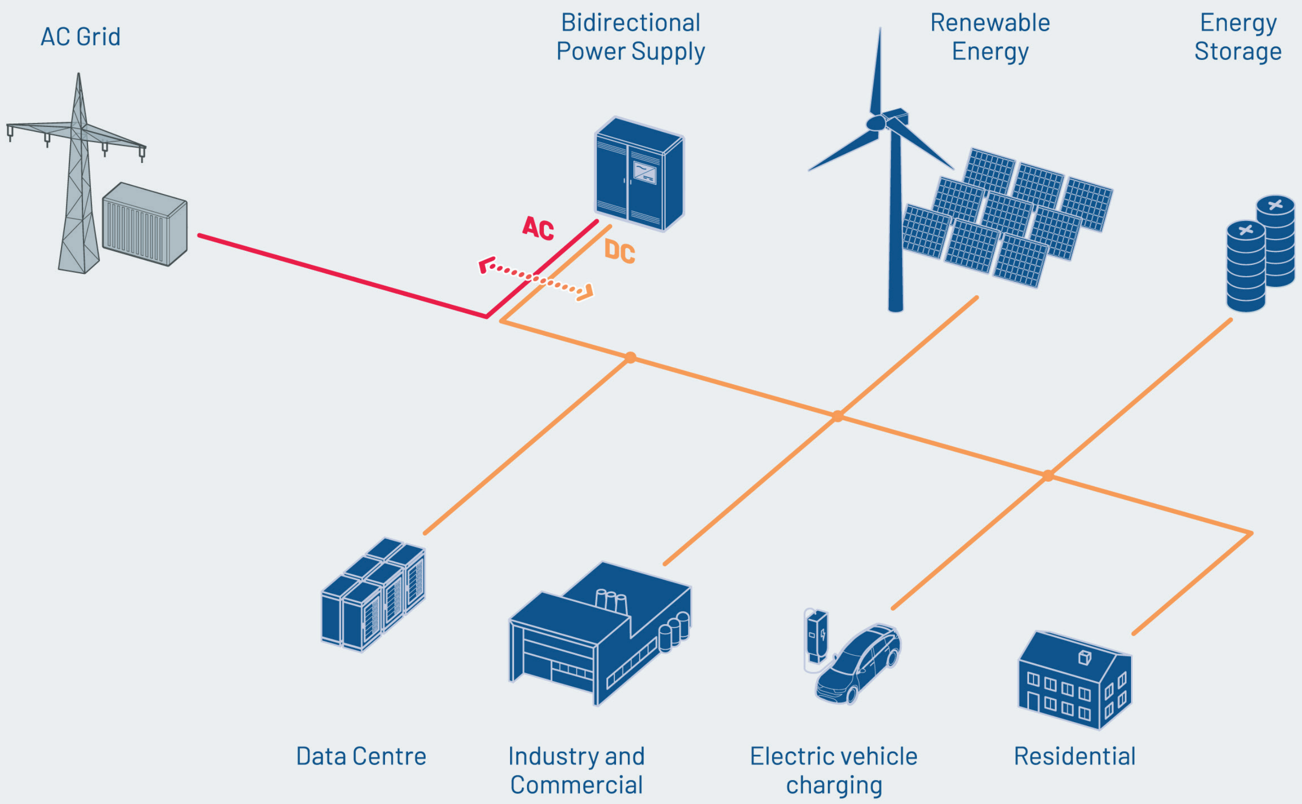
VDE SPEC



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System Description DC-INDUSTRIE

VDE SPEC 90037 V1.1 (en)

VDE

Foreword

Publication date of this VDE SPEC is 06.07.2026.

This document was initially developed within the DC-INDUSTRIE and DC-INDUSTRIE2 consortium projects (funding code: 03EI6002A-Q) and was further improved within the Open DC Alliance (ODCA, https://odca.zvei.org/). Editors were Johann Austermann (TH OWL/Weidmüller) and Hartwig Stammberger (Eaton). See the complete list of authors in Annex E, list of DC-INDUSTRIE2 project partners in Annex F.

Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

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1 Scope

The initial version of this document was prepared within the scope of the „DC-INDUSTRIE" (funding code 03ET7558A-N) and „DC-INDUSTRIE2" (funding code 03EI6002A-Q) projects supported by the German Federal Ministry for Economic Affairs and Climate Action [1]. It describes an industrial DC grid that has been conscientiously developed, verified, and approved for publication by the parties involved in the projects. It makes no claim to completeness or freedom from errors.

The transition to renewables is one of many prerequisites for becoming a more sustainable society. The goal is to reduce human consumption of natural resources to a level that no longer exceeds the Earth's capacity for regenerating itself. In the case of electric power, this is only possible by increasing efficiency and using zero-carbon renewable energy sources. Manufacturing must also become more digital, integrated, and customized. In view of the increasing use of electronics and sensitive production processes, it is essential for the supply of electric power to be as reliable and secure as possible. Europe's existing power grid typically is more than 130 years old and unfit for this purpose. With this in mind, the supply of electricity to industry must be transformed.

This system concept describes industrial **low-voltage direct current (LVDC) installations**. It has been developed with **45 industrial and research partners** within the scope of the government-funded DC-INDUSTRIE and DC-INDUSTRIE2 projects by more than 100 engineers and researchers. It has been **successfully tested in many model applications in industry and on research sites** and is applicable to a wide range of sectors such as manufacturing, electromobility, chemical industry, process industry, as well as commercial, office, and residential buildings.

DC-INDUSTRIE has defined specifications for an open, simple electric power supply system for users and device manufacturers that supports rapid implementation. The concept enables a high degree of energy efficiency, easy integration of renewable energy sources, flexible energy management, and high availability to users.

- A DC-INDUSTRIE grid typically includes:
- Multiple DC sectors, in other words more than a single machine
- Power management designed for stability (droop curves)
- Operation of electrical drives
- A protection concept, including short-circuit and selectivity
- Bidirectional energy flow, at least in parts of the installation (e.g., energy recuperation or storage)
- Voltage bands and the definition of the voltage-time behavior in these bands

Summing up, low-voltage DC-INDUSTRIE grids enable an open system that efficiently integrates green energy, reduces the use of resources, optimizes energy consumption, reduces feed-in power, and increases system availability.

[1] When the project began, it was still called the German Federal Ministry for Economic Affairs and Energy (BMWi).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

DIN 18014, *Earthing systems for buildings – Planning, execution and documentation*

DIN EN 50162, *Testing of clad steels; determination of shear strength between cladding metal and parent metal in shear test*

DIN EN IEC 62477-1 (VDE 0558-477-1), *Safety requirements for power electronic converter systems and equipment – Part 1: General*

DIN EN IEC 55011 (VDE 0875-11), *Industrial, scientific and medical equipment – Radio-frequency disturbance characteristics – Limits and methods of measurement*

DIN EN 55016-1-2 (VDE 0876-16-1-2), *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-2: Radio disturbance and immunity measuring apparatus – Coupling devices for conducted disturbance measurements*

EN 62305 (all parts), *Protection against lightning*

IEC 60038, *IEC standard voltages*

IEC 60269-1, *Low-voltage fuses – Part 1: General requirements*

IEC 60269-6, *Low-voltage fuses – Part 6: Supplementary requirements for fuse-links for the protection of solar photovoltaic energy systems*

IEC 60364-1, *Low-voltage electrical installations – Part 1: Fundamental principles, assessment of general characteristics, definitions*

IEC 60364-4-44, *Low-voltage electrical installations – Part 4-44: Protection for safety – Protection against voltage disturbances and electromagnetic disturbances*

IEC 60364-5-52, *Low-voltage electrical installations – Part 5-52: Selection and erection of electrical equipment – Wiring systems*

IEC 60364-5-53, *Low-voltage electrical installations – Part 5-53: Selection and erection of electrical equipment – Devices for protection for safety, isolation, switching, control and monitoring*

IEC 60364-6, *Low voltage electrical installations – Part 6: Verification*

IEC 60364-8-82, *Low-voltage electrical installations – Part 8-82: Functional aspects – Prosumer's low-voltage electrical installations*

IEC 60479-1, *Effects of current on human beings and livestock – Part 1: General aspects*

IEC 60664-1, *Insulation coordination for equipment within low-voltage supply systems – Part 1: Principles, requirements and tests*

IEC 60947-1, *Low-voltage switchgear and controlgear – Part 1: General rules*

IEC 60947-2, *Low-voltage switchgear and controlgear – Part 2: Circuit-breakers*

IEC 60947-3, *Low-voltage switchgear and controlgear – Part 3: Switches, disconnectors, switch-disconnectors and fuse-combination units*

IEC 60947-10 (in development)

IEC 61000-4-5, *Electromagnetic compatibility (EMC) – Part 4-5: Testing and measurement techniques – Surge immunity test*

IEC 61000-6-2, *Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity standard for industrial environments*

IEC 61000-6-4, *Electromagnetic compatibility (EMC) – Part 4-6: Testing and measurement techniques – Immunity to conducted*

IEC 61140, *Protection against electric shock – Common aspects for installations and equipment*

IEC 61643-32, *Low-voltage surge protective devices – Part 32: Surge protective devices connected to the d.c. side of photovoltaic installations – Selection and application principles*

IEC 61800-3, *Adjustable speed electrical power drive systems – Part 3: EMC requirements and specific test methods for PDS and machine tools*

IEC 61800-5-1, *Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy*

IEC 62440, *Electric cables with a rated voltage not exceeding 450/750 V - Guide to use*

IEC 62477-1, *Safety requirements for power electronic converter systems and equipment – Part 1: General*

IEC 63027, *Photovoltaic power systems – DC arc detection and interruption*

IEC 63112, *Photovoltaic (PV) arrays – Earth fault protection equipment – Safety and safety-related functionality*

IEC/TR 62066, *Surge overvoltages and surge protection in low-voltage a.c. power systems – General basic information*

IEC TS 61200-102, *Electrical installation guide – Part 102: Application guidelines for low-voltage direct current electrical installations not intended to be connected to a public distribution network*

IEC TS 62578, *Power electronics systems and equipment – Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz*

3 Terms

For the purposes of this document, the following terms and definitions apply.

DIN and DKE maintain terminological databases for use in standardization at the following addresses:

- DIN-TERMinologieportal: available at https://www.din.de/go/din-term
- DKE-IEV: available at https://www.dke.de/DKE-IEV

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at https://www.iso.org/obp
- IEC Electropedia: available at https://www.electropedia.org

Figure 3.1 shows an overview of the DC grid. The terms used are explained in the subsections of this chapter.

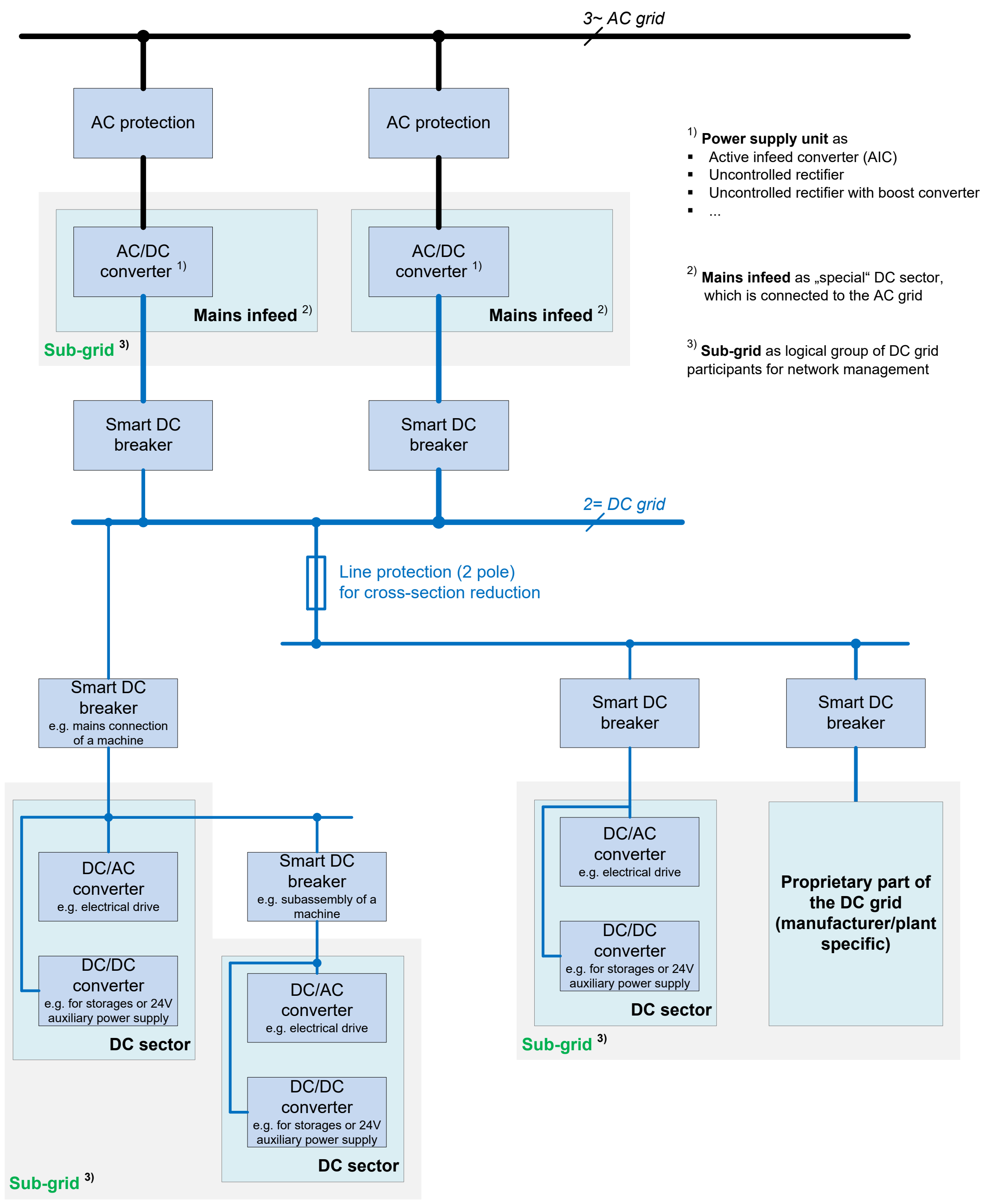

Figure 3.1: Graphical depiction of definitions in a DC grid

3.1 Active Infeed Converter (AIC)

An active infeed converter (AIC) is a combination of a pulse width-modulated inverter and an appropriate filter (see also section 6.2). AICs are mainly used to convert power from an AC grid into regulable DC voltage and current and feed them into a DC grid, but if required they can also work in the opposite direction. The term „active front end" (AFE) is occasionally used to designate the same thing. These terms are defined in the IEC TS 62578 standard.

3.2 Smart Breakers

These are protective devices that are inserted between the DC busbar and individual DC sectors (see section 3.3 for a concise definition). A smart breaker provides protection in the event of a fault such as an overcurrent, short circuit, or ground fault. Depending on the grounding approach used (see Chapter 8), high-speed protective devices are required at one or both poles. Smart breakers are described in greater detail in section 6.1 and illustrated with examples in Figure 6.2.

3.3 DC Sectors

A DC sector is a group of DC grid elements (1 … n) that together constitute a functional unit and are connected to the DC grid via a shared smart breaker (see section 5.3).

Generally speaking, energy flows bidirectionally between a DC Sector and the DC grid. Depending on the technology of the connected consumers, however, there can be exceptions to this rule. For example, a DC Sector with uncontrolled rectifiers or one with solar modules and DC/DC converters could exclusively feed power into the DC grid, while a DC Sector containing passive consumers only takes power from it.

3.4 Power Supply Unit

A power supply unit is a power-electronic component whose primary purpose is to transfer power from an external source (AC grid, photovoltaic module etc.) into the DC grid. The terms supplier, infeed device, supply unit, and power supply are used synonymously in this document. See also section 6.2. In IEC standards, they are also referred to as „interlink converters".

3.5 Circuit Breaker

A circuit breaker in the sense of this document is a switch that automatically detects fault currents in the circuit it is responsible for protecting and responds by switching it off to separate it from the attached voltage. It can be a circuit breaker as defined in IEC 60947-2 [1.].[2]

3.6 Electronic Breaker / Semiconductor Circuit Breaker

This is a circuit breaker with semiconductor power electronics for carrying and switching current. In a DC grid, it is implemented bidirectionally to enable exchanging and/or recovery of power.

3.7 Hybrid Breaker

A semiconductor circuit breaker has mechanical contacts arranged in parallel to power electronics. The mechanical contacts provide a low-loss path for continuously carrying current while the power electronics perform the switching operations (on and off).

3.8 Hierarchical Level

The term hierarchical level is used to indicate the number of successively switched cascading Smart Breakers; as a rule, different levels also have different current-carrying capacities. The DC grid formed by the power supply units typically constitutes the first hierarchical level for DC Sectors. The next hierarchical level is within a DC Sector and may have additional Smart Breakers connected to it.

3.9 DC Subsystem

A proprietary DC subnetwork does not possess all of the specified attributes of DC-INDUSTRIE; it can, for example, have a different voltage level or other diverging attributes. Where a subnetwork connects to the DC grid, appropriate decoupling measures must be implemented in order to prevent the former from negatively affecting the latter. These subgrids are not addressed in greater detail within the scope of DC-INDUSTRIE, however, being treated instead as proprietary or equipment-specific.

2 An international standard on semiconductor and hybrid circuit breakers is in preparation: IEC 60947-10.

3.10 Auxiliary Power Supply Equipment

Auxiliary power supply units provide auxiliary power (e.g. 24 V DC). They can be fed from the DC grid or AC grid or both (for example during a black start, i.e. the process of restoring all or part of the grid without relying on an external electric power network). The current flow is typically unipolar.

3.11 Consumers

Consumers are components that convert electrical energy to drive a production process. If the consumers are regenerative, they are referred to as bidirectional. If a consumer's state can be directly or indirectly influenced by how the grid is managed, it can be utilized to optimize operational management.

3.12 Grid Management

The role of grid management is to purposefully distribute and provide electric power in the required quality and quantity while striving for the best possible economic and environmental results and ensuring continued operation in the event of a fault. This is discussed in greater detail in section 5.6.

3.13 Energy Management

As used in this document, the term energy management refers to a control circuit that uses technical means to identify the current energy state, calculates a target state, and then applies technical control data to beneficially influence the energy flow. Energy management affects source management (see section 3.14), which in turn applies energy management specifications for further regulation. The time required to do this ranges from quarter-hours to days.

The concept of energy management as used in this document differs from what is defined in DIN ISO 50001, where it is understood as organizational energy management.

3.14 Source Management

Source management performs the task of optimized operational management of the DC grid with the goal of making the best possible use of power supply units (section 3.4) and energy storage. This is achieved by influencing how the power flow is controlled (section 3.15).

Derivative functions include, for example, prioritizing suppliers, adjusting droop curves for supplying power, and ensuring use of the full voltage range of the DC grid by dynamically adjusting the average grid voltage. The time required to perform these adjustments is in the order of seconds and minutes.

3.15 Power Flow Management

Power flow management involves measures to directly regulate power levels and maintain the voltage range within certain bounds (see section7). In the context of group control (see section 10.1.2), this is accomplished with the aid of droop curves (see section 3.17). The speed of this control is in the realm of milliseconds and less.

3.16 Components

All of the devices participating a DC grid can be assigned to different functional groups for grid management purposes. The components as defined in this document are suppliers, storage systems, consumers, Smart Breakers, and sensors. Components are referred to as active components when their power consumption or delivery can be regulated using a droop curve (see section 10.2). If a higher-level communication system is also available, power flow management is able to modify the parameters of active components' droop curves in real time.

There can be components that switch between active and passive behavior depending on their internal states. An example is consumers that, like ventilation systems, draw flexible amounts of power.

3.17 Droop Curves

A droop curve indicates how much power a device consumes or emits as a function of the measured voltage. This voltage-dependent function ensures a balance between supply and demand while keeping the voltage within the nominal band B3 (see Chapter 7). Additional details are provided in section 10.3.

3.18 Selectivity

Selectivity is a grid's ability to shut down only a faulty current branch. This is more challenging in DC grids – in which many storage systems can contribute to fault current – than in AC systems, where power flows from the grid to the fault. **Total** selectivity is given if, across all fault situations, only the protective device for a faulty branch is operated. With **partial** selectivity, other protective devices may also be triggered. See section 12.1.5 for more detailed information.

4 Abbreviations

Table 4.1 lists abbreviations and acronyms used in this document.

Table 4.1: Abbreviations and Acronyms

AIC	Active infeed converter
AMN	Artificial mains networks
CHPP	Combined heat and power plant
CM filter	Common-mode filter
HSDC	Auxiliary power supply
IGBT	Insulated gate bipolar transistor
IMD	Insulation monitoring device
OVC	Overvoltage category
PV	Photovoltaics
SCCB	Semiconductor circuit breaker[3]
SCHCB	Semiconductor hybrid circuit breaker[4]
SOC	State of charge
STO	Safe torque off
TOV	Temporary overvoltage

3 In this document, also referred to simply as „circuit breaker".

4 In this document, also referred to simply as „hybrid circuit breaker"

5 Description of an Industrial DC Grid

In industry, electric motors account for about 70% of the total electric power consumed. To achieve flexible speed control, many motors are operated via frequency converters, which typically use DC links. The importance of DC is also increasing for power generation. For example, solar panels directly generate it, and in many cases the alternating current generated by wind turbines is also buffered by a DC link. It therefore makes sense to directly use DC without a detour via alternating current (AC).

The DC-INDUSTRIE and DC-INDUSTRIE2 projects have taken advantage of this to advance the energy transition with direct current grids and make better use of available energy. The goal is to make industrial production more flexible, intelligent, and energy-efficient across all sectors. Attention is focusing on the system, in which savings can be achieved by addressing the overall application and the ways in which the participating components (suppliers, protective devices, drives, storages, etc.) interact. The individual components are already largely optimized in terms of their power consumption. Their coordinated interactions ensure an efficient and flexible electric power supply system, which is described in greater detail below.

5.1 Purpose

The DC grid is an open system that carries low voltages (in the range from 400 to 800 V, see section 7) for industrial facilities. It is well scalable:

- Relatively small facilities (approximately between 10 m and 25 m extension) with several devices supplied with electric power via the DC grid, e. g., coupled drives for recuperation of kinetic braking energy.
- Midsized facilities (approximately between 25 m and 75 m extension) with one or more mainly smaller systems powered via the DC grid, e.g., the integration of storage units for the reduction of peak power.
- Large facilities (> 75 m extension), serving as the main source of power for a factory hall in which all electrical consumers and generators are connected to the DC grid. For instance with integration of photovoltaics and measures for grid-beneficial behavior at the connection to the AC grid.

The essential attribute of systems for connecting power generators and consumers to the DC grid is an exchange of power. Electrical drives are bidirectional consumers that, owing to their underlying processes, are able to both take power from the DC grid and feed it in.

The DC grid is an open system that lets users integrate any desired compatible suppliers and consumers and enables suppliers to develop equipment for these purposes.

The capabilities of the DC grid are scalable. In other words, it is not necessary to implement all of the system's possibilities in every single application, and not all specified functions must be supported by every component.

The following sections describe the structure, components, and limitations of the DC grid.

5.2 Limitations

This section presents the inherent limitations of the DC-INDUSTRIE system. Constraints are deliberately applied so that the industrial DC grid can be implemented with manageable costs and development effort.

- **Compatibility with other DC grids:** The system does not need to be compatible with other grids, such as those for in-building systems or data centers. Consequently, parameters such as voltages, EMC etc. can also be chosen independently of other grids. Although the scope of DC-INDUSTRIE project does not include connections to other DC grids, this can be accomplished with DC/DC converters if required.
- **Integration of renewable energy sources:** DC-INDUSTRIE focusses on the functional interaction of electrical drives, supply equipment, and storage facilities. The ease with which renewable energy suppliers can be integrated is a major argument in favor of DC grids. DC-INDUSTRIE is devoted to enabling efficient connections to energy sources, not to actually creating them.

- **EMC environment:** This specified DC grid is intended for supplying industrial facilities and especially drive-related components [5]. The two basic standards EN IEC 61000-6-2 (immunity for industrial environments) and EN IEC 61000-6-4 (a generic emission standard for industrial environments) should therefore be used as a framework unless product-specific standards are applicable. For drives, IEC 61800-3 can be alternatively applied to the second case since it largely matches the general requirements of the basic standard.
- **Connection to the AC grid and power infeed:** The use of generated power energy and integration of renewable energy sources are important secondary objectives of DC-INDUSTRIE. While the primary direction of power flow is typically from the AC grid to the DC grid, surplus renewable energy should also be made available and fed back into the AC grid. This can be easily achieved by reversing the direction of energy flow when using an AIC as the power source. Relevant regulations need to be followed; Table 5.1 provides an overview of the technical rules for connecting to the AC grid in Europe (EN) and Germany (VDE).

Table 5.1: Connection requirements for AC grids in Europe and Germany

Grid connection point[6]	With infeed[7]	Without infeed
Low voltage	EN 50549-1 VDE-AR-N 4105	VDE-AR-N 4100
Medium voltage	EN 50549-2 VDE-AR-N 4110	
High voltage	VDE-AR-N 4120	

- **System size:** In accordance with the underlying concept, the spatial extension of the DC grid is in principle unlimited. The focus is on production facilities („factory halls").
- **Propriety subgrids:** Proprietary local DC subgrids are basically allowed. They can be connected to the DC-INDUSTRIE grid as distinct DC sectors in their own right or else created within a sector, and interfaces between them must comply with all relevant requirements of DC-INDUSTRIE. DC-INDUSTRIE does not extend to investigating proprietary subgrids.
- **Residual current devices (RCDs)** are only deployed in the industrial domain in special cases. A 300 mA RCD is often specified for fire protection purposes[8]; however, the concept is compatible with this without mandating its use. The development of RCDs for DC grids is therefore not a focus of DC-INDUSTRIE.

5.3 Division into DC Sectors

A DC Sector is defined as a group of DC devices that are directly connected to one another in terms of power flow and are switched and protected as a unit by a Smart Breaker (shown in yellow in Figure 5.1). All of the devices within a DC Sector constitute a logical and functional unit that is entirely cut off from the DC grid if a fault occurs. A short circuit in a device within a DC sector can also cause other

5 A DC grid in the public grid domain must also comply with the EN IEC 61000-6-3 (emission requirements) standard, which calls for even lower levels (similar to those defined by IEC 61800-3 for the initial environment). The interference immunity requirements are met by complying with industry values. In this case, there are also current-dependent requirements regarding repercussions on the grid.

6 The grid connection point is where power passes from the grid operator to the customer. The rules listed in Table 5.1 apply to power generation systems that must support the AC grid. The primary objective of a DC-INDUSTRIE grid is to reliably supply power for industrial processes. The objectives pursued with a DC-INDUSTRIE grid may therefore conflict with the requirements of the grid infeed guidelines. The latter should be supplemented in order to appropriately consider industrial facilities.

7 Infeed: a generator or storage system is connected to the grid via the AIC for the purpose of feeding power into the grid. This definition does not cover regenerative braking within the DC grid.

8 The 300 mA are from power of 70 W that has caused wood containing fire accelerants to ignite in 230 V circuits. The value of 300 mA has been incorporated into guidelines and standards, also by insurers, but without taking the voltage into account.

devices of the same DC Sector to cease functioning, but it will not affect the continued operation of other DC Sectors (selective protection by the Smart Breaker).

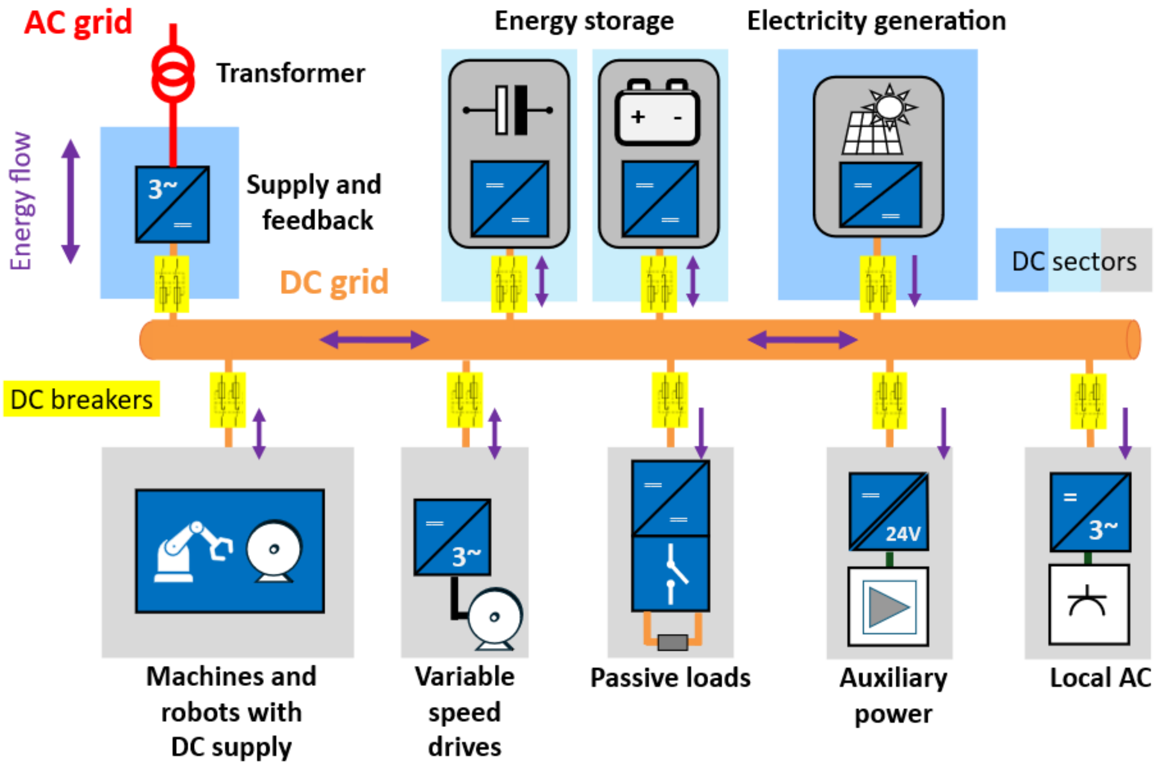

Figure 5.1: DC-INDUSTRIE grid divided into DC Sectors

Figure 5.1 shows some examples of DC Sectors:

- Connection to the AC grid (infeed and feed back)
- Power storage and generation
- DC-supplied machines or robots
- Variable-speed drives
- Passive loads such as lighting/heating
- Auxiliary voltage supplies (24 V, AC 230 V etc.)

A fault in one DC Sector should not cause any other sector to shut down. It is therefore important for its Smart Breaker to provide sufficiently rapid protection (see section 12.1).

Proprietary subgrids are permissible in the form of separate DC Sectors. This involves connecting a group of DC-INDUSTRIE-noncompliant devices to the DC grid. However, all relevant specifications of DC-INDUSTRIE must be met at the connection point.

DC Sectors can disconnect from the DC grid and, if they have their own storage systems or generators, continue operating autonomously. Cascading of DC Sectors is allowed.

5.4 Hierarchical Levels

Figure 5.2 shows the structure of a typical DC grid with three levels, each of which has a different current-carrying capacity (high, medium, and low ampacity) as well as two hierarchical levels for the DC Sector (first and second).

The following rules apply to arranging and connecting grids.

Power infeed points (as special DC Sector connected to the AC grid)

- Power is typically supplied from the AC grid to the highest hierarchical level used in the system.

- Large power storage units (e.g. battery storage systems) are normally connected to the highest hierarchical level being used in the system. It is connected to the DC grid via Smart Breakers and converters.
- Central power generators (e.g. solar panels or fuel cells) are typically connected to the highest hierarchical level used in the system. It is connected to the DC grid via Smart Breakers and converters.

Levels of current-carrying ability

- Dedicated outlet boxes are used to connect levels with different current-carrying capacities. A given hierarchical level can have several such outlet boxes linking it to lower levels. However, lower levels may not be connected to one another (to avoid loops).

DC Sectors

- Each DC Sector is connected via a separate Smart Breaker (section 6.1).
- There may be DC Sectors (see section 5.3) at every current-carrying level, and they may be cascaded. This yields multiple hierarchical levels. Each level is designated by the number of Smart Breakers between it and the main DC grid.
- Each Smart Breaker must be geared to the expected current while taking all directly integrated components as well as all subordinate DC sectors into a account.

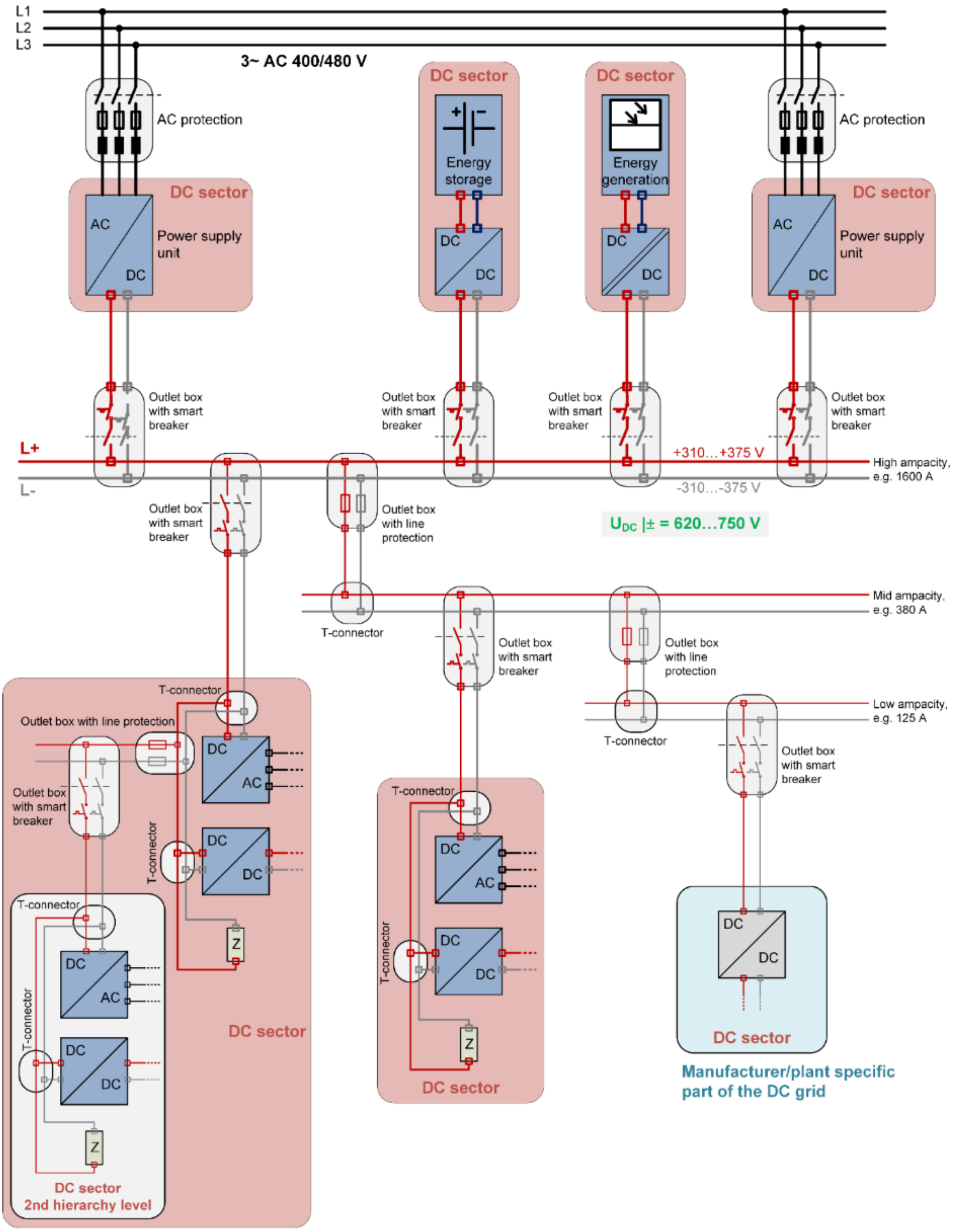

Figure 5.2: Structure of the industrial DC grid, see also Figure 3.1

5.5 Grid Topologies

The main DC grid can comprise a bus or ring structure with at least two DC Sectors (see Figure 5.3). Compared to a bus structure, a ring has the advantage of making it possible to continue supplying power to all DC Sectors if an individual DC line is interrupted (e.g. in a tap-off box). However, a ring requires the integration of additional protective devices in order to separate a faulty ring segment and thus reliably supply power.

A hierarchical sublayer consisting of a bus or ring can be optionally added to each Smart Breaker, and this can theoretically be repeated „downward" any number of times. Steps must be taken, however, to ensure that a higher-level Smart Breaker will always also switch all DC sectors integrated below it.

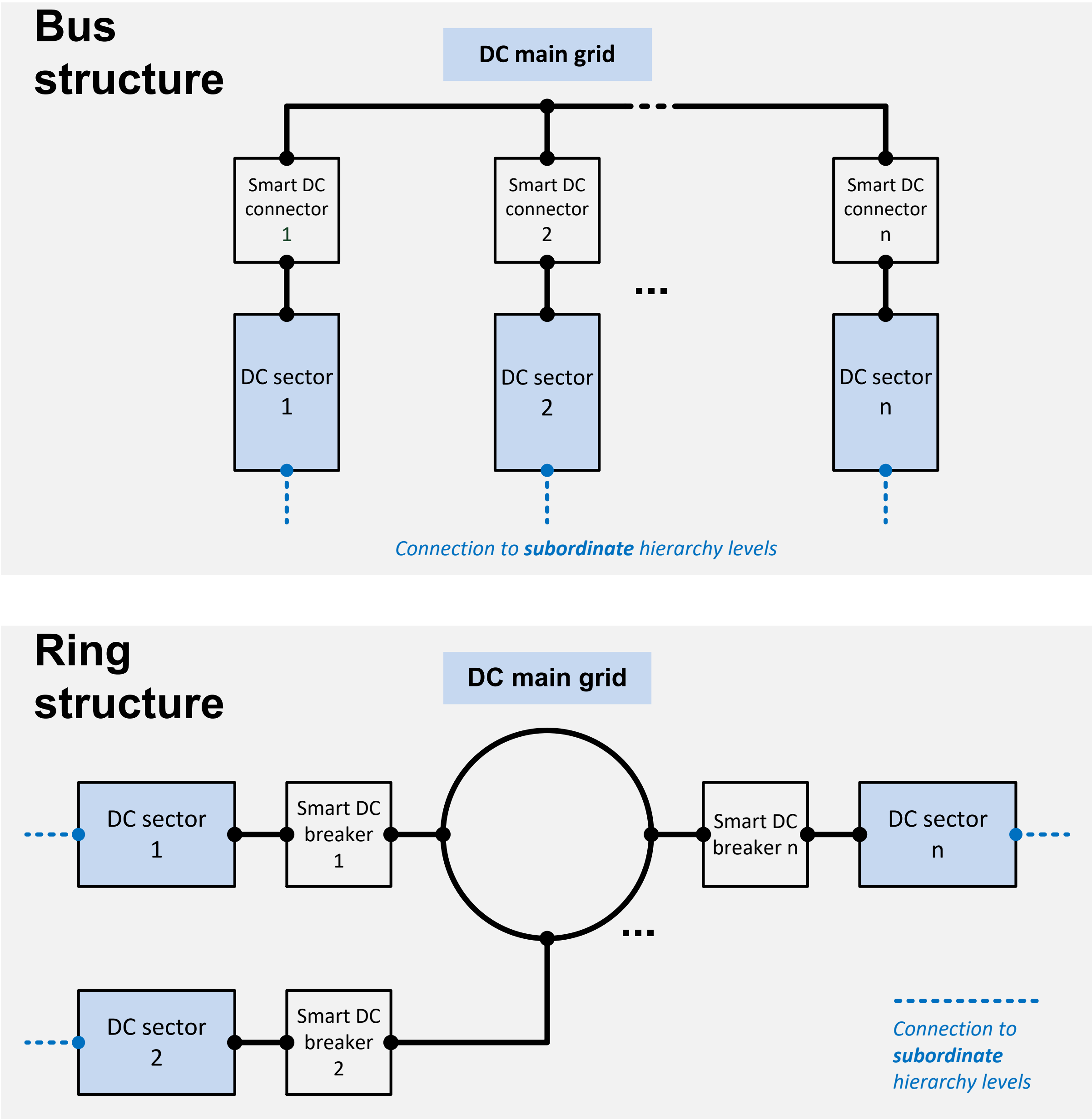

Figure 5.3: Permissible topologies for the DC grid: bus (top) and ring (bottom)

5.6 Grid Management

DC grid management is part of a hierarchical control process within an industrial production system. Basic control processes such as production planning and production management take precedence over DC grid management and affect its functions. Conversely, the control processes are also influenced by DC grid management (see Figure 5.4).

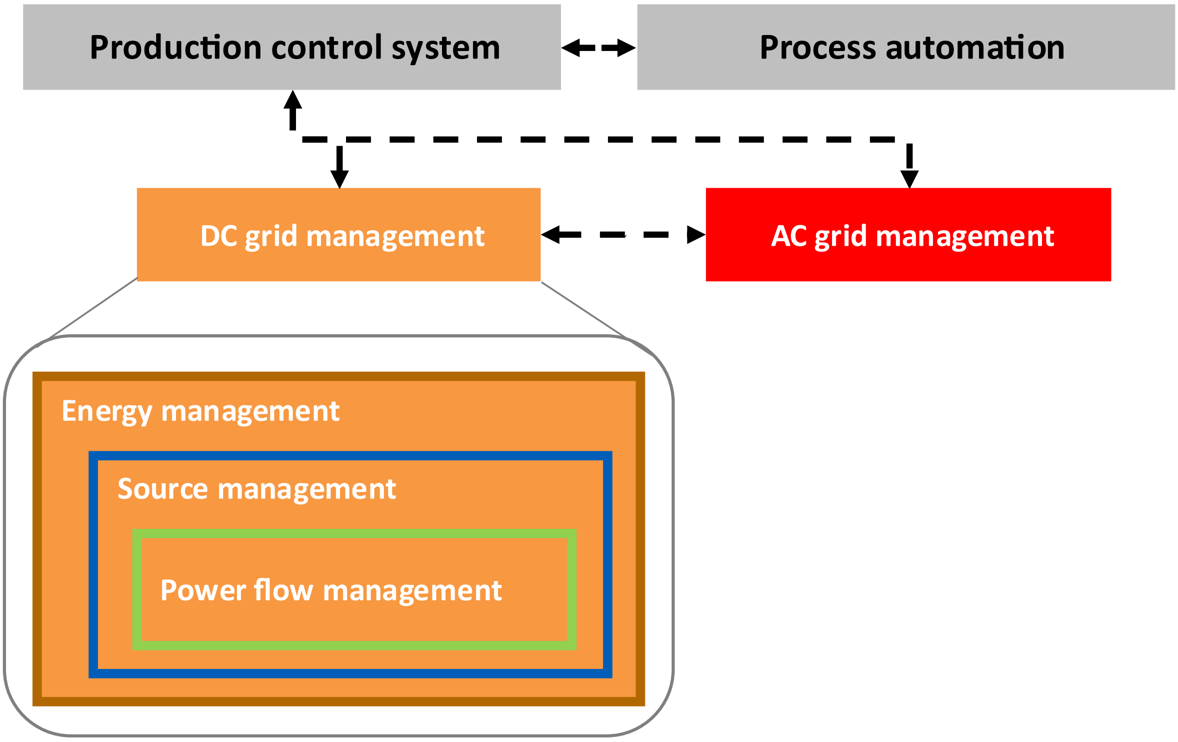

Figure 5.4: Relationship of DC grid management to the production system and AC grid management

The **production control system** directly impacts production by controlling processes and manufacturing and storage facilities. It achieves the goals of production planning and business reporting and is directly networked with the process automation systems.

Energy management is part of **DC grid management** and interfaces with the production control system and AC grid management. It pursues goals such as reducing energy costs and increasing the use of locally generated power by optimizing power flows within production systems.

These goals are pursued while taking relevant local and external factors into account such as anticipated future power requirements, production plans, forecasted weather, and requirements posed by an external power grid.

Source management is subordinate to energy management. It applies power management measures to the sources (= active grid components). The positive or negative contribution of these sources can be managed in ways that are influenced by source management parameters, for example an offset value in the droop curve (see section 10.3.6).

Both **energy management** and **source management** require a communication infrastructure. They have response times in the range between a few seconds and a few minutes and are therefore not involved in ensuring the DC grid's stability.

Subordinate to source management, **power flow management** regulates the supply of power from the sources and is responsible for consistently ensuring balanced performance. In an actively controlled DC grid, the prerequisite for this is voltage-dependent current control, which is also called characteristic-based control (see section 10.2). The communication medium is the grid voltage itself, which reflects the balance between the required power and the supplied power:

- Voltage increases when more power is available than needed to meet requirements.
- Voltage decreases when power demand is higher than supplied power.

Source management offsets this variation by influencing the control functions in the active components, e.g., by using an offset current to adjust the droop curve.

6 Components of an Industrial DC Grid

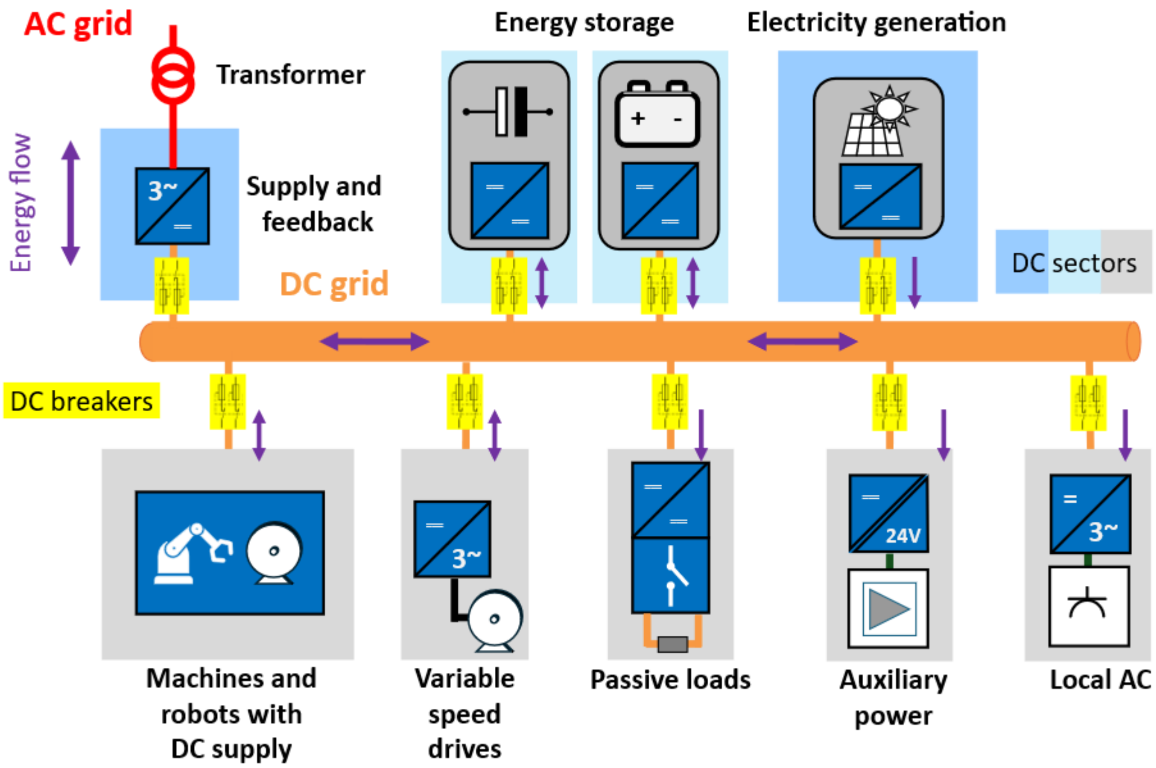

Figure 6.1: Overview of an industrial DC grid

The basic structure of the industrial DC grid as described here is shown in Figure 6.1 with its principal components. The DC grid (**orange**) links various DC Sectors (colored), with each DC Sector connected via a Smart Breaker (**yellow**). The DC sectors contain electronic power converters (**blue**) that can be supply devices, DC/DC converters, inverters, or auxiliary power supply units. By combining multiple converters (which can be identical or different), it is also possible for entire machines or robots (**green**) to comprise a DC Sector.

6.1 Smart Breakers

A Smart Breaker (yellow in Figure 6.1) protects a DC Sector by uncoupling it from the main DC grid or next-higher hierarchical level. If a fault occurs in a DC sector, the Smart Breaker reduces its repercussions on the wider DC grid sufficiently to allow the equipment there to continue operating without any major constraints. The voltage ranges shown in Table 7.1 have to be maintained well enough so that in this case, unaffected devices can continue operating in operating state A3 or A4 (Ch. 7.4). In order for work to be safely performed on an affected DC sector, the Smart Breaker needs to provide safe insulation from the upstream DC grid.

Figure 6.2 shows an example schematic of a smart breaker. The contacts designated as S_E are the main ones; typically, these are implemented as semiconductor or hybrid breakers (see sections 3.6 and 3.7). They are followed by current measurement to provide protection against overloads and short circuits, as well as mechanical contacts for isolation (S_I) to ensure reliable disconnection of the circuit if required. As an option, a precharging device may be included, which in this example it realized as a precharging resistor that is turned on and off by switch S_V.

