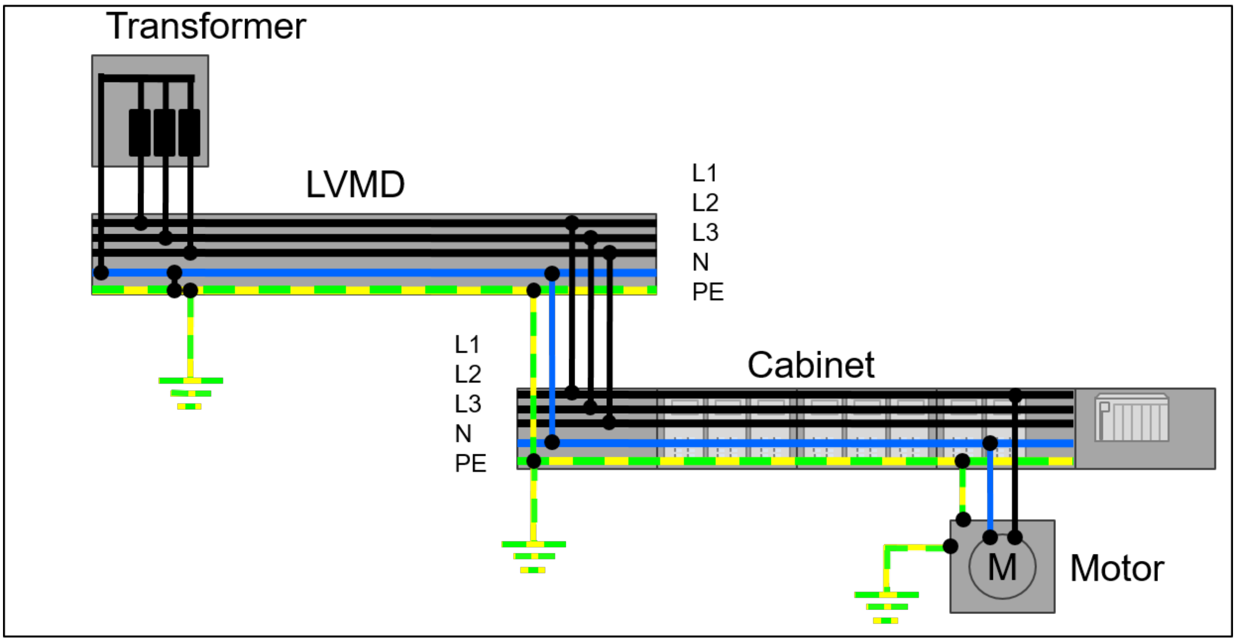


Figure 27: TN-S system with load

When considering the (red) current flow in Figure 28, it is noticeable that no current flows through the equipotential bonding system, although the housings of the equipment units feature multiple earthing. The current flows from the transformer across conductor line L1 to the load and returns to the transformer through the neutral conductor. This is the TN-S system's major advantage over the TN-C system.

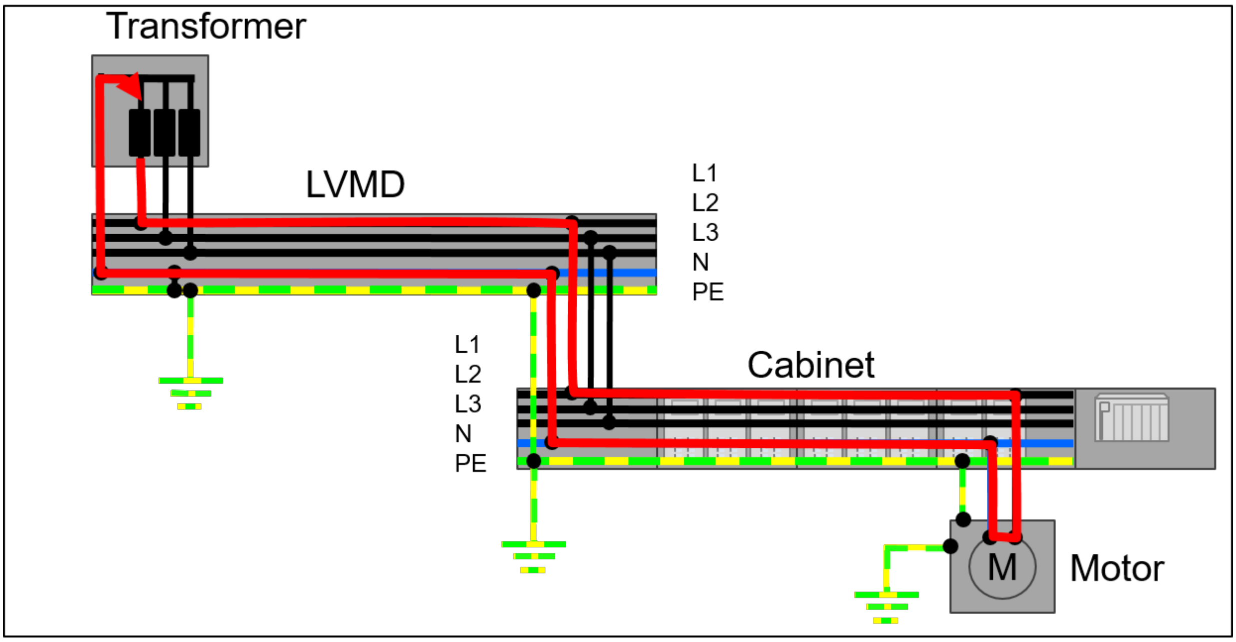


Figure 28: TN-S system with load and current flow

Figure 29 shows a fault that is often encountered with TN-S system in practice. Besides the necessary PEN bridge in the LVMD, another PEN bridge has been erroneously installed in the cabinet.

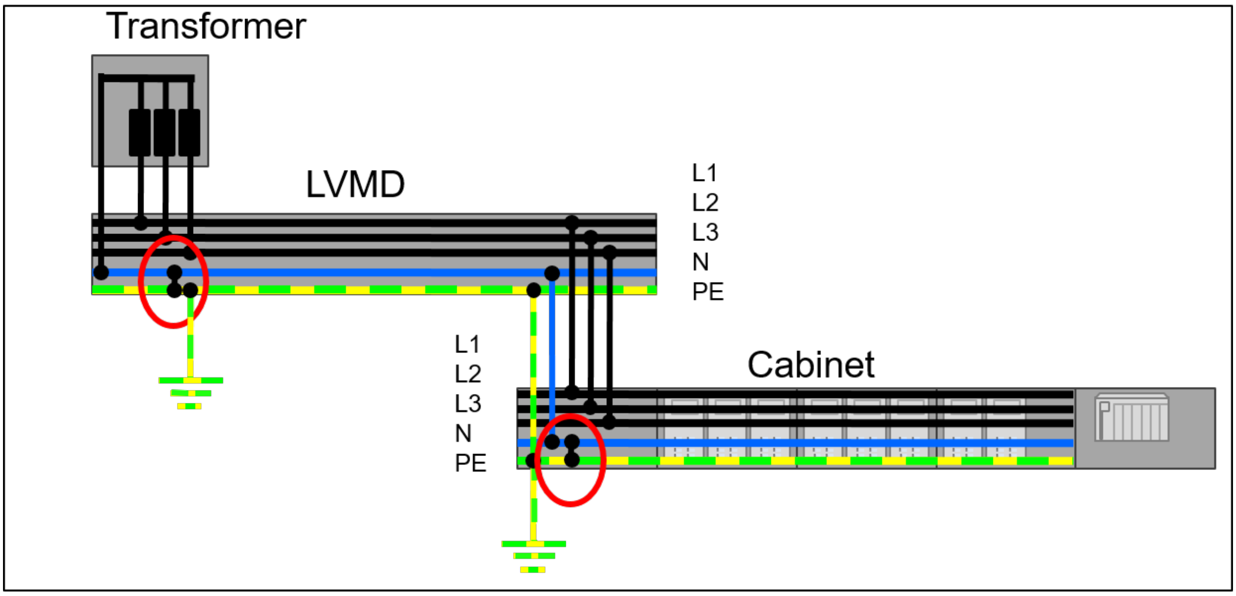


Figure 29: TN-S system with two PEN bridges

According to [DIN-EN 60204-1], implementing a second PEN bridge in the cabinet is forbidden. The reason for this is clearly seen in Figure 30.

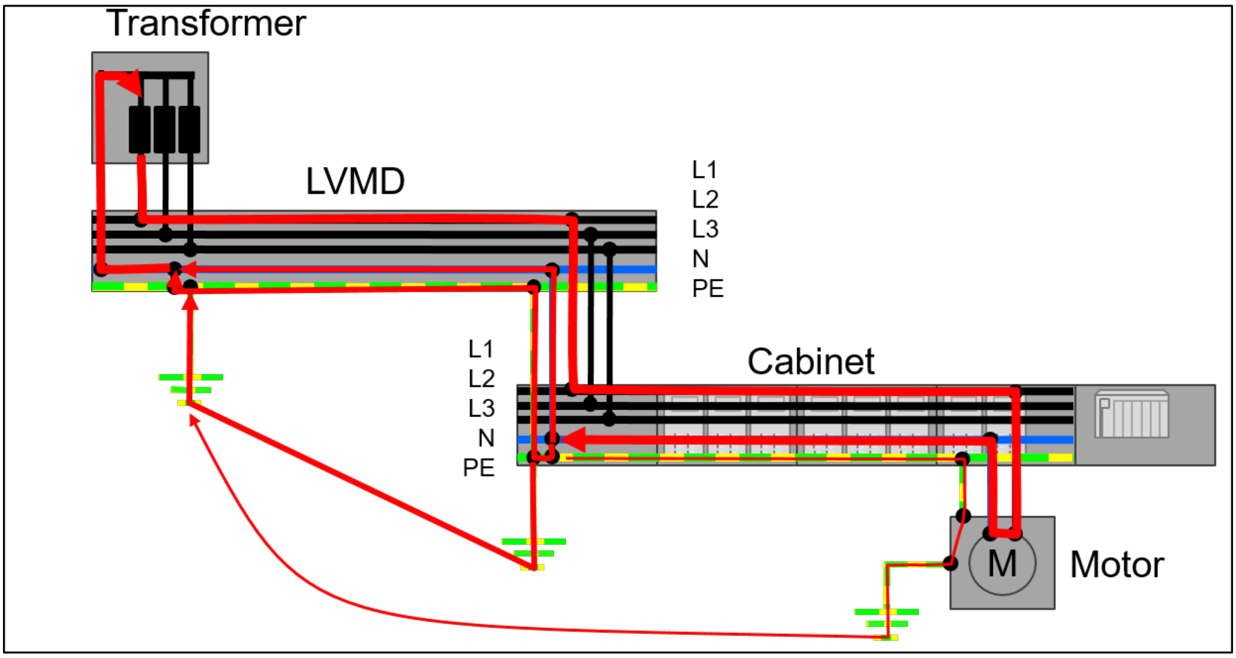


Figure 30: TN-S system with two PEN bridges, load and current flow

The current flow shown in Figure 30 in red first flows from the transformer through L1 to the load, as already discussed above. At this point, however, the current reaches the neutral conductor of the cabinet and flows to the incorrectly installed PEN bridge. At the PEN bridge, the total current is divided into several partial currents. As a result, there is a parallel back current via the equipotential bonding system, the protective conductor and the neutral conductor to the transformer. The current flow in the equipotential bonding system causes a potential difference between the two earthing points. This potential difference creates difficulties, as it may cause, among other things, current flows in the cables shields (see section 2.1.1).

4.2.2 Descriptions in the relevant standards and specialist literature

According to [DIN-EN 50310] and [IEC 60364-4-44], TN-C systems are not suitable for installations in buildings with IT equipment, due to non-compliance with EMC requirements. This is mainly due to the PEN conductor. For operational reasons, the PEN conductor leads neutral conductor currents which may cause potential differences in the equipotential bonding system due to multiple connections with it. Moreover, the currents in the equipotential bonding system also flow through the cable shields of motor and data lines which have to be earthed at each end in order to ensure their active shielding effect. The currents flowing in the cable shields cause disturbances in the plant [SCH2008], because they affect the communication between the connected devices. These disturbances may even result in plant down times.

For this reason, the designers and constructors of new buildings/plants with IT equipment are requested in [DIN-EN 50310] and [IEC 60364-4-44] to use TN-S systems only.

4.2.3 Recommendations for PROFIBUS and PROFINET

Due to the advancing digitalization in the process and manufacturing industries, it must be assumed that all buildings in manufacturing plants (will) have IT equipment. To ensure electromagnetic compatibility, it is recommended to use only TN-S systems, TN-C-S-systems, where the PE and the N conductor are preferably already separated in the LVMD or TT-systems. If a TN-C system exists already for power supply from the energy supply company, it should be converted into a TN-S system in the low voltage main distributor system as early as possible, for EMC reasons. To achieve this, a PEN bridge should be installed close to the central earthing point. In a TN-S system, there may be several parallel connections, for example from the cabinet to the equipotential bonding system, without any operating currents flowing through the equipotential bonding system.

Additionally, current monitoring at the PEN bridge is possible, as shown in Figure 31. For current monitoring, the direct and alternating currents across the PEN bridge are measured and evaluated; the current monitoring equipment should be installed and handled by qualified personnel. Current monitoring allows for early recognition of impermissible currents. Early recognition facilitates the recognition of currents flowing in the equipotential bonding system as well as impermissible multiple connections between the neutral conductor and the protective conductor.

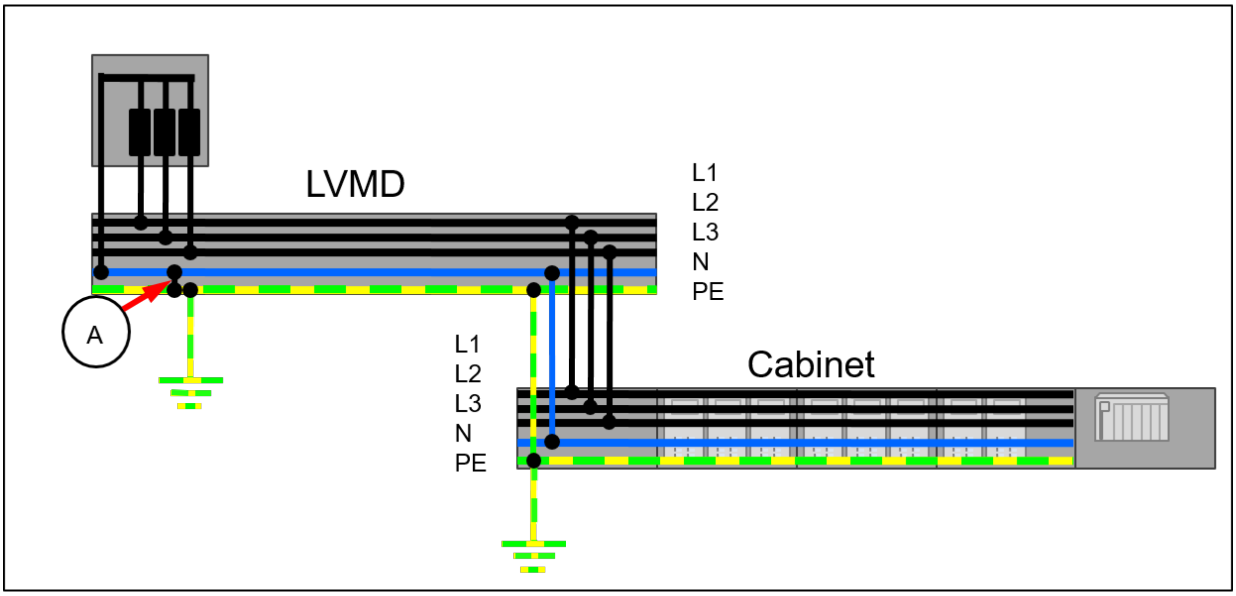


Figure 31: Ideal TN-S system

When modernizing the power supply equipment in existing buildings, it is often necessary to change the TN-C systems used so far into TN-S systems. For this purpose, a new protective conductor is installed and the equipment is connected to it. The previously used PEN conductor can only be re-used as a neutral conductor, provided that it has an appropriate cross sectional area (CSA) and is in a re-usable state. It must be ensured that there is only one connection between the protective conductor and the previously used PEN conductor in the LVMD. Any additional connection must be avoided in the TN-S system [WOL2015].

From this section of the document, the second recommendation R2 is derived:

Preferably use a 230/400 V power supply using a TN-S system.

4.3 Equipotential bonding system

A plant example from the manufacturing industry is used here for explanation. Of course, the principles of equipotential bonding are also applicable to plants in the process industry.

At present, equipotential bonding systems are usually implemented in a star or tree topology. Figure 32 shows an equipotential bonding system with star topology. The loads/devices in the plant are not only connected to the equipotential bonding system, but also to additional protective conductors in the connection cables of the devices. This is due to the fact that every power cable has a protective conductor which additionally provides for protective earthing of the equipment.

