atp magazin

SPECIAL PRINT

Transforming Automation
Issue 04 2019

EMC-compliant installation of automation networks

Functional equipotential bonding and shielding of PROFIBUS and PROFINET

EMC-compliant installation of automation networks – Functional equipotential bonding and shielding of PROFIBUS and PROFINET
The topic of electromagnetic compatibility (EMC) remains an important aspect during the planning, installation and operation of automation systems. Communication networks, such as PROFIBUS and PROFINET, are known to be robust and reliable transmission systems. Nevertheless, it is important that a number of fundamental principles needs to be observed to ensure fault-free operation over a long plant lifetime. This paper first describes a number of principles of EMC. On the basis of these principles, six recommendations for action are then developed which are to be observed during the planning of an automation system for use in the manufacturing industry. Finally, an overview is provided of future work for systems in the process industry.

KEYWORDS Electromagnetic compatibility / EMC / equipotential bonding / Profibus / Profinet

PEER Review 24.09.2018

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This paper summarizes the results of the working group"CB/PG3 Installation Guides PB and PN" of PROFIBUS and PROFINET International (PI). Over the past two years, this working group has fundamentally examined the topic of functional equipotential bonding and shielding for PROFIBUS and PROFINET.

The results of the aforementioned working group are available since the spring of 2018 in the format of a guideline in German [1] and English [2]. Focus of previous work was on the manufacturing industry.

Looking at the state of the art of electromagnetic compatibility (EMC), it should be assumed that the underlying issues have been examined and resolved since the 1990s, as all devices that have been brought to market in the EU since this time must undergo corresponding EMC testing within the scope of CE marking [3] [4]. Furthermore, with IEC 61131-2 [5] there has been existed for many years a standard in place which, in addition to functional requirements, also defines requirements with respect to the EMC of programmable logic controllers and their peripherals. It is therefore all the more surprising that a significant number of problems with EMC in production systems continue to occur even today. For example, a company that works in the area of troubleshooting and diagnosis of industrial bus systems attributes the source of 23% of all errors, ascertained during service calls, to EMC [6].

Taking a closer look, it can be found that much of the electromagnetic interference arises from the interaction of different components and from the influence of the energy supply and grounding system. For this reason, the working group addressed, in particular, issues that occur in distributed manufacturing plants and developed appropriate suggestions for avoiding or at least reducing EMC problems in distributed systems.

1. FUNDAMENTALS

The fundamentals of electromagnetic compatibility are described in various textbooks. Some of them focus on electronic assemblies or the devices [7–9], others on EMC aspects for electrical installations and systems [10–12]. This paper first deals with aspects of EMC that can be influenced by the system planner and then develops corresponding recommendations for action in Chapter 2.

1.1 Couplings between source of disturbance and susceptible device

Present in every automation system are sources of disturbance (welding systems, frequency converters, power switches) and susceptible devices (electronic components of the automation system) on which the disturbances act. A source of disturbance can act on a susceptible device in different ways. Figure 1 shows the most important types of coupling.

The coupling types shown in Figure 1 can be classified as follows:

- Line-conducted: If a section of wire is connected to two different circuits, conductive coupling occurs between these two circuits. Current flow in one circuit thereby acts on the second circuit. Example: If the negative conductor of a supply circuit is grounded at two locations, current flowing in the grounding system can also flow through the supply circuit and cause disturbances or voltage drops there.