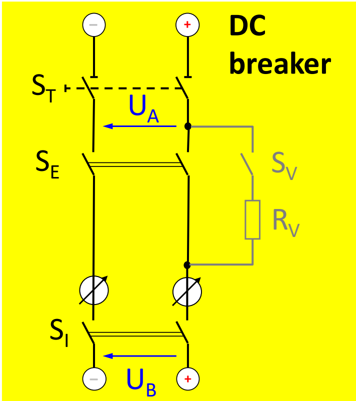

Figure 6.2: Example of a Smart Breaker, with connection U_A to the main DC grid and connection U_B to the DC sector

6.1.1 Mandatory Functions of a Smart Breaker

- **Short-circuit protection**

  Short-circuit protection prevents a fault in one DC Sector from impermissibly influencing other DC Sectors (especially with overvoltage or undervoltage). For this purpose, the smart breaker must be equipped with a fast-acting overcurrent protection device. This (switch SE in Figure 6.2) can take the form of a purely electronic breaker, a hybrid breaker, or a very fast-acting fuse. The advantages and disadvantages of the various possibilities are explained in section 12.1 (especially selectivity; see section 3.18). Independently of this, the shutdown conditions required to prevent injury to people must always be met (see Table 12.6).

- **Line protection**

  The implemented line protection must be appropriate for the conductor cross-sections in the DC sector while complying with the usual requirements (e.g., IEC 60364-5-52). Line protection can be combined with short-circuit protection or implemented in a separate device. For only providing line protection in the DC grid, slow circuit breakers or fuses can also be used.

- **Reliable isolation**

  When in a switched-off state, the Smart Breaker provides reliable isolation (see S_I in Figure 6.2). The isolation solution must comply with IEC/EN61140 and IEC/EN60947-1 in conjunction with IEC60664-1 and may be automatically and/or manually switched.

6.1.2 Optional Functions of a Smart Breaker

- **Maintenance**

  A maintenance breaker is used to manually disconnect a DC Sector, for example in order to perform maintenance work. It must be implemented with two poles, ensure reliable separation, and meet the relevant requirements, such as those of IEC60947-3.

- **Precharging**

  The capacitors of all devices in a DC Sector must always be precharged to prevent high inrush currents. Therefore it is necessary to integrate a precharging function in the Smart Breaker if not all connected devices have their own precharge procedure (as described in Chapter 9). The simplest way to accomplish this is with a precharging resistor R_V (see Figure 6.2).

- **Switch-off above the permissible voltage range**

  If the permissible voltage range for the DC grid is exceeded (section 7.3), the Smart Breaker isolates the DC Sector. The corresponding switch-off conditions are described in section 7.1 and there particularly in subsection 7.1.5.

- **Switch-off below the permissible voltage range**

  If the voltage in the DC grid drops below the applicable minimum value (see section 7.1 and especially subsection 7.1.5), the DC Sector must be isolated from the DC grid. This is necessary so that the precharging process can be reinitiated at lower voltages as described in Chapter 9.

- **Monitoring of current, voltage, and power**

It is important to monitor current and voltage in order to capture and optimize power flows. Anomalies can indicate an imminent device failure, and this information can be taken advantage of to perform preventive maintenance. Current and voltage are often already captured for other reasons, so in many cases no additional effort is required for this.

- **Active discharging**

  DC Sectors are conceptually designed to discharge via the connected devices in the sector itself. The devices have to do this within five minutes via internal consumers (such as balancing resistors).

- **Ground fault monitoring**

  Detection of ground faults is mandatory in the IT systems. It can be integrated in the Smart Breaker. IT systems without continued operation after a first ground fault (see section 8.3 may not be operated continuously after that first fault. Either the entire DC grid or only the directly affected DC Sector or sectors must be shut down. Section 12.1.2 contains additional information on detecting ground faults.

In principle it is permissible to integrate some or all of a Smart Breaker's functionality in other components. For example, overcurrent protection can be included in a drive power inverter or supply device.

6.1.3 Voltage Supply to a Smart Breaker

If an auxiliary voltage is required for a smart breaker, it can either be externally supplied (see section 6.3) or generated internally from the voltage across the smart breaker's terminals.

6.2 Supply Devices

Supply devices enable different grids to exchange current. They can be AC/DC converters that connect the DC grid to the AC grid, or else DC/DC converters operating between the DC-INDUSTRIE grid and, for example, a DC photovoltaic grid. At this stage of developing the system's concept, priority is being attached to the properties of active infeed converters (AICs) with two voltage levels (two-level AICs), since these are widely used. IEC TS 62578 also describes the characteristics of three-level and multi-level AICs. Additionally, it is possible to use active AC/DC supply devices without feedback to the grid; examples include PFC circuits and Vienna rectifiers. The system is designed to also accommodate these types of supply devices. However, the supply device may only generate a small common-mode shift of the DC voltage with respect to ground (for limit values, see section 11.2).

6.2.1 Active Infeed Converters (AICs)

In larger grids, the supply device is typically an active AC/DC converter, referred in standards as active infeed converter AIC (IEC TS 62578); common implementations are presented in sections 6.2.2 and 6.2.3. AICs are used in many proprietary interconnected DC grids because they allow both sinusoidal current consumption and active support for the AC grid (with harmonic and reactive power infeed). They are also able to regulate the current flow between AC and DC grids and can therefore play an active role in grid management. It is important to note that typical active infeed converters can only operate at a DC voltage that is greater than the peak value of the line-to-line voltage of the AC grid. If the DC voltage drops below this value, the active infeed converters are no longer controllable and also unable to protect themselves against overcurrents. The biggest drawback of typical AICs without common-mode filters or isolating transformers is that the generated DC voltage has a high-frequency common-mode component to ground (see Figure 6.3).

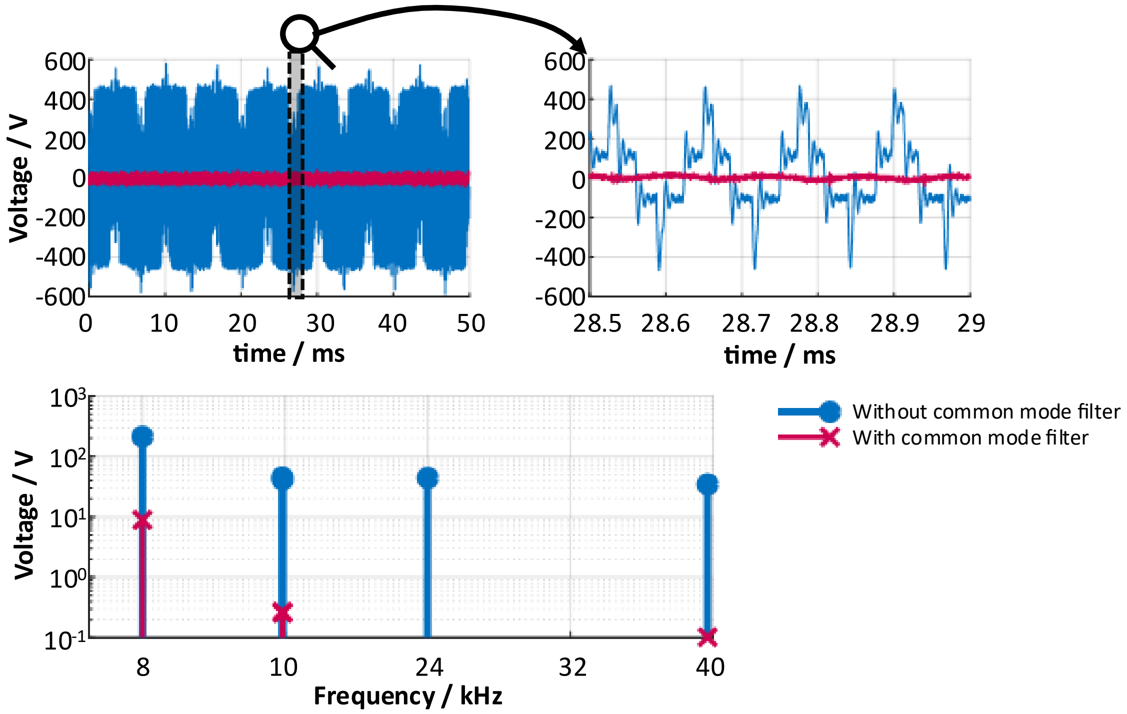

Figure 6.3: DC voltage of an AIC with and without common mode filter, boundary conditions: $U_{\mathrm{DC}} = 680\ \mathrm{V}$, $f_{\mathrm{sw,AIC}} = 8\ \mathrm{kHz}$

These high-frequency voltage shifts compared to ground are problematic for the following reasons:

- They will cause high leakage currents in the Y capacitors and/or EMC filters of equipment connected to the DC grid.
- The common mode currents will cause impermissibly high emitted emissions (for limit values, see section 11.2).
- Parallel operation of multiple AICs is constrained by the fact that unsynchronized modulation can cause currents to circulate among them. These currents negatively impact the AIC, also in idling mode, and restrict the usable current. They can also saturate EMC filters and cause them to fail.

The common-mode voltage shift can be reduced by, for example, installing an upstream transformer or common-mode filter.

6.2.2 Active AC/DC Infeed Converters (AICs) with Upstream Isolating Transformer

One way to suppress common-mode voltage is to use an upstream isolating transformer. As described in sections 8.3, 8.4, and 8.5, ground reference shall be provided on the DC side. Parallel operation of multiple AIC converters is especially easy when each device has its own isolating transformer (or its own winding). This makes it easy to prevent currents from circulating among the devices connected in parallel. It also eliminates the need to synchronize them.

6.2.3 Active AC/DC Infeed Converters (AICs) without an Additional Transformer

An alternative to operation with an isolating transformer is the use of suitable common-mode filters (CM filters), which attenuate the high-frequency components of the common-mode voltage to ensure that they remain below the limits described in section 11.2. The diagrams in Figure 6.3 illustrate typical waveforms of AIC common-mode voltages and amplitude spectra with and without a common-mode filter. It can be observed that the unfiltered AIC generates a common-mode voltage with high spectral components at the switching frequency and multiples of it. When using a common-mode filter, these components are significantly reduced.

Filtration minimizes the currents circulating between the AIC converters and protects the Y capacitors of the devices connected to the DC grid from overloading while also reducing electromagnetic emissions. In contrast to isolating transformers, these common-mode filters increase energy efficiency and reduce costs while also saving space, since they are smaller. When using a common-mode filter without galvanic isolation, grounding is accomplished via the neutral point of the upstream AC grid (see section 8.2).

6.2.4 Uncontrolled Supply Devices for Grids with AC Grounding

In most industrial frequency converters, uncontrolled rectifiers are considered „state of the art" for generating DC link voltage. They have good efficiency and are cost-effective to implement. The drawback is unregulated currents (. The DC voltage therefore depends on factors such as the AC grid voltage, the load, impedances in the current path, and capacitance in the DC grid. Due to the presence of harmonic currents, the power factor is also significantly less than one.

Integration in a droop curve-based power flow management system is only possible if uncontrolled rectifiers are preceded by a sufficiently large grid choke that controls how the AC grid impedance behaves at the connection point under all operating conditions. The impedance of the grid choke imposes an intrinsic droop curve on the rectifier that can be measured and used for power flow management together with the other generators of the DC grid.[9]

For the reasons stated, uncontrolled rectifiers are often used in simple, cost-sensitive applications. Uncontrolled rectifiers inherently exhibit a 150 Hz common-mode voltage relative to ground,[10] which leads to leakage currents at this frequency via the EMC capacitors. In conceptual terms, this 150 Hz common-mode voltage is considered noncritical. Primarily due to its low frequency, it is not expected to result in impermissible electromagnetic emissions. Parallel operation of multiple uncontrolled power infeeds is possible; in this case, the current is distributed via appropriately matched grid chokes (all of which have the same u_k values[11]).

6.2.5 DC/DC Converters for the Main Power Flow

DC/DC converters for the main power flow are power electronic devices that are mainly required in order to establish a defined load flow between the industrial DC grid and other power sources and loads that also natively operate on DC voltage. These can be PV systems, battery storage systems, fuel cell and electrolysis systems, and the DC link capacitors of converter systems for small wind turbines and CHP plants if the operating voltage ranges significantly deviate from the permissible voltage range of the industrial DC grid. Another application for high-power DC/DC converters is interfaces between the industrial DC distribution grid and another DC distribution grid with a significantly higher or lower DC nominal voltage range. The latter is the case, for example, in applications in telecommunications and data centers for which nominal voltages in the range of 380 V have been established.

6.2.6 Parallel Connection of Multiple Supply Devices

It is possible for a system to take power from multiple supply devices. When connecting multiple power supply units in parallel, it makes sense to create a separate DC sector for each source to provide redundancy.

6.2.6.1 Uncontrolled Power Supply Units

With **uncontrolled power supply units**, the current can be distributed across the upstream chokes; a standard inductance based on a short circuit voltage u_k of 4% is suggested.

6.2.6.2 Active Power Supply Units, Each with Its Own Isolating Transformer

In the case of active power supply units, each of which has its own isolating transformer (section 6.2.2), parallel operation is also unproblematic because the transformer suppresses circulating common-mode currents. With regulated supply devices, power distribution is controlled by grid management, for example by adjusting the droop curve (section 10.3.2).

6.2.6.3 Active Power Supply Units with Synchronized Switching Signals

It is possible to switch units in parallel by synchronizing the switching signals, thus eliminating the need for large-volume common-mode filters. This is technically challenging, however, and typically not

9 If it is not possible to install an AC line choke but a regulated DC voltage is nevertheless required (for example, to achieve independence from the AC voltage level, better utilization of components, or integration in grid management), a boost converter can be connected downstream of the uncontrolled rectifier.

10 Only when supplied from the 50 Hz grid.

11 The rated short circuit voltage u_k must be applied at the input side of a choke in order for the rated current to continue flowing if the output terminals are short circuited.

feasible across different manufacturers. Units connected in parallel in this way are therefore treated logically as a single unit.

6.2.6.4 Active Power Supply Units with Common-Mode Filters

Active power supply units with common-mode filters (section 6.2.3) can be switched in parallel using suitable components. Since unsynchronized pulse patterns can result in common-mode currents saturation of the common-mode chokes must be prevented.

Despite the common-mode filter, a small amount of common-mode voltage is still present at the output of each active power supply device; its intensity can vary depending on the filter design (see Figure 6.4). The common-mode voltage is calculated using the following formula:

$$U_{CM} = \frac{U_{L+,PE} + U_{L-,PE}}{2}$$

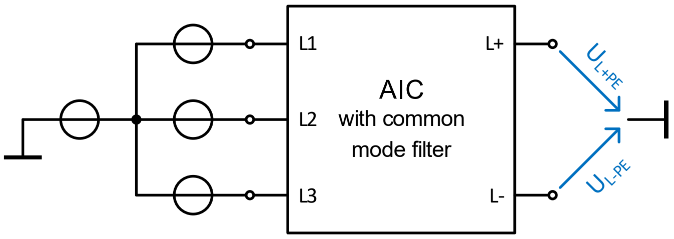

Figure 6.4: Equivalent circuit diagram of an active power supply device

The amplitude and phase of the common-mode voltage varies depending on the modulation scheme, switching frequency, and timing. Figure 6.5 shows the amplitude spectra of two comparable active power supply devices.[12] Despite the similar setups, however, their common-mode voltages differ. Even larger differences can occur with active power supply devices that use different topologies and modulation schemes.

12 Two-level topology, similar common mode filters, identical switching frequency (8 kHz), space vector modulation without the 3rd harmonic, unsynchronized modulation.

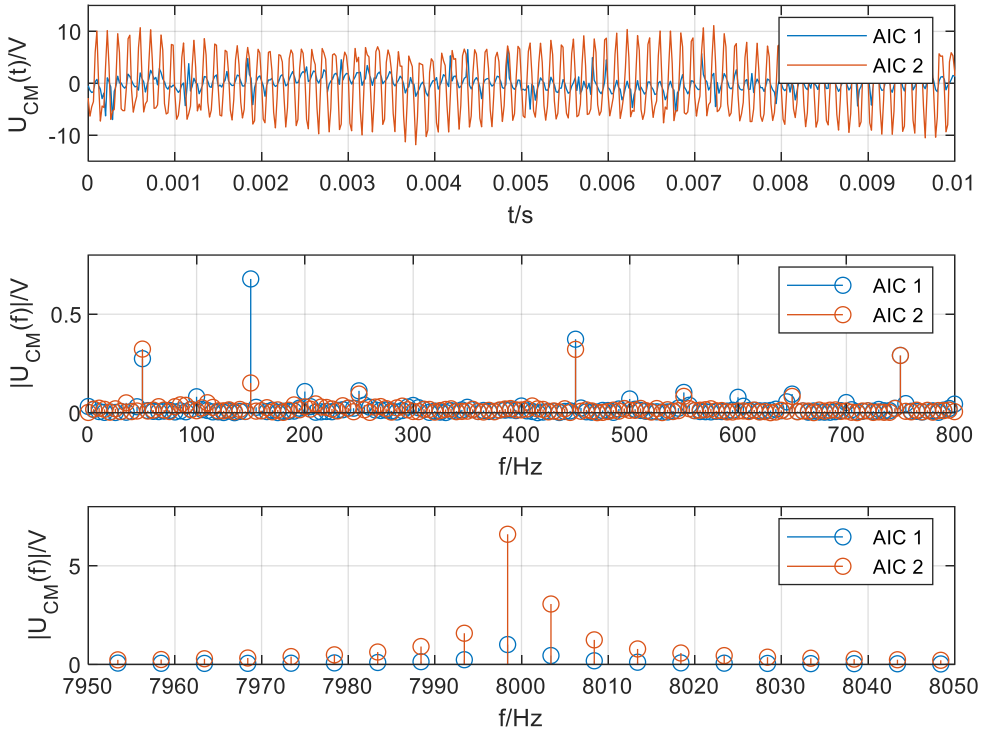

Figure 6.5: Comparison of common-mode voltages at the outputs of two different active power supply units

If these power supply devices are connected in parallel to a DC grid, the difference in voltage causes a common-mode current to flow between the devices (circulating current). Although this current is limited by the common-mode inductors in the active power supply devices, it can still cause saturation of the filter inductors. The common-mode current can be reduced in the following ways:

- Large common-mode inductances can be used to suppress the common-mode current as far as possible.
- Alternatively, small common-mode inductances with a high saturation resistance can be used. This prevents saturation effects in the filter elements when the amplitude of the common-mode current increases. It is essential to take all filter elements into account, including those integrated in the power supply devices.
- Low-frequency common-mode currents can be reduced by aligning the common-mode voltages of the power supply devices via their internal regulations. Smaller common-mode inductances are then enough to attenuate the higher-frequency common-mode currents.

By way of example, Figure 6.6 shows two active power supply devices connected in parallel, each of which has an additional common-mode choke.

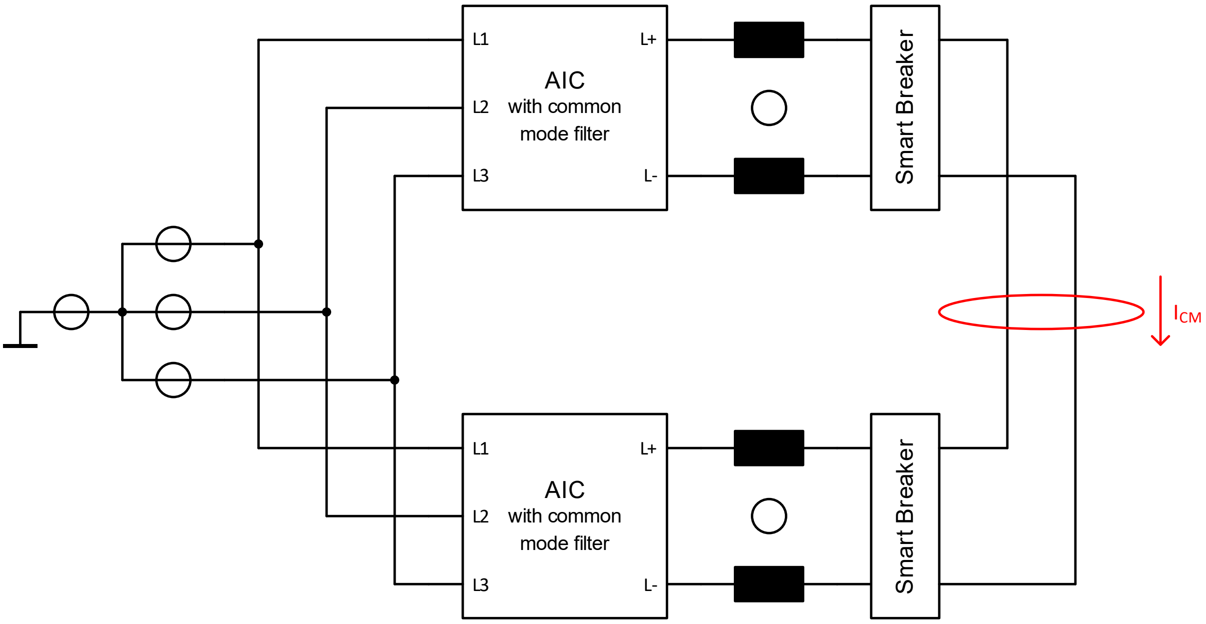

Figure 6.6: Active power supply devices connected in parallel, each equipped with a common-mode choke

The common-mode current decreases when the inductance of the common-mode chokes increases; Figure 6.7 shows an example for the time-domain and for frequencies up to 800 Hz and around 8 000 Hz. The inductance must be appropriately adjusted for each power supply unit.

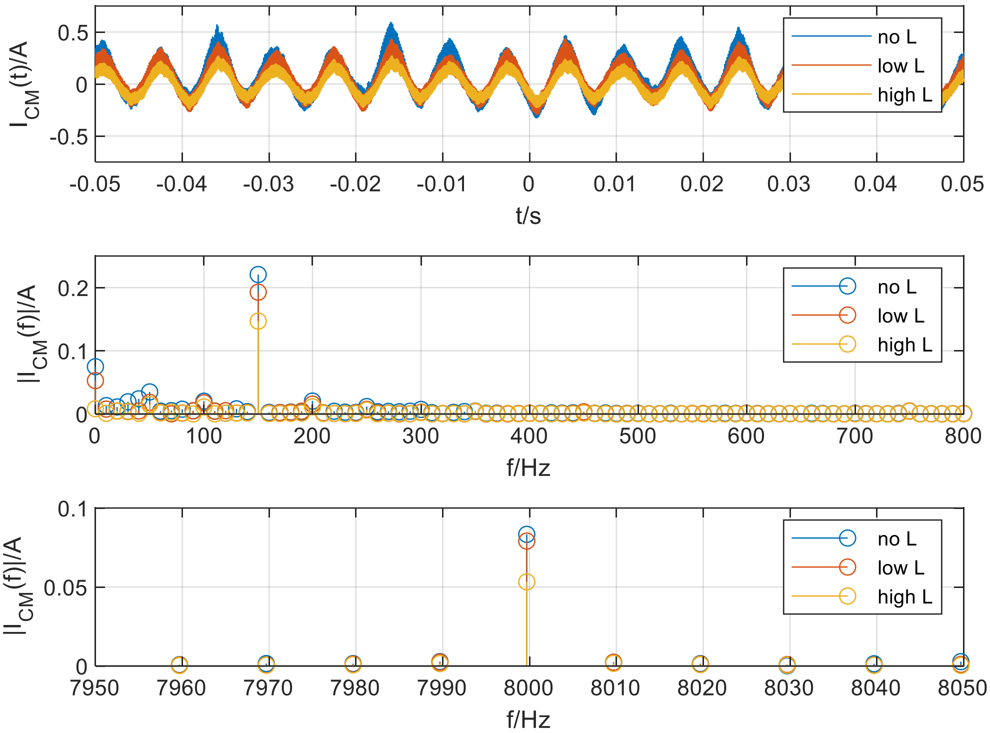

Figure 6.7 Influence of the inductance of common-mode chokes on common-mode currents flowing between power supply units

Common-mode current must be reduced to a level that the active power supply devices can tolerate. The filter elements in the power supply devices must be prevented from becoming saturated so they will continue operating properly in this parallel configuration without any malfunctions. The circulating currents can also result in a reduction in power, however.

Besides common-mode inductances, other effects can occur in units that are connected in parallel:

- In AC-grounded DC grids, high Y-capacitances in the DC grid can cause increased leakage currents that preload the common-mode chokes.
- Common-mode voltage components already present in the AC grid voltage can also occur in the DC grid voltage and lead to common-mode currents when power supply units for different AC grids are connected in parallel on the DC side.

Summing up, parallel operation is possible provided that the common-mode voltages and inductances are properly matched. The measurements performed on this are contained in Annex D.1.

6.2.7 Behavior of AC/DC Power Supply Units in Case of AC Power Failures

During AC power failures lasting several tens of milliseconds, the DC grid can only continue operating with the aid of power storage systems and/or distributed power generation (photovoltaic or combined heat and power systems), which need to be appropriately dimensioned to supply the required power for the duration of a grid failure. The capacitance of devices installed within the DC grid is typically low and unable to meet the system's power requirements for more than a few milliseconds.

Without the AC/DC power sources, the DC voltage drops off in accordance with the implemented droop curve (section 10.2). Unless consumers (e.g. switchable loads such as heaters etc.) shut off in response to the reduced DC voltage, the energy storage systems must continue supplying the same amount of power as before.[13] When the AC grid resumes operating, the power supply units must re-connect to the DC grid. However, if the DC voltage is less than the rectified value of the line to line grid voltage, the power supply cannot automatically precharge itself because this would require the DC grid voltage to increase to at least the rectified value. During precharging, a continuous current flows across the precharging resistors and the remaining voltage difference prevents equalization. This means that when the power returns, the energy storage system must first raise the DC voltage back to a level at which precharging is possible (deviating from the droop curve for normal operation).

During **brief AC power failures** (lasting only a few milliseconds) and voltage dips, the power suppliers should, if at all possible, remain connected to the DC grid until the voltage drops all the way to the undervoltage trip threshold (section 7.3.1). These phenomena can be caused at the distribution level by brief events such as lightning strikes, arc faults in overhead lines, or, in rare cases, switching errors in switchgear or substations. In the AC grid, drops in the voltage amplitude can then be observed in one or all three phases. Due to the configuration of the grid transformers (phase coupling via a switching group), single-phase power failures may occasionally occur. More commonly, asymmetrical voltage distribution occurs with a decrease across all phases, typically lasting around 300 ms, which corresponds to the switching time of medium-voltage circuit breakers.

During a brief power interruption, all DC Sectors are supplied from the energy stored in the DC grid. The capacitances that are directly connected to the DC grid discharge first, until long-term energy storage devices (if present) take over to supply the loads in accordance with the droop curve.

When the AC power returns, the capacitances of the DC grid are abruptly charged via the inverse diodes in the supply units (AICs) at a voltage that is significantly higher than the rectified grid voltage. This overcompensation is due to a resonant circuit comprising the inductances of the power supply unit's filter and the capacitances of the DC grid. Similar stresses are imposed on uncontrolled rectifiers. For studies on this topic, see [2.].

The demands placed on power semiconductors (and especially inverse diodes) when power returns increase with the capacitance of the DC grid and its discharge to below the rectification level of uncontrolled rectifiers. Conversely, they diminish if the grid-side inductance drops and there are grid-side commutating or filter chokes. Within the voltage range proposed in DC-INDUSTRIE, recharging currents more than five times the rated value can occur [2.]. However, typical inverse diodes only have a limited overload capacity (low i^2t value), which allows AC/DC power supply devices to shut down to protect themselves before reaching the undervoltage trip threshold. The shutdown can be triggered by the AC contactor of the AIC or by a dedicated smart breaker monitoring the i^2t of the power supply unit.

13 Devices such as drive inverters usually have a constant power consumption.

The following guidelines apply to designing power semiconductors, commutation chokes, and fuses:

- The i^2t capability of the infeed diodes should be as large as possible.
- The i^2t trip limit of the Smart Breaker is determined by the current-carrying capacity of the power semiconductor devices in the power supply. The manufacturers of the power supplies specify the maximum permissible i^2t trip value for the corresponding smart breaker and optionally also the corresponding capacitance of the DC grid.

Conceptual Approach

The best way to bridge short-time interruptions is to have a sufficiently large number of energy storage devices for preventing the DC voltage from dropping significantly. These storage devices should be connected via DC/DC converters.

6.2.8 Behavior of AICs with Overcurrents

Depending on the type of overcurrent event, different challenges arise when using AICs. These are briefly described in the following. It is crucial to ensure protection of the device in every case, with selectivity and availability being optional. Meeting these two criteria requires a different amount of effort depending on the fault scenario. The basic protection concept of DC-INDUSTRIE2 is described in section 9.

6.2.8.1 Behavior of AICs with Short Circuits

In the event of a short circuit in the DC grid, the AICs initially feed the fault current almost entirely by discharging their own DC link capacitance. In most cases, this energy or the resulting current is sufficient to trigger the corresponding protective devices and isolate the fault location from the grid. However, if the capacitor of the AIC discharges to the point at which the DC voltage drops below the peak value of the external line to line voltage, an additional fault current flows from the supplying AC grid across the freewheeling diodes of the AIC (comparable to the ground fault scenario).

6.2.8.2 Behavior of AICs with Ground Faults

Ground faults in the DC grid pose a special challenge for AICs if the DC grid is grounded at the neutral point of the supplying transformer (AC-side grounding, see section 8.2). Unlike what happens with a short circuit, in this case the DC link capacitance do not discharge and the fault current therefore flows exclusively from the supplying AC grid across the freewheeling diodes of the AIC. A parallel B6 rectifier with more robust diodes can be used to protect the semiconductors of the AICs by accepting most of the fault current.

Due to its technical relevance, the ground fault scenario is discussed in greater detail in a separate section (12.1.2.1) within the scope of the protection concept of DC-INDUSTRIE2. It has also been tested in connection with measurements with the model systems documented in Annex D.9.

6.2.8.3 Behavior of AICs with Overloads

AICs typically include devices for measuring AC current, since they also use this parameter for internal control. These sensing mechanisms are also used to protect the devices from being damaged by overload currents. This is achieved, for example, by continuously calculating i^2t or i-t integrals and monitoring the absolute maximum current. Since overload events have significantly larger time constants than ground faults and short circuits, AICs can use mechanical switching elements (such as grid contactors) to disconnect from the AC grid and protect themselves from overloads.

6.2.9 AC Grid serviceability

AICs can also perform, besides their main function as active rectifiers, auxiliary functions above and beyond what is required by the technical connection rules (VDE-AR-N 41xx for Germany). These optional functions can positively influence the AC grid. Typical examples include injecting reactive power, compensating for harmonics, symmetrizing the AC grid, and temporarily supplying AC sub grids from sources within the DC grid. However, it should be kept in mind that these auxiliary functions can cause additional losses or lead to a power derating of the AIC.

If energy sources and/or storage capacity inside the DC grid are comparatively large compared to the energy requirements of production, the idea of supplying the AC side will gain importance. Particularly in the event of a total failure of the AC mains over a lengthy period, the AIC should be able to define the AC as a grid-forming component – in the same phase position and amplitude of the three phase voltages as can be expected when the mains supply[14] returns.

In the industrial AC grid, the function of filtering voltage harmonics is of particular interest. If an AIC is able to provide this function, deploying a DC grid becomes an economically much more attractive option. However, filtering the AC grid can only be regarded as a „secondary function" of an AIC. Its primary purpose is always to reliably supply the DC grid. This means that filtration can only be performed using the AIC's power reserve.

Figure 6.8 shows an example of such a measurement. The voltage waveform and frequency components of an unfiltered industrial AC grid are shown on the left. The 5th and 7th harmonics are quite pronounced. Now the selective filtering function is applied to these two voltage harmonics. Filtration is tuned such that these two voltage harmonics are reduced by almost 50 %. This is shown in the diagram on the right Figure 6.8.

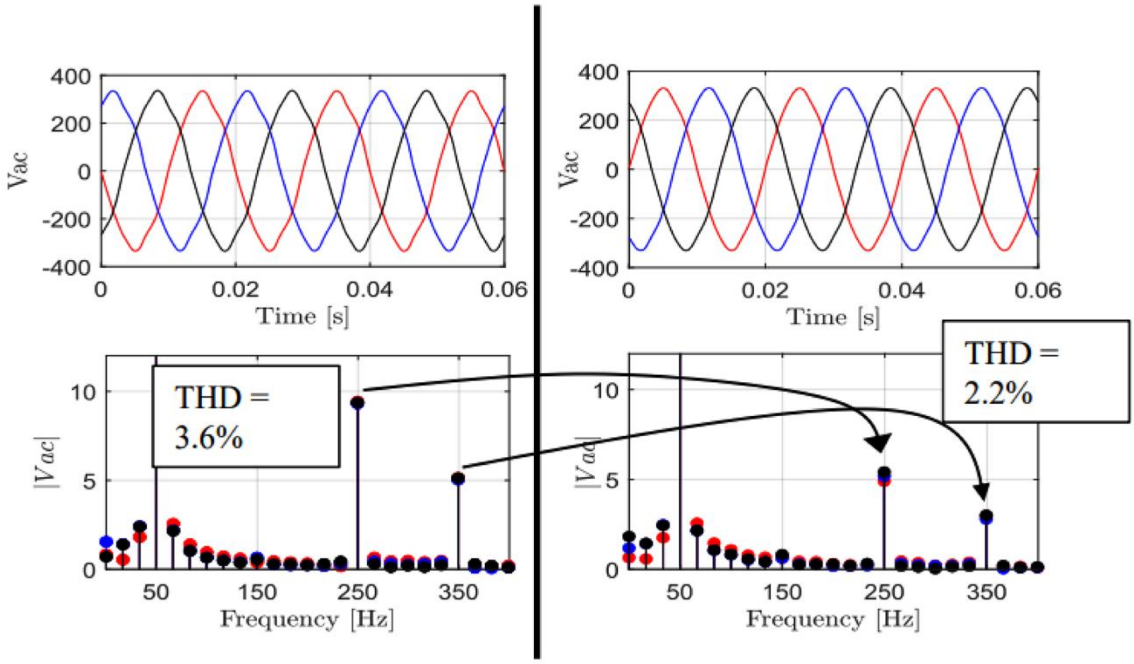

Figure 6.8: Measurement of the sensitive and selective filter function applied to different AC voltage harmonics in an industrial grid

Left: The filtration function is disabled. Right: the filtration function is set to the 5th and 7th harmonics in order to reduce them by half.

6.3 Auxiliary Voltage Supply Unit

Auxiliary power supply devices are used to generate voltages from an AC or DC grid that are separate from the main power flow. Examples are 24 V supply (for control cards, controllers, or contactors) or 230 V AC power for wall sockets (with a lower power level, for example for operating PCs). Figure 6.9 shows examples that are explained in the following sections.

14 "Mains supply" is defined in ch. 3.1.2 of [31.]

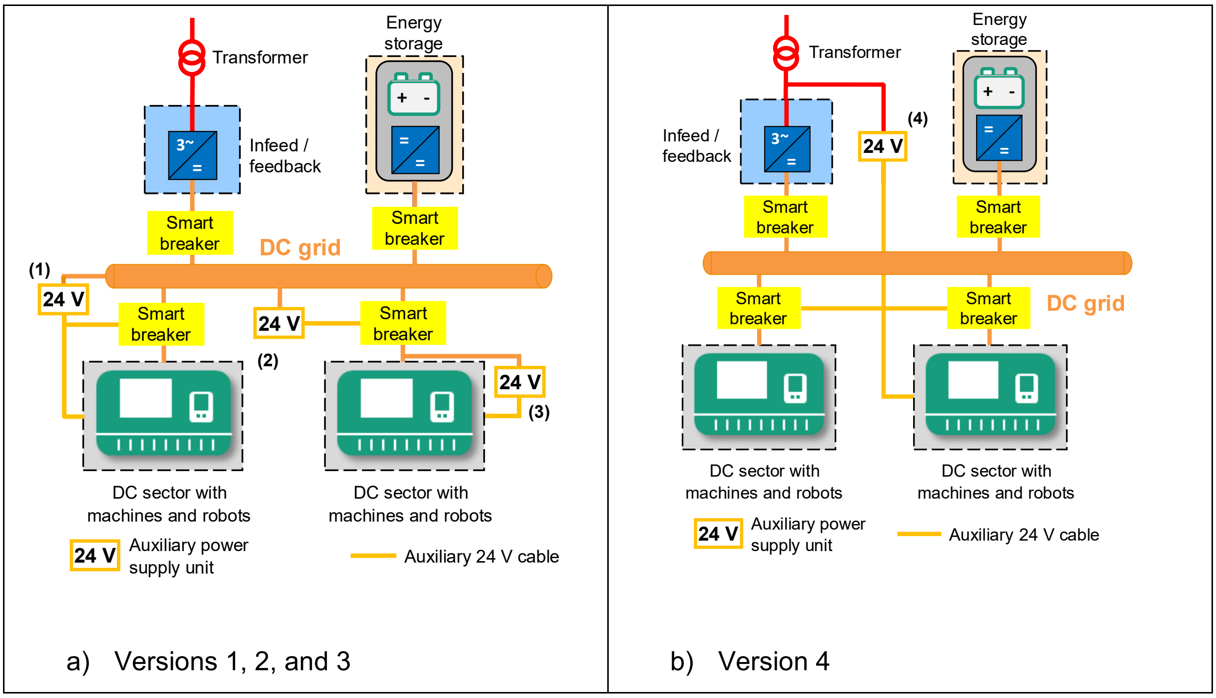

Figure 6.9: Auxiliary power supply variants

6.3.1 Central Auxiliary Power Supply

A central auxiliary power supply is a device that generates a required auxiliary voltage, such as DC 24 V and/or DC 48 V, for an entire facility or factory hall. Its input is directly supplied from the DC grid as shown in variant (1) in Figure 6.9 a). Variant 4 in Figure 6.9 b) shows the alternative of connecting the auxiliary voltage to the AC grid. To ensure black start capability, the device may have an additional input for power from the AC grid, at least during the startup phase. To make the power supply failsafe, it can be complemented by an uninterruptible power supply (UPS) system.

6.3.2 Distributed Supply of Auxiliary Power

A decentralized auxiliary power supply provides auxiliary power for devices such as inverters, controls, contactors/relays, control cabinet lighting, etc. The most common voltage ranges are 24 V DC for controllers and 48 to 80 V DC for low-power inverters. In this context, decentralized means that the power supply only provides a small part of the required auxiliary energy at the location where it is needed. This means that components such as Smart Breakers or control cabinets for robots have their own individual power supplies. This is shown as variants 2 and 3 in Figure 6.9.

In variants 1 and 2, it should be noted that faults in the auxiliary power supplies themselves are not shut down by the smart breaker of the corresponding DC Sector and therefore have to be protected separately.

6.3.3 Auxiliary Voltage Converter for DC to AC 230 V/3ph 400 V AC

In order to still be able to operate small loads (such as programming devices / laptop / oscilloscope / small electrical tools, device fans) that require 230 V or 3 × 400 V AC directly on-site, small inverters can be provided to take over this power supply. Care must be taken to ensure that the relevant standards for AC networks are complied with (e.g. sinusoidal voltages, earthing). Figure 6.10 shows a possible setup for a single-phase DC/AC auxiliary voltage converter.

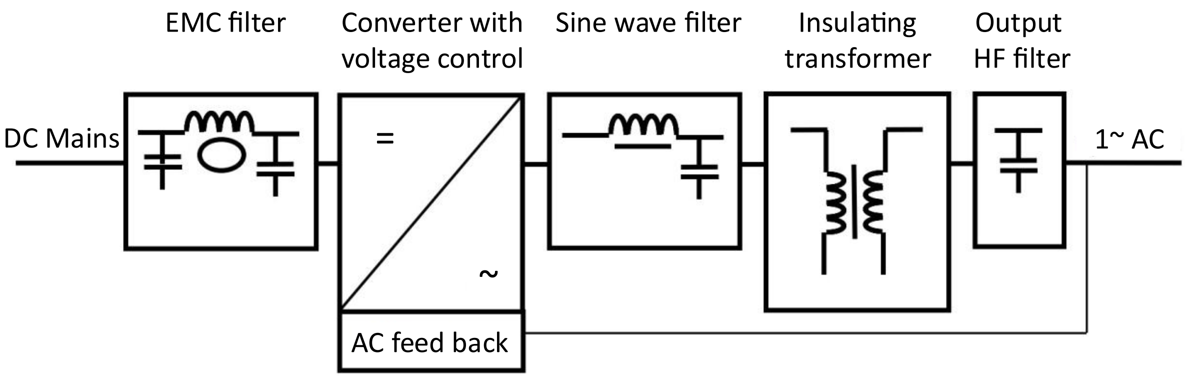

Figure 6.10: Setup of an auxiliary voltage converter for DC to AC

6.4 Power drive systems

6.4.1 Control cabinet inverters

A typical drive system consists of an inverter, a shielded motor cable and a motor. The inverter is the component directly connected to the DC grid; in this case, it is installed inside a cabinet.

The following methods are available for connecting central power inverters:

- *Busbar*, typically used to directly interconnect adjacent devices of the same manufacturer.
- *Cable connection for a single point-to-point link* between an external busbar or distribution panel and the device.
- *Cable connection in a daisy-chain configuration*, implemented as a Y splitter or with two separate terminals for DC-In and DC-Out.
  Preassembled hybrid cable, including a fieldbus and/or additional control cables in addition to the DC power line (see Figure 6.13). This is advantageous if a consistent connection approach with distributed drives is wished.
- Multi-axis devices: here a single device supplies multiple motors. The main advantages are lower costs for control electronics, connections, housing, and cooling and reduced space requirements for the cabinet. Moreover, fieldbus connections and I/O terminals only need to be implemented once.

6.4.2 Decentralized drives

Decentralized drives are characterized by the fact that the inverters are arranged outside the control cabinet. Distributed drives derive especially great benefits from the use of hybrid cables (Figure 6.13) since these result in highly compact drive systems with less wiring.

The following types of distributed drive inverters are usual:

- Inverters integrated in a motor: distributed drives in which the inverter and motor form a unit and share a housing.
- Motor-mounted inverters: the inverter is installed directly on the motor.
- Inverter installed near the motor: the inverter has its own housing and is installed close to the motor. The inverter and motor are joined by cables.

Special features of distributed drives:

- Design of the DC link capacitors: Especially with motor-integrated inverters, the capacitors are exposed to increased operating temperatures. Film capacitors are therefore often used. Their capacitance and equivalent series resistance (ESR) values are less than those of electrolytic capacitors.
- Inductance of the supply cable: to prevent resonances, the device connections should have the lowest possible impedances (section 10.4). With distributed drives, the cables running between neighboring drives can be up to about 100 m long. The resulting cable inductance can be relevant for resonances.

6.5 Distributed Power Generation

Distributed power generation systems (e.g. PVs or CHPPs) are especially easy to connect to the DC grid. Another advantage is that if there is an AC power failure, the DC grid can continue operating with the integrated power generators and storage systems.

Distributed generators are connected to the DC grid via a converter, which is typically integrated as its own DC Sector (as shown in the blue area at the top right in Figure 6.1).

6.5.1 Photovoltaic Systems

PV systems are always connected to the DC grid via a DC/DC converter. The DC/DC converter regulates the PV system to keep it operating close to the maximum power point (MPP tracking). When selecting the converter topology (boost or buck converter), it is important to consider the large operating voltage range of the DC grid (Chapter 7) and the string voltage that develops in the PV system during operation.
PV modules often have a relatively high parasitic capacitance and relatively low insulation resistance to ground, both increase with the system size. The CRD to UL 62109-1:2014-07-18 contains information on the adjustable lower limit for monitoring insulation resistance depending on the system size, as shown in Table 6.1.

Table 6.1: Lower setting limit of the insulation resistance of PV systems as a function of system size (source: CRD on UL 62109-1:2014-07-18)

Lower limit of insulation resistance
$R_{\text{iso,min}} = \frac{P_{\text{mod}} \cdot R_{\text{array}}}{P_{\text{PV,max}}}$ (but not less than 1 kΩ)
Where: $P_{\text{mod}} = 150\,\frac{\text{W}}{\text{m}^2}$ $P_{\text{PV,max}}$= max. permissible PV generator output that may be connected to the PV inverter $R_{\text{array}} = 13$ MΩ·m²

The leakage capacitance is about 60 nF to 160 nF per kW of installed power, depending on the module technology [3.]. If the insulation resistance is too low owing to the cell type and the system's design and size, it may only be connected to a DC IT grid using a galvanically isolated DC/DC converter (see section 8.4). For galvanically isolated PV systems, it is mandatory to monitor the insulation resistance to ground. The requirements, limits, and exceptions are described in IEC 63112 [4.]. In grids with low-impedance grounding (see sections 8.2 and 8.5), it is also possible to use converters that are not galvanically isolated and therefore typically much more efficient. The DC leakage current must be monitored when using these converters, and for fire safety reasons it may not exceed 300 mA (RMS) in systems up to 30 kW and 10 mA/kW in systems above 30 kW. In addition, to ensure personal safety it is essential to monitor the leakage current in order to detect any jumps by 30 mA or more. The insulation resistance to ground must be measured when connecting the PV system. The requirements regarding the smallest permissible insulation resistance and exceptions to them are described in IEC 63112 [4.]. For coordinating the insulation (regarding the creepage distance, see also section 12.3.2), a working voltage of 800 V (open-circuit voltage of 1000 V) may not be exceeded with this direct connection to the string. Connection via long overhead lines also is not allowed, since this would result in a higher overvoltage category (see section 12.3.1).[15]

6.5.2 Cogeneration Plants

As opposed to other types of power generation plants, cogeneration plants are characterized by very good efficiency relative to their primary energy requirements, due to the fact that both electric power and heat from them can be used concurrently. In DC grids, cogeneration plants can be regulated in a thermally or electrically controlled manner. With electrical-based regulation, the required electric power is appropriately controlled in the grid and the resulting heat is emitted (for example) into a local district heating network. This type of operation makes sense if, for example, it is wished to enable continued operation of the cogeneration plant in the event of an AC power failure by taking power from the DC

15 Overvoltage protection devices for PV systems must be selected and installed in accordance with DIN EN 62305-3, supplement 5.

grid. In the second case, the cogeneration plant's output is adjusted to meet the local demand for heat. The additionally generated electric power is fed into the DC grid.

6.6 Energy Storage Systems

Energy storage systems are designed to keep the voltage of the DC grid within the operating range for as long as possible after an AC power failure occurs. They can also be integrated into grid management systems to help reduce load peaks.

There are different types of energy storage systems. They can be classified based on the type of energy that they store (physical classification) [5.]:

- Mechanical storage, which involves storing kinetic energy in mechanical systems such as flywheels.
- Electrical storage, with energy being stored in an electrostatic field. This includes storing energy in capacitors.
- Electrochemical storage, with electrical energy being converted into chemical compounds of electrodes. This includes various types of electrochemical batteries such as lithium ion and lead batteries.
- Chemical storage, in which energy is stored in chemical compounds. The power-to-gas approach is an example.
- Thermal storage, with energy being stored in the form of heat or cold. Three storage modes are distinguished: sensitive, latent, and thermochemical.

The scope of the DC-INDUSTRIE projects included the integration of mechanical, electrical, and electrochemical storage systems in the DC grid. These are suitable for short-term energy storage, alternately charging and discharging electrical energy as current [6.]. Chemical and thermal storage systems therefore are not considered here since they are more suitable for medium- to long-term energy storage [7.].

Energy storage systems are predominantly connected via a smart breaker to the DC grid. This lets a storage system constitute its own DC Sector (see Figure 6.1). Capacitive storage systems are intended to be mainly linked via DC/DC converters, since passive capacitors that are directly connected to the DC grid can result in very high recharging currents after brief grid failures (see section 6.2.7). Rotational and flywheel energy storage systems are connected to the DC grid via drive inverters.

Since disconnected DC sectors with storage can continue to operate autonomously if the main DC grid fails, the earth connection must be ensured. With AC-side grounding, the grounding mode can change to DC IT. Also in this case, steps must be taken to ensure electrical safety (protection of personnel and equipment) (see section 12.3). In addition, when using energy storage systems in DC Sector it is always essential to include a suitable discharge or isolating device.

6.7 Connectivity

This section describes connectors, cables, and appropriate insulation materials. Two kinds of cables are used (shown on the right in Figure 6.11): DC bus cables and hybrid cables. The choice of connectors and connections depends on the cable design, and when scaling up the system the corresponding specifications must also be appropriately extended.