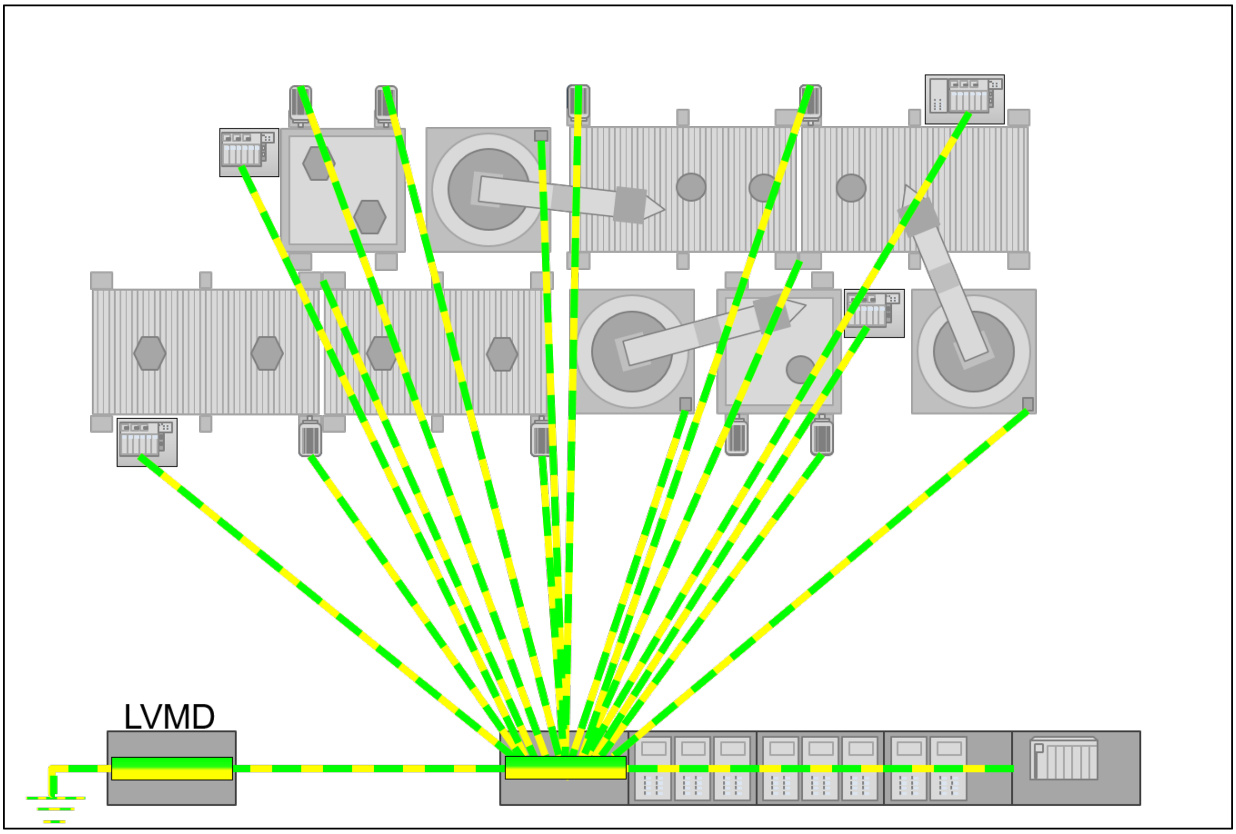


Figure 32: Star-type equipotential bonding

It is, however, more cost-saving to implement the equipotential bonding system in a tree topology rather than using a pure star topology (Figure 33). In a tree topology, several neutral points are combined in a central neutral point.

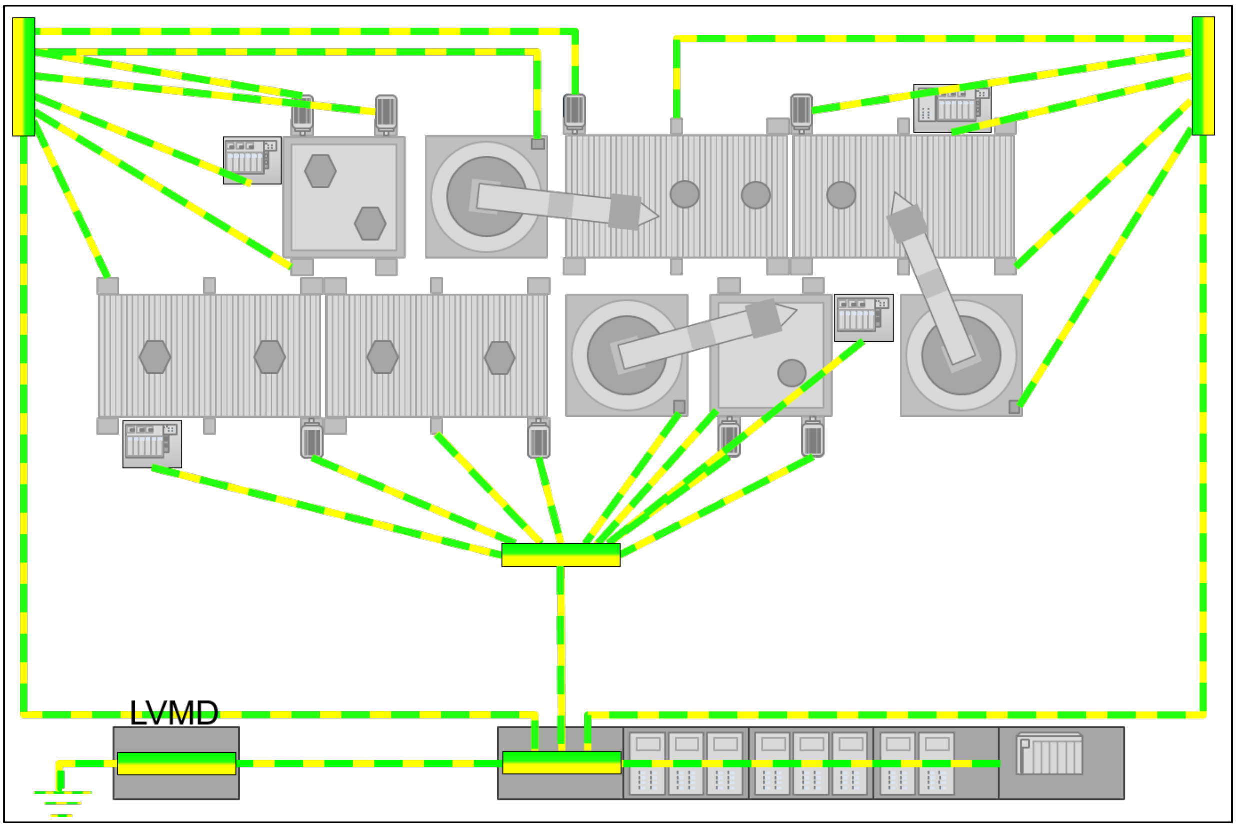


Figure 33: Tree-type equipotential bonding

4.3.1 Problem description

The problems that may arise due to equipotential bonding are almost the same for star topologies and for tree topologies. Therefore, only star topology equipotential bonding systems will be considered in the following sections.

In Figure 34, you can see a star topology equipotential bonding system in green and yellow and a PROFIBUS line in violet. The PROFIBUS line in the example could also be replaced with a PROFINET line, as both network types allow for a line-type system structure.

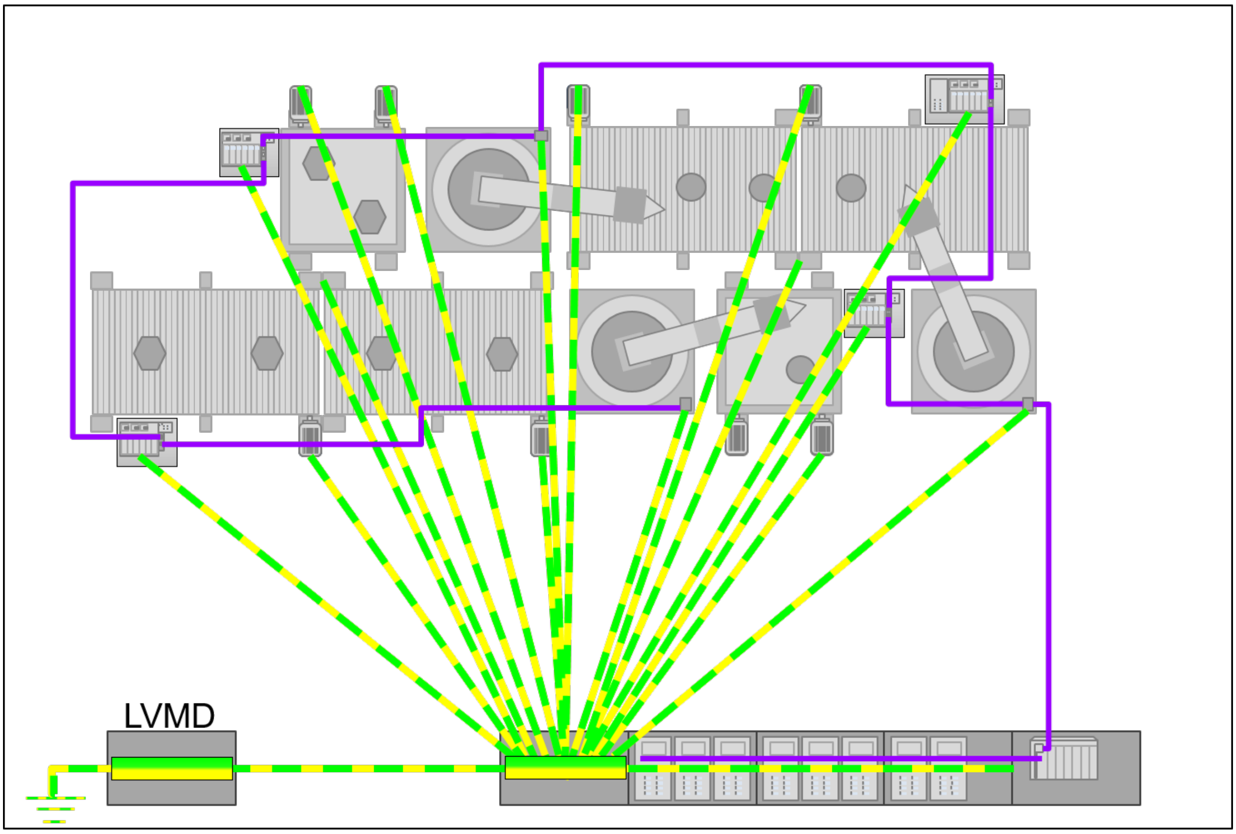


Figure 34: Equipotential bonding system in star topology with PROFIBUS lines

PROFIBUS and PROFINET lines are shielded two-wire, four-wire or – in the future – eight-wire lines. Usually the cable shields are connected to the housings of the connectors and through this with the housings of the devices. Through this conneciton, the shields are connected to the common bonding network (CBN) of the plant. This is important for the protective function of the cable shield in terms of EMC, because cable shields that are not connected to the common bonding network (CBN) or are only connected at one end do not provide for active shielding against magnetic fields (see section 3.1.2).

Figure 35 shows details of the connection between the cable shield and the equipotential bonding system. The green and yellow lines of the equipotential bonding system with saturated colors have direct connections to the cable shields of the PROFIBUS line. The pale-colored lines of the equipotential bonding system have no direct connection to the cable shield and are not relevant for further considerations. As a result, these pale-colored lines are hidden in the following illustrations.

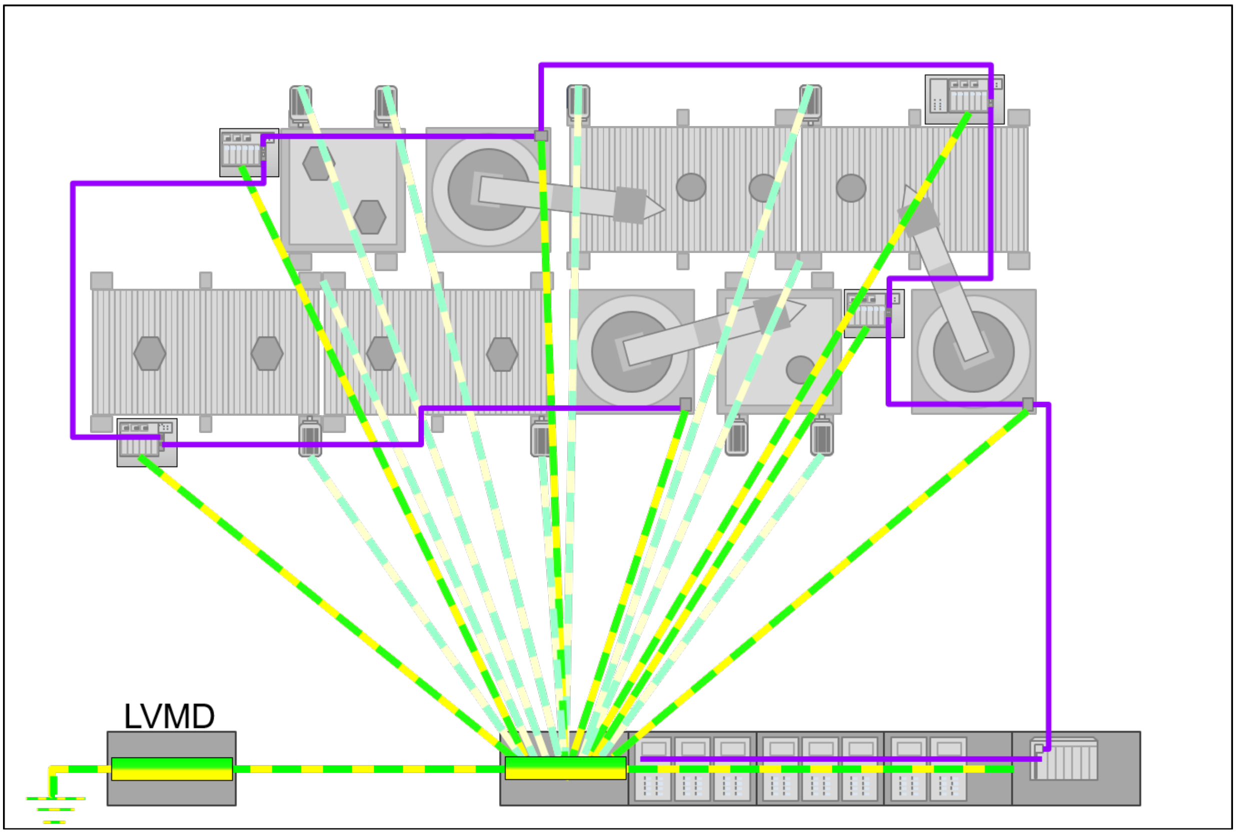


Figure 35: Equipotential bonding system in star topology with PROFIBUS lines 2

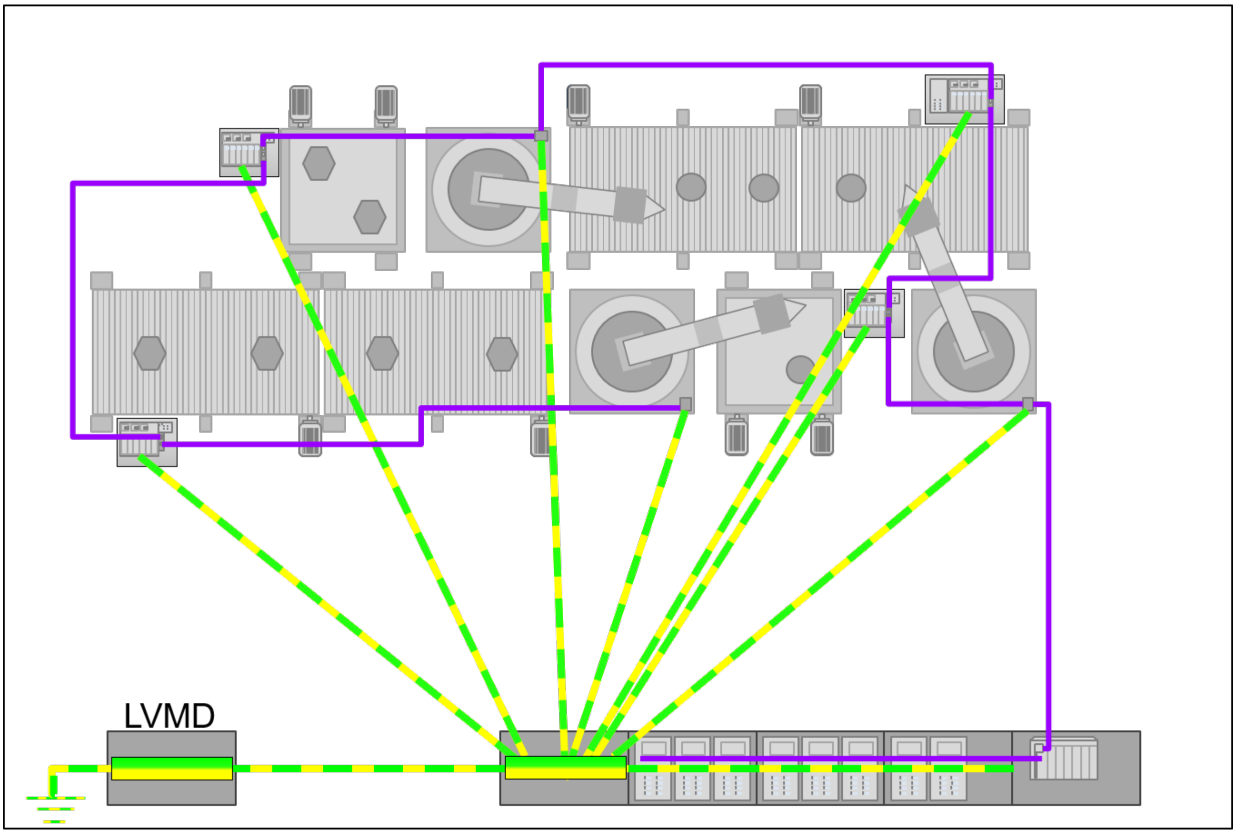


Figure 36: Equipotential bonding system in star topology with PROFIBUS lines 3

The connections of the equipotential bonding system's neutral points to the cable shields of the PROFIBUS line connected to these points form the meshes shown in red in Figure 37. If the mesh conductors are exposed to magnetic fields, voltages may be inductively coupled into them. Due to the in-coupled voltage, a current flows in the mesh conductors and, hence, through the cable shield of the PROFIBUS line.

Additionally, an equipotential bonding system in star topology has long transmission routes. The long transmission routes cause high impedances of the equipotential bonding lines. If a current is coupled into the equipotential bonding lines, the resulting current flows through the shield of the PROFIBUS line (see section 2.1.1). The resulting current flowing through the cable shield couples disturbances into the data wires of the PROFIBUS line.