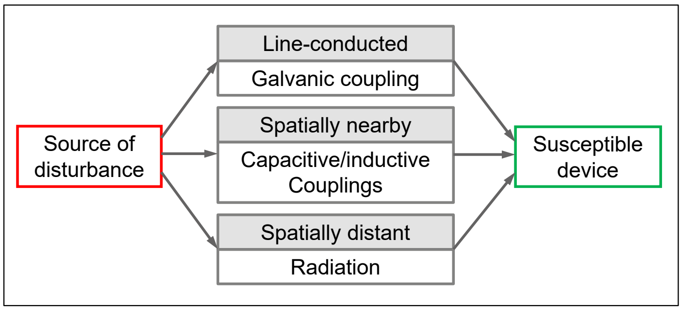

FIGURE 1: Coupling types between source of disturbance and a susceptible device

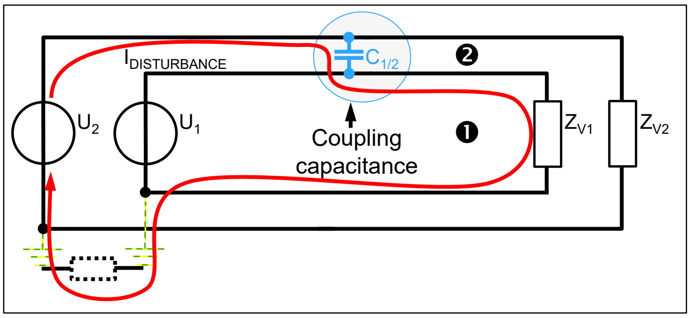

FIGURE 2: Capacitive coupling between two circuits

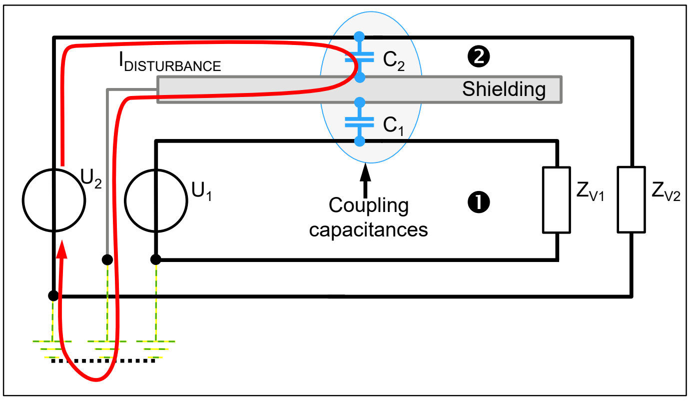

FIGURE 3: Shielding as a measure against capacitive coupling

- Spatially nearby: This type of coupling generally affects parallel lines. A power cable can, for example, capacitively or inductively couple into a signal cable. The degree of coupling increases the longer the cables are arranged in parallel. The influence of both coupling types can be reduced by increasing the distance between the power cable and signal cable or by means of metallic separators in the cable duct. Twisted pairs offer additional protection against inductive coupling. The effect of cable shielding is discussed below in Section 1.2.
- Spatially distant: This type of coupling arises through electromagnetic waves (radio waves). An example of this is the effect of mobile phones or wireless devices on automation components or the emission of radio waves by devices or cables.

Because spatially distant coupling causes problems in industrial automation relatively seldom, this paper deals with line-conducted and spatially nearby couplings in the following.

1.2 Shielding of communication cables and power cables

Capacitive coupling can occur between parallel conductors of circuits that have a common reference point (e.g., the connection to the equipotential bonding system). Figure 2 shows an example of capacitive coupling.

The following exceptions apply: Circuit (1) is a DC circuit with voltage source U_1. Circuit (2) is an AC circuit with AC voltage source U_2 = 230 V. The lines of both circuits run in parallel for a distance in a cable duct. As a result of the parallel routing, a coupling capacitance $C_{1/2}$ forms between the conductors, the magnitude of which is dependent on the distance and on the insulation material of the conductors and on the length of the parallel routing. Because both circuits are connected to the equipotential bonding system, a current $I_{DISTURBANCE}$ can flow from circuit (2) to circuit (1) via a coupling capacitance and falsify the voltage at impedance Z_{V1}.

A known means to counter capacitive disturbances, is the shielding of the signal line. Figure 3 shows the two circuits with shielding between the two circuits.

It can be seen that the coupling capacitance C_1 forms between circuit (1) and the shielding, and coupling capacitance C_2 forms between circuit (2) and the shielding. Because the shielding is connected to the equipotential bonding system, the disturbance current $I_{DISTURBANCE}$ now flows via the shielding instead of through circuit (1). The voltage at impedance Z_{V1} is no longer falsified. Because circuit (2) carries DC current, coupling capacitance C_1 is irrelevant. In addition to the shielding, another measure against capacitive coupling is increasing the distance between the cables. This reduces the coupling capacitance. Furthermore, the use of metallic, grounded separators between power cables and signal lines is useful. In principle, these function the same as shown in Figure 3. To counter capacitive disturbances, it is, in principle, sufficient to connect the shielding to the equipotential bonding system at one point.

In addition to shielded signal cables, power cables can be shielded as well. The functional priciple is identical. The shielding of power cables prevents the emission of electrical fields from the cables. The shielding of signal cables prevents the penetration of electrical fields into the interior of the cable.