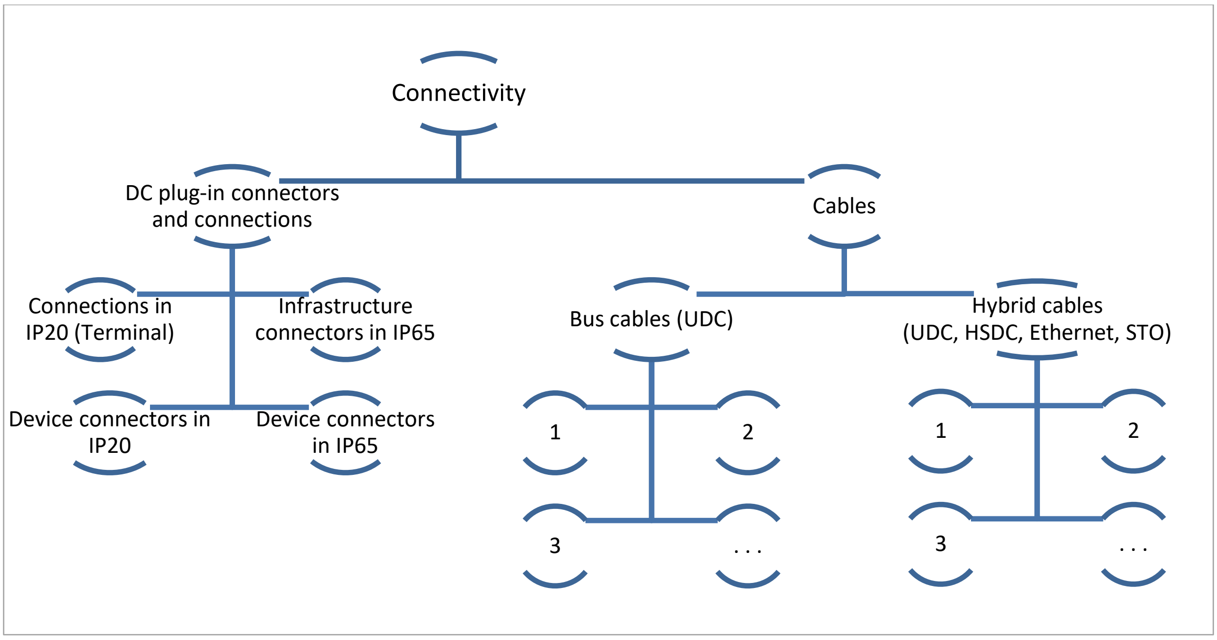

Figure 6.11 Schematic overview of connectivity components

6.7.1 Current Carrying Capacity of cabling

A **rated voltage in the DC grid** of uncontrolled infeed converters is used for determining the current carrying capacity (as defined in IEC 60364-5-52) of multi-core cables based on their cross-sectional area, since the current required to provide power is correspondingly greater owing to the lower voltage. An ambient temperature of 50°C is also assumed. Installation must comply with the relevant technical specifications [8.]. This results in the power values shown in Table 6.2:

Table 6.2: Selection of connectivity performance values at 540 V

Power / kW	Current[16] / A	Conductor cross-section / mm²	Current-carrying capacity @30°C / A	Current-carrying capacity @50°C/ A
9	16.7	**2.5**	26	**18.5**
15	27.8	**6**	44	**31.2**
28	51.9	**16**	82	**58.2**
50	92.6	**35**	158 (*)	**112.2**

(*): here single core cable, not multi-core cables as with the other cross sections

6.7.2 Conductor Designations

The conductors are color-coded as per EN 60445: 2018-02:

- RED for the positive outer conductor
- WHITE for the negative outer conductor
- BLUE for the midpoint conductor (if required)

6.7.3 Insulation Materials for Electrical Connections

Insulation materials can behave differently with DC and AC due to polarization and conduction processes. This is strongly influenced by operational factors such as temperature and electric field strength, as well as by environmental factors such as moisture.

16 This is the current with nominal load at the rated voltage 540 V DC.

6.7.3.1 Insulation Materials for Devices

Within the project, possible changes in electrical insulation properties after **aging in the presence of heat** and DC voltage were investigated for typical enclosure materials, e.g. mounting rail components and protective housing of connectors. These plastic materials were selected from the portfolios of the participating companies:

- PA66 FR
- PA66 GF FR
- PBT GF FR
- PPA GF FR

It was also important to investigate the influence of different flame retardant components. The following parameters were considered:

- Dielectric constant
- Power loss factor
- Surface resistivity
- Specific volume resistivity
- Dielectric strength
- Partial discharge
- Tensile strength

A special test setup was developed to ensure a homogeneous electrical DC field. Aging was accelerated by exposing the samples to elevated temperatures in a heat cabinet (at 90°C or 130°C depending on the material), both with and without a 1000 V DC operating voltage. Samples were taken five times, the last after 3000 hours. Their surfaces were assessed both visually and using material analysis methods.

In a second, separate series of trials, the **interactions** between the plastics and typical metal surfaces **in a humid environment** were studied by exposing them to an environment of 60°C/75% relative humidity for 1000 hours at 1000 V DC in a climate chamber. The observed effects were documented and analyzed. All possible combinations of the above-mentioned plastics and the following metal surfaces were considered:

- Brass MS58
- Stainless steel ST1.4301
- Galvanic silver surface
- Galvanic tin surface
- Galvanic nickel surface

The applied voltage of 1000 V DC did not cause any observable changes in the tested electrical and mechanical properties of the materials **after aging at elevated temperatures** for up to 3000 hours. **This confirms the suitability of these plastics for DC applications.** Some of the plastics changed their appearance, which during analysis was partly attributed to the presence of flame retardants or possibly flow aids. However, these surface effects did not affect the electrical properties of the plastic specimens.

Studies of **interactions in a moist climate** clearly revealed electrolytic reactions that were in turn dependent on the polarity. Clear signs of corrosion were observed on some of the metal electrodes. These possible interactions therefore need to be retested during product development.

6.7.3.2 Insulation Materials for DC Cables

Within the scope of the project, typical insulation materials used in AC cables and conductors were extensively studied in the laboratory. This included subjecting them to accelerated aging for 2500 hours at 70°C and a voltage of 1 kV. As is standard practice for AC cables (in accordance with HD 603 S1/A3), the studies were carried out concurrently in a water bath and a heat chamber. The insulation materials studied included various combinations of:

- PVC

- (Cross-linked) polyethylene (PE and VPE)
- Polypropylene (PP)
- Thermoplastic elastomers (TPE-E and TPE-V)
- PO-based halogen-free mixtures

Under these test conditions, the studied compositions of insulation materials withstand DC voltages at the selected reference temperature of 70°C. However, it was evident that this was significantly influenced by the ambient medium (air or water). Whereas the insulation materials show no signs of failure under dry conditions, in water for some PVC- and halogen-free PO-based mixtures involving special fillers and additives electric breakdown was observed.

Summing up, it can be concluded that **materials based on PE, VPE, PP, TPE E, and TPE V can be used without concerns**. The suitability of other materials will need to be studied on a case-to-case basis.

6.7.4 Operating Voltages of Cables

Cables are normally chosen based on the rated voltage that they will carry; this is typically expressed as an AC value U_0/U[17] expressed in volts. In a DC system, the rated voltage may not exceed the values shown in Table 2 of IEC 62440, section 5.2. The operating voltage is the highest voltage that can be continuously applied. According to Table 2 of IEC 62440, cables with a nominal voltage of at least 300/500 V that are rated for operating voltages up to 820 V DC between L+ and L- (corresponding to H05) must be used for DC-INDUSTRIE.

Note: If cables with different rated voltages are bundled, it is essential to adequately separate them (see for example IEC 60364-5-52).

6.7.5 Multi-Conductor DC Cables

Cables made specifically for DC installations are used. Their design is based on standard EN 50525-1.

Unshielded three-core cables are used for the DC grid; an example with a PVC jacket is shown in Figure 6.12. Table 6.3 lists some electrical properties of these cables. The figures for capacitance, and inductance are theoretical values calculated for 800 Hz.

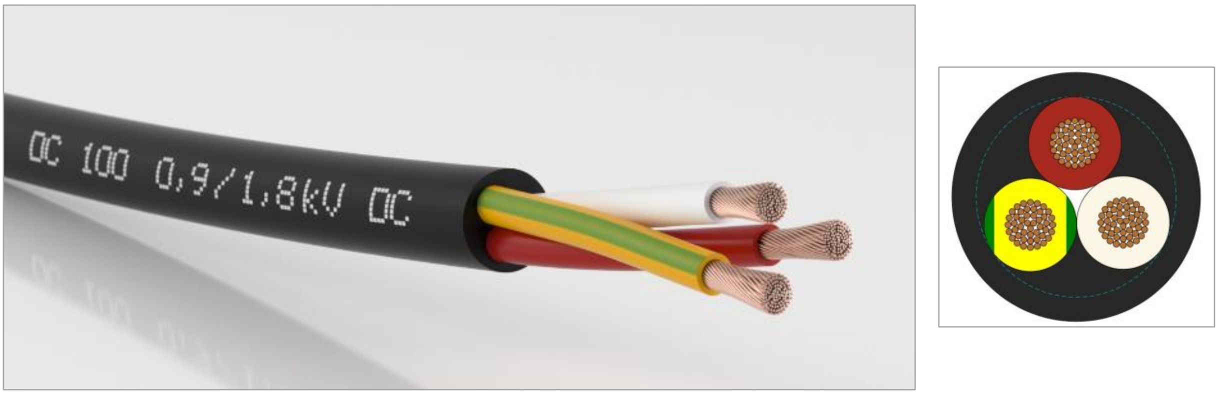

Figure 6.12 Three-conductor DC cable

17 U_0: The RMS (root mean square) value between a phase conductor and ground; U is the RMS between two phase conductors.

Table 6.3 Electrical properties of cables
[*: Copper resistance at 20°C for one conductor]

Cross section mm²	Capacitance (core/core) nF/km	Loop inductance (core/core) mH/km	Conductor resistance* Ω/km
1.5	88	0.53	13.3
2.5	91	0.51	7.98
4	101	0.47	4.95
6	107	0.44	3.30
10	109	0.43	1.91
16	116	0.41	1.21
25	119	0.40	0.78
35	125	0.38	0.55

The loop-inductance of a two-wire DC cable with round conductors can be calculated as [9.] (ta-ble 2.12):

$$L_{loop}/m = \mu_0/\pi \cdot \left(ln\frac{2a}{d} + 0.25\right)$$

With a: central distance of the conductors

d: diameter of the wire (for different diameters d_1, d_2 use $\sqrt{d_1 \cdot d_2}$ instead of d).

$\mu_0 = 4\pi \cdot 10^{-7}\mathrm{Vs/Am}$: Permeability of vacuum

6.7.6 DC Hybrid Cable

Especially for supplying distributed drives, a special DC hybrid cable can be used. This cable contains power conductors (700 V and 24 V) as well as a STO[18] (safe torque off) circuit and a data line, as shown by way of example in Figure 6.13. In particular, hybrid cables enable compact, easy-to-connect drive systems as described in section 6.4.2.

18 The STO (safe torque off) function shuts off the inverter's pulses as quickly as possible, causing the drive to coast to a stop. This corresponds to stop category 0 according to EN 60204-1.

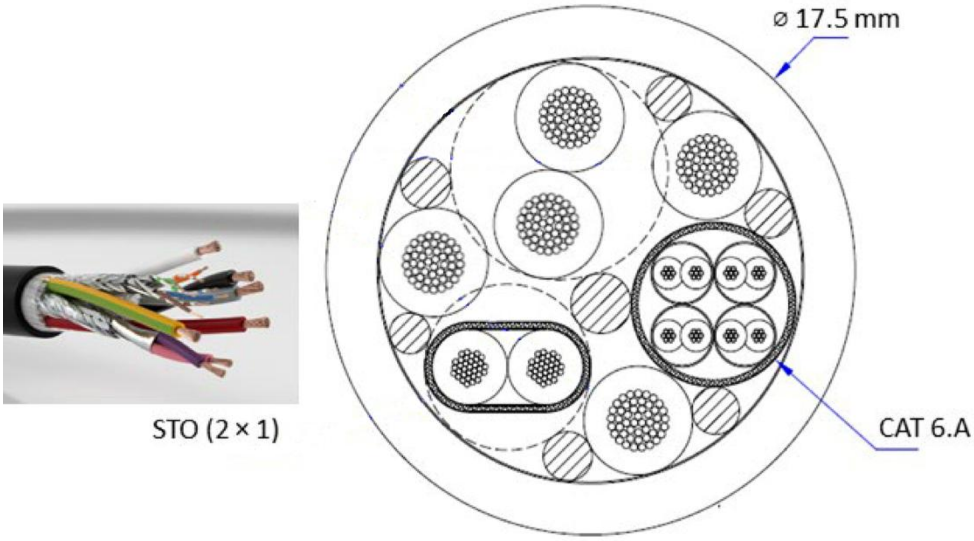

Figure 6.13: Design of a DC hybrid cable

6.7.7 DC Plug Connectors and Connections

For connectivity, it is especially important to ensure interchangeability of the connection technology used (as defined by IEC in IEV 581-24-03). This means that the shapes, dimensions, functionality, and technical characteristics of connectors used in drives, switching devices, power supply devices, and infrastructure components of a particular power and installation class (hybrid or exclusively DC power) must be identical even if they are from different sources. In other words, it must be possible to replace a connector from manufacturer A with one from manufacturer B while ensuring the overall connection's functionality in all technical respects (electrical, mechanical, and climatic). Meeting these basic requirements accounts for a major part of the concept's economic benefits for users.

Especially where connectors in hybrid cables are concerned, it is important to minimize the number of versions by taking a scalable and/or modular approach. The plugs and sockets used to join electrical conductors come in two basic types, namely household and industrial. Household plugs (plug and socket outlets, IEV 442-03-03) are intended for use by laypersons, while industrial versions (plug connectors, IEV 442-07-09) are designed for use by electricians and other professionals. They often differ in terms of how they work: plugs can be easily and repeatedly inserted and withdrawn, but this is generally not the case with connectors. Essentially the same safety rules apply to both AC and DC voltages. Safety rules, like making sure that a circuit is powered down before joining or separating plug connections, must be strictly observed in industrial and power supply applications. Household plugs are technically more complex than connectors, even when their ratings are identical. A typical household plug can be rated for 16 A while an industrial plug of the same size can be rated for up to 45 A. Industrial products could include devices to enable plugging and unplugging under load, but this would incur additional costs. In the case of DC grids, it is therefore imperative to ensure that plugging and unplugging connectors under load

- is not the standard procedure,
- only causes limited damage to plugs if done by mistake,
- and under no circumstances may cause harm or injury to persons.

Selected plug types (round and modular) for IP6x hybrid plug connections are illustrated in Figure 6.14 and Figure 6.15. Several connectors for three-core cables (DC Bus) with their typical cross sections (1.5 …35mm²) are specified in pin assignment and configuration, too.

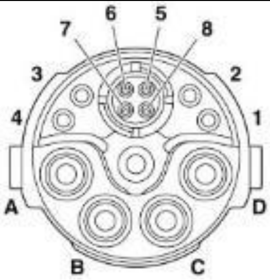

Figure 6.14: Round connector

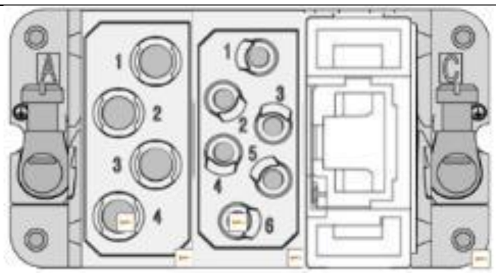

Figure 6.15: Modular rectangular connector

The pin assignments of these selected hybrid connectors are shown in Table 6.4 and Table 6.5.

Table 6.4: Pin assignments of an IP6x round plug connector, see Figure 6.14

Parameter		A	B	C	D	PE	1	2	3	4	5	6	7	8	Housing
DC grid	**L+**		x												
	L-	x													
	PE					x									x
DC 24 V	**+HSDC**			x											
	-HSDC				x										
STO	**+STO**							x							
	-STO								x						
	shieldSTO														x
Ethernet	**TD+**										x				
	TD-												x		
	RD+											x			
	RD-													x	
Not connected	**nc**						x			x					

Table 6.5: Pin assignments of a modular IP6x rectangular connector, see Figure 6.15

		Module 1				Housing	Module 2						Module 3
Parameters		**1**	**2**	**3**	**4**	**PE**	**1**	**2**	**3**	**4**	**5**	**6**	**RJ45**
DC grid	**nc**	x											
	L+		x										
	L-				x								
	nc			x									
	PE					x							
DC 24 V	**+HSDC**						x						
	-HSDC							x					
	nc								x				
STO	**+STO**									x			
	-STO										x		

		Module 1				Housing	Module 2						Module 3
Parameters		**1**	**2**	**3**	**4**	**PE**	**1**	**2**	**3**	**4**	**5**	**6**	**RJ45**
	shieldSTO											x	
Ethernet	**RJ45**												x

The results obtained in the project make it advisable to extend the scope of standardization for proven plug connectors in DC grids. In addition to stipulating general requirements for connectivity, it is important to prevent unauthorized separation of plugs and sockets. Different locking levels have therefore been defined:

- Level 1: This locking level prevents accidental disconnection.
- Level 2: Deliberate manual unlocking (for example, by releasing a safety catch or unscrewing a knurled screw) is required.
- Level 3: An additional deliberate unlocking step using a standard tool (such as a screwdriver) is required.
- Level 4: Unlocking with a key (such as a lockable bracket or e.g. NFC) or special tool.
- Level 5a: Automatic locking in response to authorized opening (voltage measurement in the control cabinet or other means of ensuring that the load is disconnected) by sending a signal to the plug connection.
- Level 5b: Approval of automatic locking by authorized opening (voltage measurement in the plug connection connector or other means of ensuring that the load is disconnected).

6.7.8 Infrastructure Components

Infrastructure components (see Figure 5.2) are used when energy, data, and signals are distributed outside the control cabinet or on its back wall. Examples include wall feedthroughs, outlets (distribution boxes), wallbox-type chargers, field boxes, and T-connectors as shown in Figure 6.16.

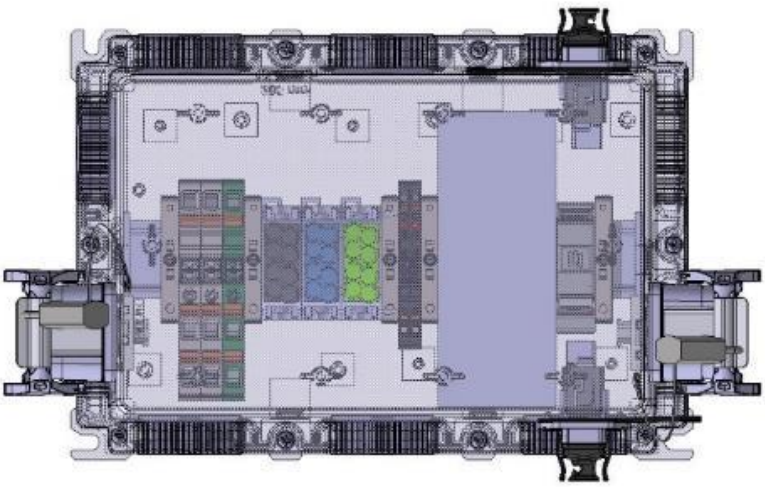

Figure 6.16: Example of an infrastructure component

6.8 Overvoltage Protection Devices

Overvoltage protection devices limit high transient voltages within nanoseconds. When such a transient overvoltage occurs, the impedance of the overvoltage protection component drops to divert the resulting impulse current. This reduces the amplitude of the overvoltage to non-critical levels.

Transient overvoltages can be caused by switching operations and lightning, among other things. A selection of protective devices is presented in section 12.4.

7 Voltage Values and Voltage Bands

This chapter describes the voltages between the active L+ and L- conductors. Permissible voltages between active conductors and ground are discussed in Chapter 8 (grounding concepts), section 12.3 (Protection from Electric Shocks) and section 12.4 (Overvoltage Protection).

The DC grid does not have a fixed operating voltage, rather it operated within a voltage range. This enables control of the load flow of power sources using characteristic-based regulation, especially in grid installations with multiple sources. This concept is introduced here and discussed in detail in Chapter 10. The operating range of the DC grid is determined by the operating ranges of its components, and especially the active and passive grid rectifiers.

7.1 Operating Ranges of Components

The components of the DC grid operate within different voltage ranges, which are listed in Figure 7.1. The gray bar at the top represents the full operating range of the DC grid.

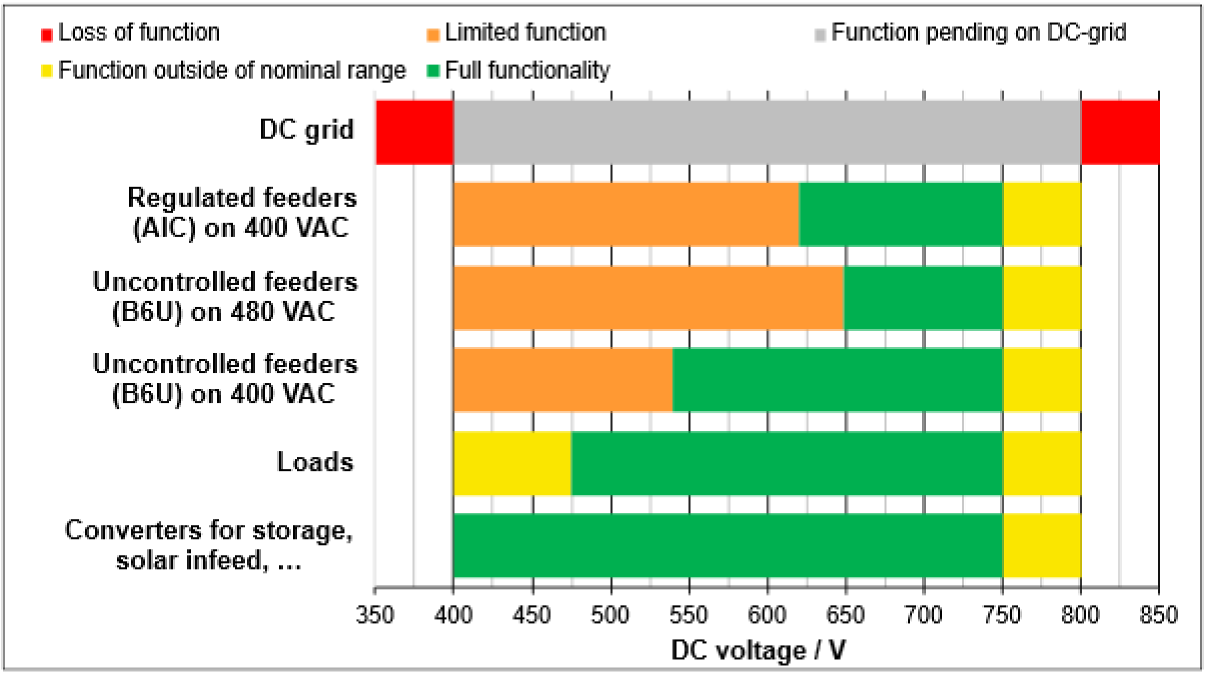

Figure 7.1: Operating ranges of components [19]

Within the operating ranges of components shown in Figure 6.1, two voltage bands are appropriate:

- a band with a nominal voltage of 700 V and
- a band with a nominal voltage of 540 V.

The nominal operating range is based on the globally widespread AC grids and ordinarily used components. This has the advantage that devices and installations in use today are suitable for deployment in the open DC grid without requiring any fundamental changes.

7.1.1 Active Infeed Converters

Active infeed converters (AICs) can only generate a DC voltage greater than the rectified AC voltage [20]. If the generated DC voltage shall not have a significant AC component (for example, at 150 Hz) relative to ground potential, it must be larger than twice the peak value of the line-to-ground AC-voltage. For a three-phase 400 V AC grid, this is approximately 650 V. If a large current is drawn from the DC grid, the DC voltage can drop to a level at which the AIC is no longer controllable. Due to the large load on the freewheeling diodes of the AIC, this state should not persist for more than a few

19 For B6U rectifiers the full green range up to 750 V can only be reached with further sources in the DC grid.

20 In a 400V three-phase AC system, this is about 565 V.

milliseconds. The operating range is limited to the components' dielectric strength. In addition, efficiency diminishes with increasing DC voltage (due to switching losses in power semiconductors).

7.1.2 Uncontrolled Infeed units

Uncontrolled power infeed at 400/480 V AC generates a voltage corresponding to the rectified value. This value in turn depends on the grid-side inductance, the load, and the actual grid voltage. Assuming the widely used inductance of 4% of the short circuit voltage u_k, the DC voltage at rated load is about $1.35 \times U_{AC}$ [21].

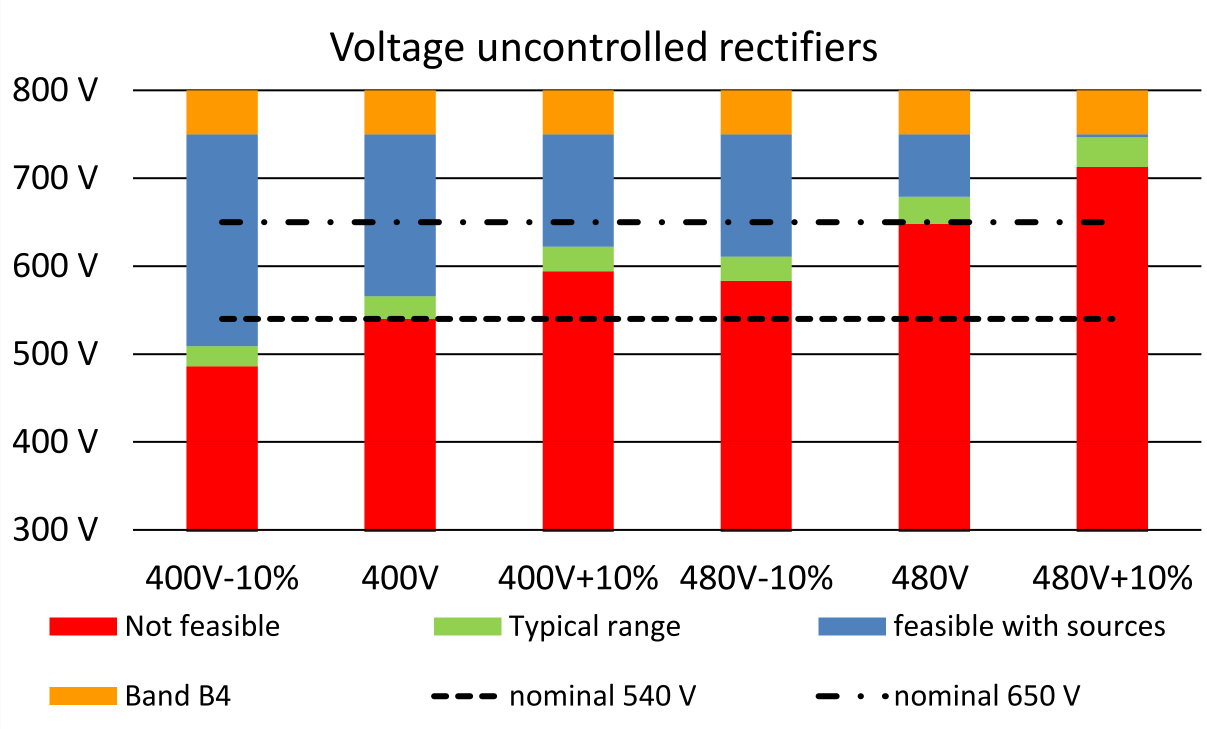

Figure 7.2: DC voltage from uncontrolled rectifiers

Figure 7.2 shows the typical DC voltage band, indicated in green, which depends on the grid voltage and permissible tolerances [10.]. The green band is delimited at its bottom by $U_{DC} = 1.35 \cdot U_{AC,eff}$ and at its top by $U_{DC} = \sqrt{2} \cdot U_{AC,eff}$. Higher voltages (blue or orange band) can occur if, for example, drives inject energy in generator mode; the orange band corresponds to voltage band B4, which is explained in greater detail in section 7.3.4 below.

7.1.3 Typical DC Loads

Typical loads include drive inverters and DC/DC converters. If the supply voltage is too low, the specified rated power cannot be ensured. The upper voltage limit is normally set by semiconductor devices (typically with a 1200 V blocking voltage) and electrolytic capacitors (typically 2 × 400 V or 2 × 450 V rated voltage in series).

7.1.4 Converters for Energy Storage or Photovoltaic Systems

Converters for energy storages or photovoltaic systems must always be adapted to the power source, so there are no fundamental restraints here.

7.1.5 Smart Breakers

Smart breakers provide protection from, for example, overvoltage and undervoltage (see section 6.1.1). They are active in voltage bands B2, B3, and B4 (sections 7.3.2 to 7.3.4 and Table 7.1) and only switched off for operational reasons and in the event of faults.

If the voltage of the DC grid exceeds the value of U5 (880 V; see section 7.3.4 and Table 7.1 and Table 7.2), the smart breaker must disconnect the DC sector within one millisecond.

21 In a 400V three-phase AC system, this is about 540 V.

If the voltage of the DC grid exceeds the value of U4 (800 V, see section 7.3.4 and Table 7.2), the smart breaker must disconnect after five seconds at the latest.

If the voltage of the DC grid drops below the value of U1 (400 V, see section 7.3.1 and Table 7.2), the smart breaker must disconnect the DC sector in less than one millisecond.

7.2 Nominal Voltage

As described in section 7.1, the DC grid does not have a fixed voltage, operating instead within a voltage band. The boundaries of this band depend on the power supply topology and the supplying AC grid. For regulated power supplies on 400 V AC the nominal voltage is set to 650 V. For unregulated power supplies on 480 V AC, the nominal voltage is set to 650 V. Unregulated power supplies connected to a 400 V AC grid have a nominal voltage of 540 V. 700 V in line with IEC 60038.

At a nominal voltage of 700 V, a standard line motor can therefore be operated at its rated power without any issues. In this case, the maximum line-to-line voltage for the motor is 540 V·0.7 ≈380 V. At a nominal voltage of 540 V, there is a slight power derating for standard line motors, but this is normal in drives supplied by inverters.

7.3 Voltage Bands and Limit Values

The defined voltage bands are based on TR 63282 [10.], which describes voltage bands and operation states but does not give any specific values for voltage limits or the corresponding times. Table 7.1 explains these voltage limit values (the upper limit UX in each case of the voltage in band BX) and describes their most important characteristics. The DC grid has a nominal operating state designated as voltage band B3. Continuous operation of the grid is permissible within this voltage band (as measured at the devices' terminals). The other voltage bands should be avoided, since the DC grid may only temporarily operate within them.

Table 7.1: Voltage bands and limit values (based on [10.]) , see footnote 26 on U6

	Band	Nominal voltage: 540 V	Nominal voltage: 700 V
	B7	**Forbidden band** - Damage of devices is very likely	
U6		**2000 V**	
	B6	**Overvoltage protection band** - Switching operations can cause this voltage range - Surge protection devices (SPDs) operate and try to protect devices	
U5		**880 V**	
	B5	**Temporary overvoltage band** - Surge protection devices (SPD) are **not** active - Breakers disconnect in this band - Insulation and components shall withstand this for up to 5 s - Devices may lose functionality in order to protect themselves	
U4		**800 V**	
	B4	**Overvoltage band** - Devices may reduce their power - This shall not last longer than 60s - Measures to reduce the voltage must be taken (e.g. charge storage, switch-on power resistors)	
U3		**750 V**	
	B3	**Nominal band** - Normal operating range - Devices shall be operated permanently - Devices perform with their rated power	
U2		**485 V**	**620 V**
	B2	**Emergency band** - Overload condition - Loads have to be reduced - AIC must only be operated for a few milliseconds	
U1		**400 V**	
	B1	**Blackout Band** - Smart Breakers disconnect - Band will be used during pre-charging - Occurs briefly during short-circuit conditions	

7.3.1 B1: Blackout Band (< 400 V)

The Smart Breakers open if the voltage drops below U1. Except during precharging, the DC grid therefore only briefly enters this band (e.g. during short circuits or other transient events).

7.3.2 B2: Emergency Band (400 V – 620 V for AIC connected to 400 V AC)

This band is characterized by a large overload. It is crucial to reduce this load to prevent the DC grid from transitioning to band B1. Devices may reduce their power level to achieve this goal. If B2 is reached due to a fault in the DC grid while the latter remains connected to the AC grid, significant compensation currents can flow through the power supply units. AICs can only operate for a few milliseconds in this state. Conversely, devices such as drive inverters can operate in B2 for an extended time period, for example if the DC grid is separated from the AC grid and supplied from a battery.

7.3.3 B3: Nominal Band (620 V – 750 V for AIC Supply at 400 V AC)

This is the normal operating band of the DC grid. It is characterized by a power balance between local generation (e.g. from PV systems), supply from the AC grid, and consumption by loads. All devices of the grid are designed for long-term operation in this voltage band [22].

7.3.4 B4: Overvoltage band (750 V – 800 V)

In this voltage band, steps must be taken to prevent devices from reaching their shutdown threshold (800 V). These steps can include, for example, feeding power back into the AC grid, charging energy storage systems, or activating load resistors. This state should not last longer than 60 seconds, and devices are allowed to reduce their power while in it. As a general rule, however, the grid must continue operating. The limitation to 60 seconds is justified by increased switching losses in the devices.

7.3.5 B5: Temporary Overvoltage band (800 V – 880 V)

Switching actions, fault conditions, and deceleration of drives can all cause overvoltages. A temporary overvoltage of up to 880 V is not problematic for typical 400 V electrolytic capacitors (two in series) [23]. However, the ability of commonly used 1200 V semiconductors to withstand higher voltages can be exceeded as a result of internal switching actions, causing them to lose the ability to protect themselves. If the voltage persists in this band for longer than five seconds (see Table 7.2 for details), the upstream smart breaker opens to protect all downstream devices [24]. When this occurs, a discharge takes place as described in section 9.9. Overvoltage protection devices are not active in this band.

7.3.6 B6: Overvoltage Protection Band (880 V – 2000 V)

Switching operations, and especially those performed by overcurrent protection devices, can cause transient overvoltages (lasting microseconds) within this voltage band. When Smart Breakers disconnect in response to an overload or short circuit, the currents that then flow through the supply lines are typically multiples of the operating current. When disconnecting, the energy stored in the parasitic inductance of the supply line needs to be dissipated.

Transient overvoltages up to U6 = 2 kV have been observed in existing DC grids without any noticeable issues. Devices that are connected to the DC grid undergo testing according to IEC 61000-4-5 with a 1.2/50 µs impulse and 2 kV (see section 12.4) anyway.

7.3.7 B7: Forbidden Band

In this voltage band, the risk that devices (such as varistors, semiconductors, and capacitors) will suffer damage is very large.

7.4 Operating States of the DC Grid

The voltage bands from B1 to B6, described in section 7.3, should only be temporarily reached, with the single exception of B3. Since transient, short-lasting overvoltages/undervoltages are considered to be less critical than prolonged ones, it is mandatory to monitor their duration. This is shown in Table

22 Limitations in device performance can be imposed by physical constraints, like the state of charge of storage units, the voltage level of the power supply units, insufficient motor voltage, or solar radiation in the case of photovoltaic (PV) systems.

23 According to [11.], it is not a problem to have 880 V last for 30 seconds when two 400 V capacitors are connected in series. For more information, please refer to IEC 60384-4, section 4.14.

24 According to [31.], a duration of up to five seconds is mentioned in section 5.4.3.2 of IEC 60664-1:2020 as the time during which the basic insulation must be able to withstand voltages 1200 V higher than the rated voltage.

7.2. The voltage band Bx and the corresponding time duration Sx are used to determine the operating state Ax. It is assumed that transient overvoltages occur so rarely that they will not significantly affect the life expectancies of devices [25].

7.4.1 Time Ranges of Operating States

S1: Transient range, typically lasting only microseconds

S2: Fault range, for example caused by switching actions, typically lasting up to 1 ms

S3a/S3b: Voltage control range; active components counteract voltage deviations

S4: Equilibrium: persistent normal operation

Table 7.2: Operating states as a function of voltage[26] and duration (based on [10.])

Upper voltage limit Ux in DC grid for nominal voltage 540 V / 700 V (Voltage ↑)	**Voltage band**	**S1:** $t < 50$ µs	**S2:** $50\ \mu s \le t \le 1$ ms	**S3a:** $1\ ms \le t \le 5$ s	**S3b:** $5\ s \le t \le 60$ s	**S4:** $t > 60$ s
	B7	A7				
U6: 2000 V	B6	A6	A7			
U5: 880 V	B5	A4	A5	A5	A7	A7
U4: 800 V	B4	A3	A3	A3	A4	A5
U3: 750 V	B3	A3	A3	A3	A3	A3
U2: 485 / 620 V	B2	A4	A4	A2	A2	A2
U1: 400 V	B1	A4	A2	A1	A1	

Time →

7.4.2 Examples of the Operating States in Table 7.2

Example 1:

- Brief voltage sags, e.g. due to a quickly eliminated short circuit
- Voltage within the B1 band for $t < 50$ µs → operating state A4
- A4: device may reduce power but must continue working

Example 2:

- Excessive voltage increase (800 V < u < 880 V) caused by emergency braking of a drive
- Voltage in band B5 for up to five seconds → operating state A5
- A5: Devices may switch off to protect themselves

7.4.3 Description of Operating States

A7: Prohibited state

- Damage to equipment is very likely.
- This state must be avoided.

A6: Overvoltage protection systems active

- Overvoltage protection systems intervene to limit the voltage to ≤ U6.

25 This refers to single events that only occur a few times during a device's lifecycle.

26 The indicated voltages are between active conductors L+ and L-. For U6 and S1, 2 kV and 50 µs were chosen based on the voltage pulse as per IEC 61000-4-5 with a crest of 2 kV and a pulse shape of 1.2/50 µs.

- Overvoltage protection devices may only operate briefly or there is a risk of overheating.
- Devices may switch off to protect themselves.
- 100% protection of equipment cannot be ensured.

A5: Overvoltage and overvoltage protection systems inactive

- The voltage is too high but not limited by overvoltage protection systems.
- Equipment may switch off to protect itself.

A4: Abnormal state

- Equipment must be able to withstand it.
- Equipment must continue operating.
- Equipment may reduce its performance.

A3: Normal working state

- Equipment must provide its own rated power.

A2: Acute undervoltage

- The sources cannot meet the power requirement.
- Equipment must continue operating.
- Equipment may reduce power.
- It may be possible to shed loads to stabilize the system.
- If power supplies are connected to the AC grid, they may switch-off to protect themselves in the event of excessively high current.

A1: Blackout state

- Shutoff of equipment
- Possibly restart of precharging

7.5 Rate of Voltage Change

Every change in load results in a change in voltage in the DC grid. The magnitude and speed of the change depend on the dynamic load variations of the specific application, the capacitance of the interlinked systems, and how the droop curves are set.

There are two mechanisms that can cause premature aging, especially of electrolytic capacitors, as a result of frequent significant changes in voltages:

- The speed with which the DC voltage changes results in a current and therefore subjects the capacitors to thermal stress (see section 7.5.1).
- In addition, large negative voltage spikes can cause temporary reverse polarization of the cathode capacitor, thus reducing their lifespans (see section 7.5.2).

If necessary, the voltage swing can be reduced with additional capacitors or highly dynamic storage systems.

7.5.1 Thermal Loads Caused by Periodic Load Fluctuations

This section describes the load fluctuations that the capacitors must be thermally designed to withstand. Typically, critical load variations only occur if there are dominant consumers with significantly fluctuating loads in the DC grid. Dominant in this context means that their power consumption is large in relation to the grid's total power. Figure 7.3 illustrates the worst-case scenario of load fluctuations, in which the capacitors are continually discharged and recharged.

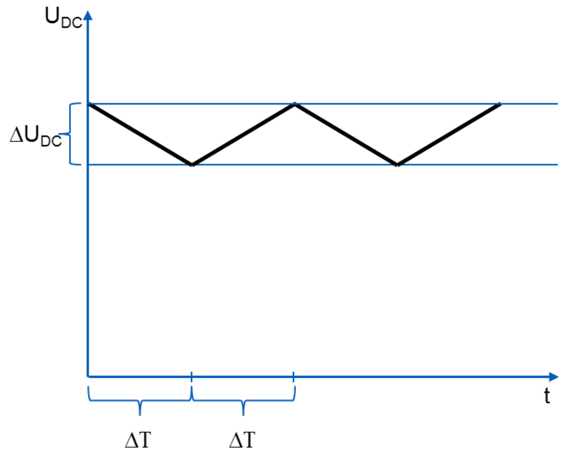

Figure 7.3: Traces of DC voltage with cyclical fluctuations

With the illustrated load fluctuations, the capacitors in the DC grid are charged and discharged with a rectangular current profile. Assuming a voltage change ΔU_{DC} of 140 V (20% of the nominated voltage) within a duration Δt of 10 ms, in a connected series this translates into a voltage change of 70 V for each individual capacitor. For a 470 µF capacitor, it results in a rectangular current of:

$$i_C = 470\ \mu F \cdot \frac{70\ \text{V}}{10\ \text{ms}} \approx 3\ A$$

The peak value of a rectangular function is equal to its RMS value. Since the high-frequency components of the current stress the electrolytic capacitor less than the low-frequency ones, a current load of 3 A at 50 Hz can be assumed as the worst-case scenario. With typical 470 µF capacitors, this current load lies within the specified limits, see, for example, datasheet of TDK capacitors series B43541 [12.]. Capacitors with smaller capacitances are less critical because they have a larger surface area (for dissipating heat) relative to their capacitance. Although capacitors with larger capacitance values have a poorer ratio of capacitance to surface area, they are typically operated with forced cooling.

When designing equipment, it is therefore assumed that the DC voltage may not vary in an extensive DC grid by more than

$$\Delta U_{DC}/\Delta T = 14\ \text{V/ms}.$$

7.5.2 Stresses Caused by Large Voltage Swings

Standard electrolytic capacitors are able to withstand a negative voltage swing of about 70 V without the cathode capacitor reversing polarity. If the polarity of this cathode capacitor is reversed too often, the foil surrounding the capacitor oxidizes, eventually leading to a short circuit fault at the cathode terminal. In a DC grid two such capacitors are always connected in series, resulting in a permissible cyclic voltage swing of 140 V. With a small safety margin to accommodate asymmetries and component tolerances (for example, symmetrizing resistors), this value is set to 130 V as already mentioned in section 7.5.1. Cyclic voltage swings of more than 130 V in the DC grid should be avoided. We assume that the absolute number of such larger voltage swings (like during shutdown or caused faults) is orders of magnitude less than 100 million times during the system's lifetime. This is a typical number of charge-discharge cycles with a lower permissible discharge voltage at which the electrolytic capacitors are still just able to maintain their specified values (listed in the datasheet as „charge-discharge endurance," see [13.]).

7.6 Protection from Overcharging

The DC grid is protected from overcharging at two different levels. In the voltage bands outside B3, and especially in overvoltage band B4, the sources and consumers perform actions defined by central or distributed grid management. Their purpose is to return the voltage to the nominal B3 band. They include reducing the infeed of local energy supply and AC/DC interfaces, increasing the infeed to energy storage systems, feeding power back to the higher-level AC grid, and increasing the consumption of flexibly controllable loads. This approach is also the basis for designing droop curves. The trip threshold (at which all control and regulation loops are shut down) is set to the value of U4 (800 V) for all devices as described in section 7.3.

On the second level, hardware-based protective measures – either internally in individual devices or externally on the busbars – can be implemented to prevent the maximum permissible voltage from being exceeded. They can include varistors, crowbar circuits, and circuit breakers for taking entire DC Sectors offline.

There are systems that are able to generate voltages above 800 V (such as energy storage systems and drives that employ a field-weakening technique with a permanently excited synchronous motor). It may be necessary to implement additional measures to protect them from overcharging.

8 Types of system earthing

The earthing of DC systems is not fundamentally different from the earthing of AC grids. IEC60364-1 ch. 312.2.4 describes different types of system earthing for direct current systems [14.]:

- DC TN-S system: One active line conductor or the active midpoint conductor is earthed. The protective earth (PE) conductor is separated from that earthed active conductor throughout the system.
- DC TN-C system: The earthed active conductor and the PE conductor are combined throughout the system.
- DC TN-C-S system: The earthed active conductor and the PE conductor are only combined in part of the system.
- DC IT system: All active conductors are isolated from earth or are connected to earth via a „sufficiently high impedance" for measurement or functional purposes only.

IEC60364-1 assumes that a DC system's potential is isolated from the AC grid [14.]. It does not describe AC-side earthing yet.

IEC TR 63282 distinguishes between unipolar and bipolar systems [10.]. In two-wire systems, only the voltage between the two outer conductors can be used (L+, L-, and PE), while three-wire systems have a loadable midpoint conductor that provides two voltage levels (L+, L-, M, and PE). These three-wire systems are significantly more complex than two-wire systems. The reasons for this are:

- Systems designed as TN-C systems with multiple earth connections are susceptible to electrical corrosion.
- If a system is designed as a TN-S system, this requires an additional conductor cable to carry twice as much current in special operating states.
- Voltage regulation and symmetrization are more complex.

For these reasons, and also because it is easy to add another voltage level using simple DC/DC converters, unipolar grids are favored in DC-INDUSTRIE. Due to the associated requirements for insulation coordination, the DC system must be symmetrical with respect to the voltage to earth.

Three different types of system earthing are described in detail. One of them has no galvanic separation from the AC grid (section 8.2) while the other two have galvanic separation from the AC grid (sections 8.3 and 8.5). Apart from power supplies, all DC equipment can be operated using any of the earthing methods described.

8.1 Connection types between AC mains and DC system

A DC system without isolating transformer may only be connected directly to a 3-phase 400/480 V 50/60 Hz AC TN system (AC-side earthing, see section 8.2) [27]. The allowed grid configurations for this type of connection are described in the following subsections.

8.1.1 Low-Voltage AC TN-C-(S) Grid

Here the system earthing electrodes (typically at the transformer) and facility earthing electrodes (in buildings) are connected by a combined PEN conductor.

Example 1: A small trade shop without its own supply transformer (local grid transformer)

Example 2: A large operation with its own supply transformer, which in turns operates other AC equipment.

8.1.2 Low-Voltage AC TT Grid

Here the system earthing (transformer star point) and facility earthing (building) are not interconnected. The transformer star point is routed into the facility as a separate N conductor.

If the DC system is implemented as a DC IT system (see section 8.3), it is always connected via an isolating transformer. In this case, functional earthing (high-resistive symmetric reference to ground) should only be implemented on the DC side (see section 8.3.4).

[27] Connection to grids with a higher voltage via step-down transformers is not allowed.

To prevent corrosion, the AC side earthing (section 8.2) should not be used in a TT system, as high DC currents can flow between the earthing electrodes.

8.1.3 Medium AC Voltage via an Onsite Transformer

Here the DC system is directly supplied from a medium-voltage grid via a dedicated transformer (or a winding reserved for this purpose) as shown in Figure 8.1 and Figure 8.2.

8.2 DC System with AC-side Earthing

This earthing method is called „AC-side grounding”. The earthing connection is made by star point earthing at the transformer of the AC system [28]. No additional low-impedance earth connections from L+ or L- to PE are allowed in either the DC system or the devices. System earthing is centrally located at the transformer as shown in Figure 8.1. If there are multiple power-supplying transformers, the star points should be interconnected with low impedance and earthed as a unit to avoid significant potential discrepancies between different earthing points (to prevent stray DC currents from causing corrosion; see section 12.5).

This type of grid has only two active poles (L+ and L-), because it is not allowed to use the neutral AC-side conductor as the DC system’s midpoint conductor; doing so would induce a direct current in the AC grid’s neutral conductor.

Only power supply devices (AC/DC converters) are allowed that do not generate a pulsed common-mode voltage in the DC system (see section 11.2 for limit values). In the simplest case, these can be diode rectifiers (section 6.2.4), but they can also be active pulsed inverters if these are equipped with an appropriate common-mode filter (section 6.2.4). The power supply devices must ensure that the potentials of the active DC conductors (L+ and L-) are symmetrical to PE. This earthing configuration is shown schematically in Figure 8.1, and a more detailed setup with different generators, storage systems and loads is shown in Figure 8.2.

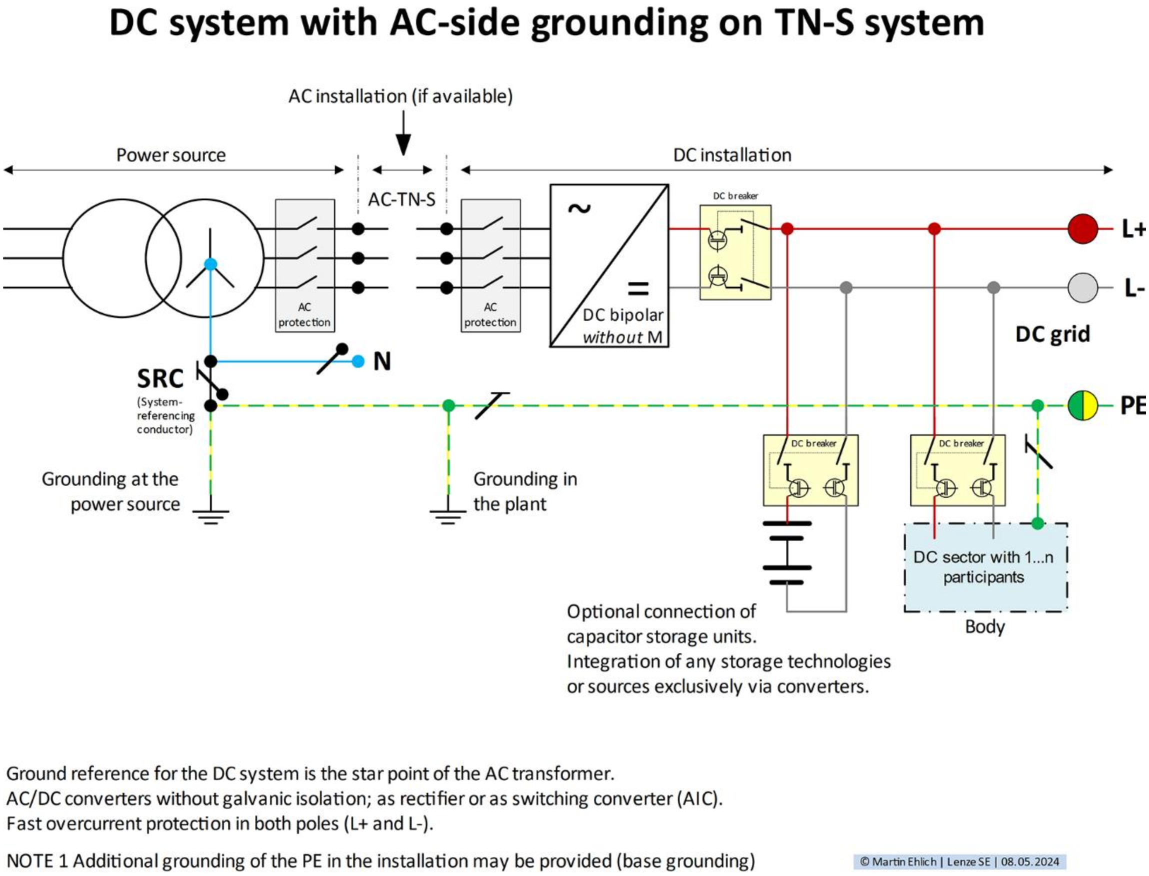

Figure 8.1: DC system with AC-side grounding

28 An MV/LV or LV/LV transformer may be used.

This earthing configuration, where the earthing point is determined by the AC grid, requires the installation of high-speed protective devices at both poles to provide protection in the event of an earth fault. Figure 8.1 shows power transistors (IGBTs) used for this purpose. These fast breakers must be designed such that they automatically turn off in the event of an earth fault in order to protect the power supply equipment from being damaged or destroyed [29]. It must also be ensured that the power supply equipment is able to output a sufficiently large fault current to trigger the breaker. If this is impossible, an auxiliary rectifier can be used.