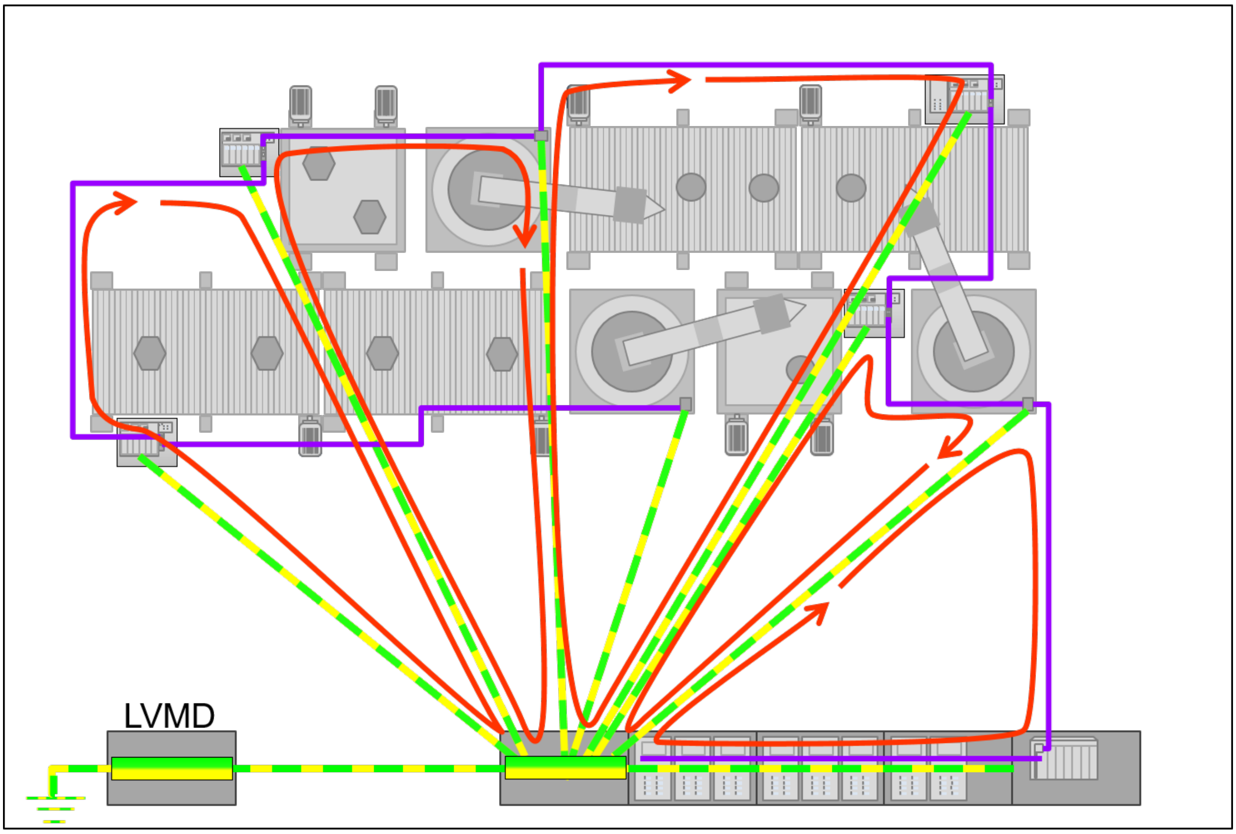


Figure 37: Meshes in an equipotential bonding system with star topology

In the past, it was recommended to use equipotential bonding lines with large cross-sectional area (CSA) and lay them in parallel with the bus line and very close to it and typically connect them only to the devices in order to avoid current flows through the PROFIBUS line shields. These lines are shown in Figure 38.

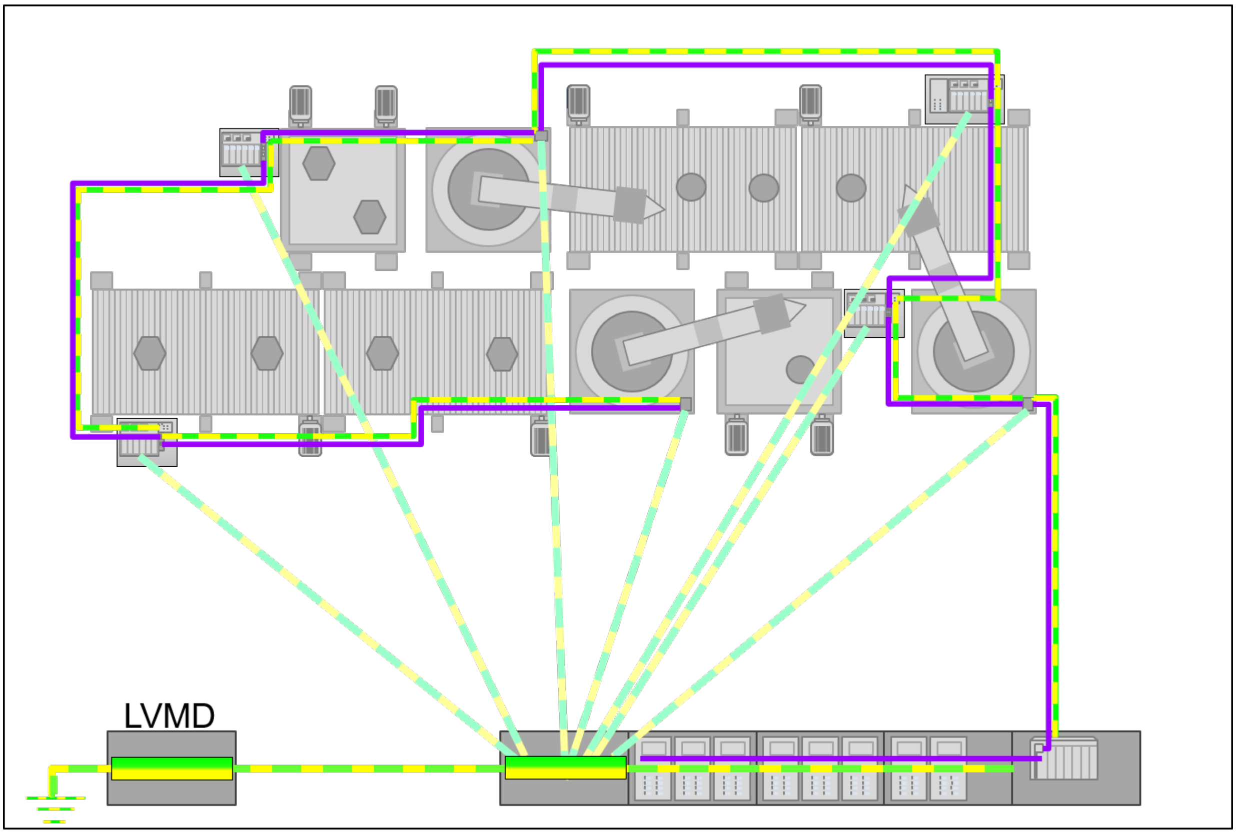


Figure 38: PROFIBUS lines and equipotential bonding lines

The main idea behind the setup shown in Figure 38 is to make disturbance currents flow through the low-resistance equipotential bonding line rather than through the cable shield of the PROFIBUS line.

As the disturbance currents in plants, usually have high frequencies (see Table 1), it is the impedance and not the ohmic resistance that is important for determining the current distribution in the equipotential bonding system. As the impedance of a cable shield is considerably lower than that of a solid copper conductor the major part of the current potentially occurring in the mesh will flow through the cable shield and not through the equipotential bonding conductor laid in parallel and intended to work as a relief line.

As can be seen in Figure 39, the additional equipotential bonding lines do not present any improvement regarding the mesh size. The meshes are still big and, thus, sensitive to inductive coupling.

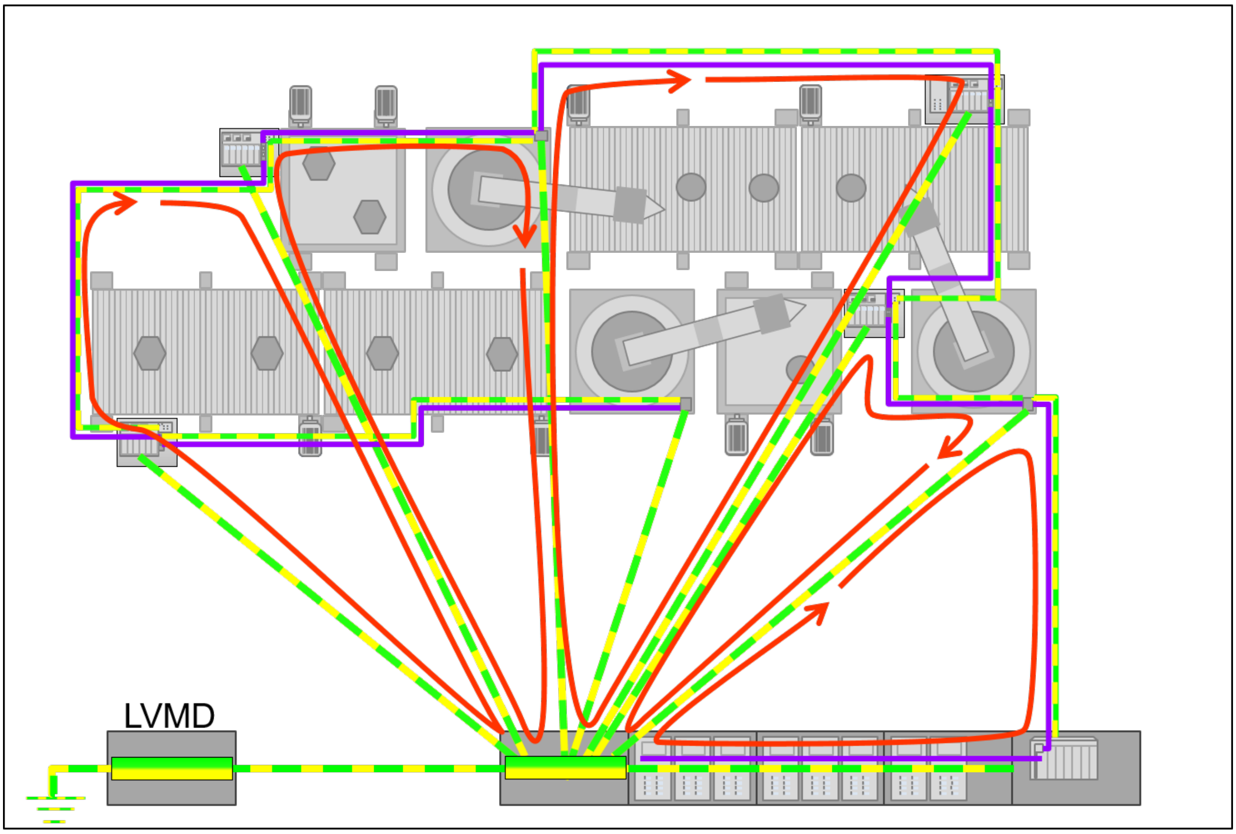


Figure 39: Meshes with PROFIBUS lines and equipotential bonding lines

4.3.2 Solutions from standards and technical literature

The standards [DIN-EN 50310] and [IEC 60364-4-44] specify the earthing and equipotential bonding measures for buildings with IT equipment. The explanations in the following section have been derived from these standards. In the [DIN-EN 50310] standard, four different types of equipotential bonding systems are distinguished, which are shown in Figure 40.

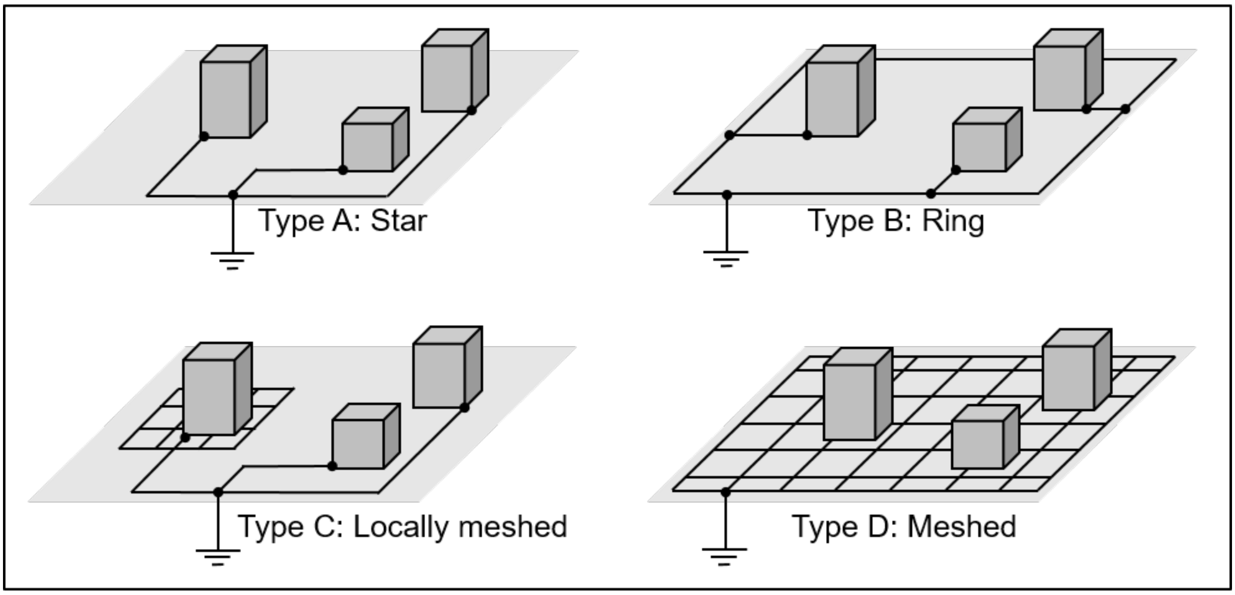


Figure 40: Equipotential bonding systems referring to [DIN-EN 50310]

The equipotential bonding system type A has a star topology. Due to the usually long transmission paths this star-topology system features high impedance between two devices. The high impedances cause poor discharge of electromagnetic disturbances coupled into the system. Seen under the aspects of EMC, type A systems are the least suitable equipotential bonding systems for buildings with IT equipment, due to their high impedance.

The equipotential bonding system type B has a ring topology. Although the ring topology reduces the length of the protective conductors between two devices, the lines may nevertheless feature high impedances, which, again, may affect or even prevent proper discharge of electromagnetic disturbances/coupling.

The equipotential bonding system of type C has a locally meshed equipotential bonding line. In the plant area, all metal parts such as cabinets, frames, supports and cable systems are locally meshed. By connecting all metal parts, a meshed equipotential bonding system is formed, which features a low impedance due to its big number of short and parallel transmission routes. A network with this kind of meshing of all conductive objects is called a Bonding Network (BN).

The equipotential bonding system of type D has meshed equipotential bonding lines distributed over the entire building. Therefore, a common system should be laid over several levels of the building (see Figure 41).

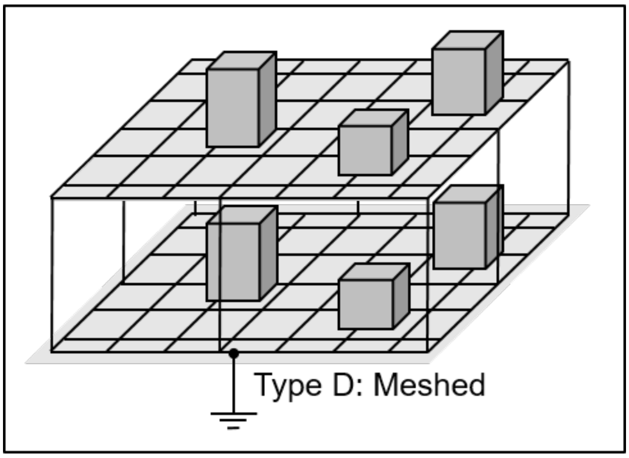


Figure 41: Meshed equipotential bonding system

The [DIN-EN 50310] recommends to use only meshed equipotential bonding system of type D for newly built IT systems. A meshed equipotential bonding system of this kind is also called a MESH-BN[1] if it is based on a common bonding network (CBN).

The goal of using a meshed equipotential bonding system is to reduce the line impedance between two devices. For this purpose, as many parallel and electrically conductive connections as possible are needed between the devices of the plant. As this would induce a tremendous cabling effort if only cables were used, the meshing is in parts realized by using the metal parts of the plant such as pipes, frames, cabinets and cable ducts. According to the [DIN-EN 62305-4] standard, it is also possible to include the foundation earth electrode and the steel arming on the building floors into the equipotential bonding system. In this case, however, the steel arming of the foundation earth electrode must be either welded or permanently connected by other measures in order to ensure electrical conductivity. [DIN 18014]

[1] A MESH-BN is a meshed equipotential bonding system in which all supports, cabinets, robots, pipes and frames of the plant equipment are connected to each other and, at many points, to the equipotential bonding system (CBN).

For new or modernized plants, a meshed equipotential bonding system can be easily implemented. For plants with already existing equipotential bonding systems in star or ring topology there are suggestions for improvement by additional connections. The suggested improvements are shown in Figure 42. On the left-hand side of the image you can see the initial equipotential bonding system, and on the right-hand side the improved system. The improvement consists in adding equipotential bonding conductors between the devices, which are represented by thick lines in the drawing.

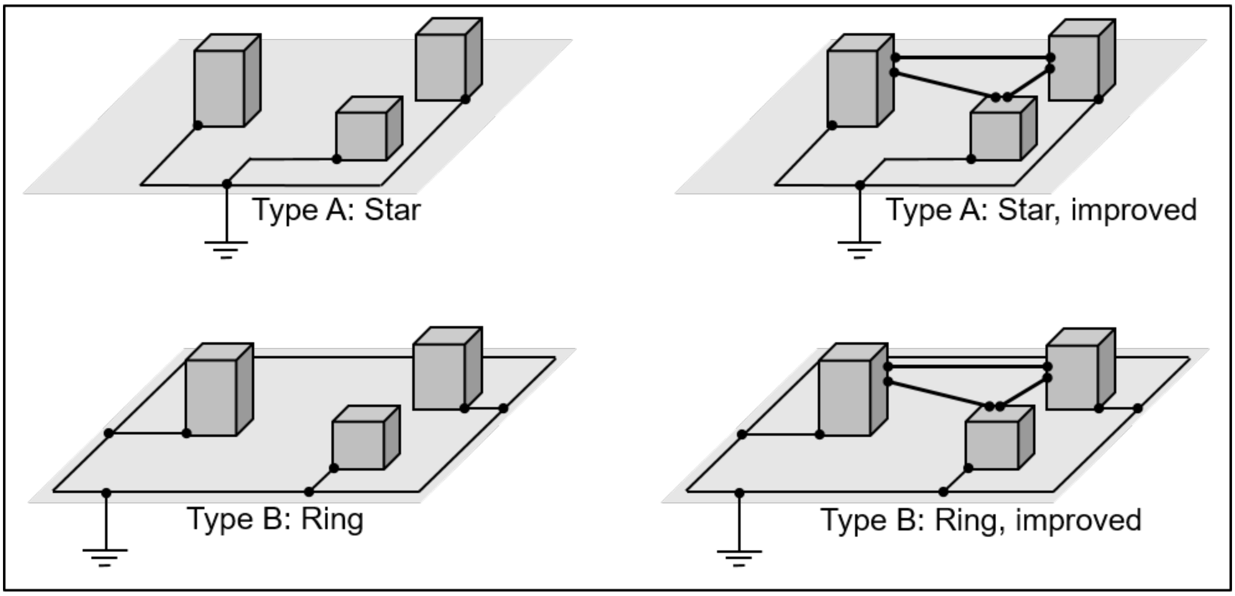


Figure 42: Improved equipotential bonding systems referring to [DIN-EN 50310]

4.3.3 Recommendations for PROFIBUS and PROFINET

The [DIN-EN 50310] standard is applicable to automation systems with PROFIBUS/PROFINET devices. When constructing or reconstructing such systems, a meshed equipotential bonding system that comprises the entire copper-based PROFIBUS/PROFINET network should be implemented. A meshed equipotential bonding system for the manufacturing plant example discussed earlier in this document could look like the example shown in Figure 43. In plants with considerable field loads such as induction furnaces or industrial microwave ovens, additional measures like double shielding or cable laying in metal pipes might be necessary.