Lines carrying an AC current, can induce an AC voltage in a signal circuit via the inductive coupling. The magnitude of the induced AC voltage is dependent on the spacing between the cables, the rate of current change *di/dt* in the power circuit and the length of the parallel routing.

The shielding material used for the lines (usually copper braiding, if necessary in combination with metalized plastic foil) can be penetrated by magnetic fields. Thus, cable shielding grounded at one end is not effective against inductive coupling.

Figure 4 shows a conductor (1) carrying an AC current I_{POWER}, thereby generating a time-varying, cylindrical magnetic field. Through the inductive coupling, the magnetic field induces a voltage in the shielding of cable (2). If both ends of the cable shielding are now connected to the equipotential bonding system, the magnetic alternating field causes an induced current, which in turn produces a magnetic field. With respect to the original magnetic field, the magnetic field of the induced currents is in the opposite direction. Because both magnetic fields are superimposed, the interior of the cable shielding remains free of magnetic fields. For the cable shielding to be effective against magnetic fields, the cable shielding is, thus, to be connected to the equipotential bonding system at each cable end. Multiple connection of the cable shielding to the equipotential bonding system increases the effectiveness. A detailed description of the principle can be found in [13].

Another protection against inductive coupling is the twisting of a pair of wires. This causes the magnetic field to act on the pair of wires in opposing direction, thereby nearly negating the induced voltages. Because, due to the geometry, twisting will never be ideal, full effectiveness is not to be expected. Another protection against magnetic coupling is increasing the distance between power cables and signal cables as well as the use of cable ducts and corresponding separators made of steel. The use of metals with especially high permeability (Mu metal) is usually not used for the construction of cable ducts due to price and handling reasons.

1.3 Protective equipotential bonding and functional equipotential bonding

With equipotential bonding, a distinction is made between protective equipotential bonding and functional equipotential bonding. Protective equipotential bonding is a protective measure against electric shock [14]. Devices that are operated with voltages that are dangerous to the touch, are generally equipped with a protective conductor (PE) that is connected to the equipotential bonding system for this purpose.

The objective of functional equipotential bonding is to reduce the effect of an insulation fault that could affect the operation of the machine. Furthermore, functional equipotential bonding is intended to reduce the effects of electrical disturbances on sensitive electrical equipment that could arise through the operation of a machine [15].

2. RECOMMENDED ACTIONS FOR THE DESIGN OF PROFIBUS AND PROFINET NETWORKS WITH LITTLE DISTURBANCE

The recommended actions listed here focus on the reliable operation of industrial communication systems, such as PROFIBUS and PROFINET. The following six recommendations are intended to lead to a safe and reliable operation of the automation system. It should be noted that these are proposals without a normative character. In certain environments, in certain technical constellations or when used in certain countries, it may be advisable to deviate from the recommendations.

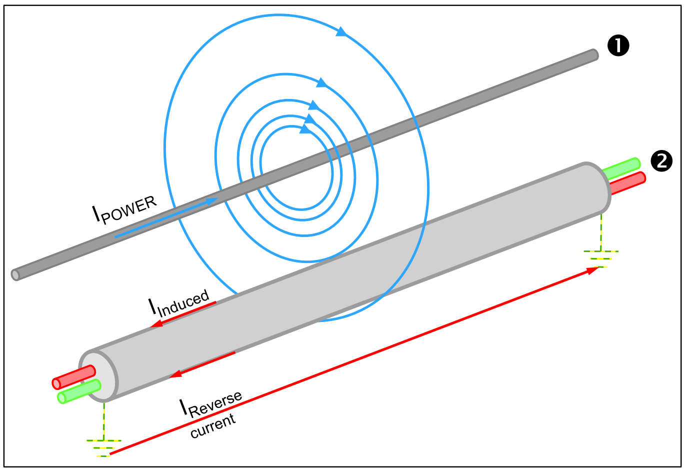

FIGURE 4: Induction in the cable shielding

2.1 Combined protective and functional equipotential bonding (CBN))

Section 1.3 described the properties of protective and functional equipotential bonding. In the past, efforts were sometimes made to separate the two systems in order to keep the functional equipotential bonding of electronic devices free of disturbances whose origin was seen protective equipotential bonding system.