When multiple sources are connected to the DC grid those sources will continue supplying the system if the connection to the AC grid is lost. Then, continued operation as an IT system or as a system with midpoint grounding on the DC side is possible if the necessary means are already installed, see chapter 8.4. If those means are not in place, all sources need to be disconnected when the connection to AC is lost, e.g., with intertripping of Smart Breakers. Examples for causes of the loss of the earth reference are power failure in the upstream AC grid, faults in all AC/DC power supply devices or earth faults on the central DC bus.

8.2.1 Advantages of AC-Side Earthing

- No AC isolating transformer is needed (advantages: reduced costs and losses and a smaller overall footprint).
- Can be operated with an existing AC-TN system.
- Easy earth fault localization: it triggers the protective device in the DC Sector where the fault occurred.
- Besides the DC system, other standard AC devices can also be powered by the same medium-voltage transformer.
- Under certain conditions, PV systems can be connected via non-galvanically isolating DC/DC converters (see section 6.5.1). This includes monitoring of leakage currents and insulation resistances on the PV side.

8.2.2 Disadvantages of AC-Side Earthing

- Fast-acting protective devices are required in both poles.
- In a DC system with many components, the control range must be limited to voltages above the rectified mains voltage[30] to limit leakage currents (no 150 Hz ripple at PE).
- Parallel connection of multiple power supplies is challenging since it is necessary to prevent circular currents across the AC grid.
- Switched AC/DC power supply devices may only be operated with a common-mode filter.
- As in all hard-earthed systems, in case of incorrect design of protective earthing DC leakage currents can occur that can lead to corrosion (see section 12.5).
- If all power sources are disconnected from the AC grid (due to a power failure or tripping of a circuit breaker) while the DC system continues operating on power from a storage system, the earthing configuration changes (see section 8.6).
- This earthing type is not covered by the published version of IEC 60364-1 (Low-voltage electrical installations - Part 1: Fundamental principles), dated in 2005; however, the new version of IEC 60364-1 soon to be published includes grounding of a DC system on the AC side.
- In the case of a single-pole earth fault, DC currents can be injected into the AC power supply grid [31]. If AC-side residual current devices (RCD) are installed between the transformer and the AIC, they must be of type B (suitable for direct current) [32].

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29 Note: the i^2t values of the breaker and power supply equipment must be coordinated.

30 The DC voltage is smooth toward ground if the voltage of every active conductor (L+/L-) is above the rectification level towards ground. In a 400 V three-phase system, this is the case at 2 x 325V = 650 V.

31 If the DC grid is supplied from a B6 rectifier, it will behave like an M3 rectifier in the event of a ground fault, resulting in corresponding DC currents flowing into the AC grid.

32 However, this is required in any case by IEC 60364-5-53 (see Figure G.1 in [26.]).

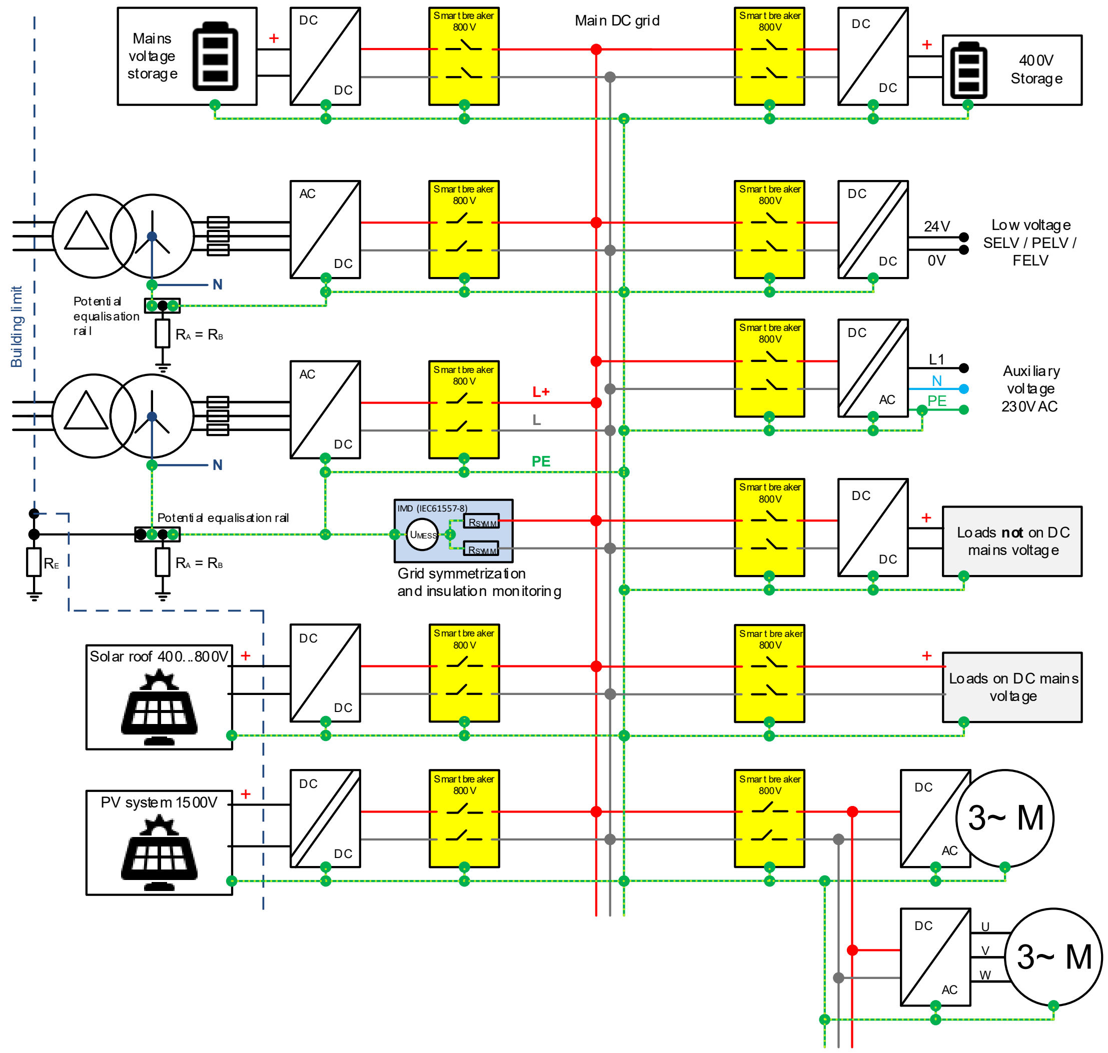


Figure 8.2: DC system grounded on the AC side with generators, storages and consumers[33]

8.3 DC IT system without continued operation (DC IT system)

In the **DC IT system** version, the DC system is galvanically isolated from the AC mains. This DC IT system may not continue to operate in the event of a first earth fault, and the fault location must be disconnected by a breaker within a maximum of 10 seconds. The reason for the shutdown is the risk of overloading the creepage path if operation continues (see section 12.3.2). For personal safety reasons HD 60364-4-41, section 411.6.3 requires the use of insulation monitoring devices (see also section 12.1.2.4) [15.].

This simplifies parallel connection of multiple power supplies [34]. Fast-acting short-circuit protection is only required in one of the two active conductors, but in case of a fault, disconnection is required in both active conductors. In case a second earth fault needs to be considered, a protective device must still be provided for each active conductor to ensure isolation and line protection. Galvanic isolation from the (earthed) AC system can be achieved with either additional isolating transformers or medium-voltage transformers that exclusively supply the DC system [35]. Another option is to use galvanically

33 The Grid symmetrization and insulation device (shown in blue) in the figure is only needed if, after a loss of connection to the AC grid, operation is continued as an IT system.

34 Standard supply equipment (see section 6.2) often generates a DC common-mode voltage that is easy for the upstream transformer to accept.

35 This ensures that every AIC is connected to a dedicated transformer and thus to a local AC-IT grid.

isolating converters. High-impedance system earthing is used on the DC side (see section 8.3.3) from L+ and L- to earth, for example using resistors or active symmetrization. In order to minimize migration effects in the insolation, ensure that the voltages are symmetrical to earth.

This earthing method is schematically depicted in Figure 8.3; Figure 8.4 shows greater detail with various generators, storage systems, and loads.

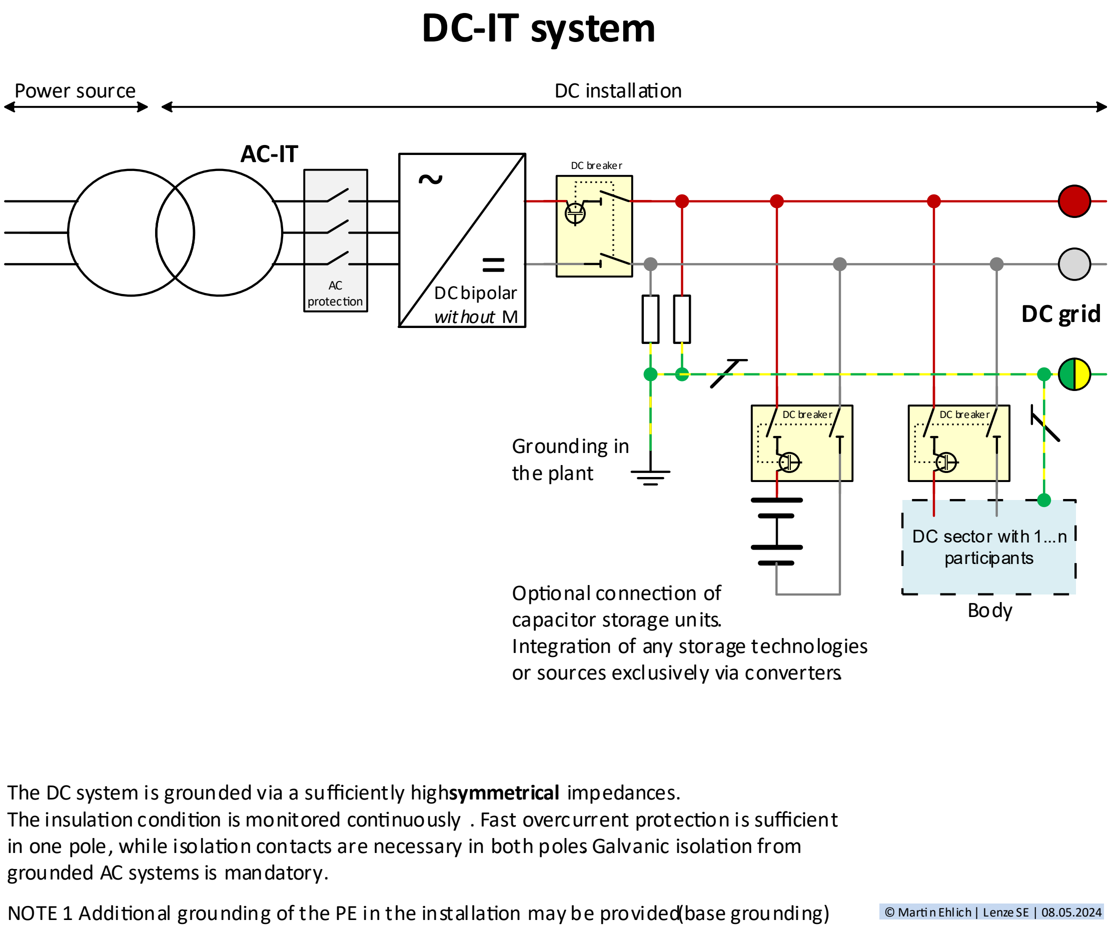


Figure 8.3: DC IT system

8.3.1 Advantages of DC IT Earthing

- Fast circuit breakers are only required at one pole.
- AC/DC power supplies do not need to additionally have a common-mode filter.
- AC/DC power supplies can be operated in parallel without problems.
- The transformer associated with the grid can adjust the AC voltage.
- No low-frequency common-mode voltage (150 Hz)
- Reduced risk of hazards, due to significantly lower fault currents in the event of an earth fault
- The leakage currents are limited, thus reducing the risk of corrosion at the earthing electrode.

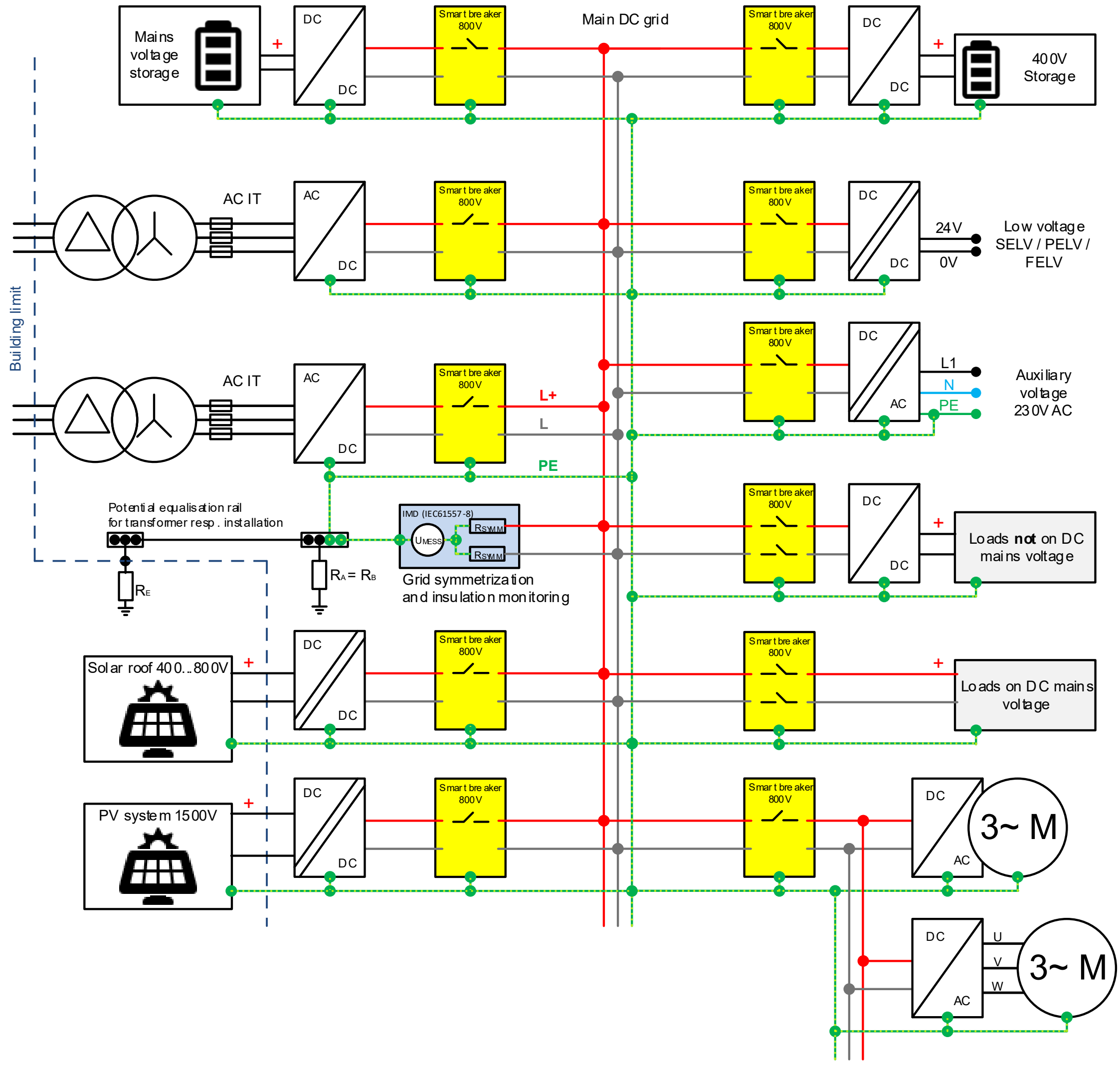


Figure 8.4: DC IT system with generators, storages and consumers

8.3.2 Drawbacks of DC IT Earthing

- The transformer incurs additional costs, takes up additional space, and causes losses unless the entire facility is implemented as a DC IT system (power supply via medium-voltage transformer).
- Symmetrization of DC potentials against PE and monitoring of the isolation are required.
- Localizing the fault (see section 12.1.2.4) is work-intensive. One possibility is to install residual current sensors (RCM) in individual DC sectors.
- Due to the common-mode voltage, other standard AC devices can not be operated at the same transformer as the AC/DC power supplies (see section 6.2.1).
- With parallel operation, each AC/DC power supply requires its own isolating transformer.
- Due to the low insulation resistance values expected with current technology, PV systems should be connected via isolated DC/DC converters.

8.3.3 Functional Earthing in DC Sectors

Functional earthing prevents the voltage from an active conductor to earth from exceeding 400 V while keeping it symmetrical with the other active conductor. In the simplest case, functional earthing can be achieved with symmetrizing resistors, which can be integrated into the power supply unit or storage device, for example. When designing the symmetrization device, care must be taken to ensure that its power loss is not too high and that no high DC currents flow continuously to earth (due to electrolytic corrosion; see also section 12.5). All devices in the DC system must therefore have a symmetrical resistance to earth at their supply points.

It is also necessary to make sure that the symmetrizing device cannot be disconnected by switching off a DC Sector. If a DC Sector that has been disconnected from the DC system is supposed to continue operating autonomously for a certain period of time, appropriate steps must be taken to ensure symmetrization. Switchable symmetrizing resistors, for example, can be used for this purpose.

8.3.3.1 Passive Symmetrization for the DC Section

When symmetrization is achieved with symmetrical resistors to earth, HD 60364-5-53:2022 (section 9.1.3) recommends an insulation resistance of 100 Ω per volt of the supply voltage. At a maximum continuous operating voltage of 750 V (see Table 7.2), it follows that the total value of all symmetrizing resistors [36] should be greater than 75 kΩ. This limits the maximum DC leakage current flowing as a result of the symmetrization to 10 mA, so that the use of residual current devices (RCD) is not excluded and reliable insulation fault location (section 12.1.2.4) is possible.

8.3.3.2 Active Symmetrization for the DC Section

Particularly in extensive systems with a large number of connected devices, passive symmetrization to earth can be disadvantageous due to unsymmetrical resistances. With active symmetrization, it’s only necessary to compensate for differences in insulation resistances. As shown in Figure 8.5, the resistance values between L+ and PE and between L- and PE are continuously adjusted to ensure that the two voltages are equal. This method can also be used to implement an „advance alarm” if necessary.

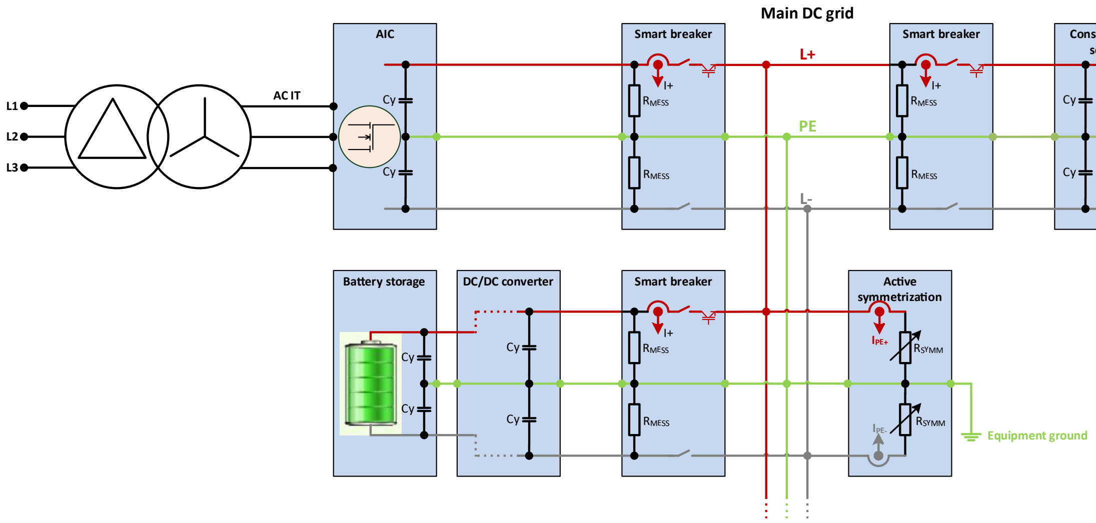


Figure 8.5: Active symmetrization in the DC IT system

Like with passive symmetrization, persistent DC leakage currents of more than 10 mA should be avoided to guard against corrosion. However, significantly greater values [37] can be tolerated for short periods, since galvanic corrosion only occurs very slowly over long time periods.

8.3.4 Protective Earthing

Protective earthing is accomplished by connecting all conductive equipment enclosures to PE (the central earthing point), which is in turn linked via a low-impedance connection to a earthing electrode. Protective earthing only ensures the safety of personal and equipment and should not be confused with functional earthing. To prevent galvanic corrosion in DC systems, it is also especially important to ensure low-impedance connections from all devices to the earthing system (see section 12.5).

36 This includes all resistances of active lines to ground.

37 Larger DC leakage currents can be intentionally applied to detect insulation faults; they can also occur as a result of temporarily activating a symmetrization device (for island operation).

8.4 DC IT System with Continued Operation after the First Earth Fault

A DC IT system that can continue to operate after an initial earth fault is always designed to meet higher system availability requirements. However, it requires larger creepage distances (see Figure 12.14) than the „AC-side grounding," „DC IT without continuous operation," and „DC midpoint grounding" approaches. Therefore, DC-INDUSTRIE does not focus on these systems. Whenever a reference is made in this document to DC IT, the assumption is always that any earth fault occurring in it will be cleared within 10 seconds.

8.5 DC Midpoint Earthing

This method involves earthing the midpoint of the DC voltage via a low-impedance connection. To accomplish this, among other things, the power supply unit must generate two DC voltages that are galvanically isolated from the AC grid and connected in series, with their midpoint connected to a low-impedance earthing point. Systems of this type are described in IEC TR 63282 [10.] and IEC 60364-1 [14.]. To reduce wiring work and complexity, it is recommended to avoid using the M conductor as an active conductor in industrial applications.

In addition to galvanic isolation, for example in the case of AC-side earthing (section 8.2), fault protection is required at both poles.

This concept poses a special challenge due to the fact that connecting multiple power sources in parallel can create imbalances that in turn result in significant DC balancing currents in the earthing system. The DC system should therefore only be earthed at one point. Due to the relatively complex topology of the power supply devices in this configuration, this earthing approach is not a focus of DC-INDUSTRIE test installations.

In the context of DC-INDUSTRIE, all specified devices (except power supply devices) can be used in such a DC system.

This earthing type is schematically depicted in Figure 8.6; Figure 8.7 shows it in greater detail with various generators, storage units and consumers.

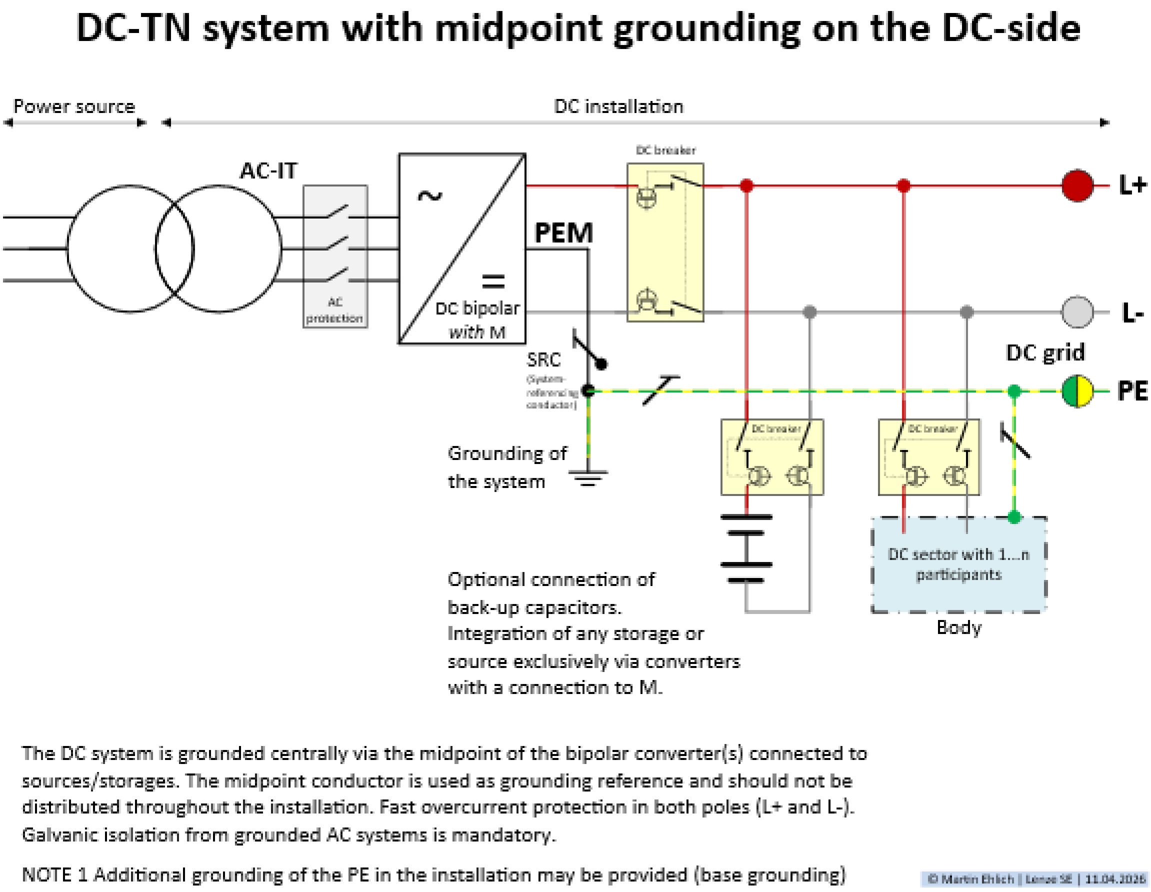


Figure 8.6: Midpoint grounding in a bipolar DC-TN-S system

If a fault in the earthed DC Sector causes it to disconnect, the earthing configuration can switch to DC IT. If operation shall be continued, the system must be equipped with the required protective and monitoring devices.

The important attributes of this system/earthing configuration are:

- Each AC/DC power supply requires its own transformer (to isolate the AC/DC converter).
- The AC/DC power supplies must provide a bipolar DC voltage (L+, M, L-). This in turn requires a characteristic control curve that takes two voltages into account (L+ to M and L- to M).
- In order to use „half DC voltage" (L+ to M or M to L-), a four-wire system must be installed (as a minimum, in these parts of the DC system).
- Both outer conductors (L+ and L-) must always be protected.
- Depending on how the different voltage levels are used, the number of variants/configurations for the smart breaker increases because the M conductor must not be switched.
- Under certain conditions, PV systems can be connected via non-galvanically isolated DC/DC converters. This includes monitoring of leakage currents and insulation resistances on the PV side.
- Bipolar converters with 3 output potentials (both AC/DC and DC/DC) are currently not available.

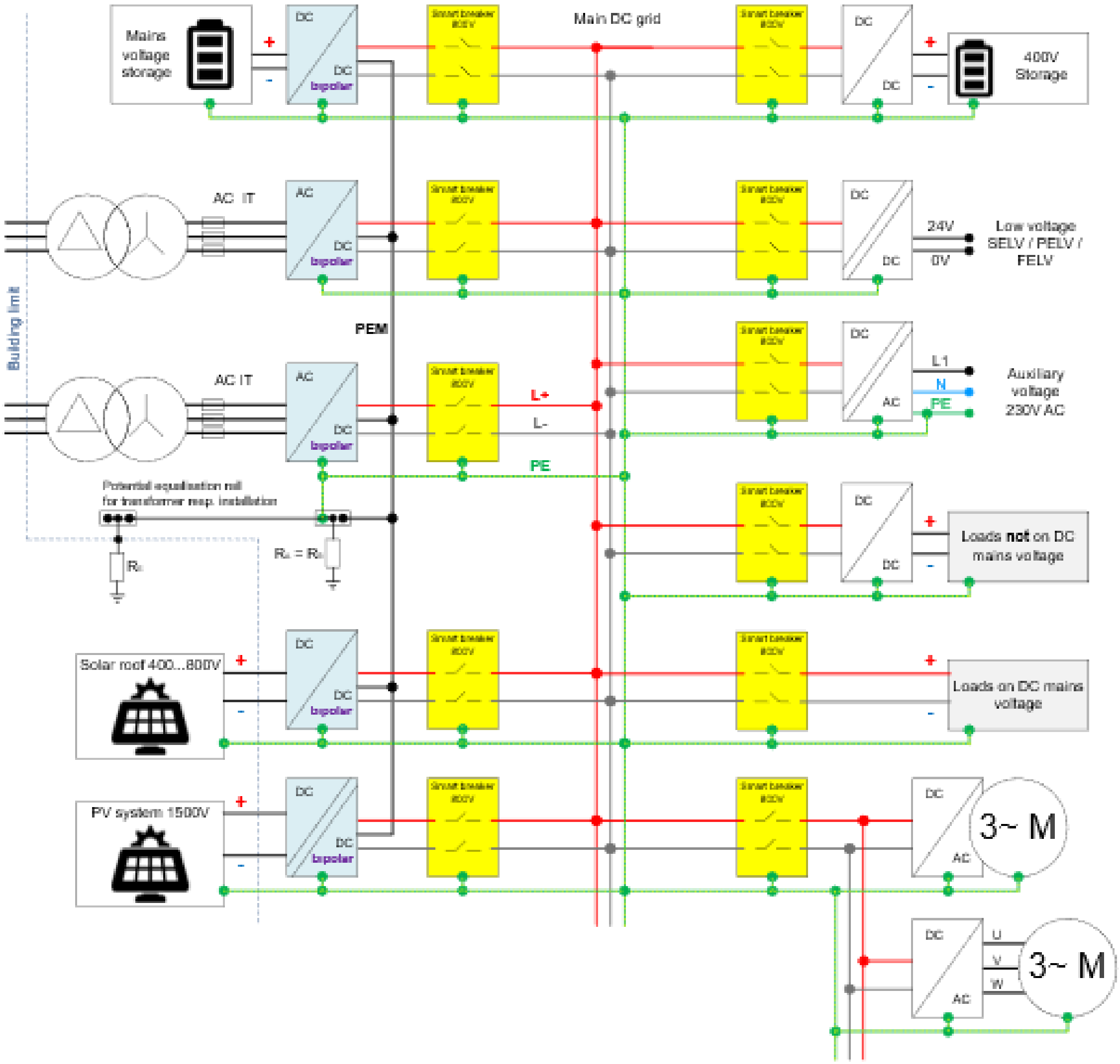


Figure 8.7: Midpoint-grounded DC-TN-S system with generators, storages and consumers

8.6 Changing the System Configuration in the Event of Failure of the Main Power Source (Islanding)

Straightforward integration of energy storage systems is a major advantage of DC systems. Especially if the upstream AC grid fails or if there are faults in the DC system, all or part of the DC system can continue operating using energy storage systems.

- With „earthing via the AC grid" (section 8.2), the active conductors lose their earth connection if the AC grid fails.
- With „DC midpoint earthing" (section 8.5), the system configuration can change as a result of disconnecting all DC sectors whose active conductors have a low-resistance connection to earth.
- With „DC IT earthing" (section 8.3), the symmetrization device can be disconnected (in this case, without changing the system configuration). This can result in the following problems:
  - Voltages are no longer symmetrical with respect to earth.
  - While disconnected from the AC grid, any short circuit currents are only fed from storage units within the DC system. Steps must therefore be taken to ensure that protective devices trigger within the prescribed interruption times (Table 12.6).

It is also possible to create islands in AC grids if the latter are equipped with a storage system (for more information IEC 60364-8-82, section 82.6.3.4). In a DC system, the following procedure can be followed:

- Continued operation as an IT system without insulation monitoring is possible for up to a maximum of 10 seconds. Overloading of the creepage distance is unlikely during such a short time [16.].
- Continued operation as a DC IT system as described in section 8.3 is possible. For this to work, it is important for the insulation resistances to already be symmetrical prior to the switchover. Residual current monitoring devices (RCM) can be used to assess the insulation resistance, also with solid earthing[38]. Another option is to monitor the insulation resistance in a de-energized state (e.g. on a daily basis) before ramping up the power. If an insulation monitoring device (IMD) is used on the DC side of an „AC-side grounded DC system" to ensure symmetrization and monitor insulation in the event of a power supply failure at the mains, it is important to disable the IMD alarm during normal operation.
- Continued operation as a DC IT system as described in section 8.4 is possible without any additional steps, if all connected devices are designed for it.
- Continued operation as a temporarily midpoint-grounded DC system:
  - Connection of a midpoint replica temporarily provides earthing as described in section 8.5 for isolated (grid-independent) operation (analogous to AC; see „switching device for islanding SDFI" in IEC 60364-8-82).
  - The midpoint replica must meet the following requirements:
    - The midpoint replica may only be active while other earthing devices are disconnected.
    - The midpoint replica must be directly connected to the equipotential bonding bar at a low impedance (with a minimum cross-sectional area of 10 mm² and a voltage drop of less than 0.2 V).
    - The midpoint replica may only be implemented directly in the energy storage system or an appropriate approved isolation component (AIC).
    - In case there is a fault, it must be ensured that the energy storage system is able to deliver the short circuit current required to trigger all relevant protective devices while in this operating state.
    - The earth connection must be monitored during isolated operation. If the midpoint replica fails, the DC system must be shut down.
    - Switchover of the earth connection must take place within 100 ms.
  - Implementation example 1: temporary midpoint earthing via an energy storage converter:
    - In technical terms, this approach is particularly advantageous with „symmetrically" configured DC-DC converters for integrating energy storage. The converter achieves symmetry between the L+ and L- terminals, thus enabling an uninterrupted midpoint potential between the secondary and primary sides. In the event of an AC grid failure, the DC grid management system detects the situation and activates midpoint earthing of the energy storage converter using a „grounder" as shown in Figure 8.8.

38 Symmetrical ground faults cannot be detected with differential current sensors.

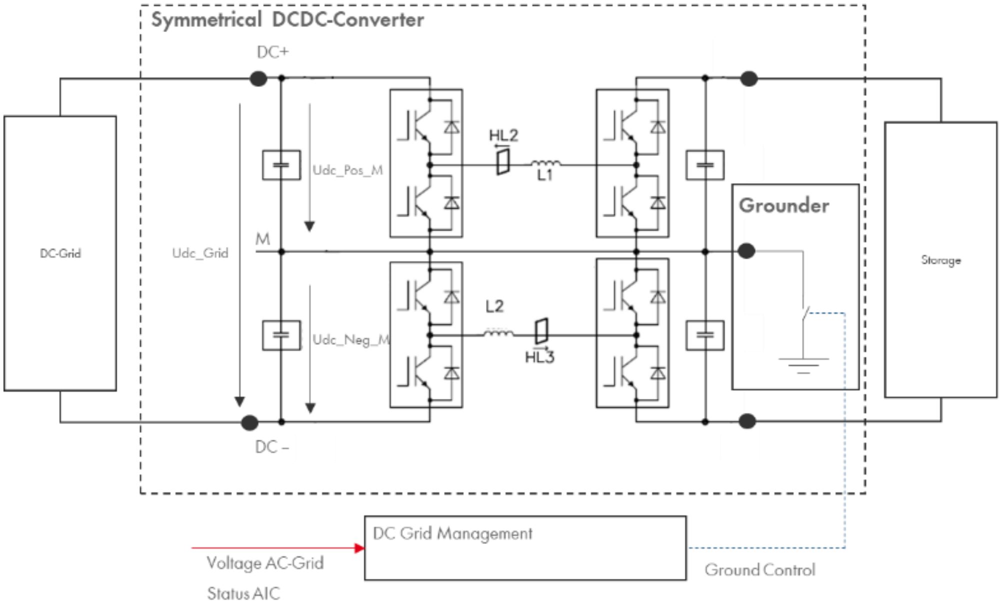


Figure 8.8: Principle of operation of temporary midpoint grounding at a symmetrical DC/DC converter in a DC system

- Implementation example 2: Temporary midpoint earthing via AIC:
  - Another temporary earthing possibility is the use of four-wire multilevel AICs. In this case, in the event of an AC grid failure the neutral conductor of the AC grid is temporarily connected to the midpoint of the AIC's DC link. Although the AIC is disconnected from the AC grid during an AC power failure, the DC side of the AIC remains connected to the DC system. This lets the N-potential of the star-earthed transformer be connected to the „potential midpoint" of the DC system. Consequently, the DC system configuration (TN system) is also maintained in the event of an AC power failure.

8.7 Voltage Stress on Motors

The voltage stress on the motors used is not greater than with typical AC-powered frequency converters. This requirement is met by the favored earthing approaches of „AC-side grounding," „DC IT system," and „midpoint-grounded DC-TN-S-C system." For conductor-to-conductor insulation, the voltage stress is ±2 times the DC system voltage, and for conductor-to-earth insulation ±1.5 times the DC system voltage. The first earth fault that occurs on a DC busbar in the DC IT system increases the voltage stress on the conductor-to-earth insulation to ±2 times the DC link voltage for the (very brief) duration of the fault.

8.8 Connection of Earthing Electrodes in a Distributed DC System

External system parts such as battery storage systems, combined heat and power plants, and solar installations all have their own earthing electrodes. To achieve equipotential bonding, these earthing electrodes and the corresponding busbars must be interconnected.

9 Pre-charging and Discharging the DC grid and its Components

The DC Sectors of a DC grid generally contain many capacitances; when uncharged capacitors are connected to a DC voltage, very high inrush currents flow which would cause the protective devices to switch-off without further measures. It therefore is essential to ensure that the inrush current is limited to levels that will not activate protective devices at power-up. This chapter describes the measures for pre-charging capacitances to limit the inrush current. All of them involve monitoring the voltage at the inputs and outputs of pre-charging devices, which are typically Smart Breakers (see section 3.2).

Pre-charging takes place sequentially across several levels. It starts with the 1st level, including power infeed devices and any energy storage systems and thus the unloaded DC grid. All other DC Sectors remain disconnected while this is happening. Following a time delay, the increase in voltage in the DC grid triggers the start of pre-charging of the DC Sectors of the 2nd level (the unloaded first hierarchical level of the DC grid). To enable correct setting of the charging current limitation for the DC Sectors, manufacturers must indicate the device-specific DC link capacitance. Figure 9.1 shows, in simplified form, a grid with its levels. If subsectors are connected within a DC sector (constituting a third hierarchical level of the DC grid), they are also pre-charged after a time delay. This staggered pre-charging process should take no more than 10 seconds per level to complete.

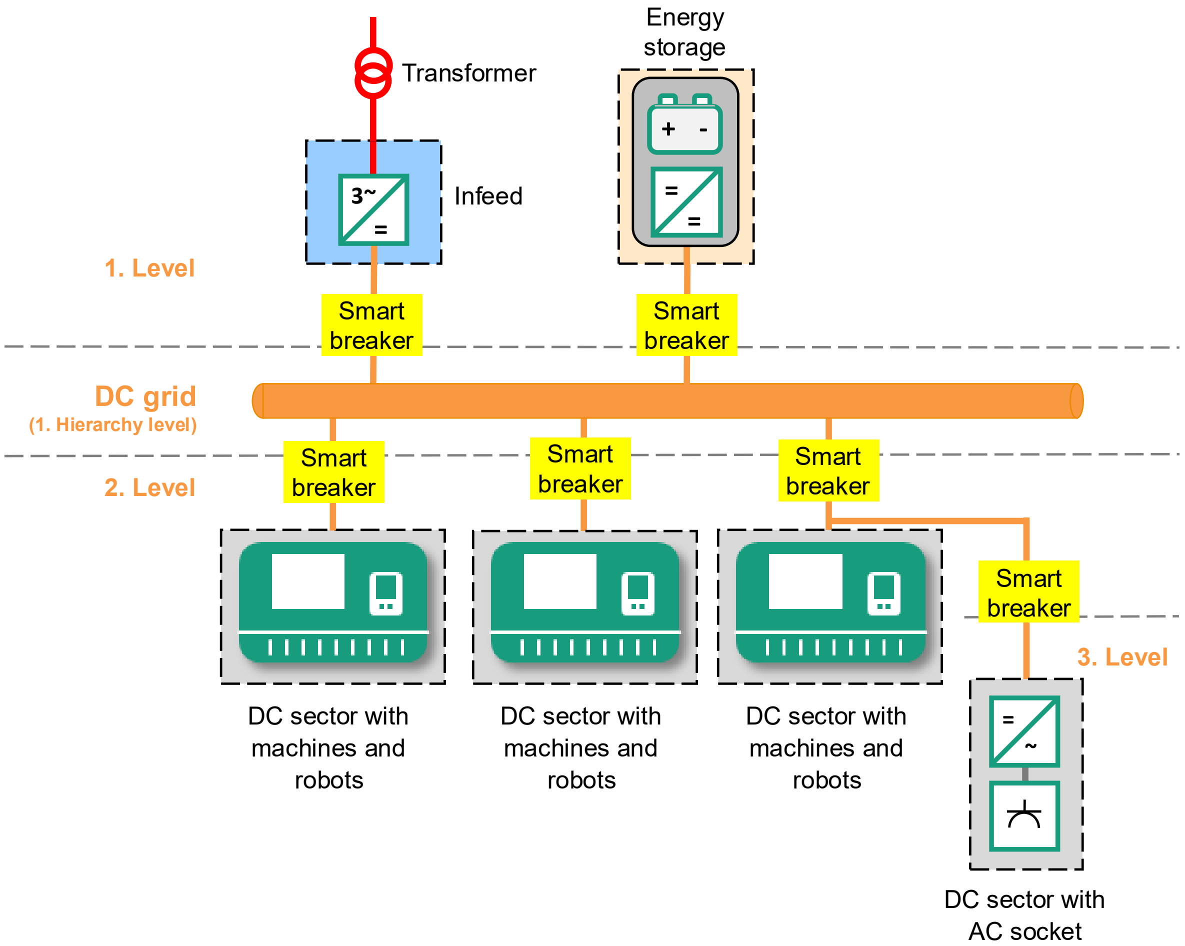
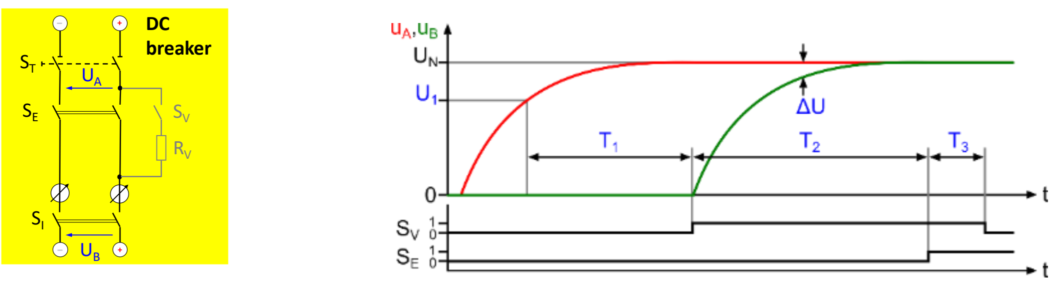


Figure 9.1: Overview of pre-charging levels

The basic principle of sequential pre-charging is shown in Figure 9.2. Port A of the Smart Breaker is connected to the next-higher hierarchy level, while port B is linked to the next-lower level. The pre-charging process is initiated by the voltage of the next-higher level (shown in red in Figure 9.2b, measured at port A). When this voltage reaches the value U_1, even though the next-higher level has not yet finished pre-charging it can be expected that the upstream level to be loadable after the time T_1 has elapsed.



a) Smart Breaker with pre-charging resistor

b) Voltages at the terminals of the Smart Breaker

Figure 9.2: Sequential pre-charging

After the waiting period T_1, by which time the upstream hierarchy level must be loadable, pre-charging of the next-lower hierarchical level begins by closing S_V. The devices connected to connection B are charged to the voltage at connection A by way of R_V [39]. If the voltage difference ΔU falls below a predetermined value, S_E is activated, thus bypassing R_V. Now level B is loadable. The resulting time constant during the charging process (see section 9.1) must be significantly smaller than T_2 since the charging process must be completed by the end of T_2. After T_3 has elapsed, S_V is opened. This breaker should also be capable of closing against the applied line voltage in the event that a fault occurs while pre-charging is ongoing. If there are additional hierarchy levels, the green voltage at port B shown in Figure 9.2 becomes the new red voltage at the new port A for the next Smart Breaker.

The following values are suggested for the voltage limits and waiting times:

- Lower voltage threshold for initiating pre-charging: $U_1 = 520\,\mathrm{V}$ (see the explanation in the following paragraph);
- differential voltage at the end of pre-charging: $\Delta U = 15\,\mathrm{V}$;
- waiting time for the start of pre-charging by the Smart Breaker: $T_1 = 5\,\mathrm{s}$;
- duration of pre-charging: $T_2 \leq 4$ seconds;
- switch-off of pre-charging after time T_2: $T_3 = 1\,\mathrm{s}$.

As a constraint, $T_1 > T_2 + T_3$ must apply to ensure that pre-charging is not initiated for a subsequent level until it has been completed on the preceding level. The time T_1 is determined by the time constant τ of the pre-charging process. After a time of $5 \cdot \tau$, the pre-charging process can be considered complete. It therefore is necessary that $T_1 > 5 \cdot \tau$. It is advantageous if the voltage difference ΔU can be adjusted on the Smart Breaker to allow for larger values as required by the application.

Depending on the type of power supply and system configuration, it may be necessary to choose a smaller value instead of the suggested voltage threshold of $U_1 = 520$ V so that the supply device can resume supplying power if the DC grid drops to below the nominal voltage band B3. Table 9.1 summarizes all of the switching thresholds and times and the corresponding states of the breakers.

Table 9.1: Switching thresholds and resulting states of the breakers for pre-charging and operation (where x = any value and * = unchanged)

State		Voltage	Voltage difference	Time	Current	Temperature	Breakers	
ID	**Name**	U_A	$\lvert U_A - U_B \rvert$	t	$\lvert I \rvert$	T_{RV}	S_V	S_E
0	No voltage (not ready)	$\leq U_{\min}$	x	x	x	x	0	0
1	Voltage present, waiting for pre-charging	$\geq U_1$	x	$t \leq T_1$	$\leq I_{V\max}$	$\leq T_{\max}$	0	0
2	Pre-charging	$\geq U_1$	x	$t \leq T_2$	$\leq I_{V\max}$	$\leq T_{\max}$	1	0
3	Main charging	$\geq U_1$	$\leq \Delta U$	$t \leq T_3$	$\leq I_{V\max}$	$\leq T_{\max}$	1	1
4	Normal operation	$\geq U_{\min}$	$\leq \Delta U$	$t \geq T_3$	$\leq I_{\max}$	$\leq T_{\max}$	0	1
5	Pre-charging error Voltage error	$\geq U_{\min}$	$\geq \Delta U$	$t \leq T_3$	$\leq I_{V\max}$	$\leq T_{\max}$	0	0
6	Pre-charging error Current error	$\geq U_{\min}$	$\leq \Delta U$	$t \leq T_2$	$\geq I_{V\max}$	$\leq T_{\max}$	0	0
7	Undervoltage error	$\leq U_{\min}$	x	$t > 0$	x	x	0	0
8	Overvoltage error	$\geq U_{\max}$	x	x	x	x	0	0
9	Overcurrent error	x	x	x	$\geq I_{V\max}$	x	0	0
10	Overtemperature error	X	x	x	x	$\geq T_{\max}$	0	*

39 Pre-charging via a resistor is just one option, chosen here in Figure 9.2 as an example.

9.1 Details of Pre-charging

During pre-charging via resistor R_V (variant a in Figure 9.6), the maximum pre-charging current is limited by R_V. The relative charging current k_V is defined based on the rated current:

$$k_V = I_V/I_N$$

I_V: Current during pre-charging (initial value)

I_N: Rated current of the DC Sector

Here $0.1 \leq k_v \leq 1$ should be chosen. At $k_v = 0.1$ the following pre-charging constant τ results (larger values of the relative charging current k_v reduce the time constants):

$$\tau = R_V \cdot C = U_N^2 \cdot C'/k_V = 106\,ms$$

U_N: nominated voltage (typ. 700 V)

C': Capacitance per nominal output (typ. $C' = 25$ µF/kW)

With this approach the practical completion of pre-charging is reached at 5 τ = 0.53 seconds or significantly less than T_2 = 4 seconds. If the DC Sector has a capacitance value greater than 25 µF/kW, the pre-charging process will still work as long as $5\,t < T_2$.