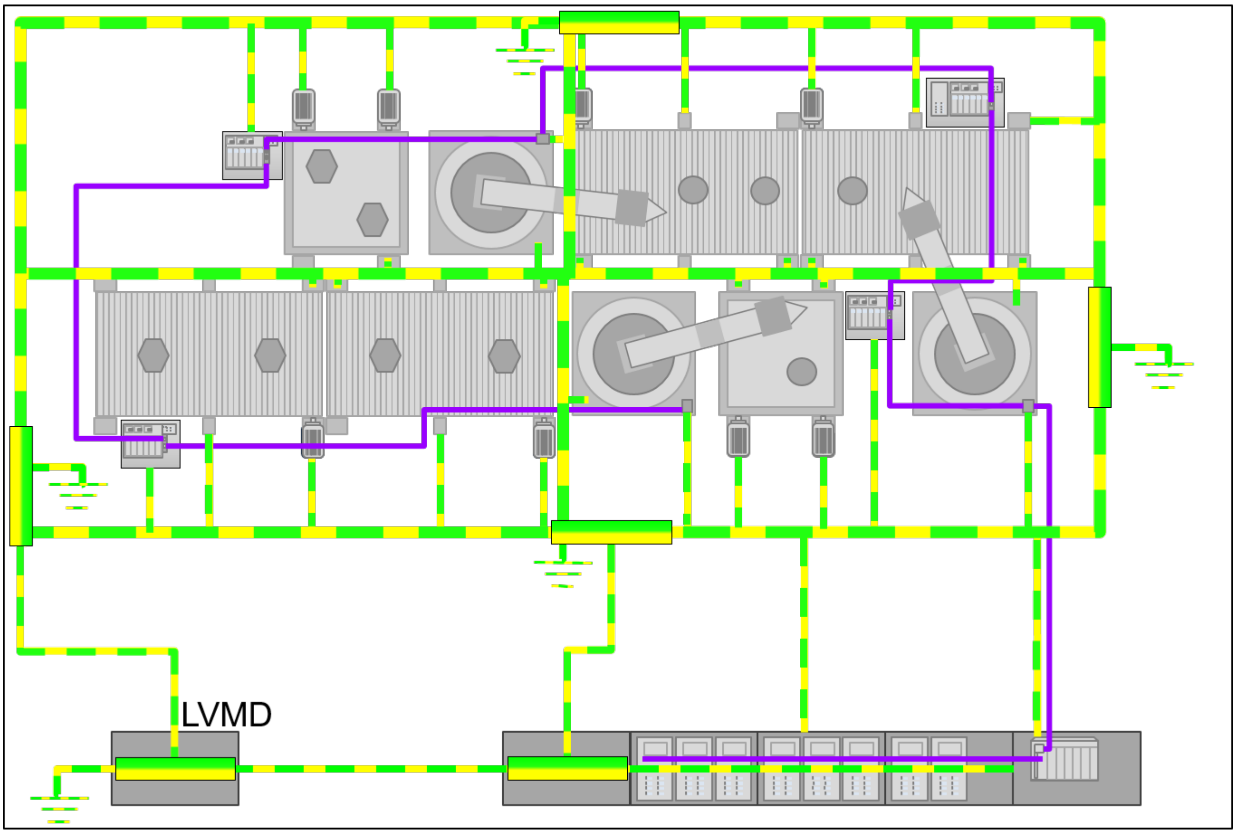


Figure 43: Meshed equipotential bonding

In the following section, meshed equipotential bonding in accordance with the [DIN-EN 50310] will be explained step by step. Lines with ring topology forming big meshes around dedicated plant sections are the basis of this type of equipotential bonding. The meshes are shown in Figure 44.

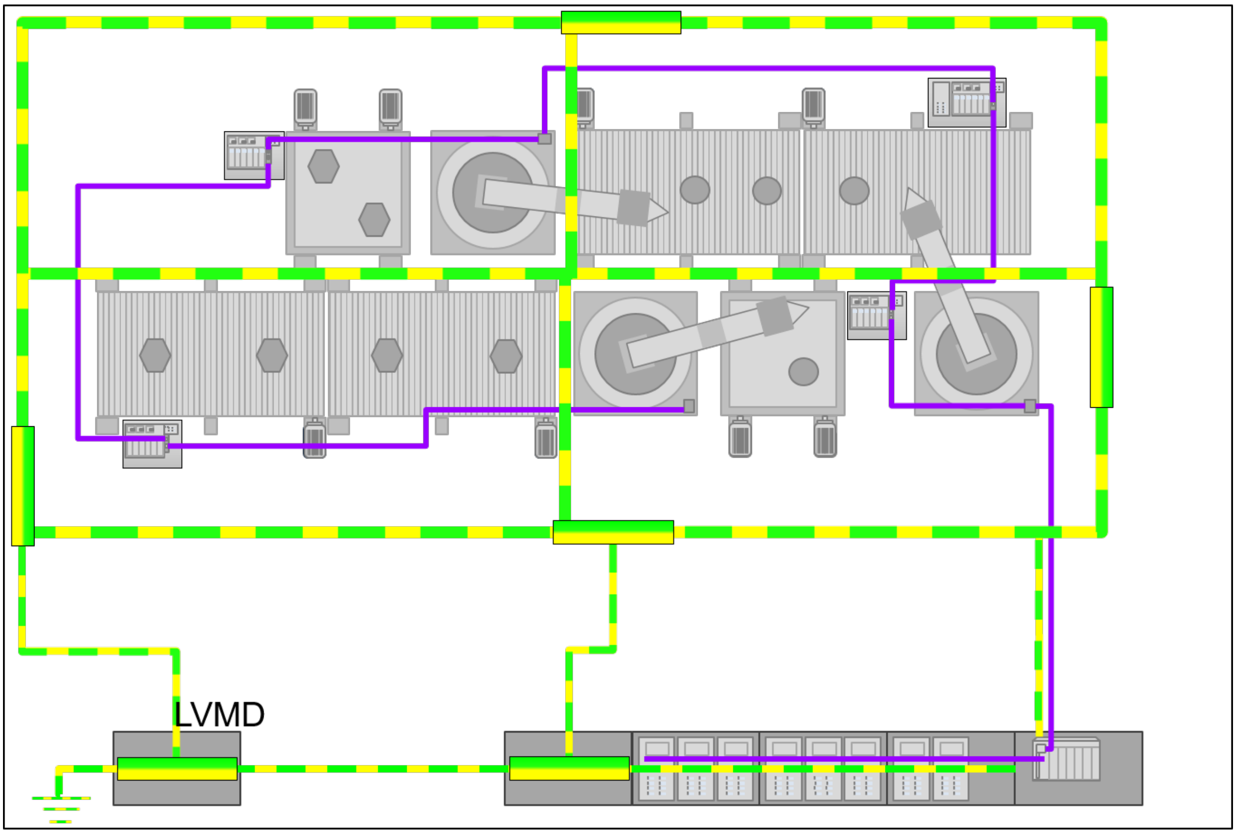


Figure 44: Ring lines in meshed equipotential bonding system

In order to ensure a low impedance, even at high frequencies, the lines shown in Figure 44 should be tin-plated or multi-wire copper lines. Lines of this type are also recommended in [DIN-EN 61918].

In Figure 45 you can see additional lines between the ring lines and the devices of the plant example. These stubs should be as short as possible. Additionally, the devices should be connected to the ring line at several points in order to form many small meshes. And the devices should be conductively interconnected to form a bonding network. All connections must comply with the requirements of protective and functional equipotential bonding, i.e. they must feature a low impedance and a sufficient ampacity. And the appropriate measures must be taken to avoid unwanted loosening of the equipotential bonding points during plant operation.

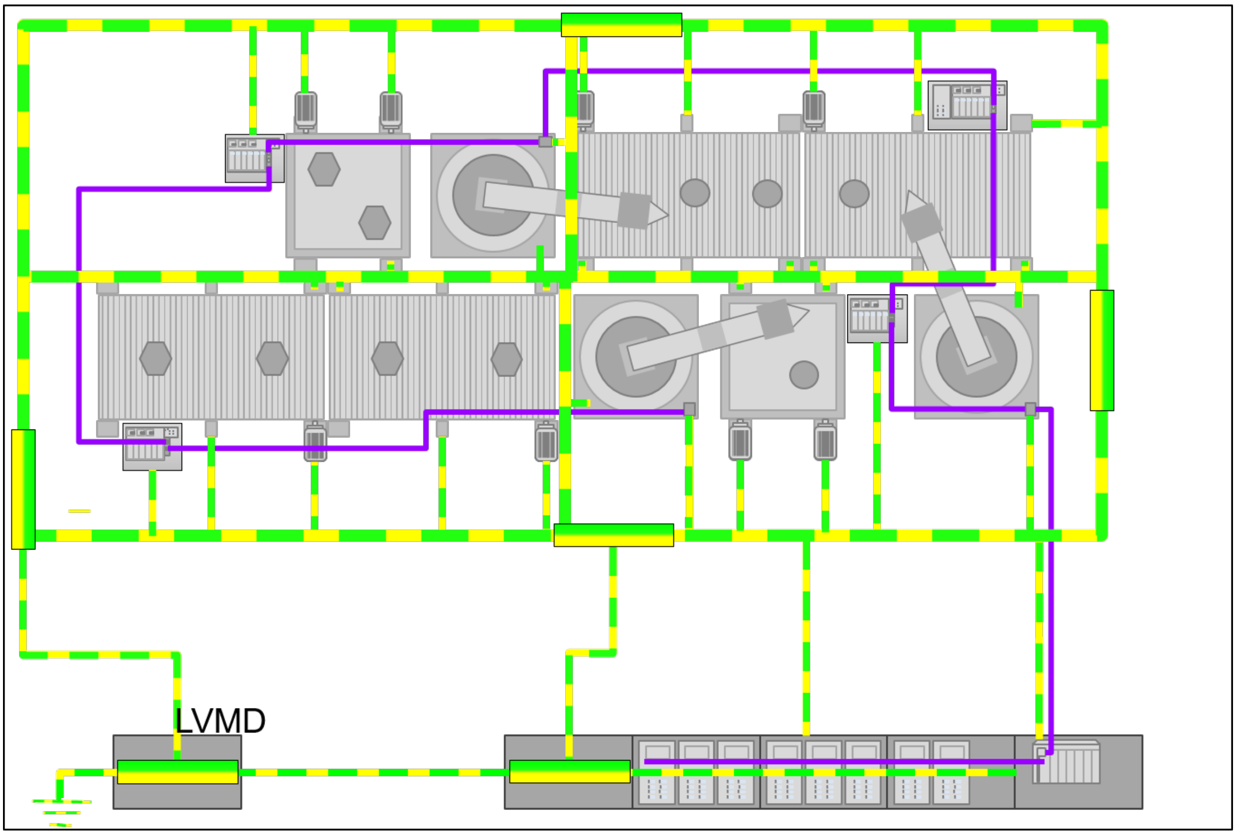


Figure 45: Stubs of the meshed equipotential bonding system

In order to keep the branching points of the stubs on the ring line as simple and cost-saving as possible, the connection blocks shown in Figure 46 and Figure 47 can be used.

The connection blocks (Figure 46) are connected to the cable tray and at the same time provide the connection of the cable trays with the CBN through the connected ring line.

Figure 46: Connection blocks (WPAK clamps)
(picture from Weidmüller, manf.)

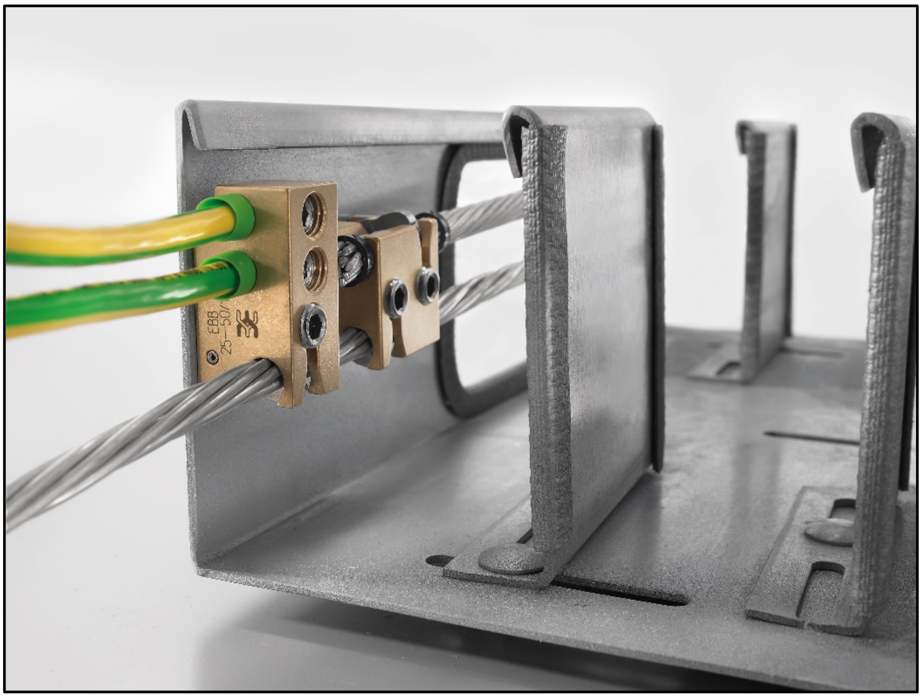


Figure 47: Stubs from ring line to devices (Picture Weidmüller)]

Figure 47 shows the fine-wire ring line of the equipotential bonding system in silver/gray color. It is screwed to the cable tray through bronze-colored connection blocks. The connection block allows connecting stubs to the devices. The connection of the stubs is shown in Figure 47. The integration of the metal cable trays into the common bonding network (CBN) gives a good basis for a low impedance-bonding network. N. B: In any case, a conductor and connection blocks have to be used. The sole use of the cable tray as CBN is not allowed.

Figure 48 shows the next optimization opportunity offered by a meshed equipotential bonding system. On the ring line, there are additional earthing points, which are marked in red in the picture. These earthing points symbolize additional connections with the equipotential bonding system of the building. These additional connections further lower the impedance of the entire equipotential bonding system.

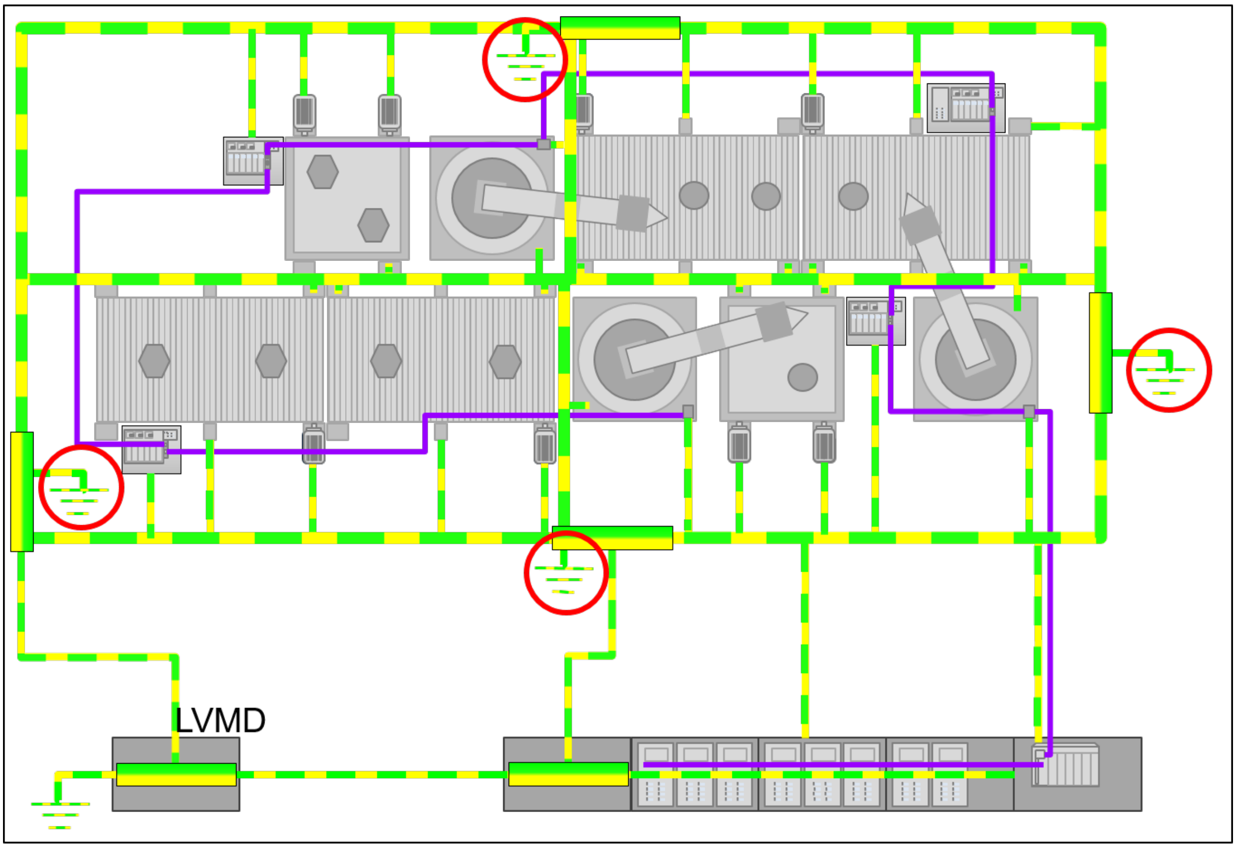


Figure 48: Meshed equipotential bonding via the foundation earth electrode

For the sake of electrical safety, the CBN must be connected to the foundation earth electrode at least at one point. By adding more connection points, the foundation earth electrode can become a part of the CBN and hence improve the local meshing of the equipotential bonding system. Moreover, an equipotential bonding system over several building levels is realized in this way, as the foundation earth electrode is integrated in the supports and columns of the building construction. These additional access points to the foundation earth electrode must be considered already in the early design phase of the building.