In practice, protective and functional equipotential bonding can only rarely be separated, as components of the automation system frequently create connections between protective and functional equipotential bonding. Moreover, a separate arrangement is costly. A common bonding network (CBN) is therefore recommended. CBN combines the protective functions that are needed for triggering circuit breakers in case of a fault and the functional equipotential bonding function for avoiding electromagnetic interference.

Note that the common protective and functional equipotential bonding conductors must satisfy the requirements for protective conductors [16]. Thus, the minimum cross sections, line impedances, minimum current carrying capacity and protection against self-loosening of equipotential bonding conductors are to be observed.

2.2 Design of the 230 V /400 V power supply

For the 230 V / 400 V power supply, network structures TN-C or TN-S [17] or a combination of both net-

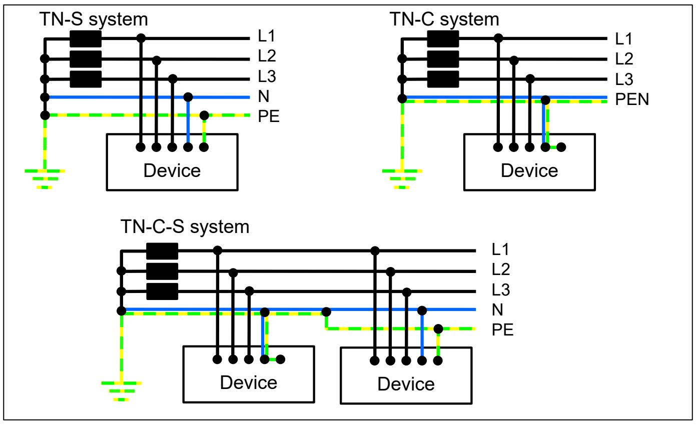

FIGURE 5: Network structures TN-S, TN-C and TN-C-S

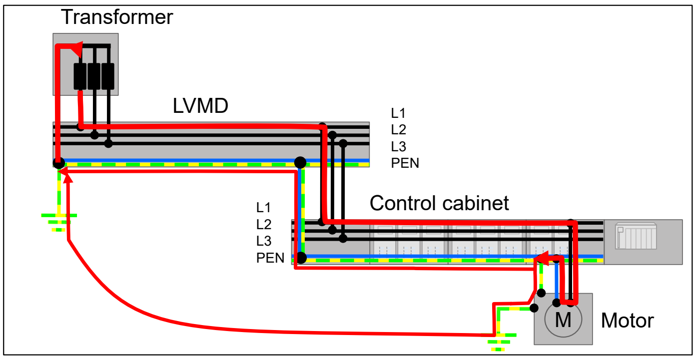

FIGURE 6: TN-C system with load and current flow

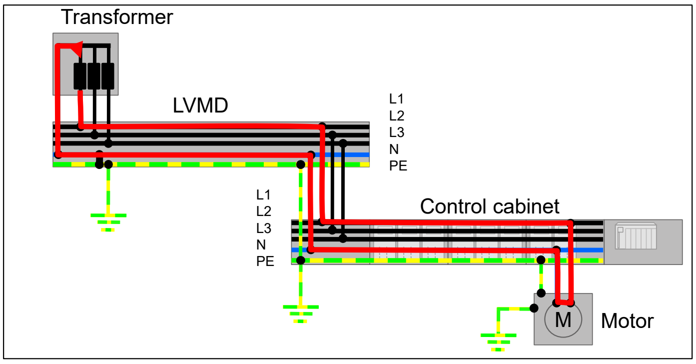

FIGURE 7: TN-S system with load and current flow

work structures (TN-C-S) are often used in automation technology.

Figure 5 shows the three described network structures. With the TN-S system, the three conductors L1, L2 and L3, the neutral conductor N and the protective conductor PE are laid separately from each other. The merging and grounding of the neutral conductor and PE takes place at the star point of the transformer. The TNC system uses a combined neutral and protective conductor (PEN), which is likewise grounded at the star point. The TN-C-S system is a combination of the two systems. Here, the PEN conductor is separated into an N conductor and a PE conductor at a certain point.

TN-C systems can be found in industrial installations, particularly in existing plants. Figure 6 illustrates the flow of current in a TN-C system with a single-phase load, depicted here as a motor.