If consumers (e.g., auxiliary power supplies for Smart Breakers, see section 6.1.3) draw power during pre-charging, a constant voltage difference ΔU_B results owing to the voltage drop across R_V. This voltage difference is compensated by closing S_E, which must be able to handle this without being tripped by overcurrent. The power consumed during pre-charging can be expressed as a value k_B relative to the rated power:

$$k_B = P_B/P_N$$

P_B: Power consumed during pre-charging

P_N: Rated power of the DC Sector

The stationary voltage difference ΔU_B is approximated by

$$\Delta U_B = U_N \cdot\ k_B/k_V.$$

At $k_V\ =\ 10\%$ and $\Delta U_B\ =\ 15\,\text{V}$, $k_B =\ 0.2\%$. With equipment with a small power rating, it is often impossible to ensure this value; in this case $I_{V\max} =\ 25$ mA is allowed.

9.2 Pre-charging of the First Power infeed Device from the AC Grid

Before starting the first power infeed device, the DC grid is discharged and disconnected from the power infeed device (S_V and S_E are open as shown in Figure 9.2). The power infeed device in the 1st level charges itself from the AC grid to the rectified grid voltage and automatically transitions to regulated operation after bypassing the inrush current block. Internal pre-charging to the rectified grid voltage happens before enabling the controller (RF) of the power infeed device. The controller release activates regulation of the voltage and current with the predefined droop curves. Then the steady-state voltage of the DC grid becomes established in the power infeed device while the DC grid itself is still voltage-free.

9.3 Pre-charging of the DC Grid

The DC grid (DC grid/1st hierarchical level) powers up via the Smart Breaker between the first power infeed device and the DC grid. The Smart Breaker monitors the voltage of the power infeed device (shown in red in Figure 9.3) and initiates pre-charging of the DC grid in response to it. The process is basically as shown in Figure 9.2. Since no uncharged capacitors are directly connected to the DC grid, charging takes place very quickly (the green voltage curve in Figure 9.3).

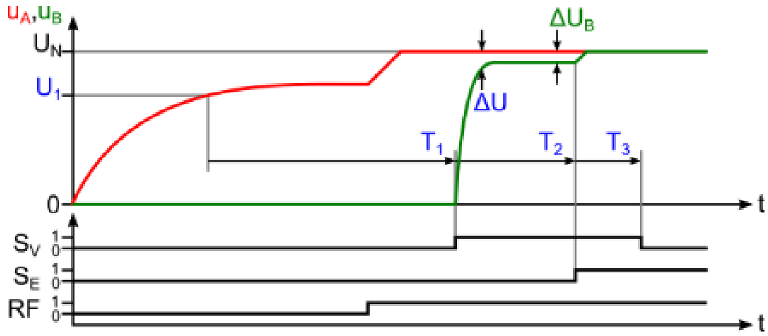


Figure 9.3: Voltage-time curves during pre-charging of the DC grid

9.4 Connection of Additional Infeed Devices

By the time that additional power infeed devices are switched on, the voltage of the DC grid has already been ramped up and is loadable. In order to connect an additional power infeed device to the DC grid, the internal DC link voltage of that device must first be matched to the DC voltage.

Constraints: Depending on the topology of the power infeed device, it may not always be possible to match the voltages. For example, AICs and uncontrolled rectifiers cannot adjust to voltages below the AC rectification voltage. If such a case occurs, the DC voltage has to be increased to a value above the AC rectification voltage. This can be achieved, for example, with a DC/DC converter connected to a battery.

If the current voltage value of the DC grid can be communicated to the power infeed device (for example, via a sensor in the preceding Smart Breaker), the power infeed device can pre-charge itself from the AC grid as described in section 9.2 and adjust its internal voltage to match the voltage in the DC grid. Connection is made when voltage equality is achieved.

Another possibility is pre-charging from the loadable DC grid (Figure 9.4). First the power infeed device pre-charges itself internally from the AC grid. However, the Smart Breaker is deployed between the power infeed device and the DC grid in order to match the DC grid voltage. The process is analogous to that shown in Figure 9.2, but with a reversed current flow [40]. Since the DC grid can be under load, the grid voltage U_B at that point in time does not necessarily correspond to the nominal voltage (U_N). It should be noted that the controller of the power infeed device must not be activated until pre-charging has been completed (RF = 1). Only then is the additional power infeed device involved in supplying power, at which time the DC grid voltage may increase slightly as shown in Figure 9.4 with RF = 1.

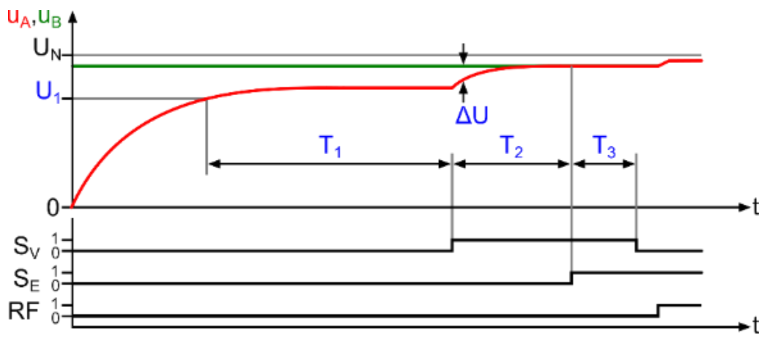


Figure 9.4: Pre-charging of an additional supply source from the loadable DC grid

9.5 Pre-charging from Storage Systems and Other DC Voltage Sources

Pre-charging from energy storage systems and other DC voltage sources takes place analogously to pre-charging from power infeed devices in the 1st level (pre-charging of the first power infeed device from the AC grid).

40 Bidirectional pre-charging is required for this.

9.6 Connecting a Device to an Operational DC Grid

If it is necessary to connect a device to an operational DC grid, it is essential to make sure that no impermissibly high charging current flows into the device. This is because neighboring devices within the same DC Sector may lack current limitation capabilities but have large DC link capacitors. The possible problems that can result from high charging currents include:

1. Damage to the connected device or the breaker's contacts.
2. The voltage in the DC Sector drops below 400 V, causing devices in the sector to shut off because of an undervoltage condition.
3. The resonance circuit formed by the capacitors of neighboring devices and wiring within the DC Sector excessively charges the DC link of the connected device. This can either trigger an interruption to guard against overvoltage or cause damage.
4. The Smart Breaker trips due to overcurrent condition.

There are two basic approaches for preventing this:

1. The device itself or the associated breaker prevents an excessively high charging current from flowing.
2. The corresponding DC Sector first has to be enabled via the corresponding smart breaker. The device is connected in a voltage-free state, then the DC Sector is switched on and pre-charged via the Smart Breaker.

These principles also apply to the use of maintenance switches. The following methods are examples of technical solutions that meet the requirements:

1. The capacitance of the device is small enough to prevent any significant charging current from flowing.
2. The maintenance switch includes a pre-charging function.
3. The maintenance switch is a signaling switch that safely operates Smart Breaker of the DC Sector in the corresponding DC sector to initiate controlled pre-charging when switched on.

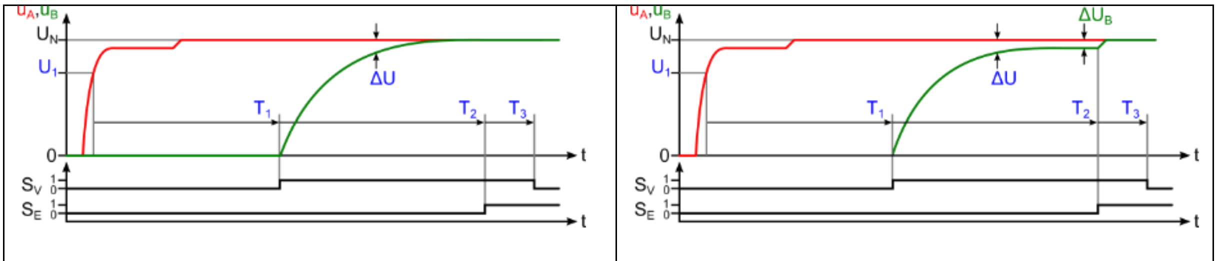
Other methods are permissible as long as they apply one of the two basic approaches described above.

9.7 Pre-charging of DC Sectors

Here the 1st and 2nd levels are connected; connection point A of the DC Sector is linked to the DC grid and connection point B to the DC Sector. The DC sector is initially in a discharged state and the loads are not yet operational. All of the components' capacitances are then charged at the same time.

The pre-charging sequence is depicted in Figure 9.5a, and the principle of sequential pre-charging is explained in the following (see also the introduction to this chapter). In summarized form, the Smart Breaker waits for the voltage in the DC grid (U_A) to increase. If U_A exceeds U_1, pre-charging starts with $S_V = 1$ after a delay of T_1. If the voltage drops to less than U_A-$U_B \leq \Delta U$ within T_2, switch S_E immediately closes at the end of T_2. If it does not drop to less than ΔU or if a problem such as an overtemperature of R_V occurs, pre-charging is aborted ($S_V = 0$) and an error message is generated. If pre-charging is successful, switch S_V is opened after the time T_3.

If the DC Sector is only lightly loaded because some consumers have already drawn power during pre-charging, a stationary deviation ΔU_B occurs as a voltage drop across pre-charging resistor R_V, which must be compensated by S_E (see Figure 9.5). This load must be limited to restrict the compensation currents.



a) Pre-charging sequence in an unloaded DC sector

b) Pre-charging sequence in a lightly loaded DC sector

Figure 9.5: Pre-charging sequences of the DC Sectors

The power for pre-charging the DC Sectors is limited by the design of R_V. Each DC Sector shall be pre-charged at a factor not exceeding $k_V = 0.1$ of its rated current. This limits the maximum power during concurrent pre-charging, and consequently the input devices cannot be overloaded, even if there is significantly more installed power in the DC Sectors than in the input devices.

9.8 Recharging after a Short Circuit or Voltage Drop

In the event of a short circuit, the voltage in the DC Sectors decreases as a result of the energy storage units partially discharging into the short circuit location. After the faulty DC Sector is disconnected, the capacitances in the unaffected DC Sectors are recharged, which may trigger the overcurrent protection device again. The subsequent pre-charging process takes place analogously to section 9.6.

9.9 Discharging

Discharging of the capacitances is distributed, taking place separately in each individual component. In order to discharge the entire grid, the Smart Breakers are disconnected. Each component uses appropriate loads (such as switching power supplies, balancing resistors, etc.) or other circuitry to ensure that the maximum voltage across the device drops to below 60 V within five seconds after disconnection. If this requirement cannot be met, it must be indicated on the device (e.g. IEC 61800-5-1 section 4.4.9). The maximum discharge time may not exceed five minutes to ensure that the DC grid is voltage-free after disconnection.

Since all devices within a common DC grid are interconnected, it cannot be guaranteed that discharging will always take place within five seconds. A discharge time of five minutes should therefore always be assumed. DC systems must be correspondingly labeled.

For energy sources that cannot be discharged within five minutes for technical reasons (e.g., limited battery storage capacity), it is necessary to have a way to safely disconnect the source from the DC Sector in case a shutdown is required. This also applies to the motor of a mechanical energy storage system if it is still capable of supplying electric power after five minutes.

If faster discharge of the grid is required, it is optionally possible to discharge individual DC Sectors or the DC grid using a switchable resistor. In this case, the pre-charging resistor of the Smart Breaker could also be used if there is a suitable circuit.

9.10 Options for Implementing Precharging

There are various possibilities for implementing pre-charging in a Smart Breaker. Examples include:

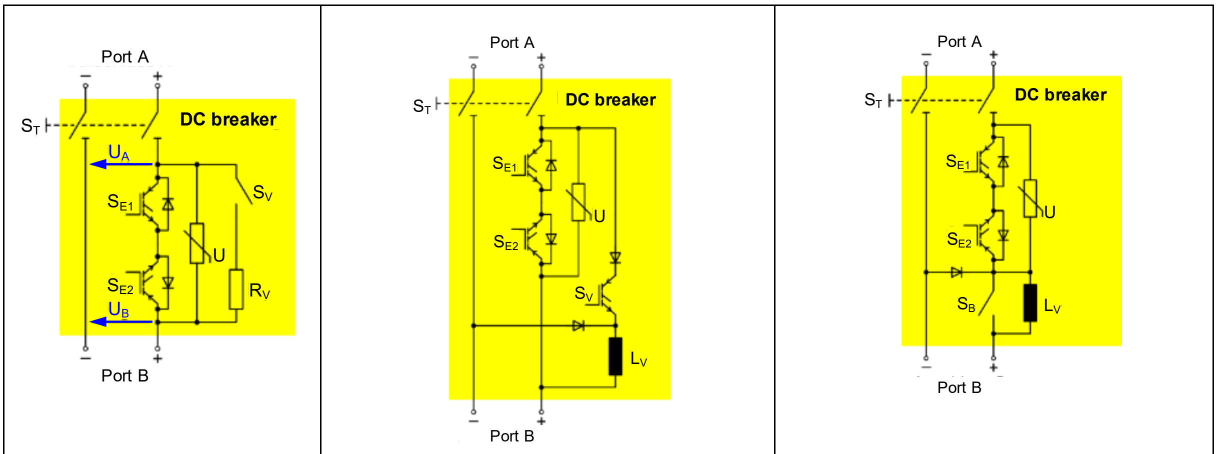
a) Pre-charging via R_V. The resistance R_V and DC contactor S_V are assigned to the switching and protective device and controlled by it.

Alternatively, a buck converter can be used for pre-charging. The benefit of this is that losses are reduced and even very large capacitances can be charged while limiting the current.

b) Via an additional IGBT S_V and choke L_V or

c) using the already present IGBTs S_{E1} and a combination of choke L_V with bypass switch $S_Ü$.

These three versions are shown in Figure 9.6.



a) Pre-charging via R_V | b) Pre-charging via buck converter using S_V | c) Pre-charging with buck converter using S_{E1} and S_B

Figure 9.6: Pre-charging variants for Smart Breakers

Pre-charging of the DC grid can also be performed by a higher-level control system. In this case, the control system chooses a logical switching sequence and directly controls the individual pre-charging and bypass switches of the DC Sectors.

9.11 Topology Versions for Pre-charging

Here four different topology versions are distinguished for pre-charging in a DC sector. In the first version (Figure 9.7), the Smart Breaker, triggers pre-charging and switches it on and off. The second version is employed when no electronic circuit breaker is used; in this case, the pre-charging unit VL controls the pre-charging sequence autonomously; when pre-charging is completed switch S_E closes. Protection is provided by fuses or load break switches. The third version is typically a distributed solution close to the machines; here as well, pre-charging takes place autonomously while S_E is responsible for bypassing the pre-charging sequence. Protection is provided at a higher level.

In the fourth version, pre-charging is integrated in the devices. If all of the devices of a DC Sector have this feature it does not need to be included in the Smart Breaker.

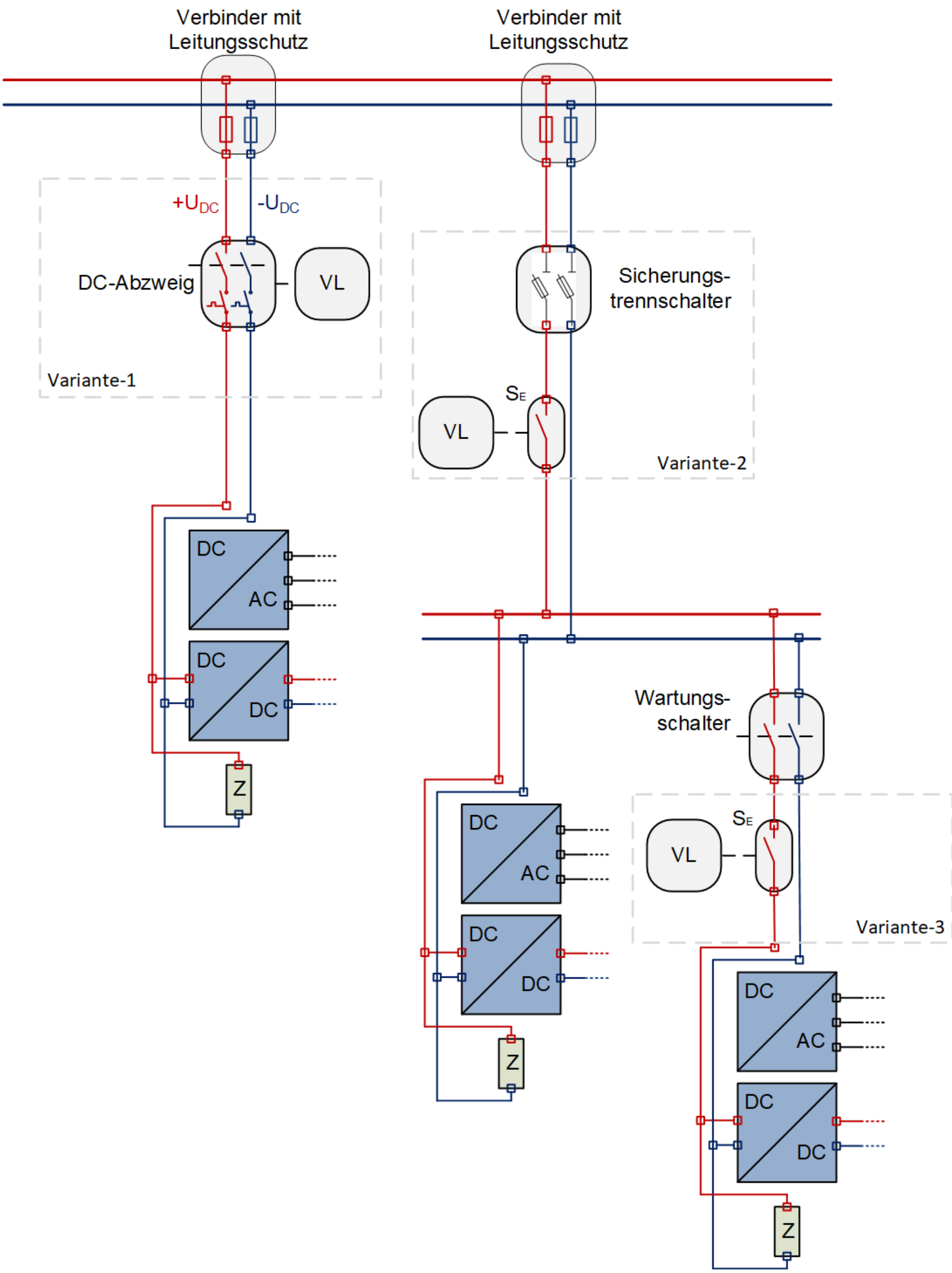


Figure 9.7: Versions 1, 2, and 3 for pre-charging, see footnote for translation[41]

41 Verbinder mit Leitungsschutz → connector with line protection; DC-Abzweig → Smart Breaker; Sicherungstrennschalter → fused switch disconnector; Wartungsschalter → maintenance switch;

10 Grid Control and Stability

Stable operation of a DC grid depends on maintaining the grid voltage within certain defined limits. This is achieved by managing the power flow at various levels, which can differ in terms of their complexity and functionality. In principle, it is possible to build both simple DC grids, for example with uncontrolled rectifiers, and complex DC grids with multiple AICs, power generators, and energy storage units.

10.1 Hierarchy of Power Flow Management

Depending on the communication relationship between the grid devices, different expansion stages of the power flow management can be defined. Four stages are defined in this work:

Basic configuration: Decentral power flow management *without* droop curves and *without* communication.

Decentral group control: Decentral power flow management *with* droop curves and *without* communication.

Extended group control: Decentral power flow management *with* droop curves and *with* communication.

Central grid control: Required values are assigned to all active components.

10.1.1 Basic configuration

This type of power flow management is completely decentralized, in other words there is no overall coordination by central PLC controllers or droop curves parameterized offline. The generators provide a DC grid voltage, and each other device applies its own control strategy depending on its intended purpose.

A typical example is a DC grid comprising a combination of uncontrolled rectifiers and multiple drives.

This configuration represents the simplest operating mode. The power flow is not controlled and can only be set to a fixed level by technically modifying it, for example to limit the output of uncontrolled rectifiers.

10.1.2 Decentral Group Control

In contrast to the basic configuration described in section 10.1.1, in this case preconfigured or adjustable droop curves are set on the converters (DC-DC converters, AICs, or inverters). The devices respond to the locally measured voltage with currents defined by the corresponding droop curves (see section 3.17). The voltage itself thus serves as information for controlling the grid's energy state.

The power flow is managed throughout the DC microgrid based on defined droop curves for the active components. The measured value for the droop curves is the voltage at the point where a device is connected to the DC microgrid ($u_{DC,meas}$). Participant management is a proprietary system of the device manufacturer and subordinate to power flow management, only locally affecting the active components. Participant management is outside the scope of DC-INDUSTRIE [17.].

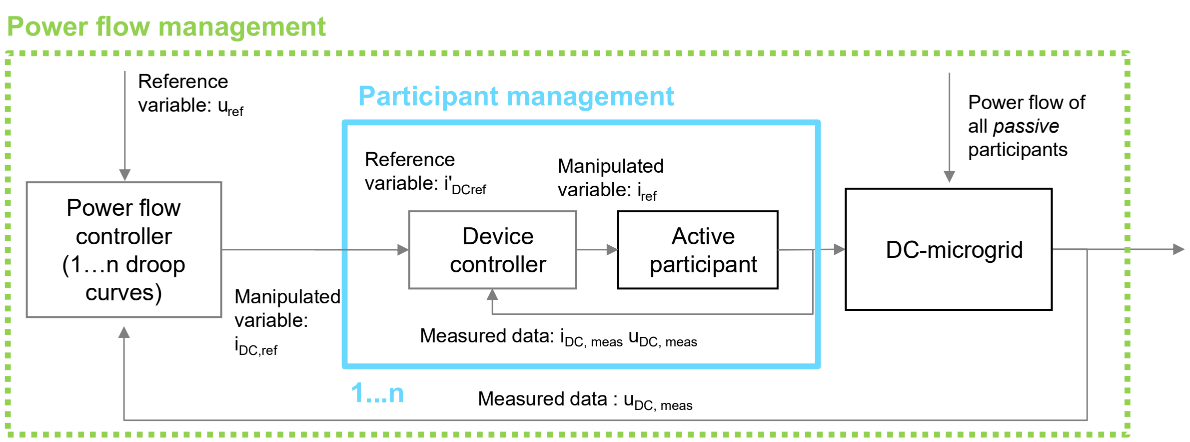


Figure 10.1: Scope of distributed group control and power flow management

Attributes:

- The droop curves of all active components are coordinated with one another on the basis of the grid configuration in each case, in other words the droop curve parameters are set when starting up the system.
- Passive components are a disturbance for the control system.
- Power flow management is based on the droop curves, which are built into the active components. The current flow (and thus the power) is autonomously controlled in each individual component based on the voltage measured at its connection point to the DC grid.
- No communication among the participating devices is required for this type of operation [42].
- Power flow management is not influenced by higher-level systems (SCADA, MES, or other higher-level grid management entities).
- To optimize operational management, droop curves can be coordinated during startup.

10.1.3 Extended Group Control

If there is an additional communication structure via a fieldbus that is used by at least one active component, **extended group control** is involved. This extended configuration enables interactions with the PLC (programmable logic controller), external control of the grid, and monitoring of the grid's state. The power flows of all devices can be influenced at runtime by a control system (source manager) that modifies droop curves in ways that benefit users. The central source manager configures the droop curves to optimize the interaction between devices.

The system can be optimized during operation by configuring the control parameters. This allows flexible control of the components; in the case of photovoltaic systems, for example, to adjust their power output to fluctuating solar radiation.

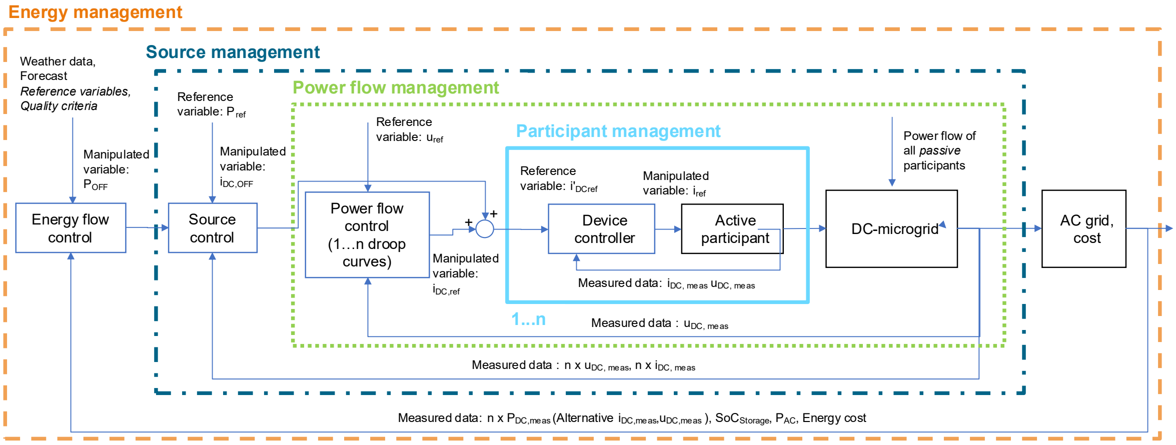


Figure 10.2: Scope of extended group control

Hierarchical control of DC microgrids as shown in Figure 10.2 includes power flow management, source management, and energy management. Source and energy management alter the power flow management by adjusting the droop curves based on local values such as voltage and current ($u_{DC,meas}$ and $i_{DC,meas}$), the state of charge (SoC) of energy storage systems, external parameters such as power at the AC grid connection point (P_{AC}), and power costs and rates [16.], [17.], [18.].

Attributes (in addition to those given in section 10.1.2):

- Source management can modify parameters of the droop curves of active components during the DC grid operation.
- Source management can take place centrally via a controller or software manager or decentralized via intercommunicating systems installed in the field devices.

42 Here the grid voltage serves as „communication medium."

- The tasks can be shared with an existing process PLC, and connection to higher-level systems (SCADA/MES) is also possible via a power management function.
- Not all of the devices that infeed power must be integrated in the communication infrastructure; control based on droop curves can be preconfigured so it will also continue working if the source management fails.

10.1.4 Central Grid Control

Central systems are regulated via a standardized open control structure such as a PLC (programmable logic controller) as per EN 61131. The PLC takes care of maintaining the DC bus at a predetermined DC voltage. The voltage can be variably adjusted during operation. The PLC specifies various control parameters and setpoints (current, voltage, power). All specifications for the DC grid components are managed by the central control system. With central grid control, all devices feeding power into the grid must be integrated in the communication infrastructure.

Attributes:

- Centralized communication with the participating components is required.
- From the grid management perspective, noncommunicating components are regarded as disturbance.
- Central power control gives voltage-dependent instructions to individual active components for maintaining the voltage within the specified band.
- Control parameters and priorities can be modified at runtime (for example, for feedforward control). Power flow management receives the corresponding parameters from higher-level systems (SCADA, MES).
- The energy flow of components can be proactively controlled in coordination with the process PLC. For example, a storage device can be charged in advance to supply the energy/power required for an upcoming load peak.

10.1.5 Overview of Differences Among Grid Types

Table 10.1 lists the main differences among the DC grid expansion levels. It directly compares them while taking into account factors such as costs, number of components, design complexity, and power management.

Table 10.1: Principal differences among DC grid management levels

Attribute	Basic grid	Decentral group control	Extended group control	Central grid control
Control type	Uncontrolled or voltage control	Decentral control using droop curves	Decentral control and adjustment of droop curves by a source manager with optional energy management	Centralized control: a grid manager specifies required values
Communication	None	None	Time-uncritical fieldbus communication (parametrized interface, NRT[43])	Time-critical fieldbus communication, cyclic (IRT[44])
Information carrier	-	Voltage band	Voltage band	Fieldbus
Advantages	■ Low priced	■ Any number of generators ■ Optimized use of locally generated energy	■ Existing communication structure can be used (for fault and state diagnosis, power monitoring)	■ Possibility of integrating preexisting components via a fieldbus interface ■ Hierarchical structure reduces

43 NRT: Non-realtime

44 IRT: Isochronous realtime

Attribute	Basic grid	Decentral group control	Extended group control	Central grid control
		■ Reduction of short-term demand peaks („peak shaving") ■ Prioritization of energy sources ■ Uninterrupted power supply	■ Any number of generators ■ Optimized use of locally generated energy ■ Reduction of short-term demand peaks („peak shaving") ■ Prioritization of the most economical energy source ■ Prioritization of consumers ■ Continued operation if communication fails	communication nodes toward the energy control system ■ Priority-controlled system modifiable during operation ■ Central access to current and target values ■ Centrally adjustable control behavior ■ Clear grid control structure
Disadvantages	■ Distribution of loads to multiple generators not controllable ■ No storage for optimizing operation ■ High AC grid load in terms of reactive power consumption	■ Devices must be preconfigured ■ Voltage measurement in every active component	■ Devices must be preconfigured ■ Optional additional integration of supply components in the communication structure ■ Voltage measurement in every active component	■ No fallback strategy if communication fails ■ Computational capacity dependent on number of components ■ Number of components limited by real-time communication ■ Every component requires a fieldbus interface

10.2 Monitoring and User Groups

A monitoring system is an essential tool for ensuring that a DC microgrid operates reliably and efficiently. The goals and requirements of a monitoring system for a DC microgrid are real-time monitoring, visualization of the grid configuration, visualization of power values and droop curves, monitoring, detection, and diagnosis of faults, and data acquisition, analysis, and exportation. By performing all these functions, the monitoring system helps ensure that the DC microgrid operates reliably and efficiently and provides insights on the system's performance.

The following functions of a DC microgrid monitoring system are of interest to different user groups:

- Commissioning engineer: responsible for ensuring the system's functionality and safety before the grid is operated.
- Operator: responsible for ensuring safe, productive operation of the system (condition monitoring)
- Maintenance personnel: responsible for timely system servicing, repairs, and replacement of components
- Grid manager: responsible for optimizing energy flows in a factory grid
- Production manager: responsible for capturing data on the system's cost-effectiveness and environmental impacts

Table 10.2 summarizes the functions of a system for monitoring DC microgrids and the corresponding stakeholders.

Table 10.2: Functions of a DC grid monitoring system

Priority	Requirement	Description	Particularly relevant to
1	Fault monitoring	Display of events and faults. A statistical report can be called up.	Commissioning engineer, operator, management personnel

Priority	Requirement	Description	Particularly relevant to
2	Visualization of grid configuration	Visualization of the DC grid at various levels and its configuration	Grid manager
3	Droop curve	Visualization of various droop curves (actual/shifted, target/actual comparison), reasons for automatic droop curves adjustments and shifts	Commissioning engineer, grid manager
4	Devices voltage and current	Devices voltages and currents can be viewed for various time intervals and visualized in diagrams (with real-time references).	Maintenance personnel, management personnel
5	Exportable reports	Predefined exportable reports containing technical and economic data should be available (MS-Word, CSV).	Operator, production manager
6	Historical data on DC sectors	Visualization of energy-relevant data on DC sectors	Maintenance personnel, grid manager
7	Statistical evaluations	It should be possible to visualize statistical evaluations of data.	Production manager

10.3 Droop Curves

Droop curves (defined in section 3.17) ensure a power balance in the DC grid by measuring the voltage and adjusting current consumption and/or generation by active devices. The approach of droop curve-based control is used to enable the parallel operation of supply and storage devices with distributed or extended group control. This is a simple approach for controlling power flows. In case of group control, droop curves must be implemented for all active power supply and storage devices. All devices are current-controlled, with the current setpoint being determined by using a droop curve based on the momentary DC grid voltage (u_{DC}). Figure 10.3 shows example control characteristics for three concurrently operated devices. The passive sign convention (shown in Figure 10.4) is applied to the quantities u_{DC} and i_{DC}.

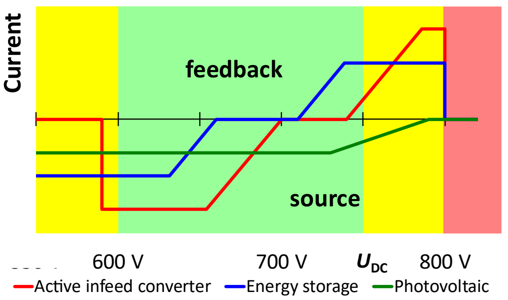


Figure 10.3: Examples of droop curves with active power control

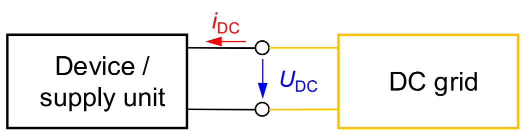


Figure 10.4: Definition of u_{DC} and i_{DC}

The infeed device (AC/DC converter as an active infeed converter (AIC) = red droop curve in Figure 10.3) can only supply energy into the DC grid if the DC voltage is higher than the rectified value of the AC grid voltage. In Figure 10.3, assuming a 400 V AC grid, the supplier operates at full power when $u_{\mathrm{DC}} \geq 565\ \mathrm{V}$. If the DC voltage increases beyond that point, the infeed current is reduced until it reaches 0 A. Finally, after around 750 V (voltage U3, see Table 7.1), power is fed back into the AC grid.

The energy storage device (energy storage with converter = blue droop curve) remains inactive in the „nominal voltage band" of the DC grid. When the DC voltage drops, it releases energy into the DC grid; if the DC voltage is too high, it counteracts the increase by absorbing energy.

PV infeed (from a solar installation via a DC/DC converter = green droop curve) can only inject energy into the DC grid. This occurs across almost the entire control range of the DC grid. Only if the DC voltage reaches the upper limit of the nominal band B3 (section 7.3.3) is it necessary to restrict this infeed to prevent to exceed the maximum value U4 = 800 V (Table 7.1) in the DC grid.

The following sections describe the implementation and parameterization of the droop curves in equipment.

10.3.1 Description of Droop Curves

The droop curves for active components define the relationship between u_{DC} and i_{DC}. u_{DC} is the DC grid voltage at a device's terminals, as shown in Figure 10.4. The passive sign convention applies, in other words current i_{DC} is positive when flowing from the DC grid into the device (consumer mode) and negative when flowing out of the device (generation mode).

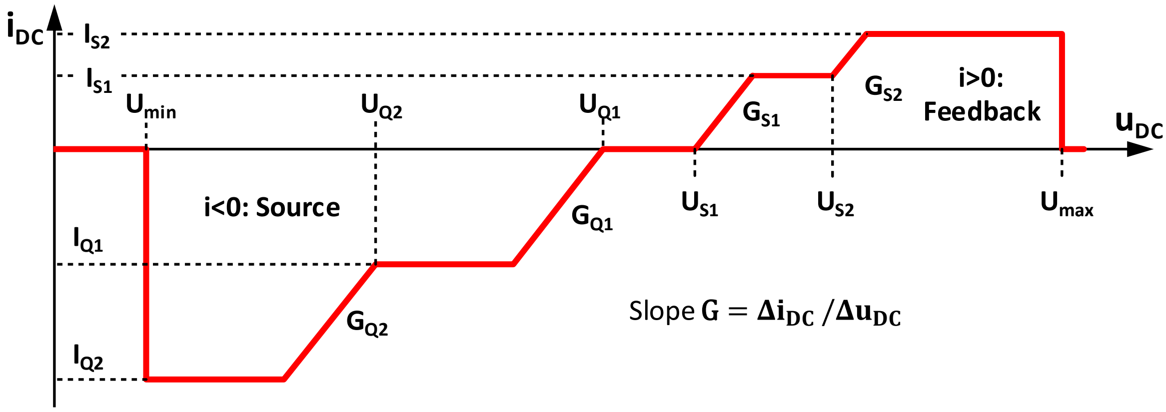


Figure 10.5: Droop curve with parameter description

The droop curve is shaped like in Figure 10.5 and determined by the 14 different parameters listed in Table 10.3.

Table 10.3: Droop curve parameters

Parameter	Description	Unit	Value range
I_{Q2}	Maximum (negative) current in generation mode	A	$I_{Q2} \leq I_{Q1}$
I_{Q1}	Plateau current in generation mode	A	$I_{Q1} \leq 0$
I_{S1}	Plateau current in consumption mode	A	$0 \leq I_{S1}$
I_{S2}	Maximum current in consumption mode	A	$I_{S1} \leq I_{S2}$
U_{min}	Minimum voltage	V	$U1 \leq U_{\mathrm{min}} < U_{\mathrm{max}}$ [45]
U_{Q2}	Voltage at the 2nd kink in generation mode	V	$U_{min} \leq U_{Q2} < U_{Q1}$
U_{Q1}	Voltage at the 1st kink in generation mode	V	$U_{Q2} < U_{Q1} \leq U_{S1}$
U_{S1}	Voltage at the 1st kink in feed-back mode	V	$U_{Q1} \leq U_{S1} < U_{S2}$
U_{S2}	Voltage at the 2nd kink in feed-back mode	V	$U_{S1} < U_{S2} \leq U_{max}$
U_{max}	Maximum voltage	V	$U_{\mathrm{min}} < U_{\mathrm{max}} \leq U4$ [46]
G_{Q2}	Slope of droop curve section 2 in generation mode	A/V	$G_{Q2} > 0$
G_{Q1}	Slope of droop curve section 1 in generation mode	A/V	$G_{Q1} > 0$

45 On U1, see Table 7.1.

46 On U4, see Table 7.1.

Parameter	Description	Unit	Value range
G_{S1}	Slope of droop curve section 1 in feed-back mode	A/V	$G_{S1} > 0$
G_{S2}	Slope of droop curve section 2 in feed-back mode	A/V	$G_{S2} > 0$

In the droop curve, current $i_{DC} = 0$ in the following voltage ranges:

- $u_{DC} \leq U_{min}$
- $U_{Q1} \leq u_{DC} \leq U_{S1}$
- $u_{DC} \geq U_{max}$.

These droop curve segments are vertically displaced by shifting the break points of the slope. The droop curve gains can be directly parameterized. The break points of the slope must be within the normal operating range of the DC grid. For U_{Q1}, the default setting for supply devices should be the nominal voltage (700 V, see section 7.2), and the gains should be set to ensure stable behavior.

If the plateau at I_{Q1} and I_{S1} is not required, then $U_{Q2} = U_{Q1} + I_{Q1}/G_{Q1}$ and $U_{S2} = U_{S1} + I_{S1}/G_{S1}$ can be chosen, resulting in the droop curve without plateaus shown in Figure 10.6.

If the break points of the slope at I_{Q1} and I_{S1} are not required, then $I_{S1} = I_{S2}$, $I_{Q1} = I_{Q2}$, $U_{min} = U_{Q2}$, and $U_{S2} = U_{max}$ are chosen. This yields the droop curve shown in Figure 10.7.

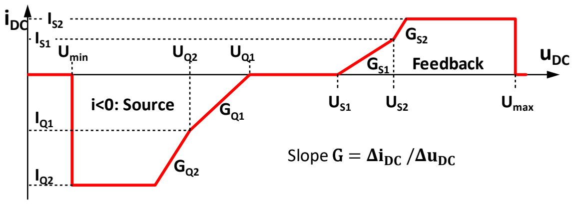


Figure 10.6: Droop curve without plateaus

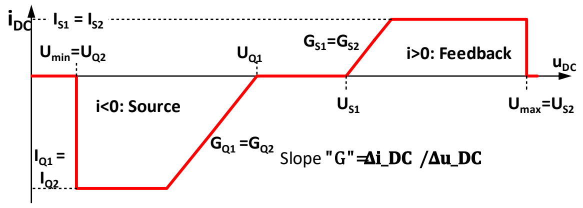


Figure 10.7: Droop curve with smooth slopes

Figure 10.8 shows the group control system to be implemented in the devices. A filter at the input influences the dynamics and ensures stability. It can be parametrized with the time constants T_{FZ} (zero point) und T_{FN} (pole point). The filter's parameters are given in Table 10.4.

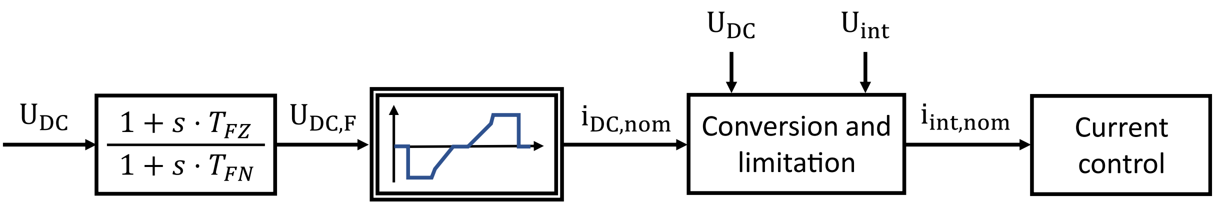


Figure 10.8: Control system of the group control based on droop curves

Table 10.4: Filter parameters

Parameter	Description	Unit	Value range
T_{FZ}	Time constant of the numerator (zero point) in the filter of u_{DC}	s	$T_{FZ} \geq 0$
T_{FN}	Time constant of the denominator (pole point) in the filter of u_{DC}	s	$T_{FN} \geq T_{FZ}$

The value $i_{DC,req.}$ is the current that must be set on the DC grid side. Depending on the type of device involved, it may need to be converted to an internal current setpoint $i_{\text{int.,req}}$ in order to set the power to $p_{DC} = u_{DC} \cdot i_{DC}$. Dynamic limitation of this setpoint needs to be implemented while taking into account the device's condition and ability to withstand overloads.

Droop curves can also be represented differently than through the 14 described parameters. A simpler approach is to define multiple pairs of numbers (U_{dn}, i_{dn}) that represent the inflection points of the droop curves. The first value is the voltage, the second is the current. You can define any number of points and intermediate values are obtained by linear interpolation. Figure 10.9 shows an example of such a droop curve.

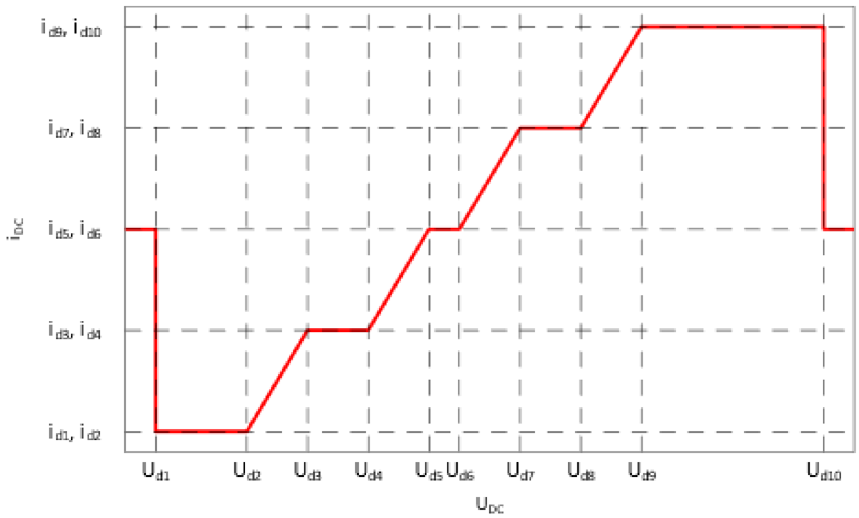


Figure 10.9: Example of droop curve with inflection point description

10.3.2 Parallel Infeed Devices

For connecting infeed devices in parallel, symmetrical distribution is easily parameterized by defining slopes. For this purpose, the voltages at break points of the slope UQ1, ... are set to the same value. The slopes (G_{Q1A} for infeed device A and G_{Q1B} for infeed device B) must be chosen in proportion to the rated currents (I_A for infeed device A and I_B for infeed device B) as follows:

$$G_{\mathrm{Q1A}}/G_{\mathrm{Q1B}} = I_{\mathrm{A}}/I_{\mathrm{B}}$$

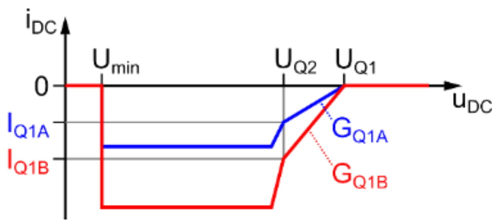


Figure 10.10: Characteristic curves for parallel operation of infeed devices

Annex D.2.1 presents example droop curves for parallel operation of infeed devices that have been tested in a model installation.

10.3.3 Operating Ranges for Variable-Power Infeed Devices

If an infeed device can only inject power (for example, from PV) that is predetermined by external factors, it is necessary to define a permitting operating range. The device can basically feed any current that is within the scope of its capabilities. However, the maximum infeed current is limited when the grid voltage approaches break points of the slope U_{Q1} and U_{Q2}.

10.3.4 Parallel Operation with Power Storage Units for Reducing Peak Power

If a regulated energy storage system is operated parallel to the infeed device to reduce peak power consumption from the AC grid, different droop curves must be specified for each component. In other words, each component has a defined voltage band within which it may actively control the grid. These bands have a droop curve with a nonzero slope. Figure 10.11 presents examples, also showing the combined droop curve of the DC grid, which is obtained by adding together the values of the two devices. The plateau in the droop curve of the infeed device is limited by the infeed power. The combined droop curve has the same slope as the other two curves, since they alternate.

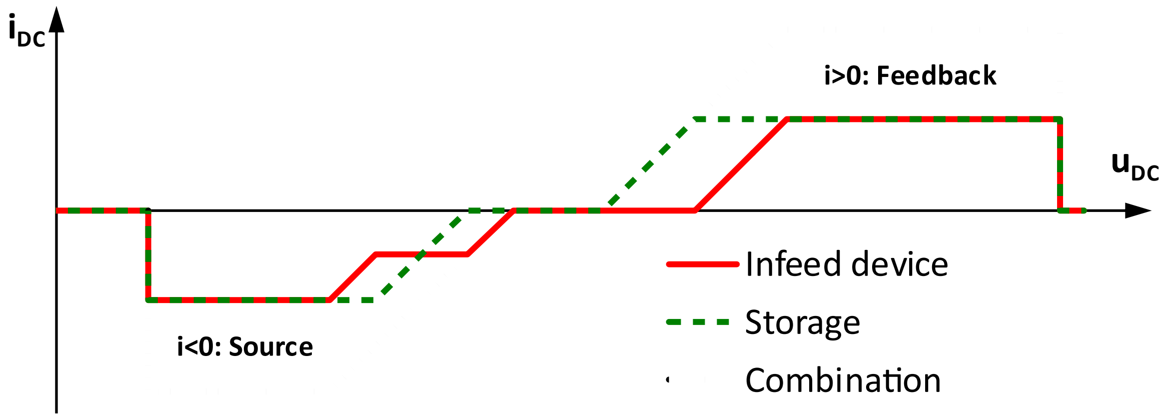


Figure 10.11: Droop curves for concurrent operation of an infeed device and an energy storage system

In section D.2.2 of the annex, specific droop curves are described for concurrent operation of an infeed device and an energy storage system and measurement values are listed to illustrate how they operate and the effects of doing so.

10.3.5 Devices With and Without Load Reduction

Al devices in the DC grid may only receive or supply current within a defined voltage range (U_{min} < u_{DC} < U_{max}). This operating range is shown in Figure 10.12. If a device exceeds or drops below the limits, it may no longer receive or supply any power.

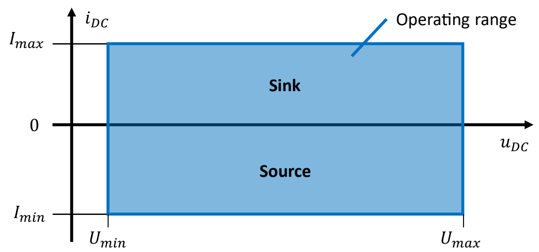


Figure 10.12: Operation range of a device without load reduction

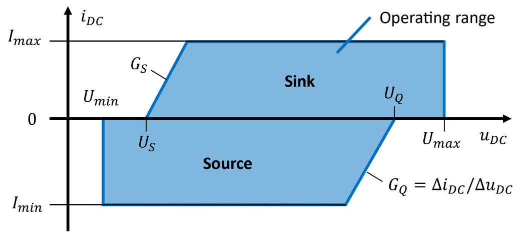


Figure 10.13: Operating range of a device with load reduction

If a device supports continuous load reduction (e.g., fan drives), the operating range is restricted as shown in Figure 10.13. This limits the maximum current that may be drawn at a low grid voltage. The maximum output current is limited in case of high grid voltages. A complete shutdown is also possible by choosing very steep slopes.

10.3.6 Secondary Control Objectives with Energy Storage Units

If the droop control is used in presence of an energy storage system, the control of the connected converter must also pursue secondary objectives. One essential secondary control function is state of charge (SoC) control, which keeps the storage system in a steady long-term average charge state.

Two approaches have been proposed for implementing this:

1. Low-frequency shifting of the droop curve in response to the state of charge, which involves applying a current offset as a control variable. Figure 10.14 shows how the curve is shifted by a constant offset γ. The additional current from the energy storage system is added to the droop curve.