Figure 49 shows how the foundation earth electrode can be integrated: it is grouted into the concrete and can be connected to the equipotential bonding system through a screw if required. [DIN-EN 62305-4]

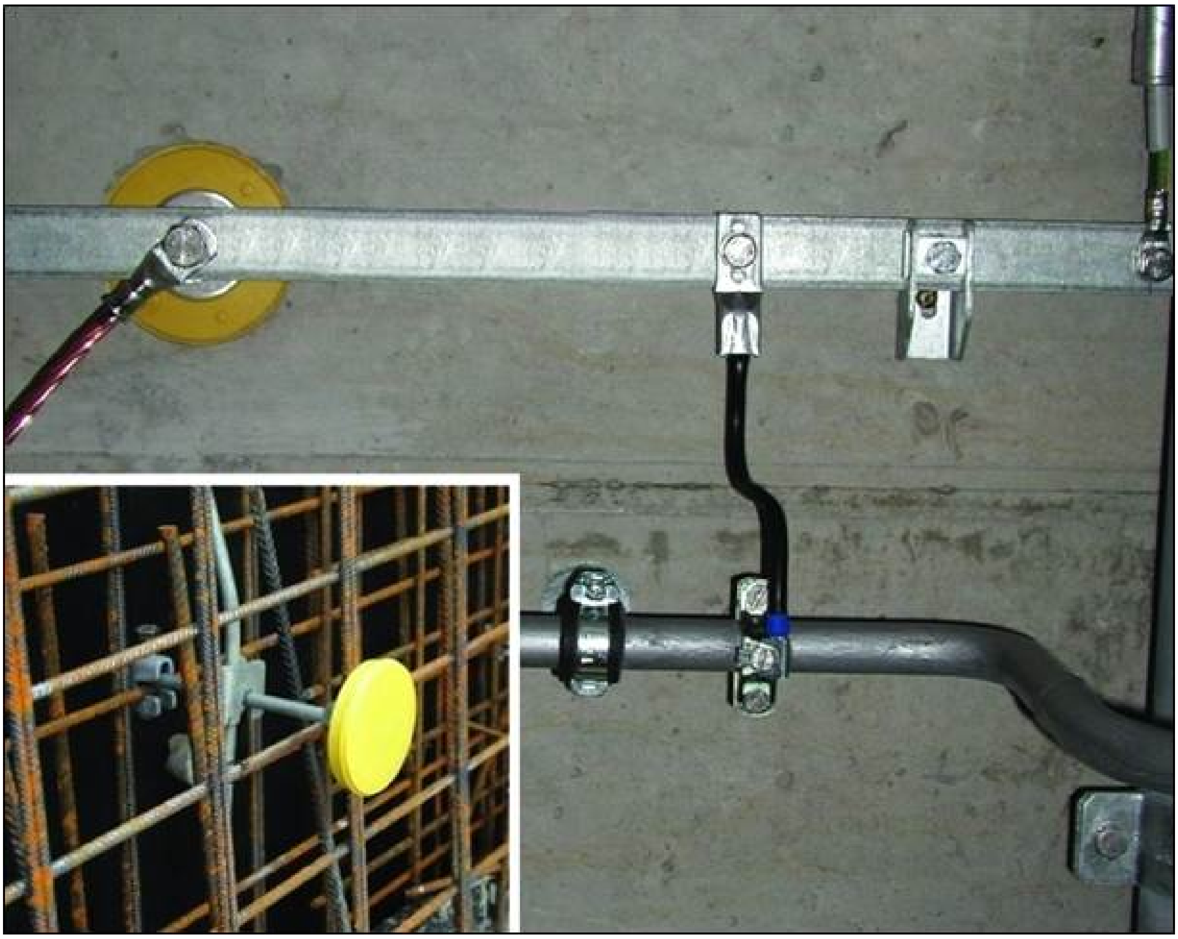


Figure 49: Earthing points [DEH2016]

The following two figures clearly show the big advantage resulting from meshed equipotential bonding. Figure 50 shows in red color a mesh formed by the cable shield of the plant's PROFIBUS line connected at each end. The meshes are considerably smaller than those used before in a star-topology equipotential bonding system (Figure 39). As a result, less inductive coupling is likely to occur in the meshes of the equipotential bonding system.

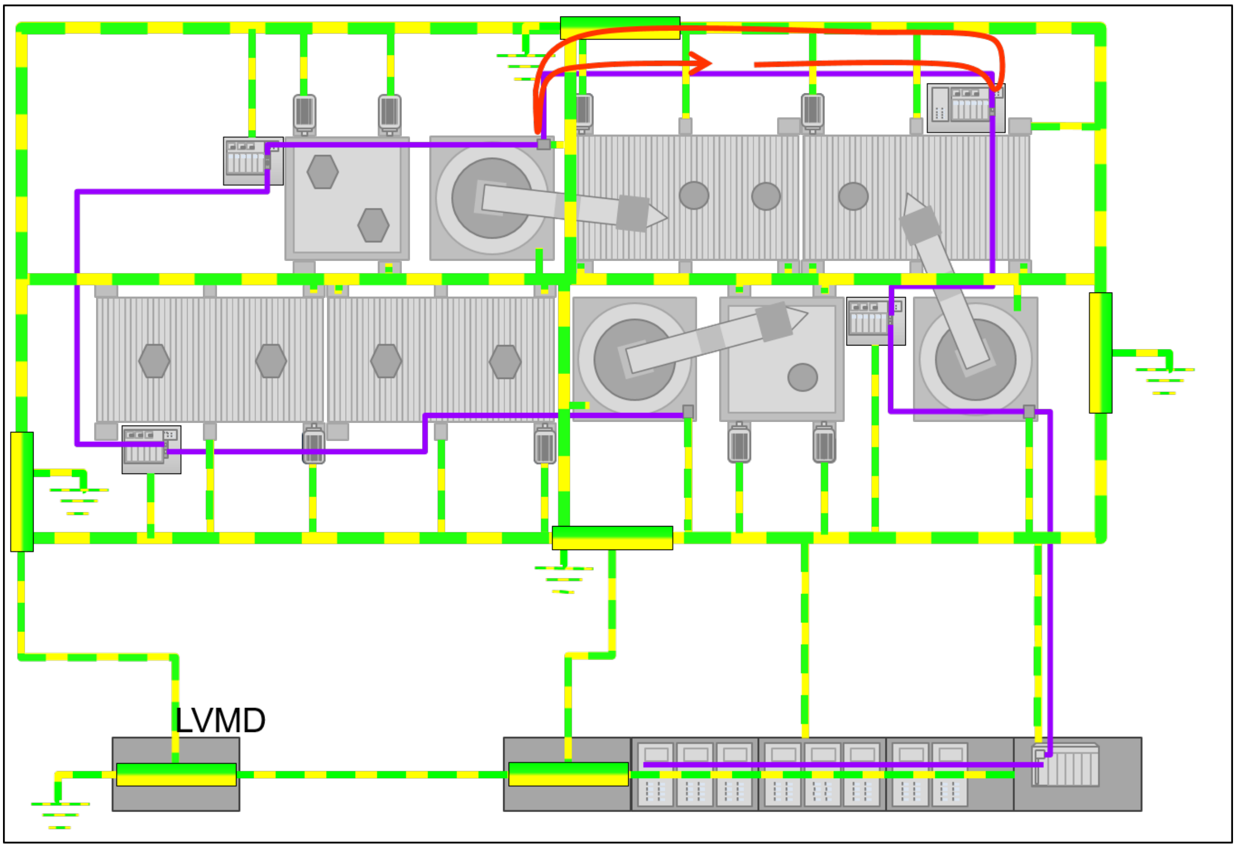


Figure 50: Mesh formed by a cable shield in a meshed equipotential bonding system

Additionally, many small meshes instead of few large ones are produced by meshing the equipotential bonding system. They are shown in the example in Figure 51. Due to the smaller meshes the equipotential bonding system has a lower impedance, which prevents potential differences.

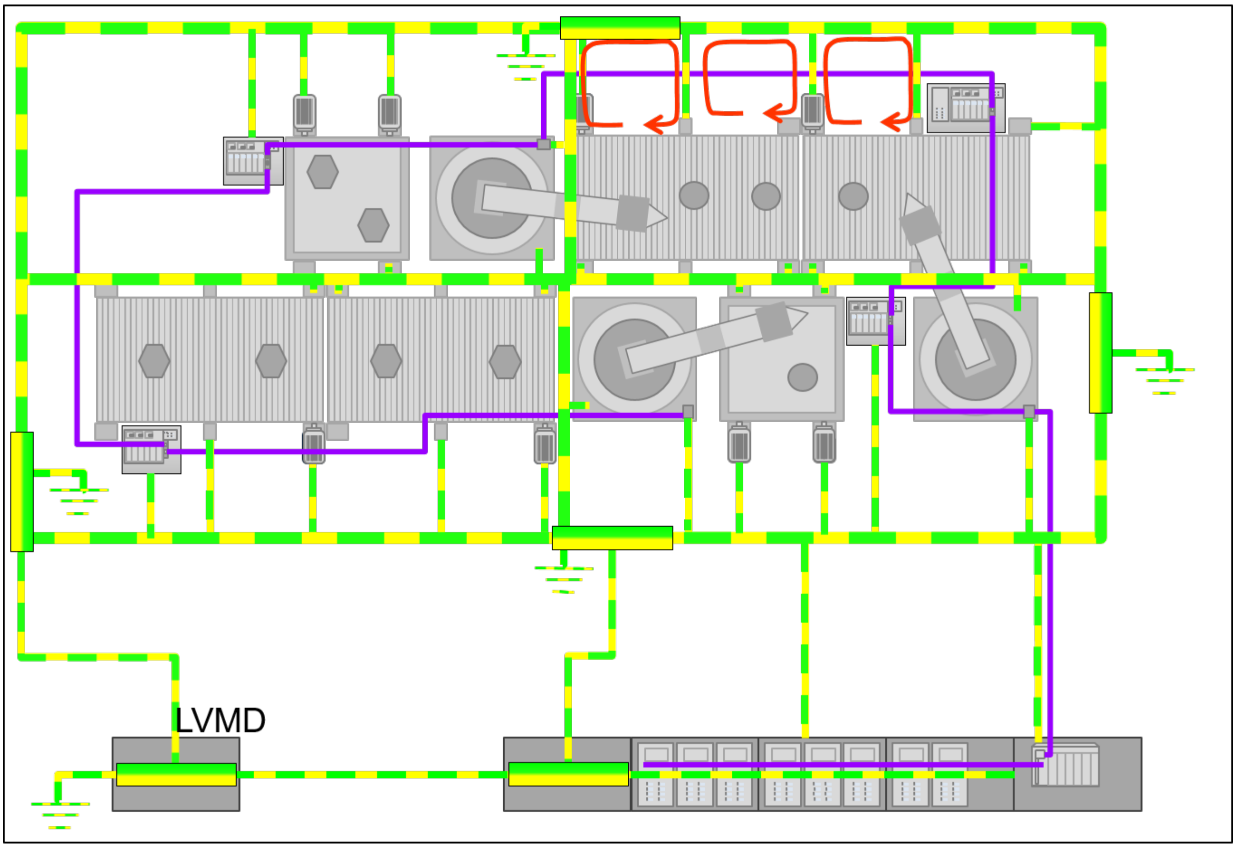


Figure 51: Many small meshes in a meshed equipotential bonding system

Besides the lower impedance, smaller meshes provide another benefit with respect to electrostatic discharge. Non-metal conveyors, e.g. made of rubber or plastics, may cause electrostatic charges in a plant.

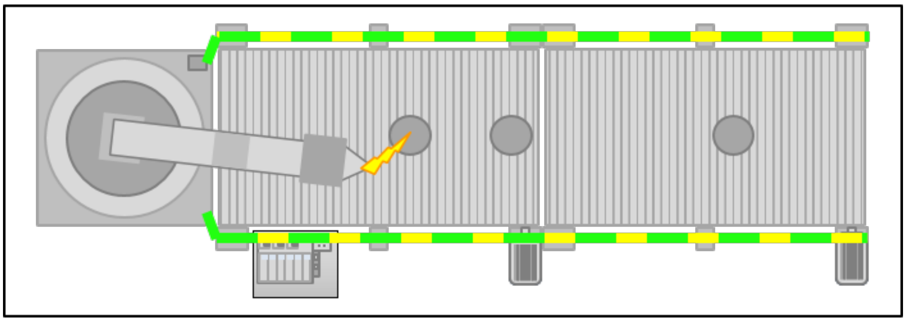


Figure 52: Example of electrostatic discharge

Upon electrostatic discharge the generated currents return to their place of origin. Therefore, plant sections where electrostatic discharge is likely to occur should be conductively interconnected. A finely meshed equipotential bonding system improves the impedance of such connections along the conveyance path.

The statements with respect to a fine granular meshed equipotential bonding system also apply to the interior of cabinets and the interconnection between cabinets. A good potential equalization should be also established inside cabinets. A blank metal mounting plate (e.g. a tinned steel sheet) in combination with blank metal DIN-rails can achieve this, for example. The mounting plate shall be tied to the common bonding network (CBN) with low impedance. When using multiple cabinets, strung together, it is recommended to connect the mounting plates of the adjacent cabinets by ground straps.

From this section of the document, the recommendation R3 is derived:

Use a common bonding network (CBN). Mesh equipotential bonding systems as finely as possible (MESH-BN).

4.4 Connection of PROFIBUS/PROFINET cable shields

The PROFIBUS or PROFINET cable shields are connected through the connector plug. Inside the connector, the cable shield is connected to the connector housing. The connector housing is connected to the equipotential bonding system, usually via the connector plug and the connected device.

4.4.1 Problem description with solutions from standards and technical literature

As the cable shield makes use of the active shielding principle, the shield should be connected to the equipotential bonding system at least at each end. Only then the currents generated by electromagnetic interference can flow through the cable shield and generate an opposing field. This opposing field produces a nearly field-free area inside the cable shield. By virtue of the field-free area, no disturbances are coupled into the data wires. Caution: Cables shields connected at both ends of a line may cause problems in hazardous areas, as sparks may be produced when the shield connection is opened. A finely meshed equipotential bonding system in combination with multiple shield contacts can minimize this problem.

In order to allow the induced current flow to emerge freely, it is important that the connection between the cable shields and the connector housings have a low impedance. For this reason, connector housings that allow for low-impedance connections on a large contact area between the cable shield and the device should be used preferably [NE 98].

However, a low-impedance connection between the connector plug and the cable shield does not, on its own, produce a low impedance path for the currents. It will also be necessary to ensure that the connected devices (PROFIBUS or PROFINET) have a low-impedance connection between the connector shroud and the connection to the common bonding network (CBN).

A low impedance connection of the cable shield, connector housing and the housing of the PROFINET-device is a requirement for a good EMC. In case a device does not yield a sufficient contact of the cable shield via the described path, an additional shield connection can be established close to the device. Figure 53 shows as an example of such a cable shield connection to the common bonding network (CBN) next to the device.

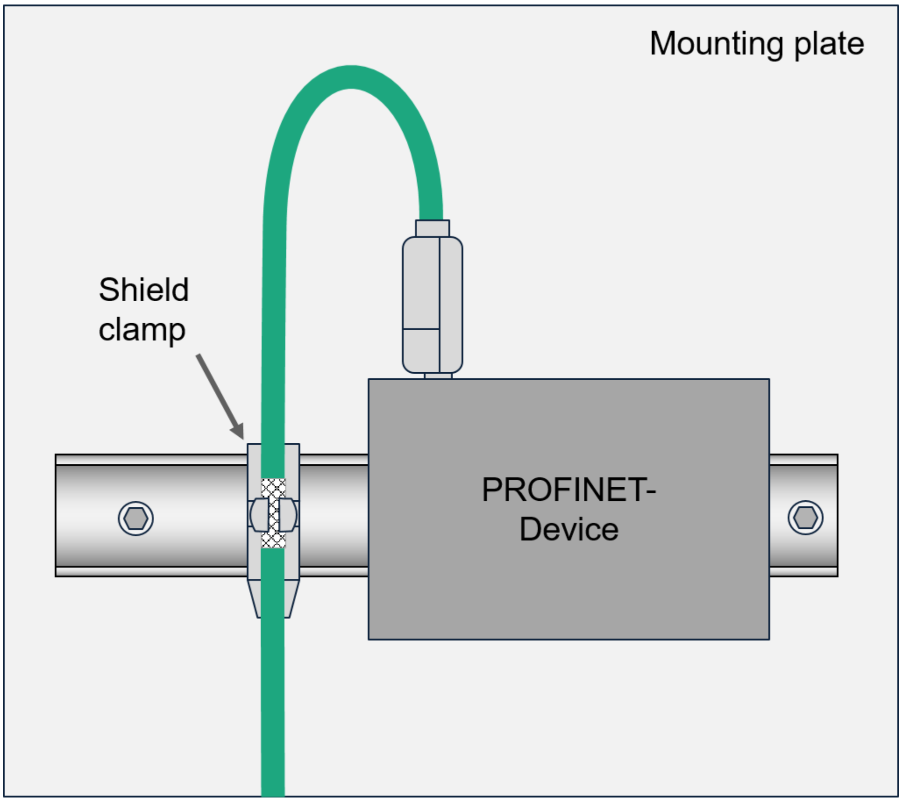


Figure 53: Connection of the cable shield to CBN close to a PROFINET device

If the environmental conditions allow for additional connections of the cable shield to the common bonding network (CBN), these are permitted according to [NE 98].