Normally, current (red line) flows via L1 through the motor and the PEN back to the transformer. The motor housing is also connected to the PEN through the protective conductor. Furthermore, the motor housing is mounted on a conductive support that is connected to the equipotential bonding system. In Figure 6 it can now be seen that the motor current (red line) is divided: One part flows through the PEN, another part through the ground system to the transformer. This means that, with a TN-C system, operational currents in the equipotential bonding system occur. These are also referred to as stray currents [18]. Because the cable shielding of communication systems is connected to the equipotential bonding at each cable end, these stray currents can also flow through the cable shielding, where they can cause communication disturbances or even damage the shielding.

Stray currents can be avoided by using a TN-S system as shown in Figure 7.

Because neutral conductor and protective conductor are separated and connected only at one point (transformer), the operational current only flows via L1 and N. Stray currents do not occur. Make certain that N and PE are connected at only one point. If there are multiple connections, the TN-S system degrades into a TN-C system with the described disadvantages. It is recommended that the 230/400 V power supply be set up as a TN-S system. This recommendation is also found in the literature [12] and in the standards [19].

2.3 Meshed equipotential bonding system

The protective conductors of devices generally form a star or tree with star-point distribution. Figure 8 shows such a star.

It can also be seen that the shielding of the communication cables, which is connected to the equipotential bonding at each cable end, connects the devices to one another, thereby forming meshes in combination with the protective conductors. In these meshes, power cables that run parallel to one another, can induce voltages. These, in turn, can lead to undesired currents in the cable shielding. Equipotential bonding conductors that run parallel to the bus lines (so-called shield relief conductors) have only limited effectiveness, as high-frequency interference in particular tends to flow through the cable shielding, even with parallel shield relief conductors.

One remedy to this problem is a mesh bonding network (MESH-BN) [20], as shown in Figure 9.

By meshing the equipotential bonding system and through the integration of conductive system parts into equipotential bonding system, the surface areas of the potential induction loops are reduced and possibly induced disturbance currents locally short circuited within a small area. The cable shielding is thereby relieved of disturbance currents. By incorporating the metal building construction through grounding points, the effectiveness of a MESH-BN can be increased. It is also possible to integrate metal cable ducts into the MESH-BN. Figure 10 shows a cable duct with screwed-on contact blocks for the connection of a circumferential ring conductor (copper, stranded, tin-plated) and for outgoing protective conductors.

It is recommended that the equipotential bonding be implemented meshed as MESH-BN and cable ducts and structural parts be included in the MESH-BN.

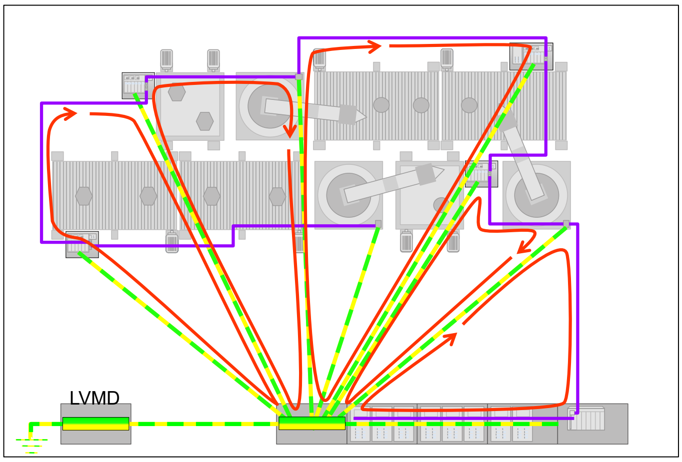

FIGURE 8: Meshes in an equipotential bonding system with star topology through cable shielding

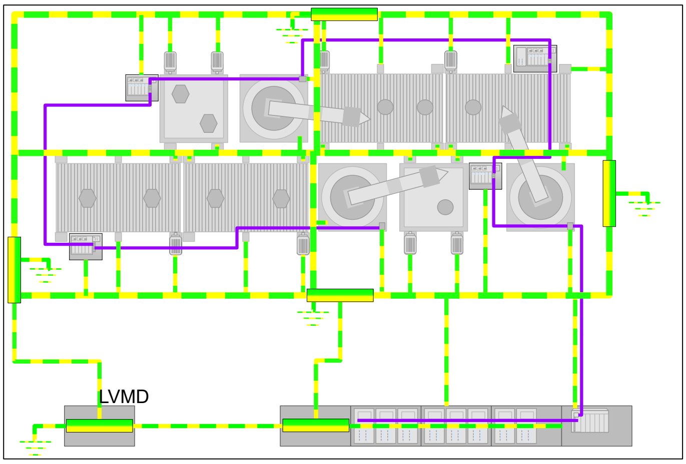

FIGURE 9: Meshed equipotential bonding system (MESH-BN)