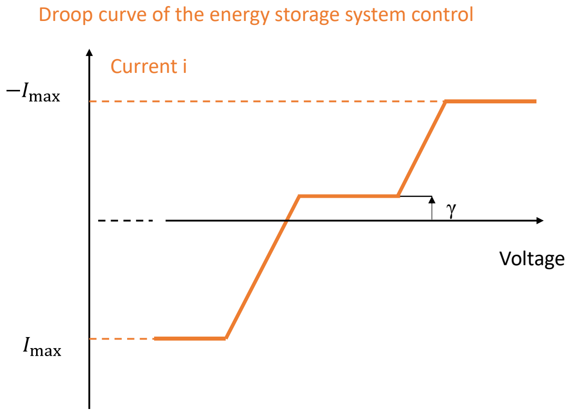


Figure 10.14 Use of a current offset to shift the droop curve

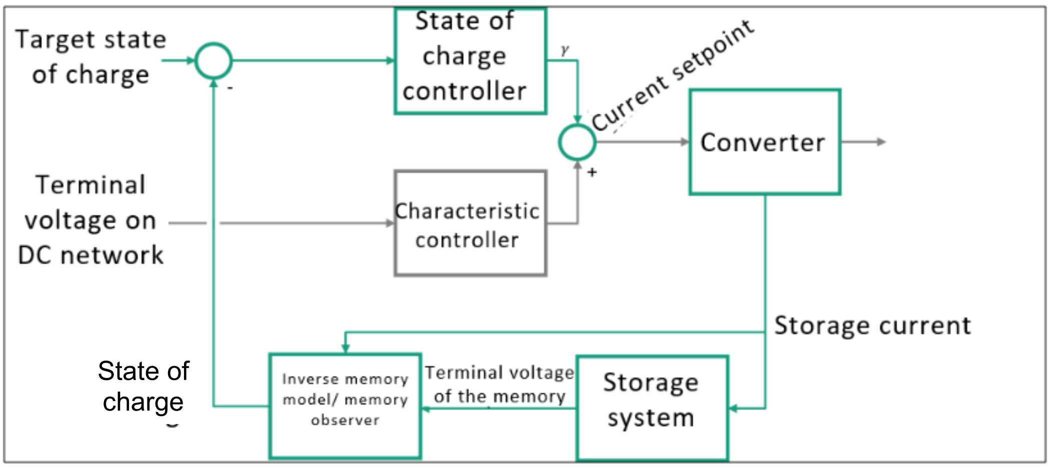


Figure 10.15 Storage control with a low-frequency shift

Figure 10.15 is a block diagram of storage control. The state of charge control loop is shown in green. The converter provides a current on the storage side, leading to a change in the voltage at the storage system's terminals. Using a storage model or an observer, the storage system's state of charge can be determined on the basis of the storage current and terminal voltage. This linearizes the secondary control loop. The controller calculates the droop curve's shift γ from the extent to which the state of charge deviates. The droop curve and storage control work against each other during operation, so the frequency range in which the respective controllers dominate must be adjusted differently. The goal should be for the state of charge controller to dominate in the low-frequency range.

2. The second option is to switch the droop curves based on the state of charge of the energy storage system. This involves the use of two curves that affect the energy storage system in different ways: one causes the storage system to discharge and the other one charges it. The two curves are shown Figure 10.16. The red dashed line is the „charging droop curve" and the solid blue line is the „discharging droop curve". They are swapped depending on the state of charge and AIC.

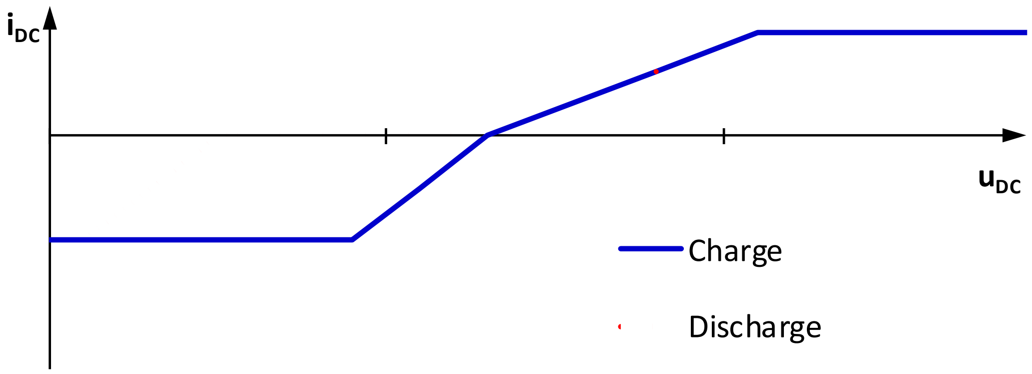


Figure 10.16: Switching between two droop curves: the dashed red for charging and solid blue for discharging

When the discharging droop curve is selected, the energy storage system releases more energy into the DC grid. When the storage system reaches a lower state of charge threshold, it switches to the charging droop curve. The latter can be configured so that charging is mainly performed using braking energy generated in the DC grid. The energy storage system is then charged until it reaches an upper threshold. At that point, the discharging droop curve is reapplied. For the secondary control goal, this results in feedback control that switches abruptly between two states („bang-bang controller").

10.4 Stability of the DC Grid

Interconnecting capacitances and inductors result in a system that can oscillate. The DC grids described here are typically highly capacitive, but they can also contain inductances. A DC grid is considered stable if the voltage oscillations induced by any excitation event (such as a change in load or a fault) within the permissible ranges steadily diminish.

Control stability can be compromised by two phenomena. One is reverse coupling of voltage measurements to the output current of power converters. The other is excitation of grid resonance points (e.g. by high-frequency switching of power electronic actuators), which can result in unstable behavior. This is referred to as **forced oscillation** of the grid.

10.4.1 Control Stability

The term „control stability" is used in connection with checking systems for deviations from steady-state operation. It is necessary to design control loops, based on the grid parameters in a given case, that will make sure that the DC grid returns to steady-state operation with sufficiently good damping and maximum dynamics. Detailed information on the system is required in order to evaluate these factors. This may not be available if a grid is still in the planning stage, but the technical literature contains recommendations on designing power sources in the context of droop curve-based control [20.].

Figure 10.17 shows a simplified model[47] of a device with a droop curve; u_{DC} designates the terminal voltage and i_{DC} the current in the DC grid.

47 As is usual in control technology, the image area is considered with complex frequency parameters.

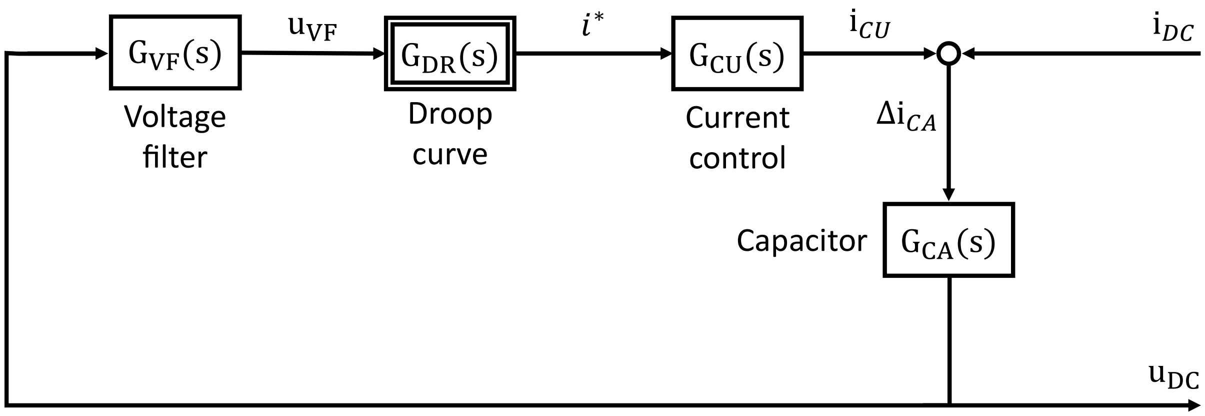


Figure 10.17 Control loop model for studying control stability

The model's core element is the current control circuit G_{CU}, which depicts the behavior of the underlying current control loop as a PT1 element with the time constant T_{CU} and a delay time T_t. Both parameters are device-specific and can be determined by experiments or simulations.

$$G_{CU} = \frac{i}{i^*} = \frac{1}{T_{CU} \cdot s + 1} \cdot e^{-s \cdot T_t}$$

The sum of current i_{DC} of the DC grid and output current i of the current control circuit Δi_{CA} acts on the capacitor and determines the terminal voltage u_{DC}. By way of simplification, it can be assumed that it is an ideal capacitance C_{CA} with the transmission function G_{CA}.

$$G_{CA} = \frac{v_n}{i_{CA}} = \frac{1}{C_{CA} \cdot s}$$

The voltage is filtered by G_{VF}. This filter can be used to appropriately influence the transfer function of the open-loop control system. It can be used either to increase the phase at the crossover frequency (to increase the phase margin as shown in Figure 10.18) or to reduce the gain in the low-frequency range (for smoothing). This filter can be designed, for example, as a lead compensator with a leading pole with time constant $T_{VF,P}$ and a following zero with the time constant $T_{VF,P}$.

$$G_{VF} = \frac{v_{VF}}{v_{DC}} = \frac{T_{VF,N} \cdot s + 1}{T_{VF,P} \cdot s + 1} \; with \; T_{VF,P} > T_{VF,N}$$

The transfer behavior G_{DR} of the droop curve is that of a proportional controller with gain G_{Q2}, G_{Q1}, G_{S1} or G_{S2} for linearly increasing sections of the droop curve and zero for plateaus.

$$G_{DR} = \frac{i^*}{v_{VF}} = \begin{cases} G_{Q2}, G_{Q1}, G_{S1}, G_{S2} & \text{Linearly increasing control characteristic sections} \\ 0 & \text{Plateau} \end{cases}$$

The open-loop transfer function of the control system is given by G_{OL}.

$$G_{OL} = G_{VF} G_{DR} G_{CU} G_{CA}$$

The impedance can be expressed, based on an open-loop control system, like this:

$$Z = \frac{v_{DC}}{i_{DC}} = \frac{G_{CA}}{1 + G_{OL}}$$

Since, according to the definition above, an open-loop control system does not have any poles to the right of the imaginary axis, it is stable when the denominator $(1 + G_{OL})$ is nonzero. This is the case for all frequencies when $G_{OL} \neq -1$. In the Bode plot, -1 corresponds to a phase shift of 180° and an amplitude of 1.

A typical measure for assessing stability is the phase margin, which can be read from the Bode plot (Figure 10.18). The phase margin is determined by finding the crossover frequency f_{PM} at which the gain of the open-loop control system intersects 1. The difference between the phase value $\varphi(f_{PM})$ and 180° corresponds to the phase margin.

$$PM = \varphi(f_{PM}) - (-180°)$$

In theory, a control system is stable at a phase margin greater than 0°. While allowing for modeling errors, to ensure sufficient stability it is generally recommended to have a phase margin of at least 20°.

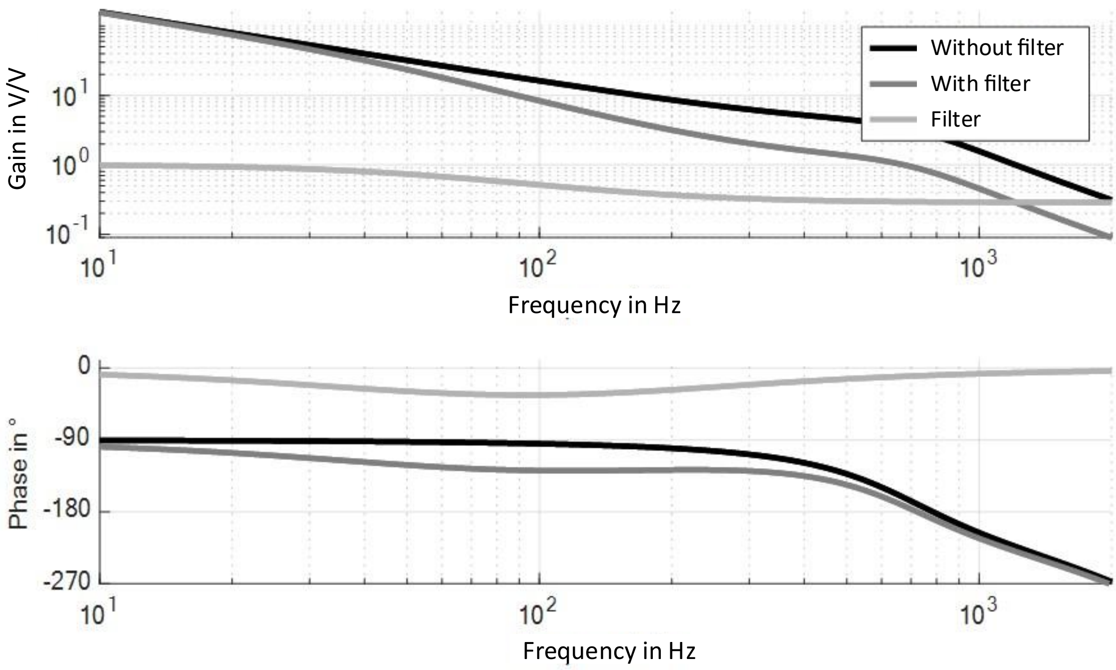


Figure 10.18: Typical behavior of an open control loop

Table 10.5 describes how the phase margin can be influenced.

Table 10.5: Factors that influence the phase margin in a control loop

Influencing factor	Capacitance C_{CA}	Gradients $G_{Q2}, G_{Q1}, G_{S1}, G_{S2}$	Filter time constants $T_{VF,P}$ $T_{VF,N}$ with proportional shift
Increase phase margin	Increase	Reduce	Increase
Reduce phase margin	Reduce	Increase	Reduce

So that the end user does not have to analyze the control circuit, the recommendation is to specify maximum droop curve gain for DC grids. For other kinds of grids and very large ones, more detailed analysis is recommended, however. The device manufacturer can determine the maximum droop curve gain by taking this approach:

1. Determine the model for current control circuit G_{CU} and capacitance C_{CA}[48].
2. Determine the phase response φ of G_N.

$$G_N = G_{VF} G_{CU} G_{CA}$$

$$\varphi(j\omega) = arg\ (G_N(j\omega)) - (-180°)$$

3. Choose the desired maximum overshoot. The minimum phase response can be chosen, for example, from Table 10.6.

48 In unknown systems, the maximum pitch can be estimated at a specific capacitance of $25\mu F/kW$.

Table 10.6: Relationship between phase response and overshoot [49]

Overshoot	21.2%	13.1%	6.6%	2.3%	0.2%	0.0%
Attenuation	0.5	0.6	0.7	0.8	0.9	1
Quality factor	1	0.83	0.71	0.62	0.56	0.5
Phase response	50°	57°	62°	66°	70.2°	70°

4. Determine the frequency ω_D at which the required phase response is attained.
5. The maximum droop curve gain G_{max} is equal to

$$G_{max} = \frac{1}{|G_N(j\omega_D)|}.$$

10.4.2 Forced Oscillations

Cyclic excitations of grid resonances can lead to persistent **forced oscillations** in the DC grid. These excitations can be caused, for example, by high-frequency switching of power electronic devices or by harmonics of the AC grid voltage that are coupled into the DC grid via rectifiers. Resonance points occur when capacitances and inductors are interconnected. The DC grids described here are typically highly capacitive but can also include inductances. Examples include the line inductances of cables and busbars, the leakage inductance of common-mode chokes, and air-core inductors of hybrid breakers. These DC grids also contain damping elements such as line resistances, contact resistances, fuses, frequency-dependent losses (such as skin effects and core losses), and internal resistances of capacitors used in the system.

Resonant oscillations are favored by high inductances with minimal damping, while a combination of high capacitance and high resistance has a damping effect on oscillations (see quality factor Q).

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Table 10.7 shows possible components and their inductance, capacitance, and resistance values as well as the resulting quality factors. The quality factor can be applied as a measure of a resonant circuit's ability to oscillate. Resonant circuits can only oscillate at a quality factor greater than 0.5.

Table 10.7: Overview of the inductance, capacitance, resistance, and quality factor of various components

Type	Inductance	Capacitance	Resistance	Quality factor
Cable	small	negligible	large	small
Busbar	medium	negligible	medium	medium
Common-mode choke (leakage inductance)	medium	negligible	medium	medium
Air coil	large	negligible	small	large
Electrolytic capacitor	small	large	small	small
Film capacitor	negligible	small	negligible	medium

It is conspicuous that, as a rule, elements with parasitic inductance exhibit small to medium quality factors. Dedicated inductors, and especially air coils, introduce high inductance and low resistance to the system, thus increasing the quality of any resonance points. Electrolytic capacitors, as opposed to film

49 The figures in Table 10.6 refer to the control model acc. to Figure 10.17 without a voltage filter.

capacitors, have high capacitance with high resistance, resulting in lower-quality resonant circuits. Resonant circuits containing film capacitors are often more poorly damped while exhibiting higher quality. Combinations of higher quality factor components, such as film capacitors and air coils, form more oscillation-capable resonance points than combinations of lower quality factor components. DC grids containing such components should therefore be examined more closely.

In order for problems to develop at a resonance point, several attributes must coincide:

1. The resonance point must be within an excited frequency range.
2. The resonance point must be of high quality, i.e. have low damping.
3. Flowing resonance currents must lead to overloading of components (e.g. DC link capacitors).

In DC grids, excitation typically occurs in three frequency ranges:

1. With highly dynamic cyclic loads in the range up to 100 Hz.
2. When uncontrolled B6 rectifiers stimulate the grid at six times the grid frequency (300 Hz in 50 Hz grids and 360 Hz in 60 Hz grids).
3. In response to high-frequency switching of power electronics at frequencies of 2 kHz or more.

Due to the large capacitances in power electronic converters, resonance points are only possible at frequencies **above 2 kHz** with very small (often parasitic) inductances, and they are therefore of very low quality. Dedicated inductances are usually so large that the resonance frequency is below the switching frequency. Frequency-dependent losses also dominate at these frequencies, and high-frequency resonance points are therefore typically well-damped and therefore not critical for industrial DC grids.

Resonance points excited by an uncontrolled B6 rectifier at 300 Hz[50] are normally not achievable with two energy storage devices, each of which has one capacitance (the total capacitance of the DC grid) and one inductance (the AC line choke). This is because the AC line choke and capacitance of an uncontrolled B6 rectifier are normally designed so that the resulting resonance point is below 300 Hz. As shown in Figure 10.19, connecting additional capacitance causes the resonance point to shift away from the excitation frequency to lower frequency ranges.

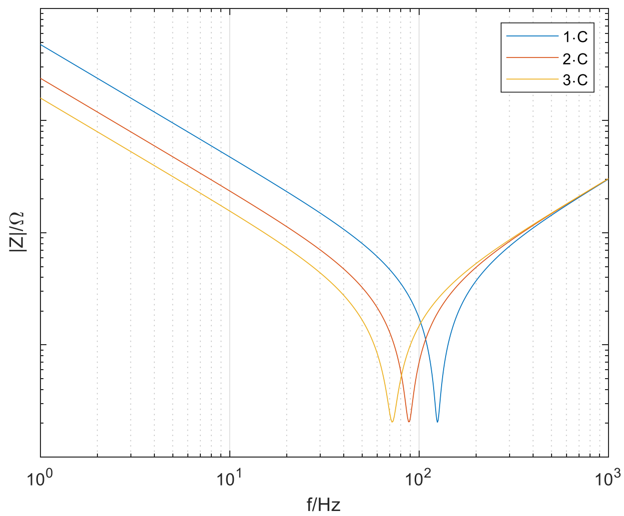


Figure 10.19: Impedance of a series resonant circuit comprising a capacitance and an inductance

However, if the connected components are uncoupled from the rectifier by high-quality DC chokes (see section 11.5) as shown in Figure 10.20, in other words if there is a system with two capacitances and two inductors, a second resonance point results (see Figure 10.21) that can then also be within the critical frequency range.

50 This applies analogously to 360 Hz in 60 Hz grids.

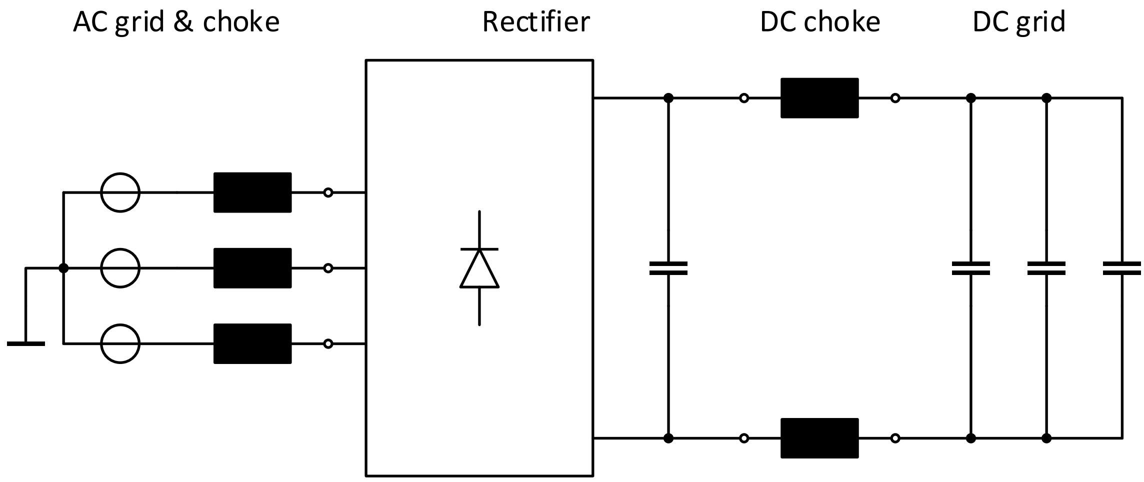


Figure 10.20 DC grid comprising a grid choke, rectifier with capacitance, DC choke and additional capacitances

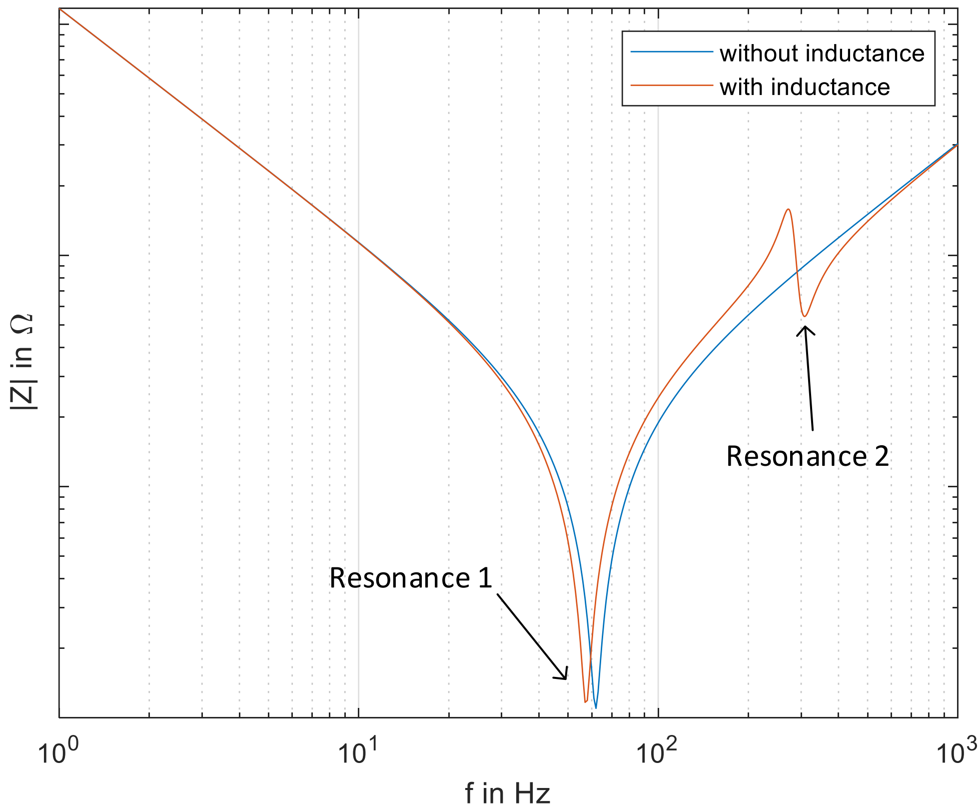


Figure 10.21 Impedance of a series resonant circuit comprising two capacitances and two inductances

In low-frequency ranges, frequency-dependent losses are usually low, with transition and line resistances dominating. Resonance points located in this range are therefore usually of high quality and can result in increased currents when excited. When using uncontrolled B6 rectifiers in combination with DC chokes, it is therefore important to closely examine the resonance points (see Appendix D.3).

Resonance points **up to 100 Hz**, which can be excited by highly dynamic loads, are similar to the 300 Hz resonance point. However, here there is often a special case in which components subjected to high dynamic loads (e.g. welding inverters) contain large internal capacitances that adequately stabilize the grid.

Summing up it can be said that not even DC-INDUSTRIE grids with unfavorable configurations have ever suffered from any problems with induced oscillations. Sufficiently large capacitances in grid components have always resulted in adequately damped resonance points, thus preventing critical resonance currents.

10.5 Operating Procedures

The term „operating sequence" refers to the operational management of a DC grid. Each operating procedure is defined by a standardized process. A total of 21 such processes are defined, grouped into four categories as shown in Table 10.8.

Table 10.8: Overview of operating procedures

Category	Process	Description
Main process	Switch on the DC grid	This process describes the procedure for switching on a DC system, from starting up the DC grid's power supply across switching on the consumers to operating the DC grid.
	Power up the DC grid	This process describes powering up the DC grid to its operating voltage.
	Precharging	Precharging of DC sectors is described here.
	Power up DC auxiliary voltage (DC/HSDC conversion)	To operate a DC grid, the active components require an auxiliary power supply. This can be provided either directly from the DC grid or from the AC grid. Two separate operating processes are defined for this.
	Power up auxiliary DC voltage (AC/HSDC conversion)	
Fault handling	Reduce power of a source	If a power balance cannot be ensured between the supplier (AIC, storage) and the consumer, this will affect the DC grid voltage. This process defines the behavior of consumers if not enough power is fed into the DC grid via the suppliers.
	AC power failure	In the event of an AC power failure, the DC grid can no longer be supplied from the primary energy source (AC grid). DC-coupled energy storage systems can be used to put the consumers into a defined state despite this.
	Short circuit in a DC sector	In the event of a short circuit in a DC sector, the fault location needs to be reliably and selectively isolated. The DC grid should not collapse if possible. Treatment of the DC grid components in this case is described here.
	Emergency stop	It is often necessary to quickly put certain components of the DC grid into a safe state. The procedure for this is explained here.
	Small insulation resistance	The insulation resistance in an IT grid has to be continuously monitored and evaluated. If it falls below a defined value, a ground fault is involved. This process describes how to deal with this fault situation.
	Failure of communication	In the event of a communication failure, active DC grid components can still be autonomously regulated via load flow management (droop curves). However, certain components must remain addressable at all times. A fallback behavior is therefore defined for all active components, describing how they should behave in the event of a communication failure.
	Failure of one pole of the DC grid	This process defines the behavior of a DC sector in response to the failure of one pole.
	Failure of DC auxiliary voltage (DC sector)	If the auxiliary voltage fails, individual components may no longer be able to operate reliably. In this case, the DC grid has to be transitioned into a state in which the intact DC sectors can continue operating.

Category	Process	Description
	Ground fault in DC-TN grid grounded on the AC side	In the event of a ground fault, the fault location must be located and switched off to permit continued stable operation of the DC grid. This process describes the DC grid's behavior in this case.
	Ground fault in DC IT grid	In an IT grid, the insulation resistance to ground is continuously measured and evaluated. If it drops below a defined lower limit, continuous operation is no longer allowed. This process describes how the ground fault is located and eliminated.
	Power management fails	A power management failure may not lead to failure of the DC grid. This is covered by this process.
Maintenance and repairs	Switch-off for electrical maintenance	These processes describe the procedure for electrical or mechanical maintenance work on machines powered by DC grids.
	Switch-off for mechanical maintenance	
	Maintenance of AIC	Since an AIC is often a system-critical component of a DC grid, the procedure for maintenance of it is described in a separate process. This process refers to other operational processes listed in the table.
Changes to topology	Bringing AICs on line	When additional AICs are connected to the DC grid, this process describes the recommended operational procedure from disconnecting the AIC until the start of production.
	Bringing a DC sector online	A DC sector is brought online by energizing the DC breaker, which performs a precharging operation.

In the course of an operational process, the DC grid or a DC sector can change its own state. Four predefined states are used in the processes:

OFF: zero potential / no power

PRECHARGE: not loadable; precharging ongoing

OPERATE: loadable; voltage in the 400-800V range; precharging complete

ERROR: DC grid not loadable, e.g. due to undervoltage, overvoltage, or a critical problem such as a ground fault.

Generators and consumers of the DC grid may also be in other device-specific states.

The operational processes are graphically depicted by flowcharts in Annex B. The operational management processes are derived from model systems developed within the scope of the DC-INDUSTRIE2 project in collaboration with users in industry.

11 Electromagnetic Compatibility (EMC) and AC Components of a DC Grid

In terms of emissions, a DC grid does not behave fundamentally differently from an AC grid. However, there is a lack of applicable standardized limit values and testing regulations. Section 11.2 presents corresponding proposals for industrial operating environments. In contrast to AC, DC coupling inherently allows energy to be exchanged with the supply grid and this is also desired. However, this must not reduce the lifetime of neighbouring devices, hence special attention is paid to the AC voltage ripple on the DC grid in section 11.1.3.

11.1 AC Component of DC Voltage

This section describes the maximum permissible AC voltage component of the DC grid (L+ to L-). This component must be limited because it would otherwise cause premature aging of electrolytic capacitors (see section 11.1.3). The cause of the alternating voltage component can be switching-frequency currents, e.g. from drive inverters, which generate the alternating component as a voltage drop at the DC grid impedance (see section 11.1.1). A further cause may be excitation due to the function of the AC/DC supply device (in particular B6 rectifier; see section 11.1.2).

11.1.1 Stimulation by Pulse Width Modulation in Equipment

Pulse width modulation (PWM) makes power electronic devices generate pulsed currents containing spectral components at the switching frequency and multiples thereof. To smooth out these currents, devices typically incorporate capacitors. The AC component of the output current creates a voltage drop across the grid impedance, which can be measured at the equipment's input terminals.

Figure 11.1 shows typical behavior of the DC grid impedance $Z_{DC-grid}(f) = \frac{u_2}{-i_2}$ without a connected device. The corresponding equivalent circuit diagram is shown in Figure 11.2, where C_1 is the device's internal capacitance and C_2 and C_3 are the capacitances of other components in the DC grid. L_σ and R_σ are the impedances of the supply cables, while $L_{\sigma f}$ und $R_{\sigma f}$ represent the impedances of filter elements (e.g. stray components of a common-mode choke). As can be seen in Figure 11.1, $Z_{DC-grid}\,(f)$ is a resonant system with multiple minima (resonant frequencies) and maxima (anti-resonant frequencies). These can be excited by high-frequency switching like that performed by a drive inverter. The AC component of u_2 can be considered to be an electromagnetic emission (a differential voltage ripple). Ideally, the grid filter of the drive inverter should be designed so that the current flowing out of the device only has a minimal AC component. The criterion for checking the permissible AC voltage component is described in section 11.1.3.

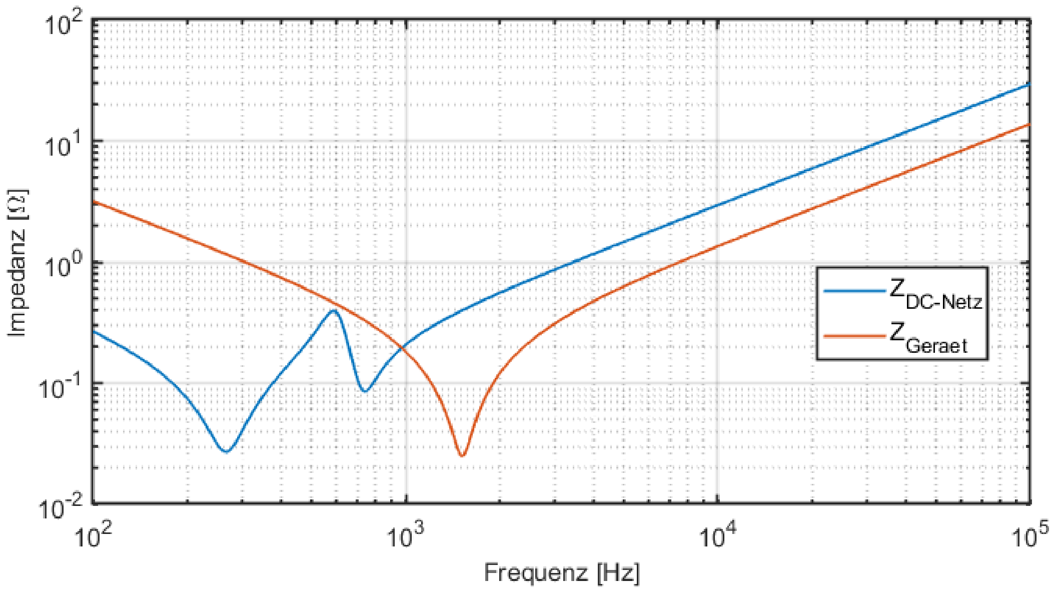


Figure 11.1: Bode diagram of a typical DC grid impedance

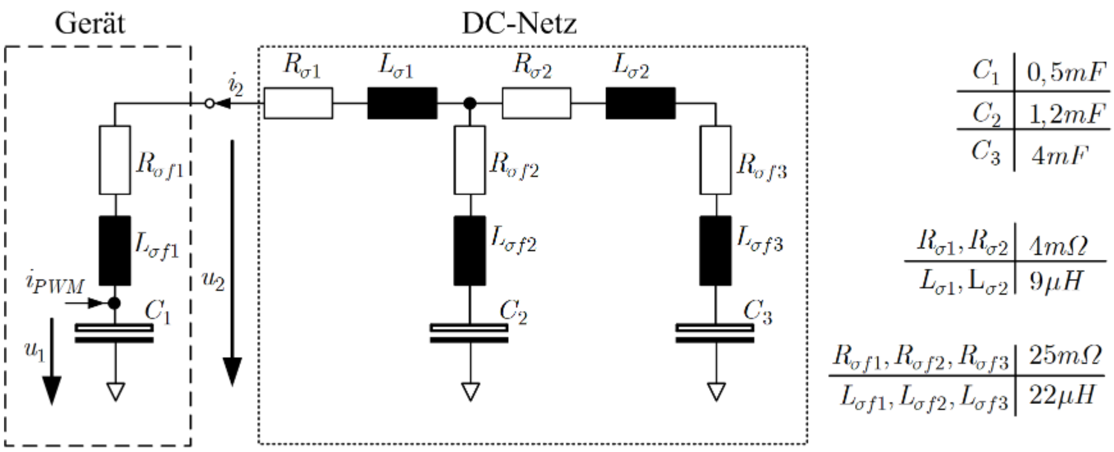


Figure 11.2: Equivalent circuit diagram of a typical DC grid impedance from the device perspective

When the DC grid impedance approaches infinity, the maximum AC voltage component u_2 appears at the device terminals. A limit value must be chosen that will avoid reducing the life expectancy of devices connected in parallel. A method for evaluating the AC voltage component by assessing u_2 in a test circuit is described in section 11.1.3.

Another aspect is the device’s immunity to interference. If the AC voltage component in u_2 is caused by other devices, the worst-case scenario is excitation at a single frequency (mono-frequency excitation) corresponding to the minimum impedance (resonance frequency) of the device's input impedance, Z_{device} (a series-resonant circuit comprising $R_{\sigma f1}, L_{\sigma f1}, C_{\sigma f1}$, shown by the orange curve in Figure 11.1). In this case, the device's internal capacitor not only receives its own ripple currents but also those of parallel devices, making it essential to avoid overloading it.

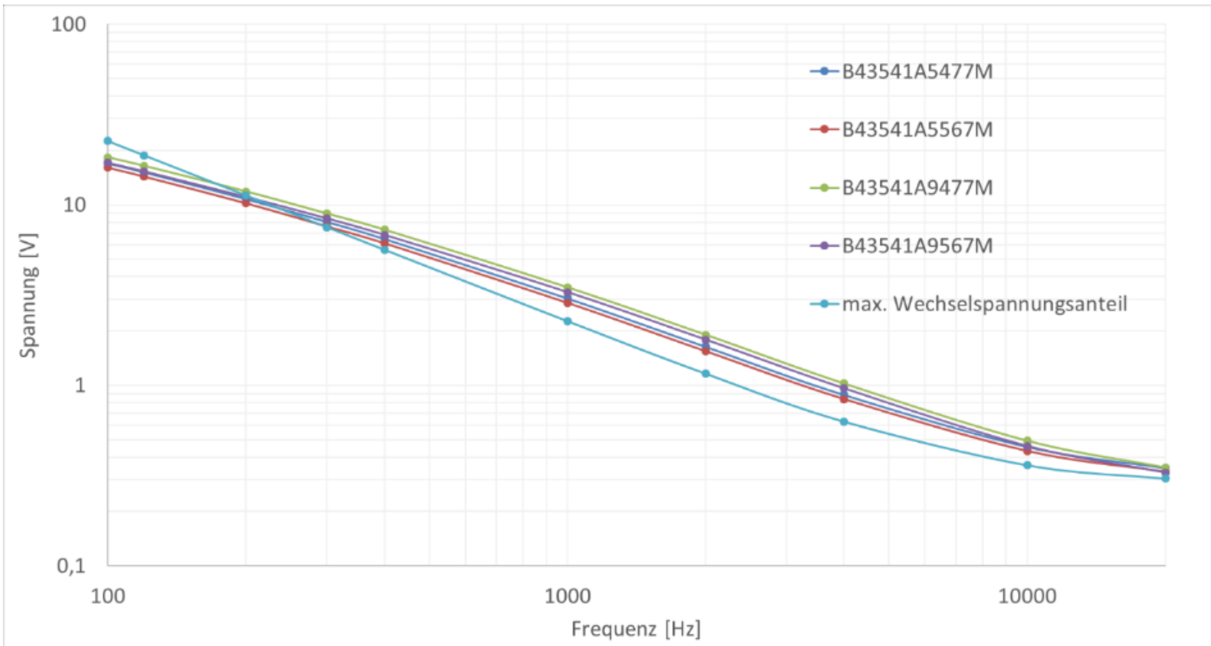


Figure 11.3: Maximum permissible AC voltage component for typical electrolytic capacitors[51] with single-frequency excitation

51 Four typical electrolytic capacitors were selected in consultation with Epcos, each with a rated voltage of 400/450 V and a capacitance of 470/560 µF. The AC voltage component was calculated by multiplying the allowable ripple currents with the impedance at each frequency. Capacitors with smaller capacitance values typically have a larger allowable ripple voltage component because they have a larger (thermally effective) surface area relative to their capacitance. The allowable AC voltage component only applies to mono-frequency excitation.

Figure 11.3 shows the maximum permissible AC voltage shares of four representative electrolytic capacitors. The permissible AC voltage share of u_2 (light blue) for DC-INDUSTRIE has been chosen so that it remains below the upper limit for capacitors at frequencies at and above 300 Hz.[52]

This maximum permissible AC voltage component should be regarded as the upper limit of what the devices must be able to continuously sustain. Here it is assumed that the AC voltage component u_2 acts on impedance $Z_{device}(f)$. The critical case occurs if excitation is exclusively at a single frequency with minimum impedance. The damping at this frequency must be sufficient to prevent premature aging of the device, also with sustained excitation.

11.1.2 300 Hz AC Voltage Share with Uncontrolled Rectifiers

In an uncontrolled rectifier, rectification of the DC voltage results in an AC component with a frequency six times that of the grid frequency. This AC component is dependent on the load, the DC link capacitance, and the grid impedance (or grid choke). Assuming that the grid impedance and DC-side capacitance are relative values (relative short circuit voltage, capacitance/power), the AC component is independent of the power level.

For an uncontrolled rectifier with a line choke ($u_\mathrm{k} = 4\%$ relative short circuit voltage) and a DC link capacitance of 25 µF/kW[53] located to both the supplier and the consumer, the AC voltage component on the DC side has been determined by simulation. For a 400 V grid with a frequency of 50 Hz, the value (peak-to-peak) is calculated to be 21 V, with an RMS value of approximately 7.5 V for the 6th harmonic.

11.1.3 AC Current Load on the DC Link Capacitors

DC coupling of capacitors in equipment enables an exchange of high-frequency currents, which is also explicitly intended. However, it must be ensured that this will not overload the capacitances of devices operating in parallel. The AC voltage component (voltage ripple) that each individual capacitance must withstand is relevant here. Electrolytic capacitors are particularly critical because they age faster than film capacitors when subjected to greater ripple currents.

The following rules must followed observed when dimensioning DC link capacitance:

- The overall capacitance of a DC Sector is equal to the sum of the individual capacitances of all of the integrated devices.
- At the connection point of the DC Sector, the maximum permissible AC voltage component for electrolytic capacitors (see Figure 11.3) may not be exceeded. Sufficient capacitance must therefore be provided in each DC sector to ensure that the AC voltage component of the integrated devices will not become unacceptably high. As a rough guide, a relative capacitance of 10-25 µF/kW can be assumed.

In order to provide a meaningful rating of the AC voltage component, DC-INDUSTRIE has developed a test circuit that simulates the DC link of an device with low DC link capacitance using electrolytic capacitor technology. This test circuit (reference network) consists of a film capacitor (C_TC) with 1 µF and a resistive element (R_TC) with 20 Ω connected in series. The AC voltage component emitted by the tested device can be assessed by measuring the current flowing into the reference grid (see Figure 11.4). The described procedure and derivation of the limit values have been described in greater detail by Puls in [21.]. In the test setup, a DC voltage source (which is decoupled for the high-frequency currents by a decoupling network (e.g. via a sufficiently large inductance)) is used to supply the tested device.

52 An AC voltage component at 300 Hz, for example, is caused by uncontrolled B6 rectifiers. No significant AC components below 300 Hz are expected.

53 See section 11.1.3 on how this value is derived.

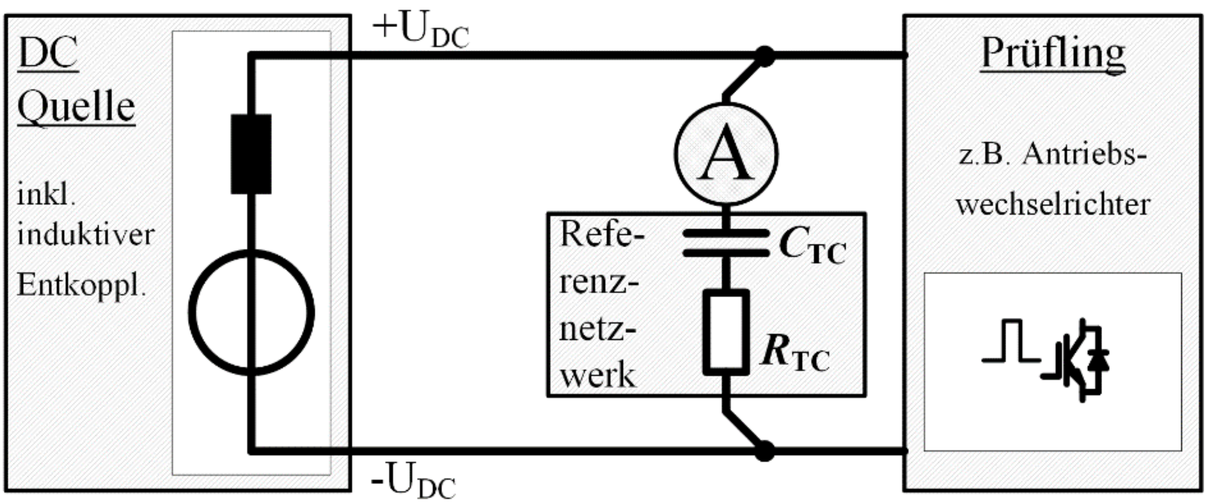


Figure 11.4: Reference network for qualifying DC grid components [54]

If the RMS current (root mean square) in the reference grid is below 40 mA,[55] it can be assumed that the test object mainly generates its switching energy from its own DC link capacitor without damaging parallel devices.

Instead of evaluating individual devices, the reference grid can also be used to assess an entire group of devices where it is connected to the DC grid. This is particularly useful for decentralized servo drive systems with film capacitors. The operation of a single device operated by itself could cause a larger ripple current, but, due to the simultaneity factor, an entire group of such devices in the DC Sector would not have an unacceptably high AC voltage component.

The reference network can also be used in existing DC grids to assess grid quality (differential-mode interference voltage between the active conductors) in different DC Sectors. However, due to the additional capacitances in the supplying DC Sectors, the RMS current in the reference grid may not exceed 28 mA [56].

Summing up:

1. An individual device or device cluster is only considered to be DC-INDUSTRIE-compliant if the RMS current is less than 40 mA when tested in the reference grid as shown in Figure 11.3. This ensures that the device or device cluster draws its switching energy from its own capacitors without impermissibly relying on the capacitances of other grid components, which would cause them to age prematurely. Neither the value nor the technology of the installed capacitances is relevant here.
2. In an operational DC-powered system, it is essential to ensure that the RMS current measured using the test circuit does not exceed 28 mA at any point within the DC grid.

54 Translation: DC Quelle → DC source ; inkl. Induktiver Entkopplung → inductive decoupling included ; Referenznetzwerk reference grid; Prüfling → device under test; z.B. Antriebswechselrichter →e.g. drive converter

55 This limit is derived from the reference network's impedance. Multiplying the RMS current and impedance yields the frequency-dependent ripple voltage limit curve for typical 400 V electrolytic capacitors (in the frequency range of 300 Hz to 50 kHz). By definition, the RMS current includes all frequency components. The current must therefore be measured using a „true-RMS" device (with a bandwidth ≥ 3 times the switching frequency). Alternatively, the voltage waveform across the resistor (RTC) can be captured using an oscilloscope and analyzed to ascertain its „true-RMS" value.

56 Here it is notable that the limit of 28 mA is lower than that measured for a decoupled high-frequency source as shown in Figure 11.4. The reason for the lower limit is that there are additional devices in the cluster (at least one supplier) with which ripple currents are exchanged. Since the ripple currents coming from different devices are statistically independent of one another (their pulse patterns are not synchronized), in the case of two devices with the same capacitance they are reduced by a factor of $1/\sqrt{2}$.

11.2 Electromagnetic Interference

Two types of electromagnetic interference are distinguished: conducted interference (measured using artificial mains networks) and radiated interference (measured using antennas). An important criterion for the practical feasibility of DC grids is the ability to install DC cables without shielding. Extensive measurements of this were carried out within the scope of the DC-INDUSTRIE project, the results of which show that this requirement can be met. The important thing is to route high-frequency leakage currents (which occur, for example, with drive inverters) directly back to the device (via Y-capacitors/EMI filters) without allowing them to flow through the upstream DC grid.

No binding limits on these emissions currently exist for DC distribution grids in the industrial sector, and limits and measurement methods have therefore been borrowed and adapted from those for low-voltage AC grids and other DC networks (photovoltaic systems) and related product standards. Figure 11.5 shows EMC-critical elements within a DC grid for which rules have been defined.

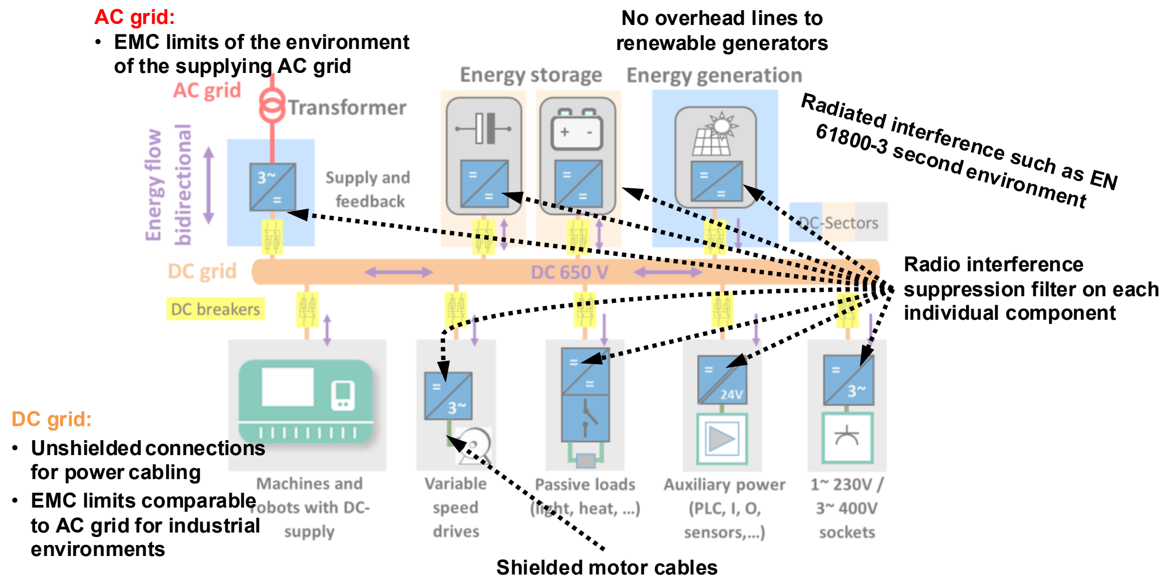


Figure 11.5: Interference suppression in an industrial DC grid

11.2.1 Conducted Interference of AC Grid Power Infeeds

The EMC requirements for the AC side are identical with those for AC grids. Every supply device must comply with the limits specified in IEC 61000-6-4.

11.2.2 Radiated Emissions from the DC Grid

If both DC lines are laid in parallel in very close proximity to one another, the interference emissions caused by differential mode currents are negligible. Those caused by common mode currents can be reduced to acceptable levels with EMC capacitors or EMI filters. For the frequency range from 30 MHz to 6 GHz, interference emissions are measured using antennas. The measurement methods and limits are not different from those used for AC systems. The IEC 61000-6-4 standard is broadly applicable to the industrial sector; here IEC 61800-3 is applied to electric drives.