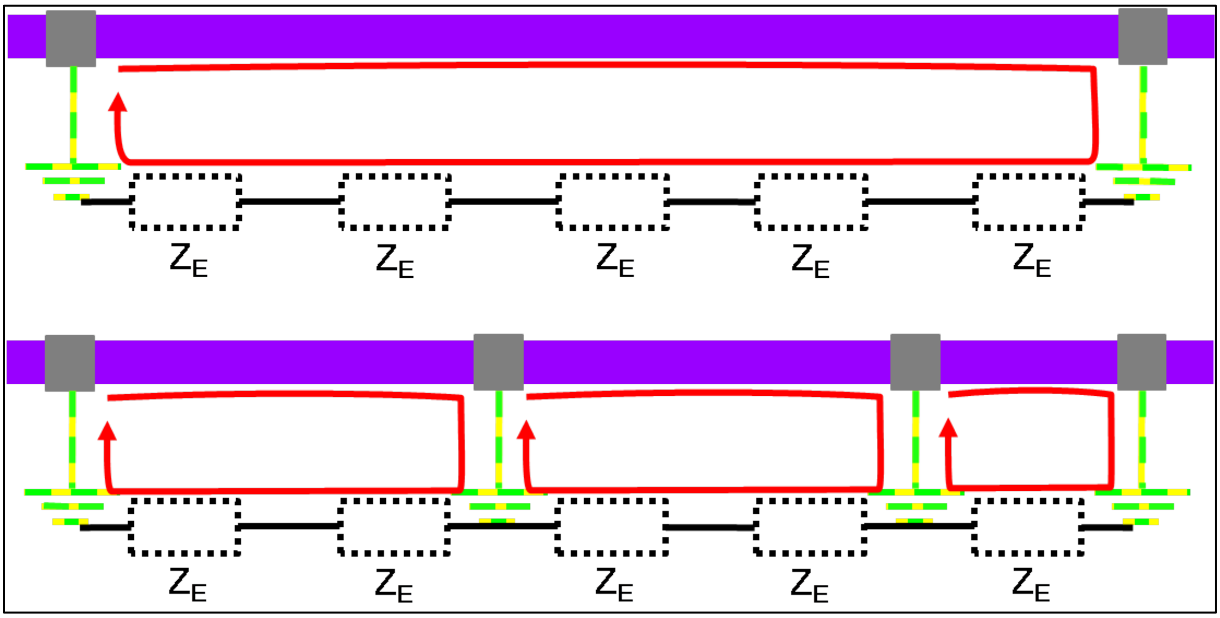


Figure 54: Multiple connection of the cable shield of a PROFIBUS line with the CBN

Figure 54 shows two PROFIBUS lines. The upper line is connected to the common bonding network (CBN) at its ends, only, whereas the lower line has two more connection points. Every supplementary connection of the cable shield of the lower PROFIBUS line shown in Figure 54 with the equipotential bonding system reduces the size of the mesh into which electromagnetic disturbances or fields could be connected. Of course the impedance of the equipotential bonding system is of major importance. For this reason, a meshed equipotential bonding system should be set up as described in section 4.3. Figure 55 shows an example of such an additional cable shield connection.

Figure 55: Additional connection of the cable shield (Product Indu Sol, Photo Niemann)

4.4.2 Recommendations for PROFIBUS and PROFINET

For PROFINET and PROFIBUS connections, special attention should be paid to the connector housing which should have a large contact surface for the cable shield. Additionally, the PROFIBUS and PROFINET devices should have a low-impedance connection to the CBN to be able to easily discharge disturbance currents. As already stipulated in the Installation Guidelines for Cabling and Assembly ([PRO2009] und [PRO2015-1]) from the PROFIBUS User Organization, the PROFINET and PROFIBUS lines can also be connected to the common bonding network (CBN) at bus nodes using respective clamps. This additional connection to the common bonding network (CBN) through clamps may bridge high impedances from the connector plugs that may occur.

From this section of the document, the recommendation R4 is derived:

Provide a connection of the PROFIBUS/PROFINET cable shields through the housings of the connectors and through the housings of the devices and thus to the common bonding network (CBN) at each cable end with big contact surfaces (low impedance).

4.5 Motor lines

This recommendation intends to reduce electromagnetic interference in a plant. Many vendors of frequency converters recommend using shielded motor lines. Shielding the motor lines avoids the emission of electrical, magnetic and electromagnetic fields by the motor lines. With this, it prevents disturbance coupling into lines laid in parallel with it.

4.5.1 Problem description

As shown in Figure 56, the cable shield is run around the active conductor lines (L1, L2, L3) and the protective earth conductor (PE) of the motor line. The shielding prevents the propagation of electromagnetic interference from inside the lines to other current circuits located near the motor line. Coupling inside the line, however, is not suppressed by the cable shield. This means that disturbances in an internal conductor of the line may be coupled into other internal conductors through electric or magnetic fields.

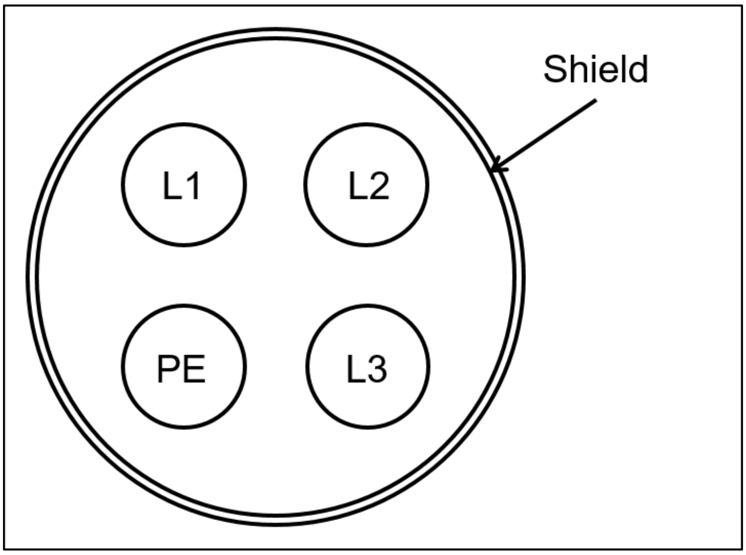


Figure 56: Shielded motor line

4.5.1.1 Capacitive coupling in motor lines

Capacitive coupling occurs as soon as there is a potential difference between two parallel lines. The potential differences between the three conductor lines L1 to L3 are produced by the 120° phase shift between the individual line voltages. Additionally, the pulse width modulation of the frequency converter causes additional capacitive currents between the individual phases of the protective conductor and the cable shield. As both the shield and the protective conductor are usually voltage-free, additionally potential differences to the conductor lines L1 to L3 occur. As a result, there a various coupling capacitances inside a motor line which are shown in Figure 57.

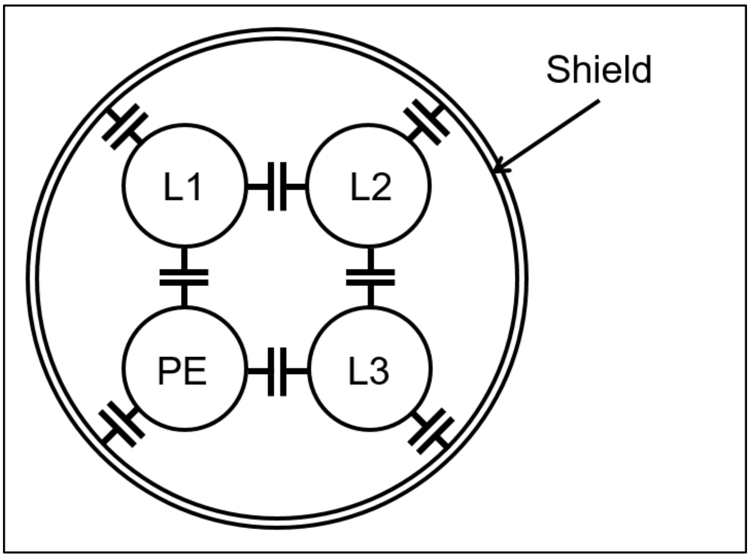


Figure 57: Capacitive coupling in shielded motor lines

4.5.1.2 Inductive coupling in motor lines

The current flow in the conductor lines L1 to L3 generates several magnetic fields in the motor line. Therefore, magnetic field lines surround every conductor in Figure 58.

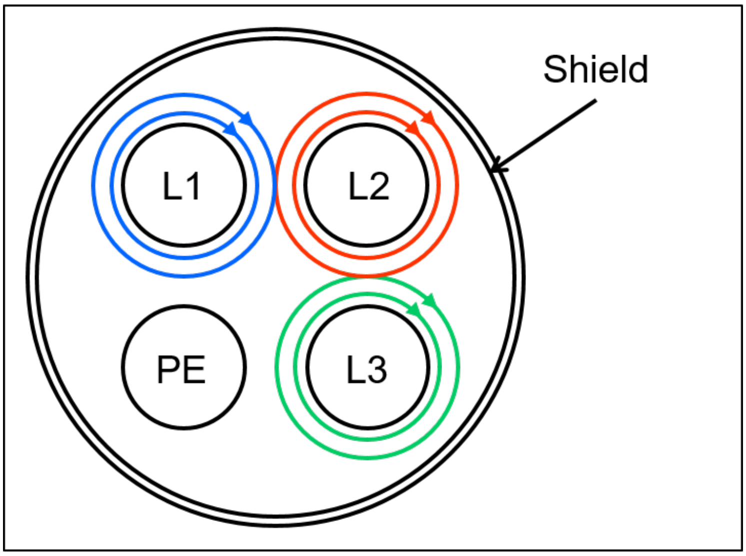


Figure 58: Magnetic field lines in a motor line

The magnetic field lines couple inductive disturbances into the other conductors of the motor line. Figure 59 illustrates this fact for a better understanding.

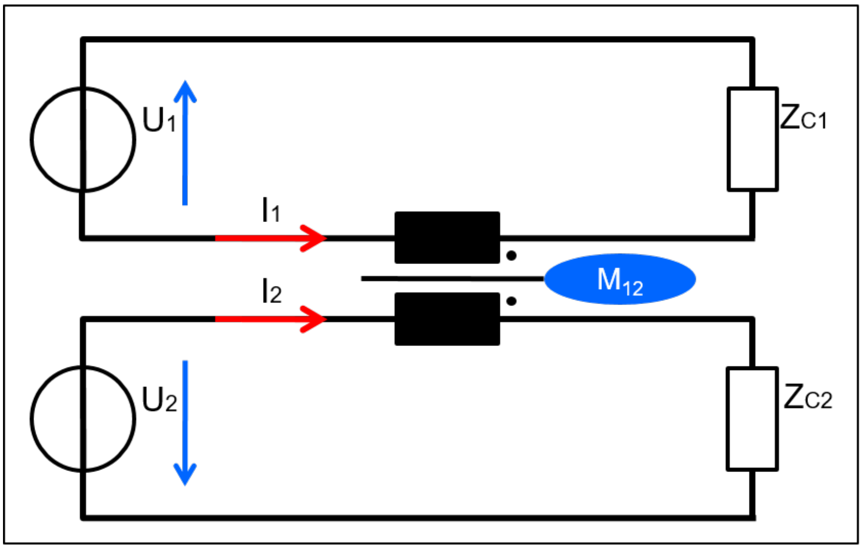


Figure 59: Inductive coupling between L1 and L2

Figure 59 shows the coupling inductance M_{12} between the two conductors $L1$ and $L2$ of the motor line. There are coupling inductances between all conductors of the motor line, where the intensity of the inductance depends not only on the current and frequency of the conductors, but also on the distance between them.

As shown in Figure 60, the distance between *L2* and the protective conductor is higher than the distance of the other two conductors, the coupling inductance M_{L2PE} is lower than the other two inductances.

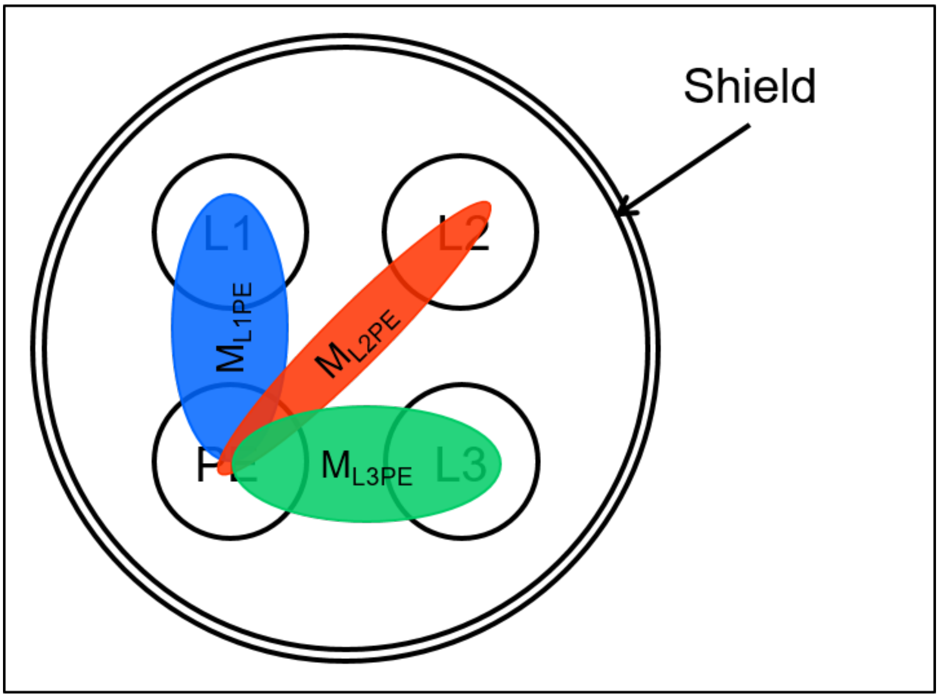


Figure 60: Inductive coupling in a motor line

Because the conductors *L1*, *L2* and *L3* induce currents of different intensity in the protective conductor -because of their different coupling inductances- the induced voltages do not compensate each other. Instead, they create a common voltage, which appears as a current flow in the protective conductor, as soon as it is connected several times to the equipotential bonding system. The current generated in the protective conductor causes potential differences in the equipotential bonding system. Experience has shown that the current flow may reach up to 10% of the phase currents.

4.5.2 Solutions from standards and specialist literature

As the motor line is an important part for CE certification, the frequency converter documentation usually specifies the cable type. This is, for example, the case in the documentation from Siemens [SIE2014], Danfoss [DAN2015], Lenze [LEN2015] and ABB [ABB2005]. All of these four vendors prescribe shielded motor lines. However, the structures of their motor lines differ in detail. The mentioned vendors are presented here as examples in order to allow for a better understanding. The list does not claim to be exhaustive. Lenze describes asymmetrical motor lines as shown in Figure 56 in its documents. ABB and Danfoss do not make any statement in their document about the type of motor line. Figure 61 shows an excerpt from the manufacturer documentation from Danfoss [DAN2015]. At ① you can see the connection line of the motor. It stands out that a separate protective conductor (PE) is to be implemented. At the connection point of the frequency converter, ② it becomes evident that the motor line has three phase lines and one cable shield only. The motor line in the figure does not have a protective conductor.

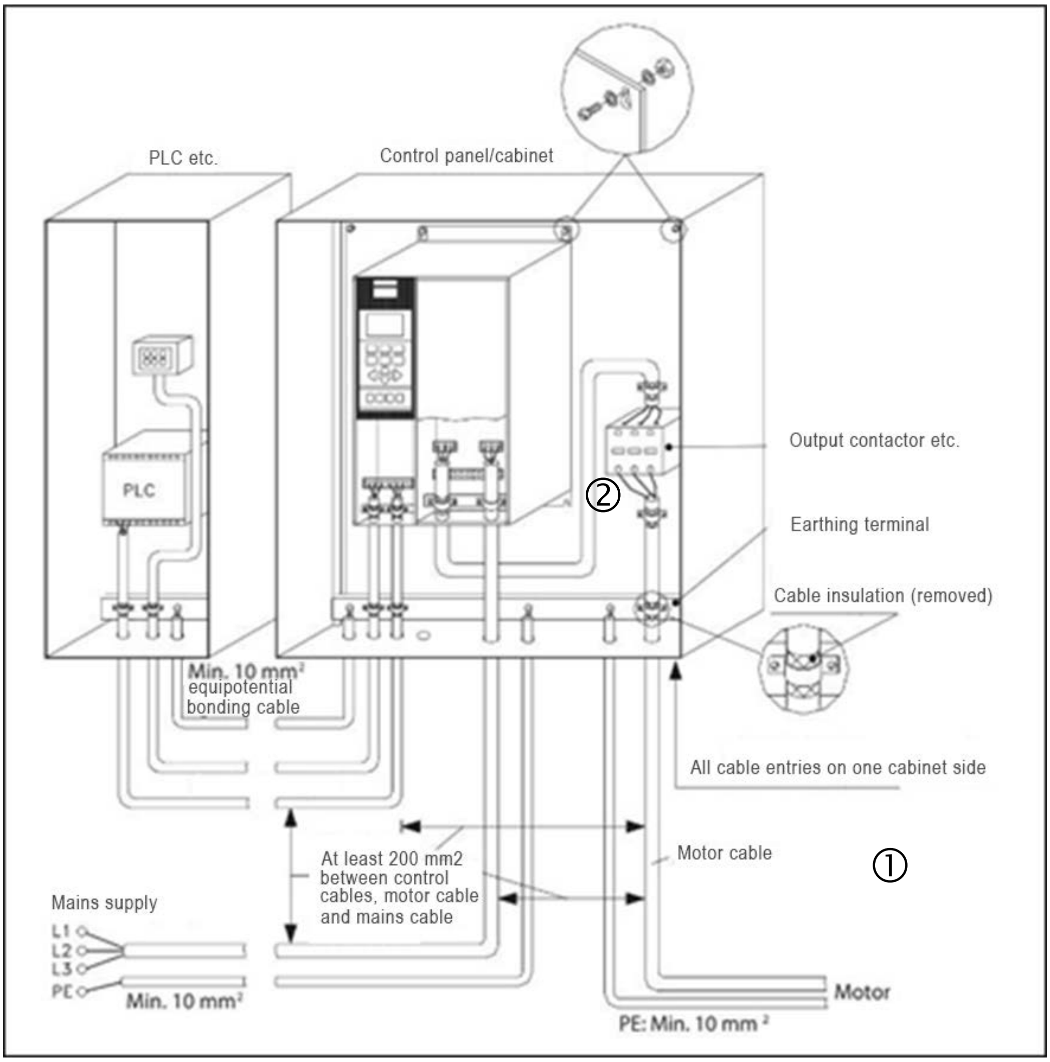


Figure 61 Typical installation of a frequency converter from [DAN2015].

Figure 62 shows an excerpt from a frequency converter documentation from ABB [ABB2005]. At the drive unit, you can see that a shielded motor cable ① is to be used for connection. It is, however, noticeable that the protective conductor of the drive unit does not run inside the shielded motor cable. This means a symmetrical motor line with a separate protective conductor is used in this case.