2.4 Connection of the PROFIBUS and PROFINET cable shielding

The shielding of cables was described in Section 1.2. On the basis of these explanations, it is recommended to connect PROFIBUS/PROFINET cable shields at both ends with large-surface contact (low impedance) of the connector housing to the housing of the devices and thus to the Common Bonding Network (CBN). This recommendation applies for systems in the manufacturing industry without explosion hazards.

Furthermore, a minimum distance between power cables and communication lines is to be ensured [19].

2.5 Motor cables

This section focuses on motor cables. This refers, in particular, to cables between frequency converter and motor.

Figure 11 shows three arrangements for motor cables. Shown at the left is a conventional, shielded motor cable. As described in Section 1.2, an inductive as well as a capacitive coupling exists between conductors L1, L2 and L3 and the protective conductor (PE). As a result, the three conductors induce a voltage in the PE, thereby causing current to flow in the PE and in the CBN, since the PE is connected to the CBN at both the frequency converter as well as at the motor. This, in turn, leads to stray currents in the CBN that may also flow through the shielding of communication cables. The shielding at both ends of the motor cable does prevent the electrical and magnetic fields of the motor cable from affecting other cables that are parallel to the motor cables. This does not prevent coupling into the PE located within, however.

The cable type shown in the middle of Figure 11 divides the PE into three conductors. By symmetrically dividing the PE in this way, the net result is that no voltage is induced in the PE. Prerequisite for the use of this line type is a suitable connection technology in the motor and frequency converter.

Figure 11 on the right shows another alternative for preventing an undesired induction of currents into the protective conductor. In this case, the protective conductor is laid outside of the shielded, three-core motor cable. The cable shielding protects the protective conductor and other conductors from being influenced by inductive or capacitive coupling. As a result, no voltage is induced in the PE. During operation, the PE remains free of larger currents. With respect to the motor cables, the following recommendation can be made:

ACKNOWLEDGMENTS

This author would like to thank all members of the "CB/PG3 Installation Guides PB and PN" working group of the PROFIBUS User Organization and the participating students of the University of Applied Sciences and Arts Hannover for their work in the creation of the guideline. Thanks as well to all external individuals who contributed to this guideline with their review comments.

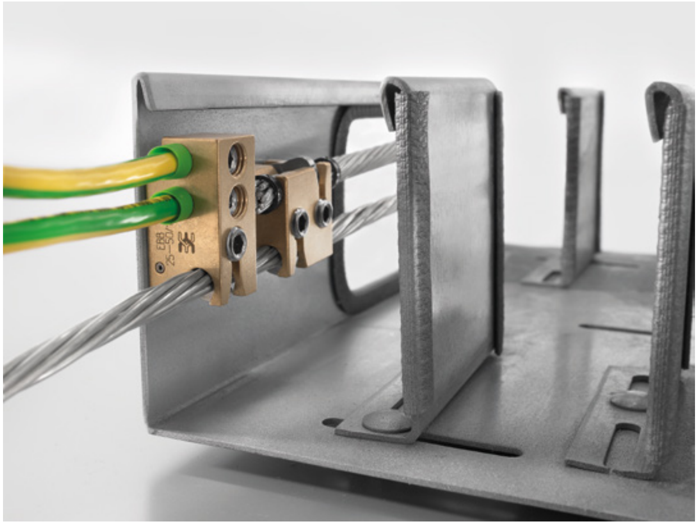

FIGURE 10: Cable duct with circumferential ring conductor and outgoing conductors (source: Weidmüller)