11.2.3 Interference Voltages in a DC Grid

For the frequency range up to 30 MHz, artificial mains networks are used to measure conducted emissions as disturbance voltages. The limit values shown in Figure 11.6 and Figure 11.7 have been derived from various guidelines. They have not yet been standardized.

- For measuring emissions in the range from 150 kHz to 30 MHz, the DC artificial mains networks described in EN 55011 should be used.
- For the frequency range from 9 kHz to 150 kHz, measurements are made using a 1.5 kΩ EMC probe (in compliance with EN 55016-1-2) and a spectrum analyzer, in each case between one pole of the grid and PE.

- Below 9 kHz, the same measurement is made using a conventional high-impedance probe and the results analyzed using FFT (fast Fourier transform) methods.

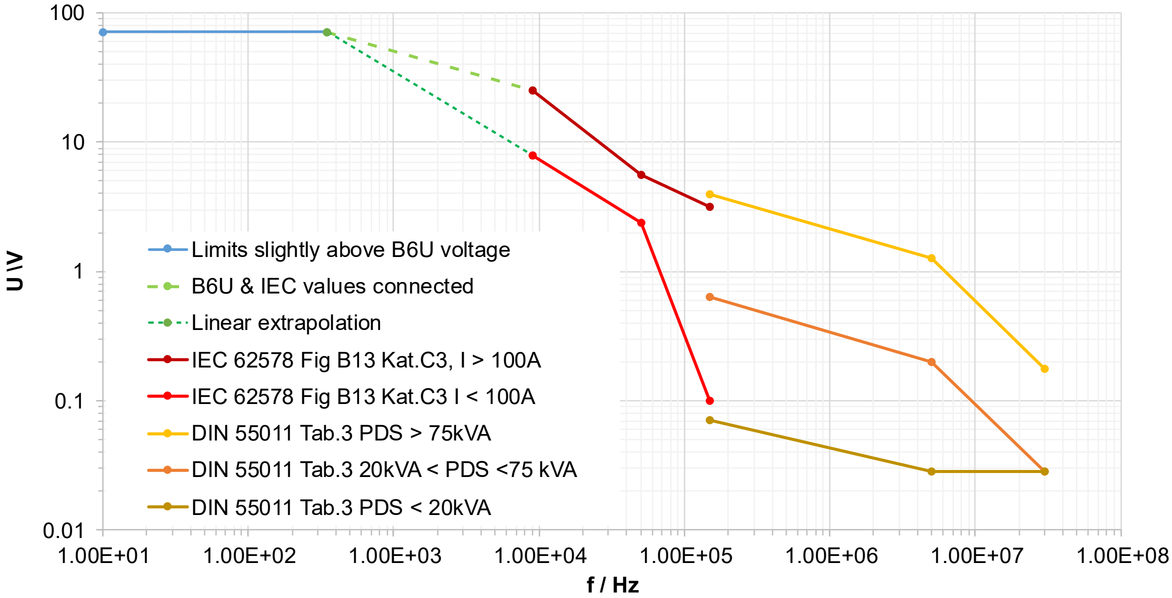


Figure 11.6: Limit values for asymmetric interference voltages in the frequency range from 10 Hz to 30 Mz (voltages shown in V (Quasipeak))

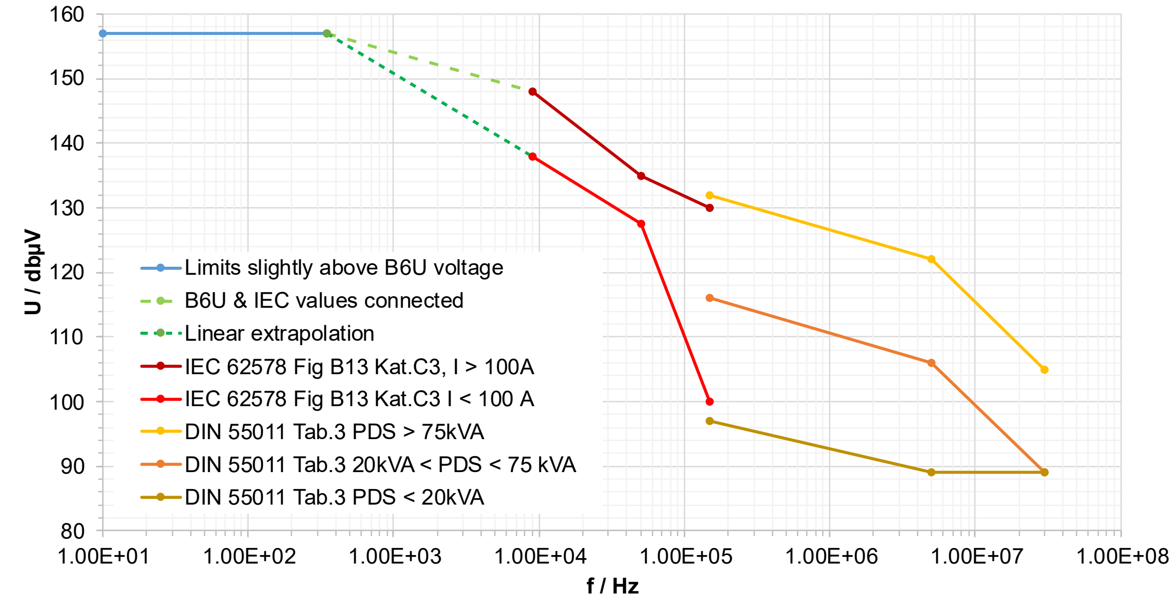


Figure 11.7: Limit values for asymmetrical interference voltages in the frequency range from 10 Hz to 30 MHz (voltages shown in dBµV (Quasipeak))

Explanations of the limit curves:

- Up to 300 Hz: The limit curve for low harmonics of the AC grid, caused by a common-mode voltage from uncontrolled six-pulse rectifiers (B6U). The limit value is about 20% higher than the highest harmonic of an ideal B6U with a resistive load.
- 300 Hz – 9 kHz: Here there is no range that can be usefully adopted from AC grids. The limit curve has therefore been extrapolated between the boundary points of ranges 1 and 3.
- 9 kHz – 150 kHz: Here the limit values proposed by IEC TS 62578 (as shown in Figure B13, Category C3) for devices with a rated current of less than 100 A and greater than 100 A have been adopted, resulting in two limit curves.

- 150 kHz – 30 MHz: Table 3 in EN 55011:2005 shows limit values for low-voltage DC grids. They are primarily intended for applications in the field of solar power generation. Three power ranges are distinguished (less than 20 kVA, 20 to 75 kVA, and greater than 75 kVA), each with its own limit curve).

11.3 High-Frequency Leakage Currents

High-frequency leakage currents are not different from those of current AC applications. Every device, and particularly all drive inverters, must be equipped with EMC capacitors to provide a low-impedance reverse path for them.[57] The capacitors must be dimensioned so as to avoid exceeding the limits on conducted emissions (for more information on the frequency range from 150 kHz to 30 MHz, see Figure 11.6 and Figure 11.7).

11.4 Current Harmonics

DC is inherently free of current harmonics since all currents contribute to active power transformation. It is desirable for devices to exchange power at low frequencies. However, these currents should not exceed impermissibly high values that lead to overloading of system components or their parts. Today the electrolytic capacitors installed in equipment are considered to be the components that limit current and voltage ripple. The dimensioning rule given in 11.1.3 is considered sufficient for ensuring the long-term fault-free operation of different DC grid components.

11.5 DC Chokes

The use of (differential-mode) DC chokes, in conjunction with capacitances, induces resonances in the DC grid. If these are only slightly damped, undesirable oscillations can result. To prevent impermissibly large oscillations, the differential-mode inductance should be kept as low as possible (see section 10.4). The risk of high oscillation amplitudes is especially great with uncontrolled B6 rectifiers, since these inherently cause considerable stimulation in the low-frequency range (e.g. the 6^{th} harmonic).

Common-mode chokes are a normal component of EMI filters. Their (differential-mode) leakage inductance is usually around 1% of the rated value. It should be kept in mind that this can result in grid resonances.

11.6 Symmetrical Configuration of DC Poles

It is important to note that if filter elements are not designed symmetrically, a common mode interference (e.g. at the terminals of a drive inverter) can become a differential mode interference on the DC grid, which causes additional load on components such as capacitors. Therefore, for example, chokes with the same inductance must be installed in both poles. This also applies to symmetrising and discharging resistors in the devices.

11.7 Interference Immunity

The interference immunity requirements are the same as those for AC devices. Measurement procedures and minimum requirements as per IEC 61000-6-2 (or IEC 61800-3 as the product standard for electric drives) are applied.

57 If EMC capacitors are arranged from L+ and L- to ground, it is necessary to deploy class Y2 Y capacitors that are suitable for long-term DC use at 800 V and dimensioned for a peak impulse voltage of 4 kV.

12 Protection and Safety

Essentially the same safety rules apply to both AC and DC voltages. The switching and protection requirements for DC voltages and currents are familiar from other applications (e.g. railroad technology and high-voltage power transmission). The special aspects of industrial DC grids are described here.

12.1 Overcurrent Protection

The grounding approach and grid topology described in chapter 8 shall be applied for managing short circuits and ground faults in the DC grid. Steps must be taken to ensure that a faulty DC Sector can be safely disconnected from the system without impairing other DC Sectors. Every input of a DC Sector must therefore be equipped with an overcurrent protection device that is able to handle short circuits, overloads, and – with low-impedance grounding systems – also ground faults.

The power levels of the DC Sectors should be distributed as evenly as possible; in other words, no single load should dominate in order to prevent any faults from affecting neighboring zones. Steps must be taken to ensure that, when a zone is switched-off, the voltages in other DC Sectors will remain within the voltage bands and operating states described in Chapter 7, and especially in Table 7.1 and Table 7.2.

12.1.1 Short Circuit Faults

12.1.1.1 Necessity of Fast Overcurrent Protection

Since DC grids generally are highly capacitive, in the event of a short circuit the fault current increases very rapidly; an increase in the order of several tens of A/µs can be realistically expected (see Figure 12.2). Very fast-acting overcurrent protection devices are therefore required to provide protection from short circuits. In addition to protecting semiconductors in the current path, high-speed overcurrent protection devices can be used to isolate a fault location quickly enough to keep the voltage on the DC bus within the permissible operating state (Table 7.2) and let unaffected system parts continue operating without any restrictions. Consequently, in a DC grid the crucial criterion for choosing protective devices is no longer whether they can stop fault currents from causing thermal or mechanical damage, but rather their ability to prevent undervoltage.

Electronic overcurrent protection devices are advantageous due to their fast response times; they stop the short circuit current quickly enough to prevent damage to parallel sectors. Simple DC fuses respond much more slowly.

12.1.1.2 Example Course of a Short Circuit Current

The course and duration of a short circuit current were simulated for a typical DC grid. Figure 12.1 shows a grid with four robot sectors and a DC Sector with an AIC as the power source, along with assumed performance data. The prospective short circuit current, in other words *without* protective devices, rises to about 9 kA within 100 µs to reach a final level of about 14 kA as shown in Figure 12.2. It can also be seen that the short circuit causes the voltage in the main DC grid to drop to 0 V after about 0.5 ms. Both the extremely rapidly appearing high short circuit current and the swiftly dropping DC voltage highlight the need for extremely fast protective devices.

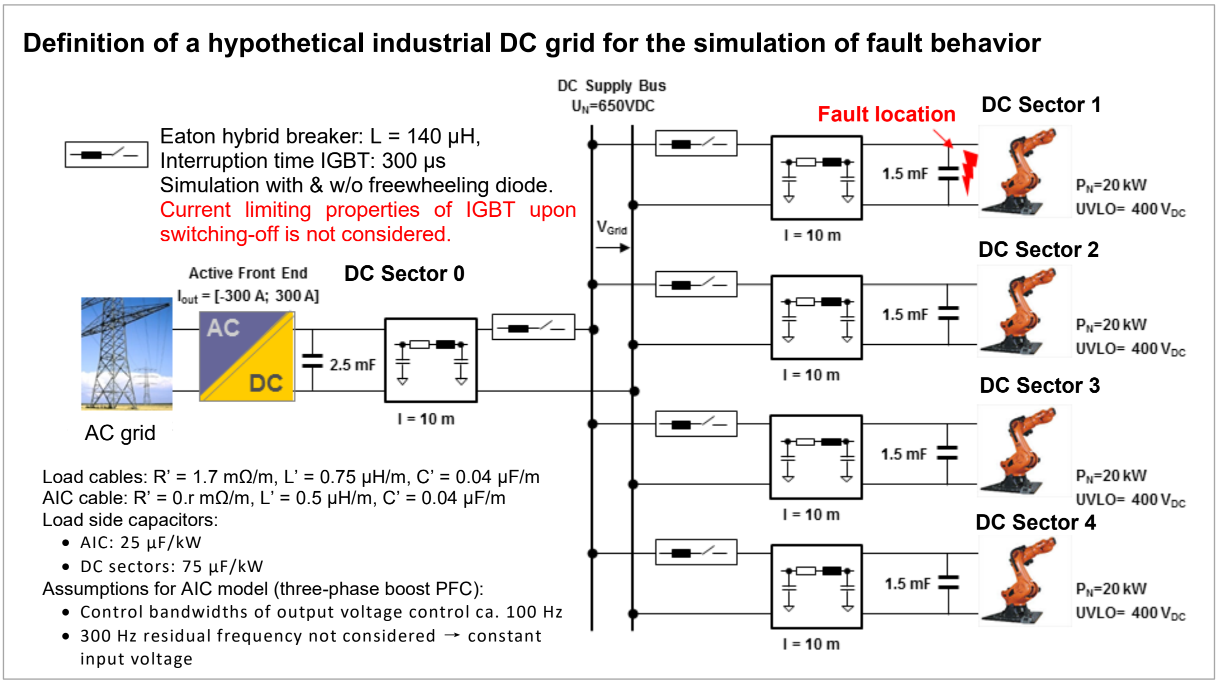


Figure 12.1: Test grid setup for simulating the behavior of a short circuit

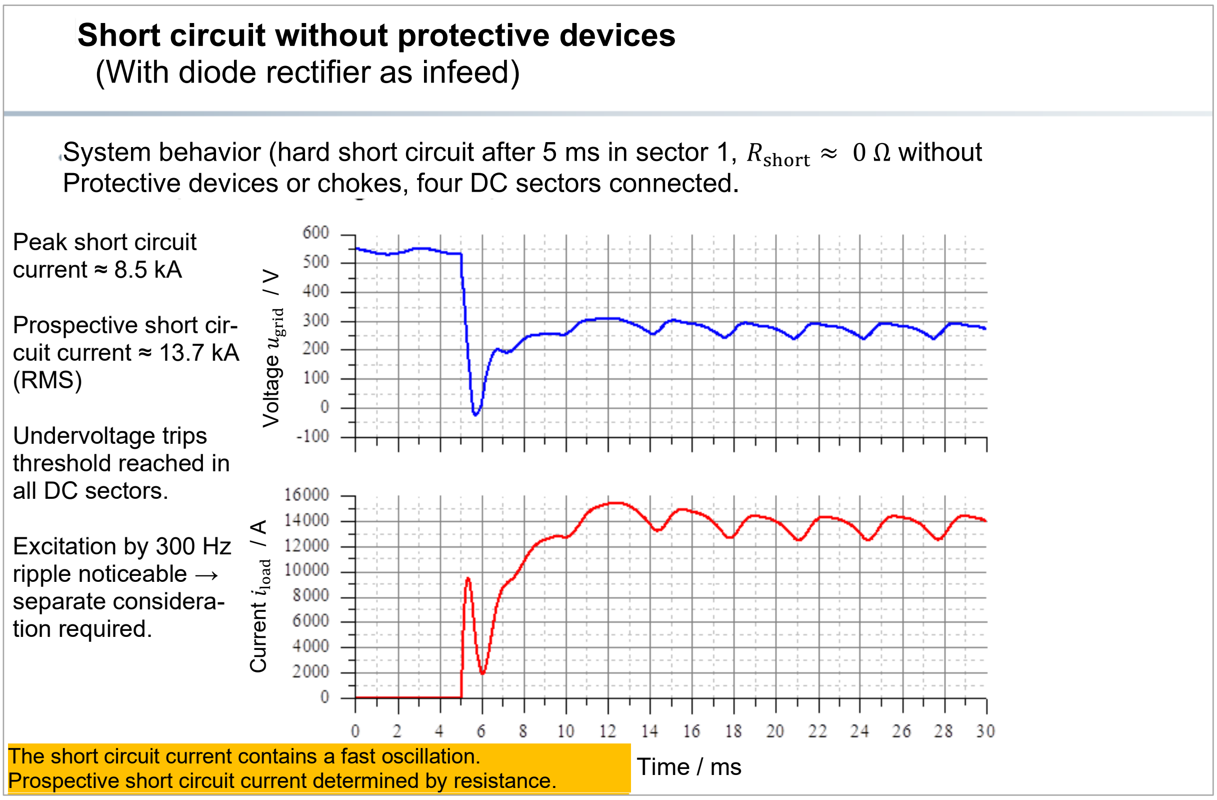


Figure 12.2: Grid voltage, overvoltage and sustained short circuit current without protective devices.

Examples of measured short circuit currents are shown in Annex D.8.

12.1.1.3 Time Constant in a Shorted Circuit

The time constant $\tau = L/R$ of a faulty circuit plays an important role in how overcurrent protection devices, and especially DC fuses, are tripped. Since a steady state is typically not achieved with fast-acting protective devices, inductance is the determinant factor. The energy $E = 0.5 \cdot L \cdot I^2$ (released by mechanical protective devices and fuses as arcs and therefore also as heat) increases with the inductance. The time constant consequently also determines the breaking capacity of DC protective devices. Table 12.1 shows a variety of typical time constants in DC applications.

Table 12.1: Typical time constants in DC circuits (p. 50 in [22.])

Application	Time constant
Industrial DC controls	≤ 10 ms
Battery circuits	≤ 5 ms
DC motors and drives	20 to 40 ms
Electromagnets	up to 1000 ms
Photovoltaic systems	1 to 3 ms
DC link inverter	1 to 3 ms

Conceptually, no large inductances should be installed in a DC grid (see section 11.5), and DC-powered devices typically have a large input capacitance. Consequently, when a short circuit occurs, the time constant is primarily determined by conductors and the parasitic properties of electromagnetic interference filters (for example, stray inductance and the resistance of common-mode chokes). In the case of conductors, inductance and resistance are normally specified as per-unit length values; the time constant is independent of the conductor's length and dependent only on its cross-sectional area. The time constants shown in Table 12.2 apply to the conductors listed in Table 6.3.

Table 12.2: Typical time constants L/R of the conductors in Table 6.3

Conductor cross-sectional area (mm²)	Resistance (Ω/km)	Inductance (mH/km)	Time constant (µs)
1.5	13.3	0.53	39.8
2.5	7.98	0.51	63.9
4	4.95	0.47	94.9
6	3.30	0.44	133.3
10	1.91	0.43	225.1
16	1.21	0.41	338.8

12.1.1.4 Fault Behavior of Devices – Device Classes

If a short circuit fault occurs in a device or wiring in a DC Sector, the possibility that it may also affect other devices in the same DC Sector cannot be ruled out. In terms of self-protection, devices fall into two classes:

- Devices of class 1 are allowed to fail if a short-circuit occurs at their DC terminals. This can include, for example, triggering of an internal fuse [58]. If the DC Sector only contains a single device, the Smart Breaker also ensures complete protection for class 1 devices. But if multiple class 1 devices are operated in parallel within a DC Sector, it cannot be ruled out that they will influence one another in the event of a short circuit.
- Class 2 devices are resistant to damage if a short circuit occurs at their DC terminals. Thus, as soon as the problem is fixed, they can be powered back up again without the need to take any additional action. We assume that such a fault will occur up to a maximum of about 10 times over the course of a device's useful life.

58 In the event of an internal fault, this internal protective device is an effective means of disconnecting the device from the DC grid and preventing a fire (CE/UL certification).

12.1.1.5 Behavior in the Event of an Internal Fault

If a fault occurs within a device, power flowing to the fault location must be limited to prevent a fire from breaking out. This power can come from the higher-level grid or from devices installed in the same DC Sector. The device manufacturer must specify the maximum allowable breaking capacity of the overcurrent protection device. The protective device can be directly associated with the device or implemented as a Smart Breaker to also protect other devices. In the case of a Smart Breaker, the device's manufacturer shall specify the maximum capacitance that may be connected in parallel to it in the same DC sector. A recommended minimum value is $10 \times 25\,\mu\mathrm{F/kW} \times P_{\mathrm{nom.,device}}$.

12.1.2 Ground Faults

The behavior of the DC grid in the event of a ground fault depends greatly on the choice of grounding configuration (cf. section 8). This section therefore describes the characteristics of each grounding method.

12.1.2.1 Ground Faults with Grounding via the AC Grid

With AC grounding, a fault loop closes via the upstream AC grid. The impedance and fault current path are depicted in the corresponding circuit diagram in Figure 12.3. Unlike a short circuit, there are no significant capacitances to ground, so the fault current is primarily driven by the AC grid voltage and always flows across the power source. As a result, the time constant in the fault loop is typically in the range of a few milliseconds and therefore comparable to that for AC systems. This has been confirmed by measurements. See Annex D.9 for detailed information.

To achieve selectivity (see section 3.18), the AIC must be coordinated with the overcurrent protection devices in the DC grid. This requires the AIC to be capable of carrying currents that are briefly significantly higher than the rated current. In the case of a ground fault, the current in the AIC commutates to the freewheeling diodes running antiparallel to the active semiconductors, thus preventing the AIC from shutting off the fault current [59]. These freewheeling diodes are protected by the overcurrent protection device associated with the AIC sector or by protective devices on the AC side [60]. To prevent the AIC sector and the entire DC grid from switching-off in the event of a ground fault, it is essential to ensure that downstream overcurrent protection devices in the DC grid are selective toward the AIC sector.

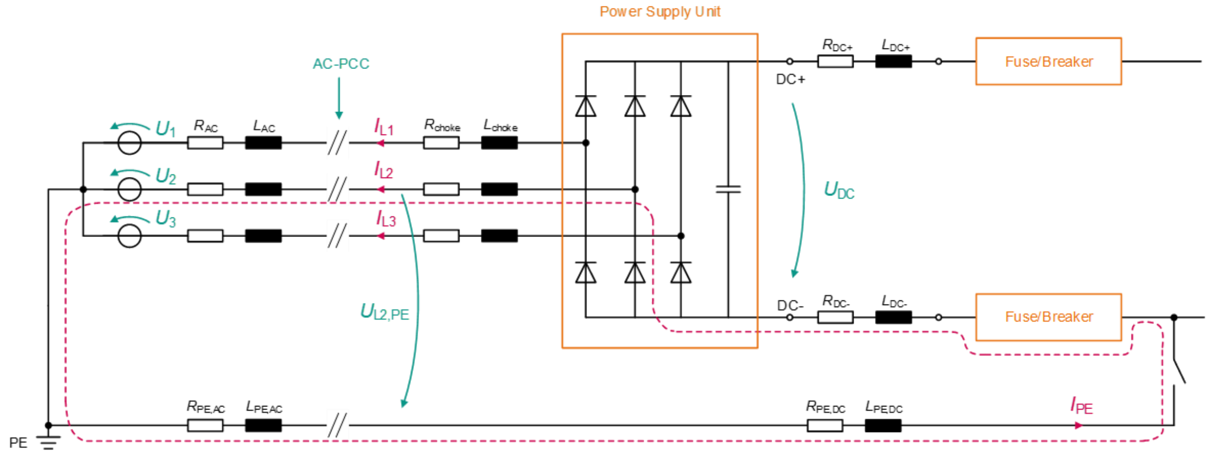


Figure 12.3: Equivalent circuit diagram for ground faults with AC-side grounding

12.1.2.2 Loop Impedance

To comply with the maximum disconnection times (0.4 seconds in TN networks up to 400 V phase-to-ground voltage, as per Table 12.6), special attention must be paid to the impedance of the fault loop (loop impedance indicated by the dashed current path in Figure 11.3). As can be seen there, the loop impedance has an AC component and a DC component. The properties of the power supply device also have to be taken into account. The loop impedance, together with the driving network voltage,

59 In the described fault scenario, the currents exceed the typical operating current by a multiple. If the freewheeling diodes are not capable of carrying this current, an additional B6 auxiliary rectifier, for example, can be installed in parallel to the AIC.

60 The maximum permissible i²t value of the freewheeling diodes must not be exceeded.

determines the prospective fault current at the fault location. The prospective fault current can in turn be applied to determine how long the overcurrent protection device takes to disconnect. The requirements for protection against electrical shock by automatic disconnection of the power supply can be considered to be met if the loop impedance Z_s of the fault meets this condition (IEC 60364-6, ch. D.6.4.3.7.3):

$$Z_S \leq \frac{2}{3} \text{ x } \frac{U_{DC,FS}}{I_a}$$

With:

Z_S: Measured impedance of the fault loop, starting and ending, respectively, at the location of the fault. It consists of an AC-part and a DC-part.

$U_{DC,FS}$: Voltage between active conductor (L+ or L+) and protective earth.

I_a: Current that causes automatic tripping of the protective device within the times given in Table 12.6.

Since no suitable device is available yet for measuring the impedance of an entire loop, it must be checked section by section [61].

The following approach is suggested for determining the loop impedance:

1. Use a typical loop impedance measurement device to measure the AC-side loop impedance $|\underline{Z}_{AC}| = \sqrt{R_{AC}^2 + (\omega \cdot L_{AC})^2}$ upstream of the infeed device.
2. Measure or calculate the ohmic resistance R_{DC} in the DC part of the fault loop (active conductor and protective conductor).
3. Arithmetic addition of both parts: $Z_S = |Z_{AC}| + R_{DC}$
4. Calculate the DC fault loop voltage across the DC fault loop. It depends on the type of rectifier and the number of pulses as shown in Table 12.3 (with U_n as line-to-line voltage on the AC-side) [24.].

Table 12.3 Voltage of ground fault loop with AC-side grounding

Circuit	Rectified voltage U_{DC}	Fault loop voltage $U_{DC,FL}$
B6 (six-pulse)	$U_{DC} = \frac{3}{\pi} \sqrt{2}\, U_n \approx 1{,}35\, U_n$	$U_{DC,FL} = \frac{1}{2} U_{DC} \approx 0{,}675\, U_n$
B12 (12-pulse)	$U_{DC} = \frac{6}{\pi} \sqrt{2}\, U_n \approx 2{,}7\, U_n$	$U_{DC,FL} = \frac{1}{2} U_{DC} \approx 1{,}35\, U_n$

5. For the calculation of the minimal earth fault current according to EN 60909-0 the **influence of temperature on the resistance of the conductors** needs to be considered, both on the AC- and the DC-side:

$$R_L = [1 + \alpha(\vartheta_e - 20°C)] \cdot R_{L20}$$

With:

R_{L20}: Resistance at 20°C

ϑ_e: Conductor temperature at the end of the earth fault

α: Temperature coefficient of the resistance (Cu: 0,00393 1/K;

Al: 0,00403 1/K)

6. Calculation of the prospective earth fault current according to EN 60909-0 with the minimal operating voltage on the AC-side:

$$I_{k,PE} = \frac{c \cdot U_{DC,FL}}{\sqrt{(R_{AC} + R_{PE,AC} + R_{Drossel} + R_{DC} + R_{PE,DC})^2 + (\omega \cdot (L_{AC} + L_{Drossel} + L_{PE,AC}))^2}}$$

61 Determination of the loop impedance of individual sections is described in section 3.4.1 of the journal *Wiederkehrende Prüfungen elektrischer Anlagen und ortsfester Betriebsmittel* (Recurring Inspections of Electrical Installations and Fixed Operating Equipment) published by the German accident insurance association, especially Figures 14.1 and 14.2 [23.].

With

$c = 0{,}9$: Faktor to consider the operating voltage for the smallest short-circuit currents in low-voltage grids

$U_{\mathrm{DC,FL}}$: Fault loop voltage, see Table 12.3

R und L: As shown in Figure 12.3, with consideration of the influence of temperature rise, see item 5 of this list.

$\omega = 2\pi f$: Circular frequency of the AC-Side with frequency f.

7. Now, the instantaneous trip current of the protection device needs to be set to a level lower than

This method does not take DC-side inductances into account because they only have a negligible influence on the prospective short circuit current when the time constant $\tau = \frac{L_{\mathrm{DC}}}{R_{\mathrm{DC}}}$ is less than 400 ms.

Moreover, the voltage drop across the power supply device (in Figure 12.3, only the forward voltage of a rectifier diode) is not taken into account. This method works well for small inductance values L_{AC}. For larger AC-side inductance values with time constants $\tau = \frac{L_{\mathrm{AC}}}{R_{\mathrm{AC}}+R_{\mathrm{DC}}} > 3\ \mathrm{ms}$, however, simulations have shown that the value calculated using this method is significantly lower than the simulated value [62]. Nevertheless, this approach ensures a safe margin. Since very high prospective short circuit currents typically occur in the industrial sector, in many cases this simple approach can be used to demonstrate that the maximum disconnection time is compliant.

12.1.2.3 Effects of DC-Side Ground Faults on AC-Side Protective Devices

In AC-grounded DC systems, if a ground fault occurs current also flows through the AC side as shown in Figure 12.3. On the AC side, parallel AC branches can be arranged between the transformer and the AIC. Residual current devices (RCD) can be installed within these branches. Figure 12.4 schematically illustrates this setup with a single-phase AC RCD (orange) on the green current path between L2 and the neutral (N) conductor. Here it is described whether or not and if so how these RCDs can be affected by ground fault currents from the DC side.

62 If the required interruption times are achieved at this excessively low value, they will definitely also be ensured with greater actual currents.

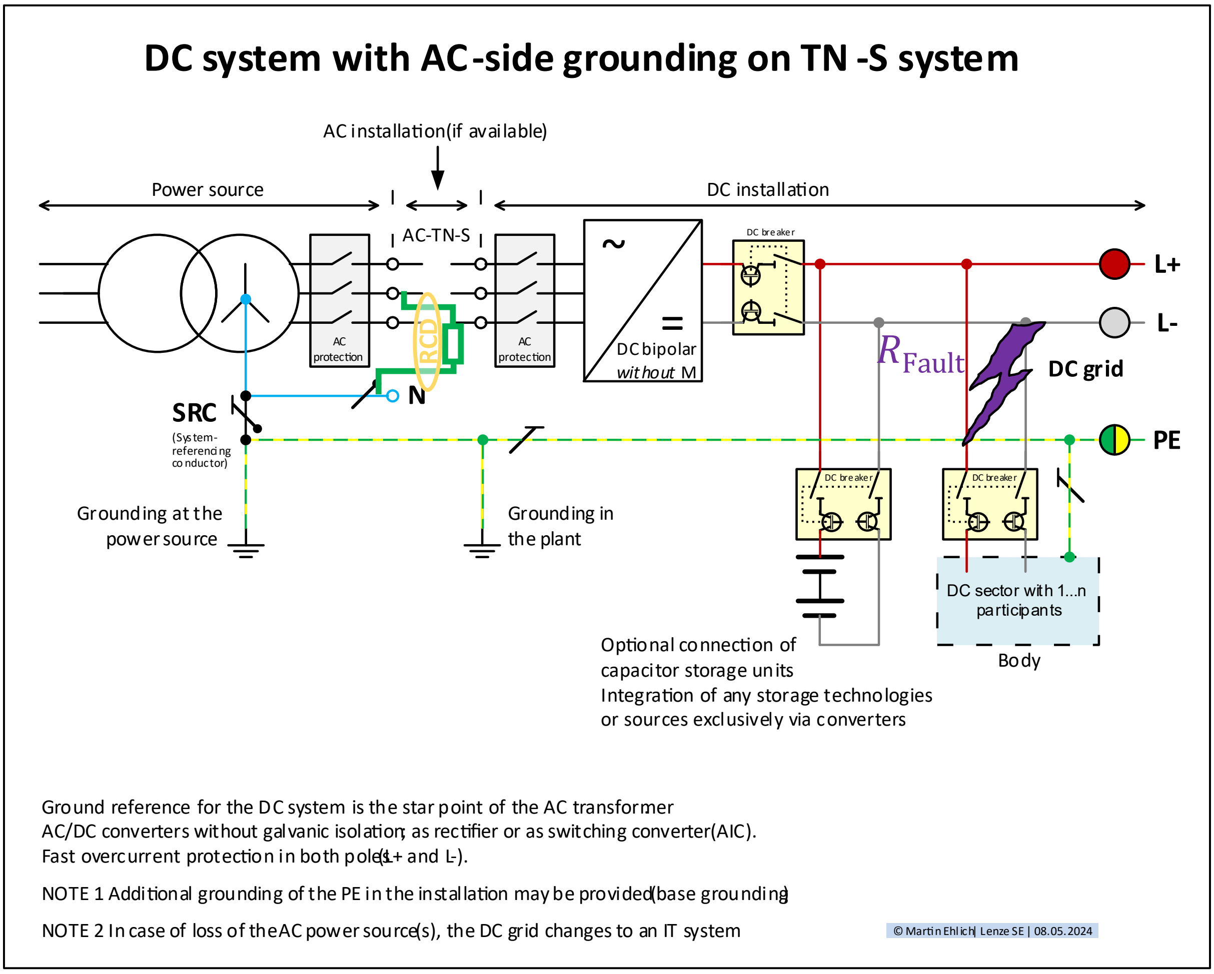


Figure 12.4: DC ground fault and AC-side circuit with RCD

Figure 12.5 shows the main ground current path (red dashed lines) through the regular grounding system and the parallel parasitic ground fault current path i_{PE_AC} (light blue). The latter passes through the RCD but does so in the opposite direction across both poles (L3 and N) of the RCD. As a result, the DC currents cancel each other out and there is no interference.

Another possible influence is the DC component of the ground fault current i_{PE} (shown in red in Figure 12.5) on the AC-side protective devices. These devices are designed, first, to not trip in the event of a DC-side ground fault (that is the job of the DC-side protective device) and second, AC short-circuit currents also have a DC short-circuit current component. They therefore are not expected to be adversely affected by these ground faults [25.].

In addition, when using RCDs in the AC grid the relevant standards require the use of type B RCDs (residual current devices sensitive to all currents) when power electronic components are present already anyway, see Figure G.1 in [26.].

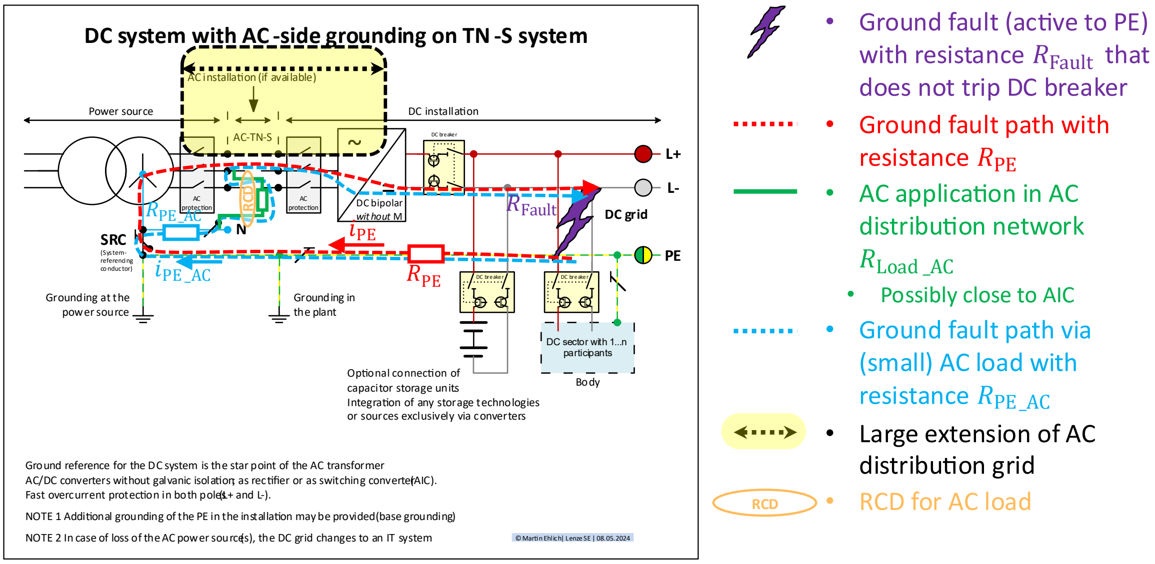


Figure 12.5: Ground fault path with AC-side RCD (see also Figure 8.1)

12.1.2.4 Ground Faults in a DC IT Grid

An earth fault in a DC IT system does not directly trigger a protective device; continued operation for a maximum of 10 s is permitted, even if equipment is used that is not designed for operation in the IT system. [63]. It is important to detect ground faults for two reasons:

1. After the first ground fault occurs, the voltage to ground can change and potentially cause overloading of the creepage path (see also section 12.3.2).
2. To guard against indirect touching (on personnel safety, see also section 12.3.4), chapter 411.6.3.1 of HD 60364-4-41 requires the use of an insulation monitoring device (IMD) [15.]. These devices, which measure the insulation resistance of the grid during operation, can have their functionality extended by adding an IEC 61557-9-compliant device for locating faults. In TN systems, if a ground fault occurs the fault location must be disconnected within the times specified in Table 12.6. In a DC IT grid, disconnection is significantly slower, taking 10 seconds. HD 60346-4-41 (ch. 411.6.3.1) therefore does not consider it to be a grid „with disconnection in the event of a fault" and additionally prescribes the use of insulation monitoring devices (IMDs) or residual current monitors (RCMs) [64]. In general, disconnection is not required in IT grids as long as the touch voltage is limited to $R_A \cdot I_d < 50\,\mathrm{V}$ (ch. 411.6.2 of HD 60346-4-41) [65]. With a low-resistance protective conductor connection and a coordinated overcurrent protection device, it is also possible to meet the requirements of $R_A \cdot I_d < 50V$ in connection with any ground fault that occurs. Whether or not an IMD is always absolutely mandatory under these conditions should be clarified in the relevant standards groups.

It is expedient to combine the functions of „insulation monitoring," and the functional grounding described in section 8.3.3 in a single device. This device can be additionally equipped with fault location capabilities (see IEC 61557-9). By temporarily activating parallel resistors, the fault current can be increased sufficiently to identify the fault's location by differential current measurement. Figure 12.6 shows a DC IT system equipped with such a device.

63 This restriction does not apply if the required creepage distances for continuous operation are adequately dimensioned for all components in the DC grid.

64 Differential current sensors are unable to detect symmetrical insulation faults and are therefore not normally used in Germany.

65 HD 60364-4-41 does not require limiting the touch voltage in direct current (DC) systems [15.]. Older versions specified a limit of DC 120V.

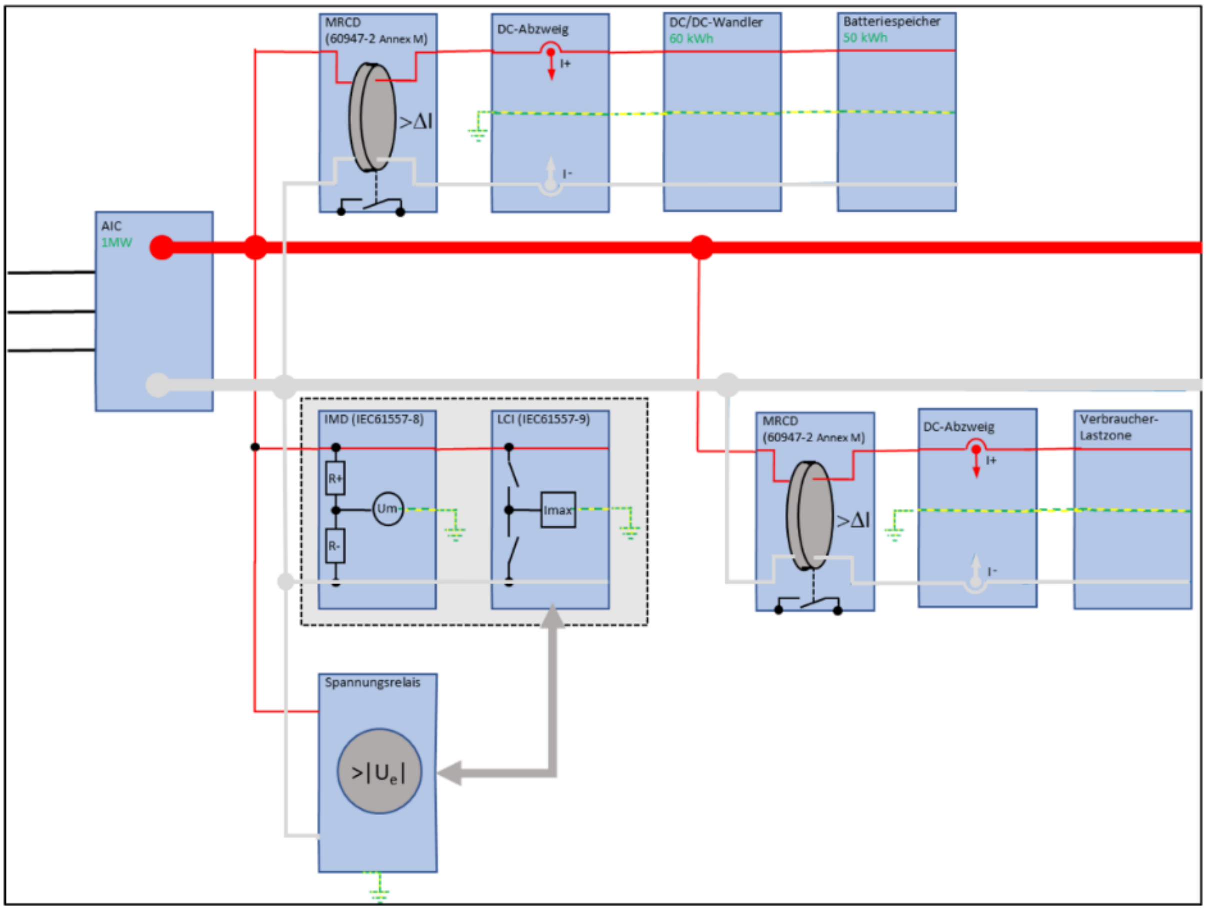


Figure 12.6: DC IT grid with ground fault monitoring (IMD) and localization, see footnote [66]

12.1.2.5 Ground Faults in Drive Inverters on the Motor Side

When operating drives, ground faults can also occur on the motor side, either in the motor cable or within the motor windings themselves, as shown in Figure 12.7.

Hard grounding (see sections 8.2 and 8.5) prevents redistribution of the Y capacitors' charge to ground. If a fault occurs, the resulting fault currents are large enough to reliably trigger overcurrent protection devices.

In a **DC IT grid**, if a ground fault occurs on the motor side, all of the Y capacitors (C_Y) present in the grid are discharged and recharged at the inverter's switching frequency. The charging current places an additional load on the inverter's power semiconductors beyond the required motor current. In a DC grid, due to its large size the capacitance C_Y to ground is also typically large enough that it will very probably overload a single device. There is a risk that the Y-capacitors themselves (film or ceramic capacitors) will be unable to sustain these rapid discharging and recharging processes over the long term. This makes it essential to detect and disconnect any ground faults as quickly as possible. This can be achieved, for example, by monitoring the insulation or common-mode voltage.

An example measurement is shown in Figure D.38 in Annex D.9.3.

66 Translation: DC-Abzweig → Smart Breaker; Wandler → converter; Batteriespeicher → Battery storage; Verbraucher-Lastzone → DC Sector with loads; Spannungsrelais → Voltage relay.

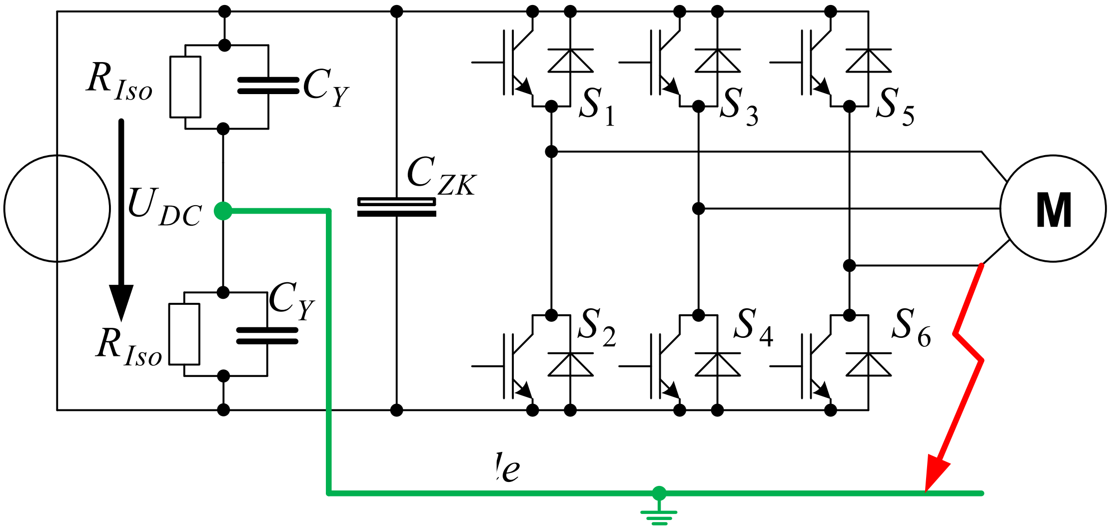


Figure 12.7 Ground fault at a motor phase in a DC IT grid

12.1.3 Overload Protection

12.1.3.1 Protection of Devices

In order to effectively protect equipment, it is essential to make sure that its permissible $\int i^2 \mathrm{d}t$ values are aligned with the triggering behavior of the protective devices used. Special attention must be paid to power semiconductors, e.g., in the power supply equipment. Unlike AC grids, DC grids always deliver power via these semiconductor devices, which have a significantly lower overload capacity than AC components (such as transformers). In order to reliably safeguard these devices, the protective devices must meet considerable requirements in terms of their dynamics [67]. For example, the semiconductors in the power supply devices can be subjected to high currents when power returns after a brief interruption (as discussed in section 6.2.7). Device protection can be ensured by monitoring the current and deploying an $\int i^2 \mathrm{d}t$-model [68] in the Smart Breaker or installing appropriate fuses.

12.1.3.2 Line Protection

If a thermal overload occurs the conductor's permissible operating temperature is the criterion for disconnection (according to IEC 60346 series). The current is typically measured in the protective device and evaluated using an $\int i^2 \mathrm{d}t$-model operating in the range of seconds or minutes. When the current-carrying capability of wiring is reduced, appropriate overcurrent protection devices must be installed.

A special case arises in a DC IT grid:

In a DC IT grid, fast-acting protective devices are theoretically only required in the L+ line (as described in section 8.3). In the event of a ground fault at the DC positive or DC negative pole, the DC grid briefly continues operating until the DC Sector is disconnected. It is also essential to ensure protection of the conductors in this operational state.

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67 Since the required dynamics cannot be ensured with purely mechanical circuit breakers, it is preferable to use electronic or hybrid breakers.

68 $I^2 t < k^2 s^2$ from EN 60204, Annex D with $k = 115$ for PVC insulation, $k = 141$ for rubber and cross-sections

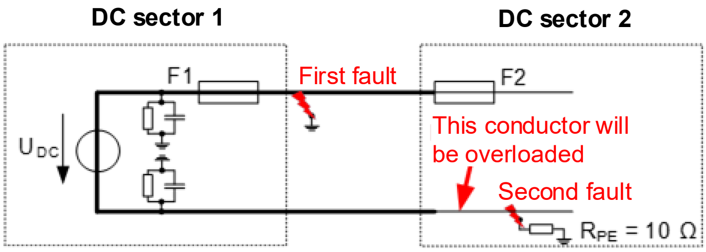

Figure 12.8: Line protection with two ground faults and different cross-sectional areas in different DC Sector

Figure 12.8 shows an example of a DC IT grid comprising two DC Sectors 1 and 2. Overcurrent protection devices are only installed in the L+ line. In this example, sector 1 is protected against a significantly higher current than sector 2. The first time a fault occurs, such as a ground fault on L+ in sector 1, a certain amount of time elapses before the faulty DC Sector disconnects from the DC grid. If a high-impedance ground fault (fault 2) occurs at the negative pole L- in sector 2 during this time without triggering fuse F1 in sector 1, a portion of the conductor in sector 2 will be overloaded. To prevent this from happening, two-pole line protection must be implemented like in conventional IT grids.

12.1.4 Overcurrent Protection Devices

The rated voltage for protective devices is U4 (800 V) in voltage band B4, shown in Table 7.1 (section 7.3.4).

Table 12.4 compares the properties of different overcurrent protection devices. Evaluation of their selectivity must also address their ability to prevent an undervoltage fault.