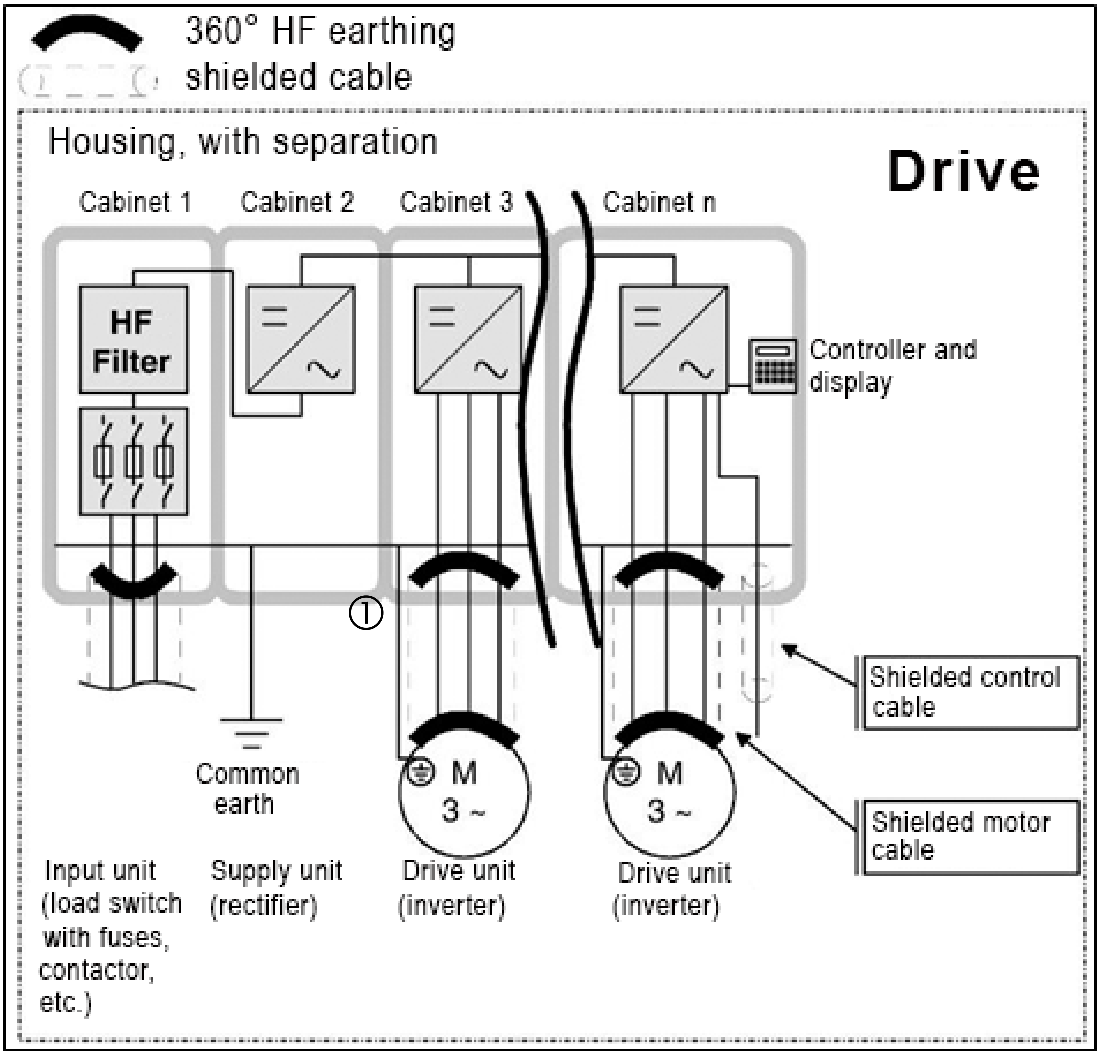


Figure 62: Drive with low voltage power supply from [ABB2005]

For a shielded motor line, a separate protective conductor as shown in Figure 61 and Figure 62 provides the advantage that no disturbances from inside the motor line can be coupled in the protective conductor.

Siemens provides in its document [SIE2014] a detailed description of the possible effects asymmetrical motor lines may have and recommends to use symmetrical three-phase current lines in order to ensure a better electromagnetic compatibility. As can be seen in Figure 63, symmetrical motor lines should have either three protective conductors inside the motor line or one protective conductor laid separately. When a motor line with three protective conductors is used, these conductors should be arranged symmetrically around the conductor lines $L1$ to $L3$. This considerably reduces the total of in-coupled voltages as the distances between the protective conductors and the corresponding conductor lines are equal.

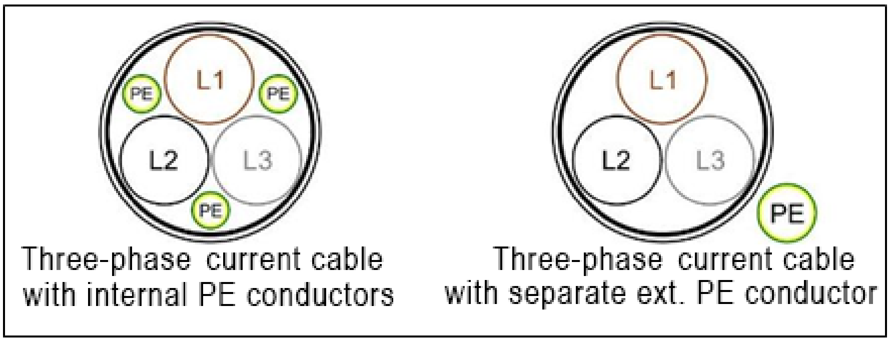


Figure 63: Symmetrical motor lines as recommended by [SIE2014]

Another measure for the reduction of disturbances when using frequency converters is the usage of filters. However, the usage of filters is vendor-specific and, therefore not considered any further in this document.

4.5.3 Recommendations for PROFIBUS and PROFINET

In order to ensure safe plant operation, the load of the equipotential bonding system through voltages and currents coupled into it should be kept as low as possible. For this reason, the vendor instructions on how to connect the motor lines should be strictly observed. Symmetrical motor lines minimize inductive and capacitive coupling into the protective conductor of the motor line. As, however, coupling cannot be fully prevented, the motor and the frequency converter should be connected to the equipotential bonding system with a low-impedance connection. Due to this connection, it is possible that the currents caused by voltages coupled into the system can flow back via the equipotential bonding system and do not affect the data transfer via the PROFIBUS/PROFINET line. From this section of the document, the recommendation R5 is derived:

- Use shielded motor cables in accordance with the manufacturer specifications and provide for big-surface connection of the shield to the common bonding network at each end (low impedance).
- Connect the motor to the common bonding network.
- If not excluded by the manufacturer of the frequency converter, preferably use symmetrical shielded three-wire motor cables with separate protective conductor.

4.6 Connecting the negative pole of 24 V power supply to the CBN

This section deals with the connection of the negative poles of 24 V power supplies to the common bonding network (CBN). Such a 24 V power supply is shown in Figure 64. In addition to the four remote I/O there is also a power supply unit in the figure.

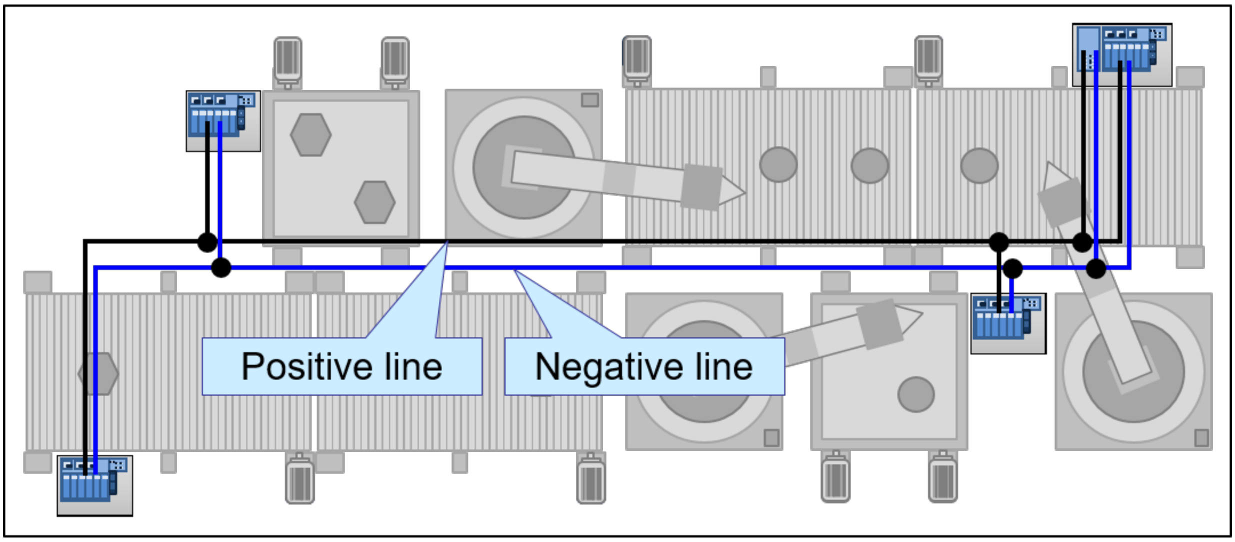


Figure 64: 24 V power supply in a manufacturing plant

According to the [DIN-EN 60204-1] and [DIN-EN 60950-1] standards there are two permissible methods to set up the protective mechanisms in 24 V power supply circuits, and they are completely different.

The first variant consists in using SELV current circuits[2]. In an emergency or in case of a fault, these current circuits carry only safety extra low voltage. For this reason, SELV current circuits are insulated from all other current circuits and from the common bonding system (CBN) of the plant. As a fuse in a SELV current circuit can be triggered only if there is a short-circuit between the positive and the negative pole, but not if a connection between the positive pole and the CBN exists, an insulation monitoring system must be provided to detect the connection to the CBN connection. Usually, such a monitoring system entails additional expenditure for the monitoring device and is therefore only used for special applications (e.g. in the oil and gas industry).

[2] SELV – Safety Extra Low Voltage

More often, however, PELV current circuits[3] are used. Current circuits of this kind also provide for protection against electrical shock. In this case, however, it is required to connect the negative pole of the power supply to the CBN at least at one point close to the power supply unit. This allows, for example, that – in case of an insulation fault – the positive pole of the 24 V power supply unit gets in contact with the common bonding system, and a current circuit is formed. The resulting short circuit current triggers the fuse.

The connection of the negative pole to the common bonding network (CBN) is shown in Figure 65. This figure is a simplified representation of the manufacturing plant example in Figure 64 and can also be applied to the process industry. For the sake of simplicity, details such as fuses or terminals have been deliberately left out.

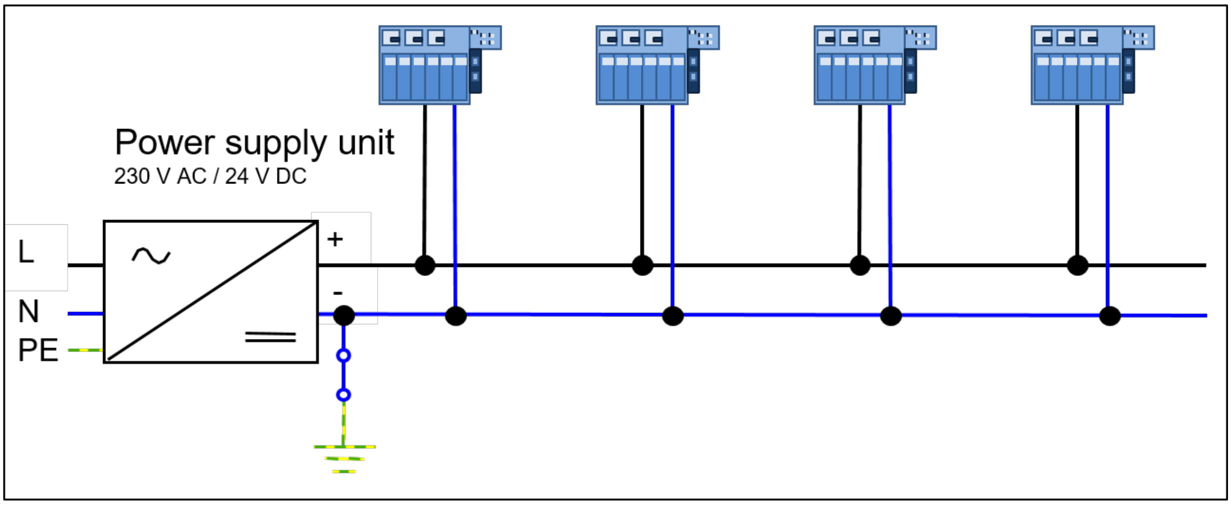


Figure 65: Simplified representation of a 24 V power supply circuit

[3] PELV – Protective Extra Low Voltage

4.6.1 Problem description

Unwanted multiple connections of the negative pole with the CBN, usually cause problems. Accordingly designed devices may cause multiple connections to the CBN, for example. In the example in Figure 66, this additional connection to the CBN is present at the outmost remote I/O. Connections of this kind usually occur when the plant builders connect the minus current circuits of a plant section to the CBN without checking if a central connection to the CBN has already been installed.

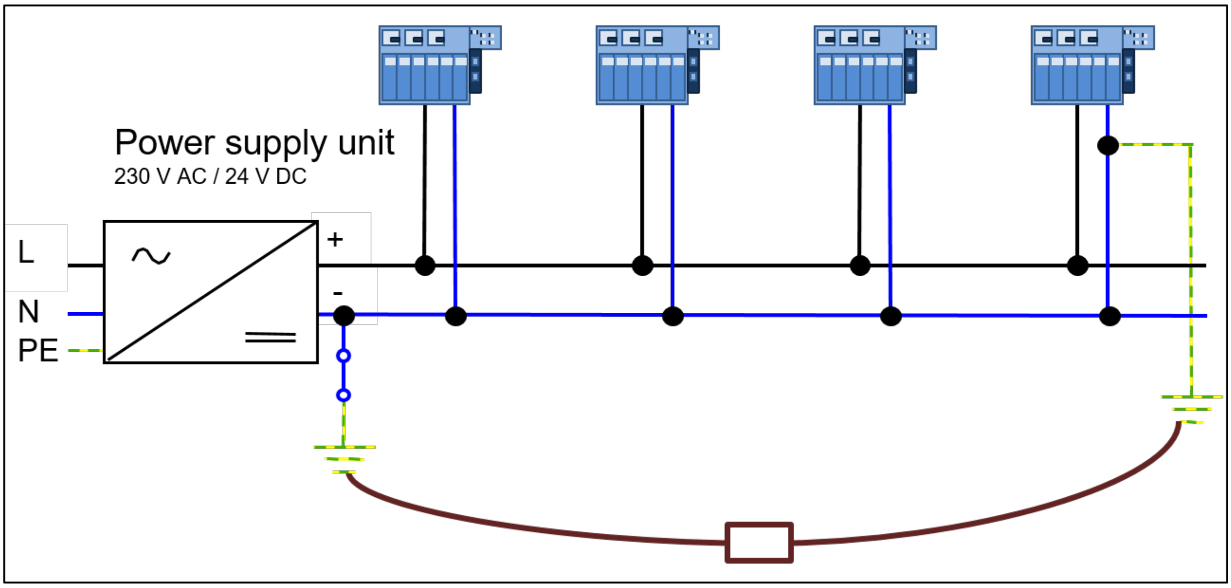


Figure 66: Multiple connections to CBN in a 24 V power supply circuit

Due to multiple connections to the common bonding network (CBN) a parallel connection to the equipotential bonding system emerges. This connection with an undefined resistance is shown in Figure 66. The resistance of the equipotential bonding system is connected in parallel with the negative line of the 24 V power supply circuit. With this parallel connection, the following scenarios are possible:

- Scenario 1: The resistance of the equipotential bonding system is lower than the line impedance.
- Scenario 2: There is a break in the negative line.
- Scenario 3: The resistance of the equipotential bonding system is higher than the line impedance.

These three scenarios are further discussed in the following subsections.

4.6.1.1 Connection of 24 V power supply circuits to CBN, scenario 1

If the 24 V power supply circuit features multiple connections to the CBN, the total current is divided at the two connection points according to the Kirchhoff Current Law. This scenario is shown in Figure 67.

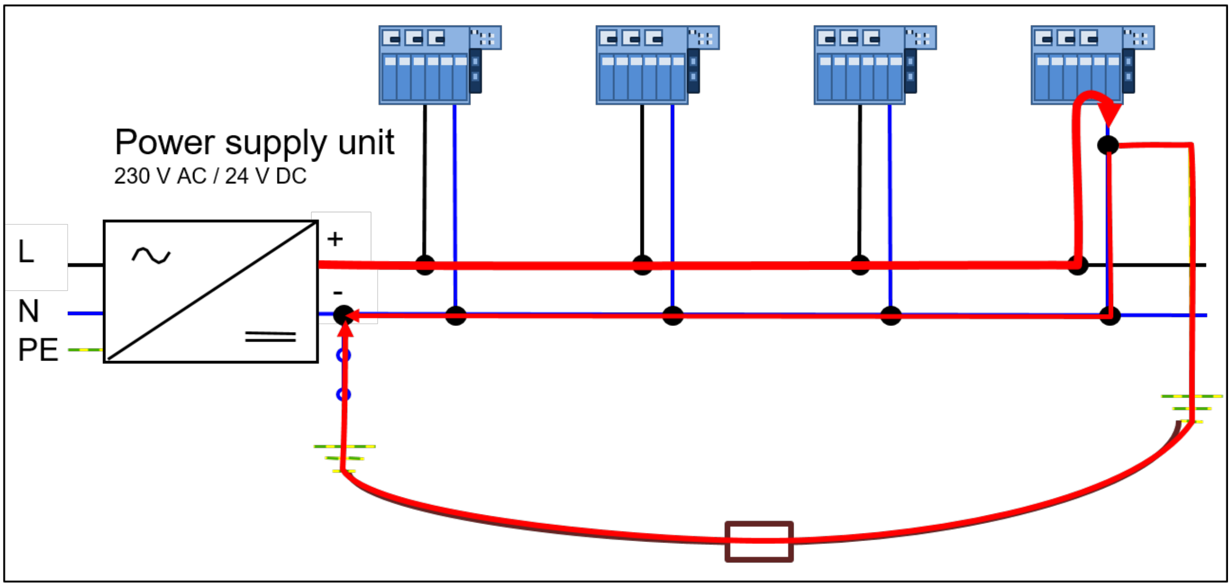


Figure 67: Connection 24 V power supply circuits to CBN, scenario 1

As, in this case, the resistance of the equipotential bonding system is lower than the impedance of the negative line, the major part of the total current flows through the equipotential bonding system. As a result, the equipotential bonding system is loaded with a direct current that should flow through the negative line of the power supply circuit. The cable shields of the data and motor lines are also connected to the equipotential bonding system at several points, so that the currents might also flow through them and damage them.