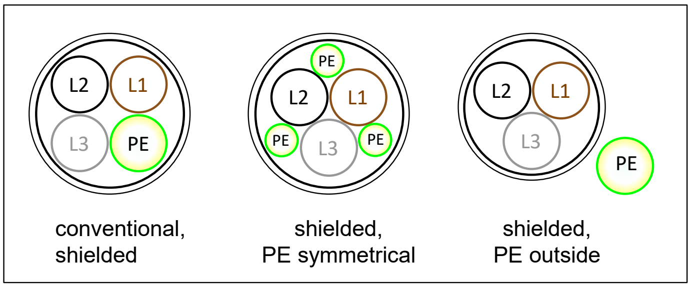

FIGURE 11: Motor lines

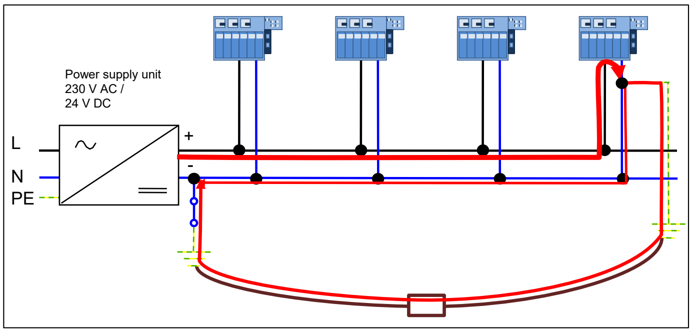

FIGURE 12: Multiple grounding of a 24 V supply circuit

- Use shielded motor cables in accordance with the manufacturer specifications and connect the shield to the common bonding network at each cable end with large contact surface (low impedance).
- Connect the motor to the common bonding network (CBN).
- Provided it is not excluded by the manufacturer of the frequency converter, the use of symmetrically shielded, three-core motor cables with separate protective conductor is preferred.

The use of EMC filters was discussed intensively in the working group. It was, however, decided to refrain from making a recommendation on this topic. Note that EMC filters reduce the energy efficiency of the drive solution.

2.6 Connecting the negative pole of a 24 V supply to the CBN

To avoid malfunctions, 24 V supply circuits must either be connected to the CBN at one point or be equipped with ground fault monitoring [20].

Figure 12 shows such a 24 V supply system. The negative terminal of the power supply unit is connected directly to the CBN via a disconnectable bridge. The current to the consumers should only flow via the positive and negative conductors of the supply circuit. If the negative conductor is now (possibly unintentionally) connected to the CBN at another location, a parallel current path is created via the CBN. The current can now flow either through the negative conductor or the CBN depending on the impedance circumstances. This results in stray currents in the equipotential bonding system with the effects described in Section 2.2. Multiple connections of a 24 V supply circuit with the CBN should be avoided for this reason.

Certain device types, e.g., frequency converters, may require that the negative conductor of the 24 V supply be connected to the CBN in the device for reasons of electromagnetic compatibility. From the perspective of the system, this results in multiple connections to the CBN. In such a case, devices of this type should be supplied by a spatially limited 24 V supply. For example, one 24 V supply could be provided for each control cabinet. This would limit the stray currents to the mounting plate of the control cabinet. In such a case, the recommendations of the manufacturer are to be observed.

3. SUMMARY OF THE RECOMMENDATIONS FOR ACTION

Table 1 summarizes the recommendations for action described in Chapter 2.

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TABLE 1: Summary of the recommendations for action for the manufacturing industry

R1	Provide combined protective and functional equipotential bonding (CBN)
R2	230/400 V power supply to be set up preferably as a TN-S system.
R3	Design common bonding network (CBN) with as fine a mesh as possible (MESH-BN)
R4	Connect PROFIBUS/PROFINET cable shielding 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 large contact surface (low impedance).
R5	• Use shielded motor cables according to the manufacturer specifications and connect cable shielding to the common bonding network at each cable end and with large contact area (CBN) (low impedance). • Connect the motor to the common bonding network (CBN). • Unless excluded by the manufacturer of the frequency converter, the use of symmetrically shielded, three-core motor cables with separate protective conductor is preferred.
R6	• Multiple connections of 24 V circuits to the common bonding network (CBN) should be avoided. • To keep the line between power supply and load as short as possible, it is recommended that several small power supplies be used instead of one large power supply.

4. OUTLOOK FOR APPLICATIONS IN THE PROCESS INDUSTRY

The recommendations given in this paper refer to applications in the manufacturing industry without risk of explosion. The CB/PG3 working group of the PROFIBUS User Organization is currently working on the applicability of the recommendations in systems in the process industry. Here, particular focus is to be placed on the requirements for potentially explosive areas and the underlying standards, e.g., [21]. Final results are not yet available.

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