4.6.1.2 Connection of 24 V power supply circuits to CBN, scenario 2

If the negative line of the 24 V power supply circuit is interrupted as shown in Figure 68, the current is not divided at the multiple connection points to the CBN at the remote I/O, but completely returns to the power supply unit through the equipotential bonding system.

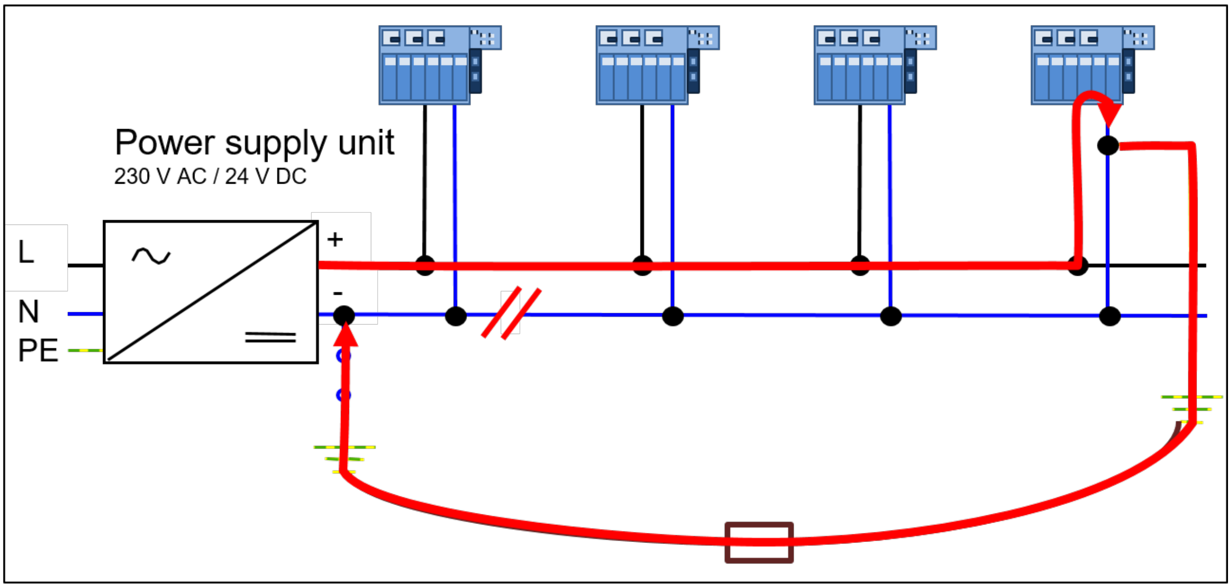


Figure 68: Connection of 24 V power supply circuits to CBN, scenario 2

If the total current completely returns to the power supply unit through the equipotential bonding system, this causes an additional load of the equipotential load system. Any load of the equipotential bonding system, be it direct current or alternating current, results in voltage drops. Moreover, shielded cables with low line impedance are in the equipotential bonding system; in order to ensure full functionality, they should be connected to the CBN at several points. As a result, however, current would also flow through the cable shield. These cable shields do not have high current ratings and are likely to be damaged by the current.

4.6.1.3 Connection of 24 V power supply circuits to the CBN, scenario 3

The third scenario is shown in Figure 69. Here, the resistance between the equipotential bonding system and the multiple connection points to the CBN is higher than the line impedance of the negative line. As a result, the currents are divided at the connecting points, as already described for scenario 1. In this case, however, a stray current from the equipotential bonding system flows through the 24 V power supply circuit. The reason why there is a stray current in the equipotential bonding system is further described in section 4.2.1.

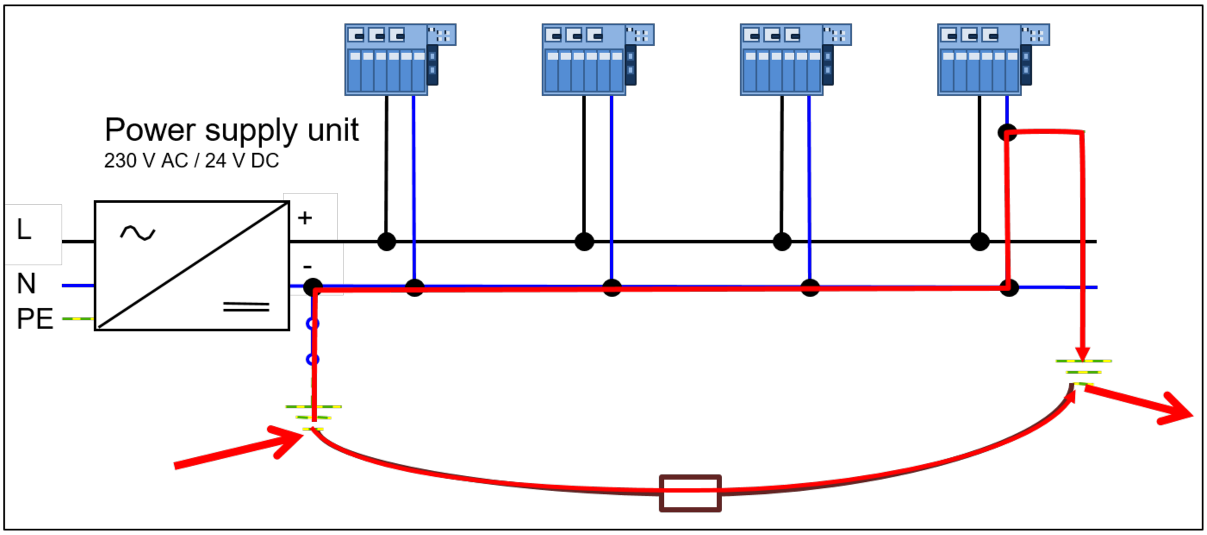


Figure 69: Connecton of 24 V power supply circuits to CBN, scenario 3

The voltage drops produced by the stray current in the equipotential bonding system result in potential differences in the negative line. The consequence of these potential differences may be that the remote I/O unit is no longer supplied with the required mains voltage and fails. Furthermore, the stray current may be either a direct current or an alternating current, and this may cause various disturbance reactions.

4.6.2 Solutions from standards and technical literature

In the [DIN-EN 60204-1], the different types of connections to the CBN are specified. A 24 V power supply circuit has to be connected to the CBN at one end or at any point of the current circuit. In addition, the standard describes how the connection should be done. The connecting point should be located close to the power supply unit or directly next to, if possible, on the installation panel; it has to be easily accessible and must be disconnectable to allow for insulation measurements. If, however, a potential free 24 V power supply circuit with power supply unit is installed, an insulation measurement must be provided in the secondary circuit according to [DIN-EN 61557-8]. In the event of an alarm, it may be used either for immediate disconnection or for outputting an optical and/or acoustic signal, depending on the risk level.

4.6.3 Recommendations for PROFIBUS and PROFINET

If a PELV current circuit is chosen for 24 V power supply, it should only be connected once to the functional equipotential bonding system/CBN directly at the power supply unit and using a disconnect terminal. When commissioning the 24 V power supply circuit, you can perform an insulation measurement and make sure that there is no additional connection to the equipotential bonding system. However, if you discover multiple connection points during this measurement, you will need to check if it is possible to remove them. Multiple connection points of 24 V power supply circuits with the CBN have to be avoided, due to the reasons described in Section 4.6.1.

Devices that have a fixed connection between functional bonding connector and the minus of the 24 V power supply circuit, create multiple connections of the 24 V power supply circuit with the CBN. In this case, the 24 V power supply circuit should have a small size, to limit the impact of a multiple connections to the CBN, described in section 4.6.1. It is also recommended to limit the size of a 24 V power supply circuit to the inner of cabinets or adjacent cabinets. A good equipotential bonding inside the cabinets and between cabinets has to be ensured. In case, 24 V power supply circuits cover larger distances, the effects described in section 4.6.1. have to be considered. A meshed equipotential bonding system with low impedance, as described in section 4.3.3. can reduce, but not eliminate, the impact of a multiple connections to the CBN.

If the multiple connections to the CBN result from internal connections inside the devices that are an integral part of the devices and cannot be removed. It may be necessary to provide a separate 24 V power supply circuit in this case. Multiple connections of 24 V power supply circuits to the CBN have to be avoided. In order to ensure that no multiple connections occur throughout long plant life-cycles, additional current monitoring of the connection to the CBN (see Figure 70) can be provided. The current monitoring equipment should be capable of measuring both direct currents and alternating current and of recognizing all potential operating faults that may result from possible future plant enhancements or from the replacement of devices.

Besides the grounded operation of 24 V power supply circuits a potential free operation is also permissible. In this case, a ground fault monitoring has to be provided.

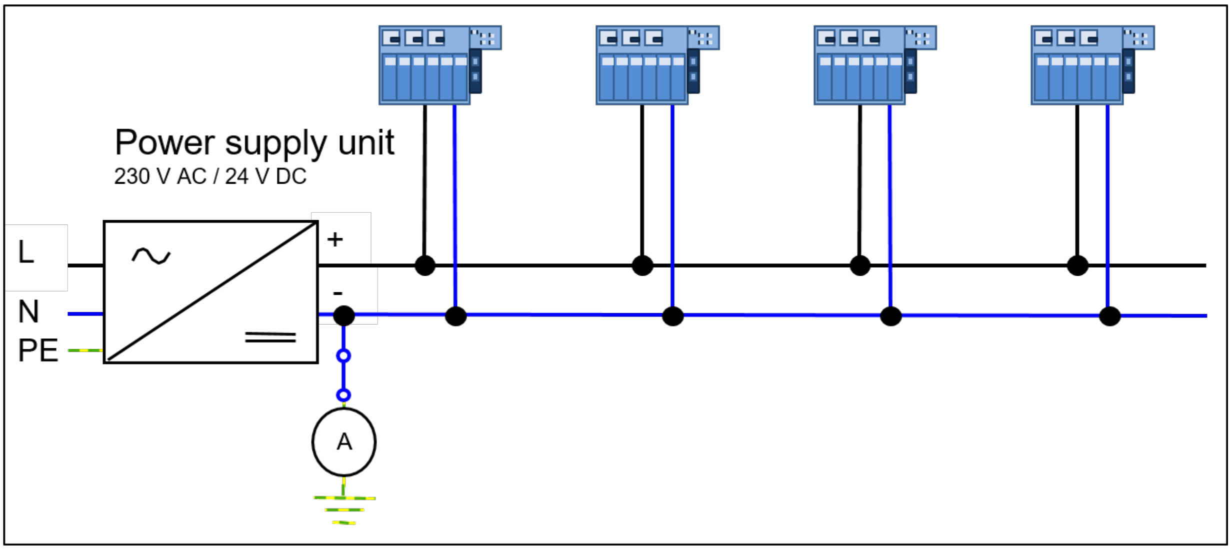


Figure 70: Optimal earthing of 24 V power supply circuits

From this section of the document, the recommendation R6 is derived:

- Multiple connections of 24-V-Supply-Circuits to the common bonding network (CBN) have to be avoided.
- In order to keep the cables between the power supply unit and the consumer as short as possible, it is recommended to use several smaller power supplies rather than a single big one.

5 Summary of the recommendations for the design of PROFIBUS and PROFINET networks with little disturbance

The six recommendations R1 to R6 help avoid disturbances by electromagnetic interference in a plant with PROFIBUS and PROFINET networks. The measures, proposed in this document have to be synchronized between planner, installer and operator of the plan.

R1	Provide both protective equipotential bonding and functional equipotential bonding through a common bonding network (CBN).
R2	Preferably realize 230/400 V power supply using a TN-S system.
R3	Use a common bonding network (CBN). Mesh equipotential bonding systems as finely as possible (MESH-BN).
R4	Provide a connection of the PROFIBUS/PROFINET cable shields through the housings of the connectors and through the housings of the devices and thus to the common bonding network (CBN) at each cable end with big contact surfaces (low impedance).
R5	• Use shielded motor cables in accordance with the manufacturer specifications and provide for big-surface connection of the shield at each end to the common bonding network (CBN) with with low impedance. • Connect the motor to the common bonding network (CBN). • If not excluded by the manufacturer of the frequency converter, preferably use symmetrical shielded three-wire motor cables with separate protective conductor.
R6	• Multiple connections of 24-V-Supply-Circuits to the common bonding network (CBN) have to be avoided. • In order to keep the cables between the power supply unit and the consumer as short as possible, it is recommended to use several smaller power supplies rather than a single big one.

When planning a system, be sure to consider all recommendations if possible. Any later plant adaptation that may become necessary in ongoing operations due to disturbances caused by electromagnetic interference implies heavy additional expenditure.

Therefore, power supply systems in new or modernized plants should be designed as TN-S systems only. The TN-S systems prevents operating currents from the neutral conductor to enter the equipotential bonding system as there is only a connection between the protective conductor and the neutral conductor in the LVMD. As a result, current flows that may cause potential differences in the equipotential bonding system are avoided.

When implementing such a system, you can also provide for common protective and functional equipotential bonding, as it is no longer possible to ensure consistent separation of these two equipotential bonding systems in modern plants. If a common bonding network (CBN) is used, make sure that it meets the requirements on proper protective and functional earthing. The equipotential bonding system must feature a sufficient ampacity and low impedance. For the sake of electromagnetic compatibility, the connections should be protected against unintentional loosening and adverse weather conditions.

Optimal low-impedance equipotential bonding can be achieved by using a meshed equipotential bonding system in compliance with DIN EN 50310. A meshed equipotential bonding system features a multitude of small meshes that reduce the impedance. Low impedance reduces the occurrence of potential differences caused by coupling.

In addition, the cable shields of PROFIBUS and PROFINET lines should be connected to the equipotential bonding system at least at both ends. The connection should be made through the connector plug of the PROFIBUS/PROFINET device. The connection between the connector shroud and the functional earth connector should also have a low impedance. Additionally, there should be further connections between the cable shields and the equipotential bonding system in order to reduce the size of the meshes for coupling (see section 4.4.1).

Currents in the equipotential bonding system could also be caused by the motor lines. Inside the motor lines, inductive and capacitive coupling may generate current. This can be avoided by using shielded motor lines, which in fact are already prescribed by the vendors of the corresponding frequency converters.

When implementing 24 V power supply circuits, multiple earthing should basically be avoided. Multiple earthing of the negative pole in a 24 V power supply circuit may allow currents from the equipotential bonding system to reach into the 24 V power supply circuit and cause potential shifts. These potential shifts may result in the failure of units when the voltage falls below their rated voltage. Moreover, currents from the 24 V power supply circuit may reach into the equipotential bonding system. This system, however, also comprises cable shields which do not feature a sufficiently high ampacity and will heat with increasing current. This means that multiple earthing of a 24 V power supply circuit may present a fire hazard (see section 4.6.1.3). In order to avoid this, 24 V power supply circuits should be earthed only once through the equipotential bonding system. A simple monitoring function established by implementing a current monitor at the single earthing point allows you to identify multiple earthing of the 24 V power supply circuit during ongoing plant operation.

6 Suggestions for possible acceptance tests

It is recommended, for future acceptance tests of PROFIBUS or PROFINET systems, to also take into account their electromagnetic compatibility. To be sure, to remember the essential points, you should use a checklist as shown in Table 2. The table has the same layout as the checklists suggested in the Installation Guideline for Commissioning from PROFIBUS User Organization.

Table 2: Suggestions for possible acceptance tests

Plant	Installation made by
	Comments

EMC checklist

No.	Check request	YES	NO	Comment
1.	Mains supply			
1.1	Mains supply network preferably implemented as TN-S system?			
1.2	PEN bridge provided in LVMD?			
1.3	No other PEN bridges installed?			
1.4	Insulation test between neutral conductor and protective conductor performed with open PEN bridge?			
1.5	Current monitoring provided at PEN bridge? (optional)			

No.	Check request	YES	NO	Comment
2.	Equipotential bonding system			
2.1	Common protective and equipotential bonding network (CBN) installed?			
2.2	Meshed equipotential bonding system installed?			
2.3	Tin-plated copper strand used to ensure low impedance of the equipotential bonding system?			
2.4	Is the current rating of the equipotential bonding conductor sufficient?			
3.	Connection of PROFIBUS/PROFINET cable shields			
3.1	Is a good connection of the connector housings to the housing of the PROFIBUS / PROFINET devices and thus a good connection to the CBN achieved?			
3.2	Do the used connector plugs have sufficiently big contact surfaces for the cable shields?			
3.3	Does the cable shield feature a low-impedance connection to the equipotential bonding system?			
4.	24 V power supply circuits			

4.1	Is the 24 V power supply circuit connected to the CBN??			
4.2	Is the connection of the negative pole in the 24 V power supply circuit to the CBN located close to the power supply unit?			
4.3	Is the 24 V power supply circuit connected only once to the CBN?			
4.4	Was the insulation test between earth and the CBN system performed with open earth connector?			
4.5	Is current monitoring of CBN connection provided (optional)?			
4.6	Where a multiple earth connection of a 24 V supply circuit to the CBN is present: Is the spatial extent of the 24 V supply circuit limited?			
4.7	Where a multiple connection of a 24 V supply circuit to the CBN is present: Is a low impedance of the CBN ensured?			
5.	Cables outside cabinets laid in cable trays			
5.1	Data lines laid separately from power supply lines?			
5.2	Minimum distances according to [DIN-EN 50174-2] and [IEC 60364-4-44] observed? If required, [NE 98] should be observed for application in the process industry			.

No.	Check request	YES	NO	Comment
6.	Motor lines			
6.1	Are motor cables according specification of the manufacturer of the frequency converter in use?			
6.2	Are the motors connected to the CBN?			
6.2	Recommended for the sake of EMC if not excluded by the manufacturer of the frequency converter: Were shielded symmetrical motor lines or shielded three-wire motor lines with separate protective conductor used?			

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