Table 12.4: Properties of different protective devices in the event of short circuits and ground faults

Fault type	Semiconductor breaker (SCCB)	Hybrid breaker (SCHCB)	Fuse protection	Mechanical overcurrent protection
Short circuit				
Rapid interruption	++	+	0	--
Selectivity (parallel and serial)	++	0	0	--
Ground fault				
Rapid interruption	++	++	+	-
Selectivity (serial)	++	0	+	--
Line protection	++	++	++	++

12.1.4.1 Hybrid Breakers

In a hybrid breaker, a mechanical low-impedance contact is connected in parallel with a semiconductor module for interruption. This configuration combines the benefits of low power loss and faster interruption than is the case with an exclusively mechanical breaker. Figure 12.9 shows a schematic diagram of a hybrid breaker with mechanical contacts (highlighted in yellow) for continuous current and power semiconductors (highlighted in orange) for interrupting the current. Parallel to both devices, a varistor limits the voltage and dissipates the remaining energy in the circuit after the semiconductor module is switched off

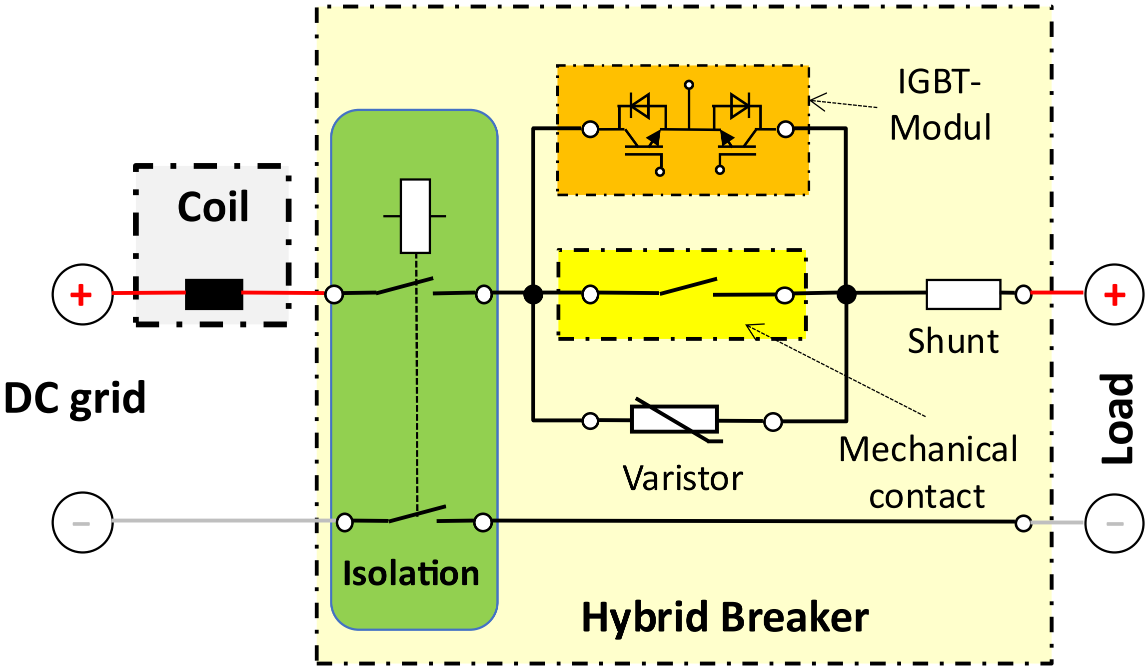

Figure 12.9: Schematic diagram of a single-pole hybrid breaker[69] [27.]

To achieve two-pole isolation, both poles are always disconnected in the event of a fault; in the figure this is shown by the isolation contacts (green). A coil (geared to the current-carrying capacity of the switching elements) is typically installed in series with the hybrid breaker to slow-down the increase in current if a fault occurs [70]. The coil, in turn, adds to power loss and requires additional installation space.

The hybrid breaker is switched off as follows (both during normal operation and in the event of a fault):

- A signal is sent to the mechanical contact's actuator to open it and put the semiconductor module in a conductive state.
- When the mechanical contact first opens, a short arc is formed with a typical voltage of about 20 volts (with the breakers used in DC-INDUSTRIE2, this occurred about 250 µs after the switch-off signal). This voltage is significantly larger than the forward voltage of the semiconductor module (approximately three volts).
- The current commutates from the mechanical contact to the semiconductor module. A small inductance in the current loop between the two current paths is crucial for fast commutation and rapid extinguishing of the arc.
- The mechanical contact continues opening. When it has opened sufficiently to withstand the returning voltage, the semiconductor is switched off and the current commutes to the parallel-connected varistor, which limits the voltage and reduces the current to zero.
- Finally, the insulation contacts are opened without any current flowing, thus completing the procedure.

The sequence is reversed at power-up. First the insulation contacts close, then the semiconductor is switched on, and finally the mechanical contacts close.

69 Shown here in a single-pole configuration. It is advantageous, however, to divide the inductance to both poles.

70 In DC-INDUSTRIE model applications, the inductance of the coils in the fault circuit was approximately 130 µH (hybrid breakers with a rated current of 100 A). The switch-off time of the hybrid breakers (i.e. from when current begins flowing until it stops flowing across the varistor) was typically less than 1 ms, and the energy $\int i^2 dt$ when interrupting short circuits was only about 1% of that of mechanical circuit breakers with the same rated current.

12.1.4.2 Semiconductor Circuit Breakers

In a semiconductor circuit breaker, bidirectional power semiconductors are responsible both for providing a continuous current flow and for switching it on and off. Since no mechanical parts need to be moved, these breakers operate very quickly (typically in less than ten microseconds) after a fault current is detected. This results in even less fault energy ($\int i^2 dt$) than with hybrid breakers. The basic structure of a semiconductor breaker is shown in Figure 12.10.

Like in a hybrid breaker, a varistor takes care of limiting the voltage, and serial isolation contacts reliably separate the two poles.

Here the switching operations are completely arc-free and the possible number of switching cycles is virtually unlimited. The current-carrying capacity can be increased, and power loss reduced by connecting semiconductor modules in parallel.

A drawback of semiconductor breakers is greater power loss at rated current, due to the forward voltage drop of the semiconductors. Steps must therefore be taken to dissipate the power loss, especially at higher rated currents.

Figure 12.11 shows an example of a characteristic tripping curve of a semiconductor breaker for a rated current of 40 A. Current/time profiles below the curve are permissible, while the breaker trips above the curve. The tripping inertia can be adjusted using four trip characteristics (TCs). The area at the upper left (< 2.5 times the rated current) is the overload range. The breaker trips significantly faster at higher currents.

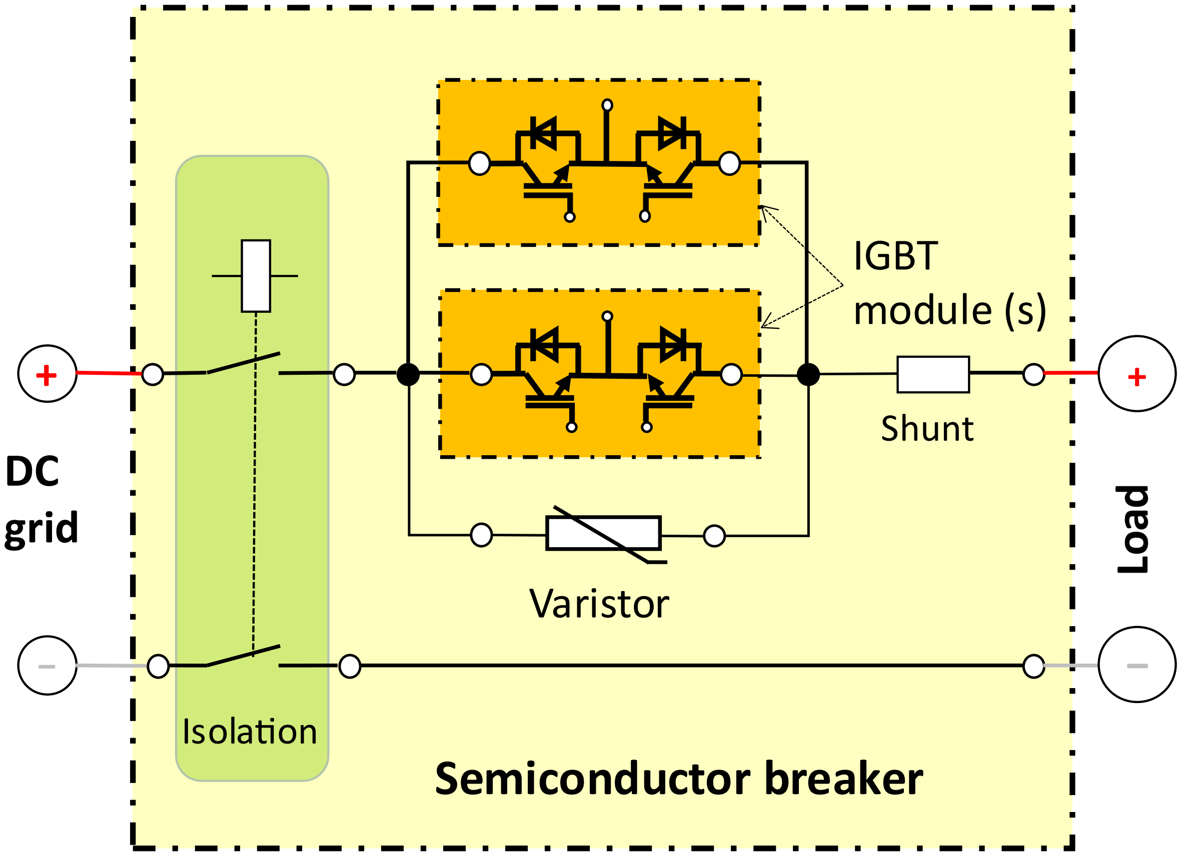

Figure 12.10 Schematic circuit diagram of a single-pole semiconductor breaker [28.]

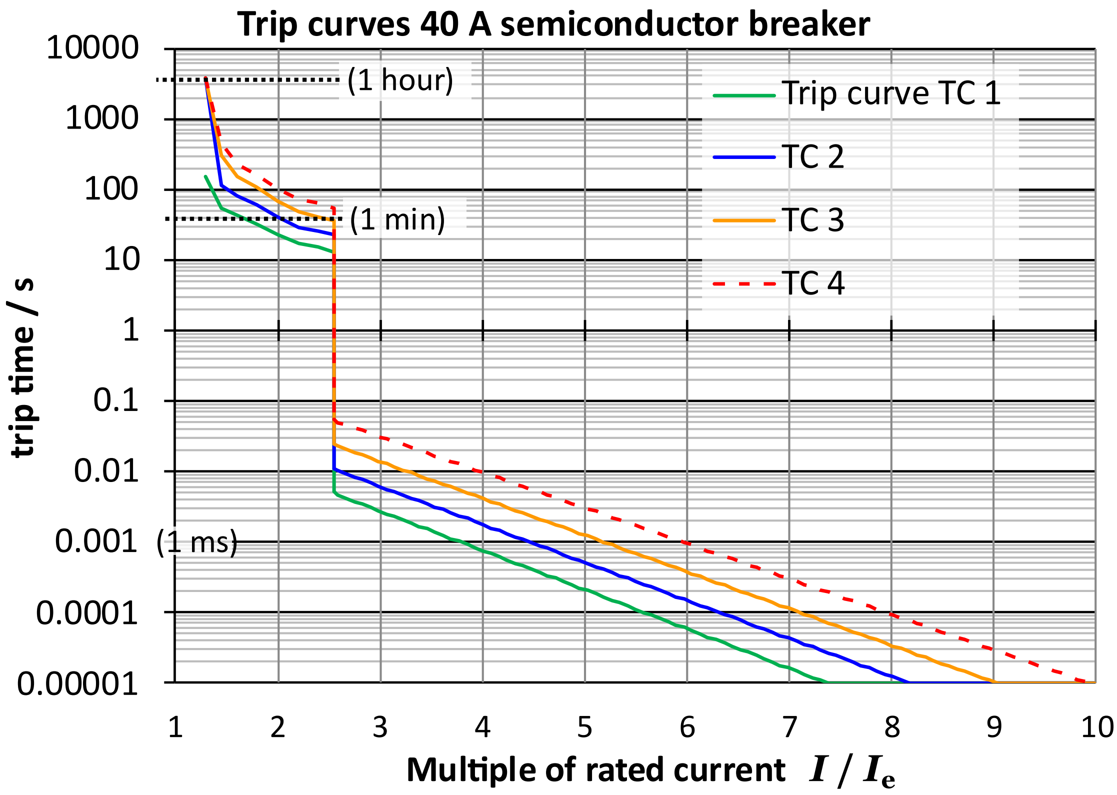

Figure 12.11: Trip curves of a semiconductor breaker [Eaton]

12.1.4.3 DC Fuses

Fuses can also be used in DC grids. They are a cost-effective alternative to circuit breakers but must be replaced or rewired, depending on the type, after tripping in response to a fault. A disadvantage of fuses is typically considerably longer tripping times than those of electronic overcurrent protection devices. As a result, it is significantly more challenging to limit a fault to the affected DC Sector than with semiconductor and hybrid breakers (see chapter 6.1 on the functions of a Smart Breaker).

In order to interrupt the circuit, fuses need to generate an internal voltage that is greater than the system's DC voltage. This is achieved with arcs, which occur when the constrictions of the metallic conductor in the fuse melt and are subsequently cooled by quartz sand filler inside the fuse. The energy $\int u_{\mathrm{arc}} \cdot i \;\mathrm{d}t$ generates a significant amount of heat in the body of the fuse, which makes it practically impossible to design slow-acting DC fuses because of their required volume.

For DC fuses, time constants of several milliseconds are specified by the regulations on short circuit tests. For short circuit currents > 20 kA, time constants of 15 to 20 ms are required [29.], while photovoltaic fuses (gPV) have specified time constants of 1 ms to 3 ms [30.]. In industrial DC applications with low inductance, the time constants are significantly smaller, with values well below 1 ms (as discussed in Table 12.2). Switching behavior at these very small time constants has not yet been understood sufficiently well and is currently being researched. The magnitudes of the time constants have been confirmed by a large number of short circuit tests in DC-INDUSTRIE model applications.

12.1.5 Selectivity

Selectivity is a system's ability to isolate only the directly affected part of a system in the event of a fault, while ensuring continued operation of the fault-free components and DC Sector as far as possible. In a DC grid with energy storage devices that are directly connected in parallel, ensuring selectivity is more challenging than in a conventional linear configuration with a central power source, since in the event of a fault all storage devices attempt to discharge into the fault location.

For selectivity, it must therefore be ensured that the protection devices in these unaffected DC Sectors will not trip when storage devices, such as capacitors, from other DC Sectors feed a current into the faulty sector via the DC grid. This can be achieved, for example, by detecting the current direction in the DC breaker. When the current flows toward the DC grid, triggering of the circuit breaker should be delayed to give the breaker in the faulty sector enough time to disconnect the fault.

It is also crucial to prevent the occurrence of undervoltage faults in the faultless part of the DC grid.

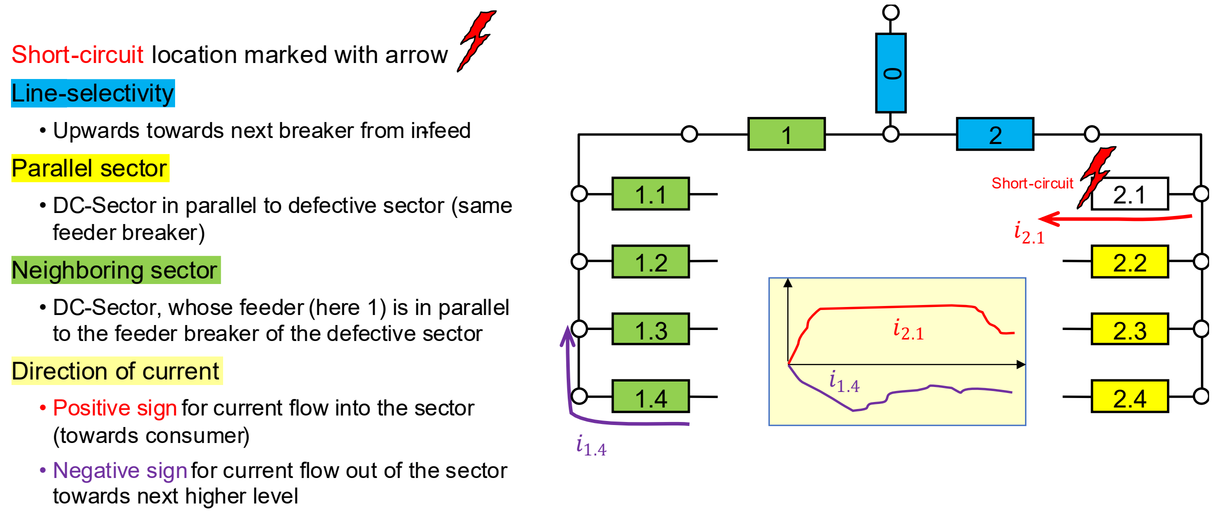

Figure 12.12: Some definitions of selectivity

In addition, in a selective system it is essential for circuit breakers on the next-higher hierarchical levels (see ch. 3.8 and 5.4 for more information on the hierarchical level) to avoid tripping in response to a short circuit in a subordinate DC Sector. In Figure 12.12, to ensure selectivity during the depicted short circuit in sector 2.1, only the circuit breaker for that DC sector should trip. The circuit breakers of the parallel DC Sector (yellow), the neighboring sectors 1.x (green), and the next-higher levels (labeled as 2 and 0 in the figure, blue boxes) should remain operational.

If a short circuit occurs on the DC busbar, all circuit breakers of the DC sectors that are able to feed energy into the fault will trip. Due to the presence of DC link capacitors, this typically includes all DC sectors. For measurement results, see annex D.8.

12.2 Series Arcs

An arc that occurs in series with the load is referred to as a series arc, in order to distinguish it from arcs that can occur parallel to the load between conductors of different potentials in response to a ground fault or short circuit. Such an arc can occur, for example, if a conductor breaks or connectors are loose. It acts as an additional load connected in series with the existing installation and is not detected by conventional circuit protection devices unless further steps are taken to enable this; this applies to both AC and DC. Series arcs can cause secondary damage such as fires or short circuits if they persist for a longer time. A major factor that can make series arcs persist is the impedance of the fault circuit; high capacitances in the DC grid reduce the risk of stable arcs, while high inductances (for example, in long cables and discrete chokes) and higher operating currents increase it. It is therefore common for the conditions for sustaining series arcs to not be met in industrial DC grids with high capacitances and short line lengths. In specific fault situations with consistently short contact distances, like in AC systems, gradual breakdowns (corona discharges) cannot be ruled out.

Within the DC-INDUSTRIE projects, series arcs have been investigated in several model installations (see Annex D.7). For this purpose, the supply line of a DC Sector was disconnected and a controlled, adjustable gap was introduced into one pole of the supply line (see Annex D.7). Only under artificial conditions was it possible to maintain such a series arc.

Arc fault detection devices for PV systems are mainly available in the U.S. market (product standard UL 1699B, also IEC 63027). These devices use spectral analysis methods. Industrial DC grids are characterized by a large number of power electronic devices that emit interference signals in the relevant frequency range, which can result in nuissance fault detections. Suitable devices are therefore not yet available, but research work is ongoing to close this gap.

It is also recommended to implement additional passive protection measures to rule out serial faults in portable electrical components and connections or those potentially endangered by cable strain or breakage. Special attention should therefore be devoted to ensuring the suitability and quality of the following equipment:

- Towing cables

- Cable strain reliefs and connector locks
- Contact shapes and materials for electrical contacts and connections of all kinds.

12.3 Protection from Electric Shocks

Like with AC, in DC systems it is essential to protect people from hazards caused by current and voltage. In the following, special considerations in connection with industrial DC grids are described. The definitions of DIN EN 62477-1 [31.] apply.

12.3.1 Overvoltage Categories and Dimensioning of Air Clearances

For dimensioning air clearances, according to DIN EN 60664-1 [32.] the following aspects must be taken into account:

- Maximum expected transient overvoltages
- Maximum expected continuous voltage
- Maximum expected periodic peak voltage
- Maximum rated impulse withstand voltage

In industrial DC grids, the procedure used to determine the impulse withstand voltage is relevant:

Overvoltage categories (OVCs) are used to determine the required impulse withstand voltage. This designates the resilience of the installation against overvoltages, such as those induced by lightning strikes. In the DC-INDUSTRIE grid, no overvoltages are generated that are higher than those that can be induced from the AC power supply grid, since these systems are limited to industrial facilities without overhead lines. The impulse withstand voltages of the DC grid are determined based on the nominal voltage of the supplying power system (here 230/400 V AC) according to Table F.1 in IEC 60664-1 [32.] or Table 7 in IEC 62477-1 [31.]. The air clearances for basic and reinforced insulation can be derived from the impulse voltage (Table 8 in [31.]). According to Table 12.5, devices that are directly connected to the low-voltage side of a medium-voltage transformer – such as meters, main distribution panels, primary overcurrent protection devices, etc. – must be designed for compliance with OVC IV. Permanently installed devices that are not directly connected to a medium-voltage transformer must be designed for OVC III. The AIC, being the interface to the AC grid, must therefore normally be designed for OVC III.

Table 12.5: Overvoltage categories, excerpt from IEC 60664-1:2020, section 4.3.2 [32.]

Category	Description
IV	Equipment for use at the origin of the installation, e.g. meters
III	equipment in fixed installations and for cases where the reliability and the availability of the equipment is subject to special requirements
II	Equipment that is supplied from a fixed installation, such as portable tools
I	Components without a direct connection to the main power supply

Other relevant factors for determining the overvoltage category (OVC) are:

- When an AC grid is supplied via an additional isolating transformer, the overvoltage category may be reduced by one level [71].
- The overvoltage category can also be reduced by installing surge protection devices (SPDs) as specified in IEC 60664-1, section 4.3.3.2.2 [32.]. This can reduce the air gap required for basic insulation. However, this approach may not be used to reduce the air gap for reinforced insulation.
- No long overhead lines without galvanic isolation may be used (for example, for PV systems), since it would increase the risk of direct lightning strikes. In such a case, all devices and equipment would have to be designed to comply with OVC IV.

71 See EN 60664-1:2008-01, section 4.3.3.6: acc. to EN 62477-1:2017-10, section 4.4.7.2.4 this is designated as non-mains supply.

- The overvoltage category does not change as a result of rectification [72].

The system voltage is determined as per IEC 62477-1:2022-05, sections 4.4.7.1.7.1 and 4.4.7.1.7.2 [31.] as follows:

- In AC TN and AC TT grids: the rated voltage between a phase earth potential
- In AC IT grids[73]: the rated voltage between a phase and the artificial neutral point (virtual star point)[74].
- In AC IT grids with enhanced reliability: the rated voltage between the phases
- If the supply voltage is generated from a rectified grid voltage, the system voltage is the RMS value of the source AC system prior to rectification.
- If devices are powered from non-mains supply[75] circuits, the system voltage is the RMS value of the supply voltage between phases. However, this does not result in an increase of the rated impulse withstand voltage, since OVC II applies to these non-mains supply systems (section 4.4.7.2.4 [31.]) and therefore, according to Table 7 of IEC 62477-1 [31.], a voltage of 900 V DC corresponds to a rated impulse withstand voltage of 4 kV (see footnote 73).

The system voltage (phase-to-ground voltage, see Table 7 in [31.] or Table F.1 in [32.]) is derived from the nominal voltage of the grid and amounts to 300 V AC / 450 V DC [76]. On this basis, the rated impulse withstand voltage is 4 kV (air gap of 3 mm) for basic insulation and 6 kV (air gap of 5.5 mm) for reinforced insulation (at an elevation of 2000 m, pollution level 2).

It should be noted that system components with non-galvanically isolated converters (such as PV systems) should not be connected via long overhead lines (as defined in IEC 62477-1, section 4.4.7.1.4, [31.]), since this would raise the overvoltage category.

12.3.2 Determination of the Creepage Distance

The creepage distance is determined based on the actually occuring operating voltage (according to IEC 62477-1, Table 9 [31.]).

- With AC grounding (see section 8.2), the operating voltage cannot reach values higher than the peak AC voltage (phase-to-ground, maximum 400 V DC).
- With DC IT grid grounding (section 8.3), the operating voltage does not exceed 400 V DC in normal operation.
- When the first ground fault occurs in a DC IT grid, it gives rise to a single-pole grounded grid and the voltage from the remaining active conductor to PE doubles (up to a maximum of 800 V). Based on the applicable standards, an IT grid therefore requires twice the creepage distance in order to continue operating after the first ground fault.

To avoid the need to increase the clearance and creepage distances in DC devices, the faulty DC Sector should be disconnected from the grid as quickly as possible (<10 s) using the Smart Breaker. This approach has not yet been described in a standard. The formation of a creepage path is time dependent. The research project „IsKoNeu," completed in 2016, investigated creepage distances for different materials with a 1 000 V DC load as a function of time [16.]. With a creepage distance of

72 In EN 60664-1 Table F.1, [32.], the OVC always refers to the rated voltage of the (AC) electric power supply system. For a 230/400V or 277/480V system, Table F.1 provides a rated impulse voltage of 4kV in OVC III. This table contains no statements on DC after rectification; EN 62477-1 provides more detailed information.

73 An AC IT grid is only considered to be a non-mains system if there is an additional isolating transformer in the building. The grid behind an ungrounded medium-voltage transformer I s not classified as a non-grid circuit.

74 EN 62477-1: 2017-10 section 4.4.7.1.6.1 states that the phase-to-artificial neutral voltage can be assumed to be well-balanced in symmetrical systems. In the event of a single fault, the system voltage may temporarily change to phase-to-phase voltage. However, in such a single-fault scenario, reducing the impulse voltage by one level is permissible and yields the same result when determining the size of the air gap.

75 "non-mains supply" is defined in IEC 62477-1, ch. 3.40 as follows: low voltage AC or DC power network that is not energized directly from the AC mains supply or DC mains supply (see footnote 14); examples of non-mains supplies are those which are isolated by a transformer or supplied by a battery, generator, solar arrays, […] not directly connected to the power distribution system.

76 After a first ground fault, the IT grid (according to 8.3) is not operated continuously and therefore does not qualify as a grid with enhanced reliability (in the sense of IEC 62477-1). The same system voltage can therefore be assumed as in the case of AC-side grounding.

2.4 mm and a printed circuit board material (CTI = 500, insulation material group II) with solder resist, no failure of the creepage distance occurred during a period of 100 days. However, in the case of a circuit board (CTI = 175-249, insulation material group IIa) without surface protection, the creepage distance failed after two days. In addition, the creepage distance on the outer layers of circuit boards should never be smaller than the clearance, which is specified as 3 mm in section 12.3.3. We therefore require the ground fault monitoring device to shut down the DC IT grid within 10 seconds after the first ground fault (see section 12.1.2). Based on the results of „IsKoNeu," applying 800 V DC to the creepage distance for 10 seconds is enough to pinpoint the fault location and this amount of time can be regarded as noncritical.

For both grounding methods, as shown in Figure 12.13, there is a minimum creepage distance on the circuit board [77] of 2 mm for basic insulation and 4 mm for reinforced insulation (voltage between either L+ or L- and ground), provided that a larger air gap is not specified [78].

12.3.3 Overview of Required Air Gaps and Creepage Distances

As described in the preceding sections, the creepage distance is determined based on the expected operating voltage, while the air gap depends on the required impulse voltage withstand capability. Figure 12.13, Figure 12.14, and Figure 12.15 provide an overview of the air gaps and creepage distances for different grounding methods from an active conductor (L+ or L-) to ground.

Here it is important to make a distinction based on whether the DC grid is connected to a mains supply or a non-mains supply circuit. In EN 60664-1 Table F.1, [32.], the overvoltage category is always referenced to the nominal voltage of the (AC) electric power supply system. For 230/400 V and 277/480 V systems, Table F.1 gives a rated impulse voltage of 4 kV in OVC III. EN 62477-1 distinguishes between DC and AC system voltages [31.]:

- If a DC voltage is generated by rectification without galvanic isolation, the system voltage is the effective value of the AC voltage prior to rectification (section 4.4.7.1.7.1). **Overvoltage category (OVC) III applies to power circuits for fixed installations** (see section 4.4.7.2.3) and the rated impulse voltage for a system voltage of 300 V is therefore 4 kV.
- If there is galvanic isolation during rectification (in the non-mains supply circuit), the system voltage is assumed to be the DC voltage between phases (section 4.4.7.1.7.2). **OVC II** (section 4.4.7.2.3) applies to **equipment supplied from a fixed installation**. This yields the same rated impulse voltage (4 kV for voltages up to 900 V DC) and therefore also the same air gap.

For coordinating the **insulation between L+ and L-**, owing to the doubled working voltage the required creepage distance must also be doubled. Because the required clearance distance between L+ and L- only depends on the required impulse voltage it can be dimensioned the same as the clearance between L+ or L- and ground. In general, the clearance distance can be shorter than the creepage distance [79].

After a first ground fault (single fault) in IT-Systems the following applies for clearance and creepage distances:

- This first ground fault leads to an increase of the system voltage. IEC 62477-1 describes in chapter 4.4.7.1.7.1 in note 2, that this increase does not lead to a higher impulse withstand voltage, [31.]. Consequently, the **clearance distance** does not change.
- For the **creepage distance** a temporary overloading is permissible when this single fault condition is removed in acceptable time as follows from the results of IsKoNeu [16.] in chapter 12.3.2.

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77 Applies to all material groups except group IIIb and contamination degree 2.

78 Since an air gap L is the shortest distance between two points, if L > K then both the air gap and the creepage distance values should be specified, meaning that the shorter creepage distance must be increased. However, if the requirement for L is smaller than that for K, the creepage distance can be extended, for example using slots or ribs. Alternatively, the air gap can be increased to match the creepage distance.

79 Example: On a PCB, the creepage distance between L+ and L- must be at least 4 mm. The required air gap is 3 mm. Both values must be ensured. This could be achieved, for example, by creating a cutout or milling a groove in the PCB.

Clearance- und Creepage distances on the DC side for AC -side grounding – no galvanic isolation				
Clearance distance between L+ or L- and ground and between L+ and L -: Three phase 277/480 V AC – OVC III → also valid in DC systems without galvanic isolation **Voltage**: IEC 60664-1 Table F.1, or IEC 62477-1 Table 7, row for AC up to 300 V / DC up to 450 V , thus 4 kV for OVC III **Distance**: IEC 60664-1 Table F.2 or IEC 62477 -1 Table 8, each for the 4 kV of OVC III				
	Altitude 2000 m, pollution degree 2			
Clearance basic insulation	**3 mm**			
Clearance safe disconnection	**5.5 mm** (one OVC level higher, i.e., 6 kV)			
Creepage distance Voltage **AC/DC 400 V** between L+ or L- vs. a grounded star point (twice that value for L+ to L -) IEC 60664-1:2020 Table F.5, or IEC 62477-1 Table 9 for pollution degree 2				
Material	**Printed circuit board**	**CTI I**	**CTI II**	**CTI III**
Creepage basis insulation	2 mm **3 mm are needed because of the clearance distance!**	2 mm	2,8 mm	**4 mm**
Creepage safe disconnection	**4 mm**	4 mm	5.6 mm	**8 mm**

Figure 12.13: Clearance and creepage distances with AC-side grounding, see section 8.2, [31.], [32.]

Clearance- und Creepage distances on the DC side for grid types DC -IT und DC-TN				
Clearance distance between L+ or L- and ground and between L+ and L -: • Three phase 277/480 V AC → OVC III → Impulse withstand voltage 4 kV → valid also in a DC system supplied by one or more dedicated MV/LV-transformers as an **AC-IT** System • **Voltage:** IEC 60664-1 table F.1 | IEC 62477-1 table 7, row for AC up to 300 V / DC up to 450 V, thus 4 kV for OVC III • **Distance:** IEC 60664-1 table F.2 or IEC 62477-1 table 8, each for the 4 kV of OVC III • Or DC grid as non-mains supply up to 900 V DC → OVC II → Impulse withstand voltage 4 kV → valid in DC grids that are supplied from the AC grid by one or more additional LV/LV isolating transformers • **Voltage:** IEC 62477-1 Ch. 4.4.7.1.7.2 and table 7, row for DC up to 900 V, thus 4 kV for OVC II • **Distance:** IEC 60664-1 table F.2 or IEC 62477-1 table 8, each for the 4 kV of OVC II				
	Altitude 2000 m, pollution degree 2			
Clearance basic insulation	**3 mm** (for 4 kV)			
Clearance safe disconnection	**5.5 mm** (one OVC level higher = 6 kV)			
Creepage distance: Working voltage **400 V** DC between L+ or L- versus the central grounding (twice that value for L+ to L -) • In **DC IT** system: grounding via symmetrical impedances with symmetry monitoring and **disconnection not later than 10 s after** a first ground fault such that creepage paths are not overloaded • In **DC TN** system: hard grounding **IEC 60664-1:2020 table F.5, or IEC 62477-1 table 9 for pollution degree 2**				
Material	**Printed circuit board**	**CTI I**	**CTI II**	**CTI III**
Creepage basic insulation	2 mm **3 mm are needed because of the clearance distance!**	2 mm	2.8 mm	**4 mm**
Creepage safe disconnection	**4 mm**	4 mm	5.6 mm	**8 mm**

Figure 12.14: Clearance and creepage distances for IT and midpoint-grounded systems, see sections 8.3 and 8.5, [31.], [32.]

Clearance- und Creepage distances on the DC side for IT systems with continued operation after a first earth fault				
Clearance distance between L+ or L- and ground and between L+ and L -: • Three phase 277/480 V AC → OVC III → Impulse withstand voltage 4 kV → valid also in a DC system supplied by one or more dedicated MV/LV-transformers as an **AC-IT** System • **Voltage:** IEC 60664-1 table F.1 | IEC 62477-1 table 7, row for AC up to 300 V / DC up to 450 V, thus 4 kV for OVC III • **Distance:** IEC 60664-1 table F.2 or IEC 62477-1 table 8, each for the 4 kV of OVC III • Or DC grid as non-mains supply up to 900 V DC → OVC II → Impulse withstand voltage 4 kV → valid in DC grids that are supplied from the AC grid by one or more additional LV/LV isolating transformers • **Voltage:** IEC 62477-1 Ch. 4.4.7.1.6.2 and table 7, row for DC up to 900 V, thus 4 kV for OVC II • **Distance:** IEC 60664-1 table F.2 or IEC 62477-1 table 8, each for the 4 kV of OVC II				
	Altitude 2000 m, pollution degree 2			
Clearance basic insulation	**3 mm** (for 4 kV)			
Clearance safe disconnection	**5.5 mm** (one OVC level higher = 6 kV)			
Creepage distance: Working voltage **800 V** DC between L+ and L- as well as between L+ or L- towards the central grounding point → valid for **continued operation after a first earth fault** **IEC 60664-1:2020 table F.5, or IEC 62477-1 table 9 for pollution degree 2**				
Material	**Printed circuit board**	**CTI I**	**CTI II**	**CTI III**
Creepage basic insulation	**4.0 mm**	4.0 mm	5.6 mm	**8.0 mm**
Creepage safe disconnection	**8.0 mm**	8.0 mm	11.2 mm	**16.0 mm**

Figure 12.15: Clearance and creepage distances in an IT system with continued operation; see sections 8.4 [31.], [32.]

12.3.4 Fault Protection (Indirect Contact with Voltage-Carrying Parts)

Fault protection is necessary in order to prevent the dangerous body currents that can occur when touching electrically conducting parts during or after an insulation failure. The contact time ranges for direct current are shown in Figure 12.16 ([31.], Figure 2). Table 12.6 shows the corresponding maximum disconnection times as per HD 60634-4-41, table 41.1.

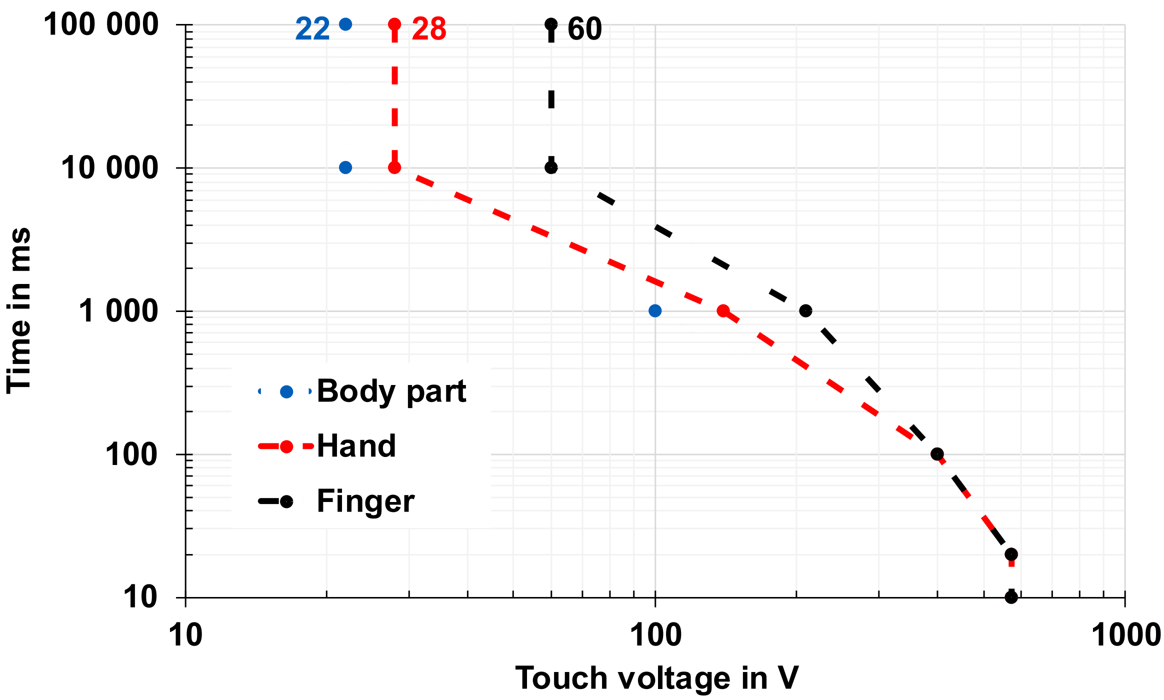

Figure 12.16: Contact duration ranges for peak DC values causing ventricular fibrillation with wet skin acc. to [33.], Figure 2

Fault protection must be provided by taking one or more of the following measures:

- Protective equipotential bonding combined with protective grounding (especially for devices with electrically conductive, touchable enclosures)

- Double or reinforced insulation of live parts from electrically conductive, touchable enclosures
- Automatic disconnection of the power supply:
  - With a power supply from a non-isolated TN grid, the ground fault is detected and disconnected within the permissible time limits (Table 12.6).
  - In the case of DC IT grids, the first ground fault is detected by the ground fault monitoring system (section 12.1.2 and the power supply is disconnected, or the fault rectified within 10 seconds [80]. By that time, electrical safety is ensured by the protective grounding conductor (PE), which keeps the touchable surface at ground potential and does not carry any high fault currents. In the event of a second fault, a fault current flows, automatically tripping the overcurrent protection device.

Table 12.6: Maximum interruption times, source: HD 60364-4-41, Table 41.1 [15.][81]

These maximum interruption times must be ensured in final circuits with a rated current not exceeding:

- 63A with one or more power sockets and
- 32A for supplying only permanently connected consumers

System	50 V<U_0<120 V		120 V<U_0<230 V		230 V<U_0<400 V		U_0>400 V	
	AC	DC	AC	DC	AC	DC	AC	DC
TN	0.8 s		0.4 s	1 s	0.2 s	0.4 s	0.1 s	0.1 s

U_0 is the nominal voltage of the active conductor to ground.

In TN systems, a maximum disconnection time of up to 5 seconds is allowed for distribution circuits and circuits not mentioned in the table.

For IT systems, the disconnection times specified for TN systems apply in the event of a second fault [HD 60364-4-41, ch. 411.6.4, Note 1].

The maximum operating voltage of the DC systems described here is 400 V to ground. Hence, a maximum disconnection time of 0.4 s derives from Table 12.6 independently of the DC-INDUSTRIE grounding concept (AC TN, DC TN, and DC IT in the event of a second ground fault) for DC Sectors with a rated current ≤ 32 A, while for DC Sectors with a rated current > 32 A the maximum disconnection time is five seconds.

12.4 Overvoltage Protection

Overvoltages are transient voltage surges (in the time range from nanoseconds to a few milliseconds) that exceed the normal operating voltage and endanger the insulation of electrical devices and systems. Unless protective measures are in place, overvoltages can lead to breakdowns within the system or insulation failures. This can then cause equipment or device failures or thermal overload of the insulation.

12.4.1 Types of Overvoltages

Overvoltages in low-voltage systems can result from various events or mechanisms. They are divided into four categories:

1. **Lightning-induced surges**: These are overvoltages induced in a low-voltage system by a direct or near lightning strike to either to a building (with or without a lightning protection system) or to the earth. Distant lightning strikes can also induce surges in the circuits of a low-voltage system.
2. **Switching overvoltages** result from switching operations in low-voltage systems. These include intentional switching of loads, such as through contactors, and unintentional switching, such as through overcurrent protection devices in case of faults. They can also result from

80 This limitation does not apply if the required creepage distance for continuous operation is sufficiently large for all components in the DC grid.

81 The disconnection times are currently under discussion, with a tendency toward making them shorter. This can be seen in Draft IEC 60364-4-41 ED6 (Document 64/2586A/CD), where Table 2 suggests the same disconnection time for both DC and AC in the relevant range of TN 230 V to 400 V: 0.2 s is suggested in Table 2.

switching operations in the public power supply network, for example faults in the low-voltage system and elimination of them.

3. **Temporary overvoltages** (also called TOVs) occur as a result of a wide range of both normal and abnormal grid conditions. Whether or not they occur is an important consideration for selecting suitable surge protection devices (SPDs). The temporary overvoltages occurring in DC-INDUSTRIE2 are described in section 7.3.
4. **Overvoltages can also be caused by interactions between two different systems**, such as power supply, telecommunications, and information systems, if a surge current flows in one of the two.

Overvoltages can occur both between active conductors (DC positive to DC negative) and between an active conductor and ground. They mainly occur between active conductors because of switching actions, for example when Smart Breakers disconnect faulty DC sectors in response to overcurrent. The causes of surges between active conductors and ground include lightning strikes and ground leakage.

The currents generated by overvoltages can reach amplitudes in the range of several hundred kiloamperes. The amplitudes of the resulting transient overvoltages often greatly exceed the maximum impulse withstand voltages for which the insulation of the systems or devices is designed.

12.4.2 Causes of Overvoltages

12.4.2.1 Switching Actions

Switching actions generate fast changes in current at speeds that usually considerably exceed those during stationary operation. Due to the length of electrical conductors, all systems exhibit inductive impedances, causing the conductors to store inductive energy. Simplifying somewhat, conductors can be assumed to have an inductance of 1 µH per meter of length. This dynamically stored energy must be balanced during all current changes (charging during current rise, discharging during current decay). Especially during fast negative current changes (as a result of switching actions, e.g. to clear short circuit faults), the voltage increases significantly on the load side of the switching point, as expressed by the equation $U = L \cdot \mathrm{d}i/\mathrm{d}t$. The magnitude of the resulting voltage depends on:

- the current amplitude,
- the conductor length, and
- the switching speed (infinitely fast switching in which *dt* approaches zero theoretically results in infinitely high voltages).

The previously described overcurrent and short circuit protective devices (see section 12.1.4) can be either fuses or electronic breakers.

Fuses require a relatively long time to switch since they exclusively utilize physical effects. They do not simply switch the current off but instead reduce it until it approaches zero (see section 12.1.4.3). As a result, when the current is interrupted voltage spikes occur that depend on the characteristics of the fuse and the magnitude and rate of rise of the short circuit current.

Semiconductor breakers and **hybrid breakers** rapidly and abruptly switch-off when certain criteria are met (see sections 12.1.4.1 and 12.1.4.2). Depending on the amplitude of the current that has flowed, the switching speed, and any inductance present, very high transient voltages can develop between active conductors. To mitigate these voltages, in some cases varistors are installed in semiconductor breakers parallel to the switching element.

12.4.2.2 Atmospheric Phenomena

Lightning is an unpreventable natural event that can affect both electric power supply systems and signal/data systems via several mechanisms. IEC TR 62066 provides an overview of these. The extent to which these mechanisms impact electrical systems is independent of the type of voltage used in them (for example, AC or DC).

Building structures can be effectively shielded from the effects of lightning events by lightning protection systems. For more detailed information, see the IEC 60364-4-44 standard and the EN 62305 series (parts 1 to 4). In the context of DC-INDUSTRIE2, it is assumed that the building involved will be adequately shielded by an EN 62305-compliant lightning protection system, and in the case of DC only the effects of indirect lightning strikes need to be considered. This can change, however, if facilities extend across multiple buildings and/or there are additional electric power supply systems (such as PV systems, battery units etc.) with connections to outside the building.

Only the DC portion of an electrical installation is evaluated here in the context of overvoltage protection.

12.4.3 How Overvoltage Protection Devices Work (SPD)

Transient overvoltages can be reliably limited by surge protection devices (SPDs). These are designed to limit transient overvoltages that have a very short duration (t ≤ 1 ms) but a large magnitude. If such a transient overvoltage occurs, the impedance of the SPD falls and the device establishes a common potential between the active conductors and protective ground (PE). This potential equalization results in significant impulse currents throughout the system, and its effect is commonly referred to as „diverting" the overvoltage. The goal of SPDs is to reduce the amplitude of an overvoltage to a level within the maximum impulse voltage withstand capabilities of the equipment, installation, and end users. This is illustrated in Figure 12.17. A typical protection level between active conductors and ground is in the range of 2.5 kV up to 3 kV. SPDs prevent insulation from being overloaded. However, SPDs are not suited for limiting larger voltages for any longer than 1 ms because they would otherwise be thermally overloaded.

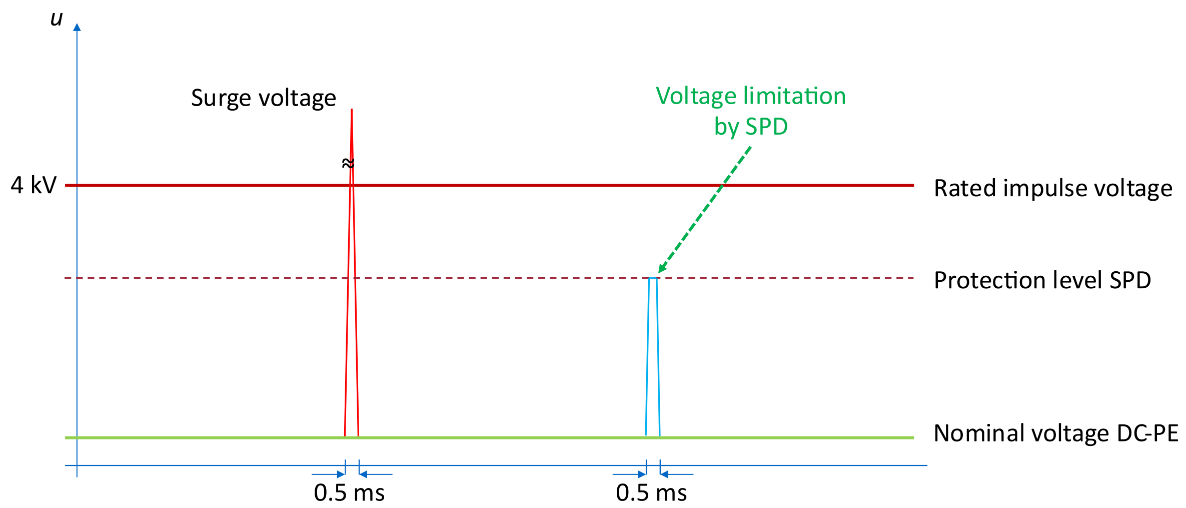

Figure 12.17: Voltage limitation by surge protection between active conductors and ground

12.4.4 Surge Protection Between Active Conductors

Transient overvoltages between active conductors are mainly caused by inrush currents in response to switching actions. In standards, these currents are described as input surge currents with a waveform of (8/20) µs as shown in Figure 12.18.

Increased currents result in higher overvoltages that last as long as the corresponding switching action. If switching is completed in less time, i.e., performed more abruptly, the overvoltages are correspondingly larger.

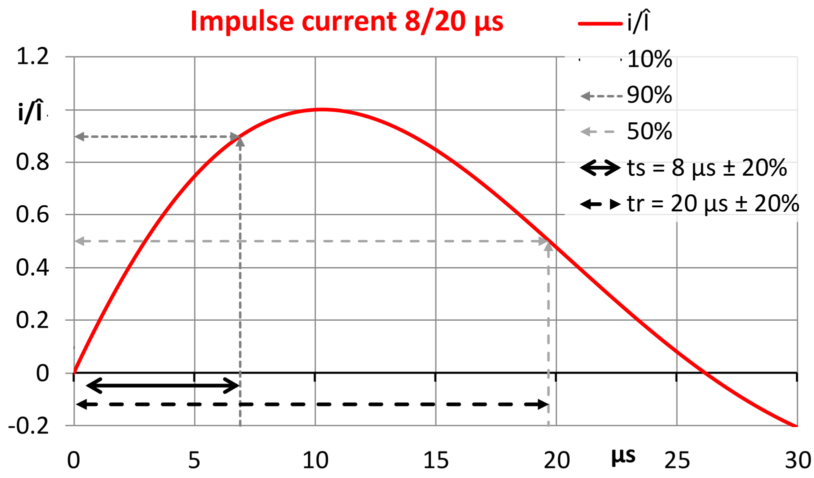

Figure 12.18: Curve shape (8/20 µs) representing impulse currents caused by switching actions, calculated as described in [34.], section 4.4

Especially overvoltages caused by opening electronic breakers (see section 12.4.2.1) can reach amplitudes that are capable of damaging connected devices or causing them to age faster. However, devices must be able to withstand voltages up to a certain amplitude in order to meet EMC robustness requirements.

Corresponding to IEC 61000-4-5, devices used in applications like those of DC-INDUSTRIE should be able to withstand voltages up to 2 kV.[82] This test voltage corresponds to the standardized (1.2/50) µs voltage impulse used for IEC 61000-4-5-compliant testing. Devices must be able to withstand these test impulses without suffering any damage.

Voltage spikes of up to 2 kV have been measured in small test installations. The connected devices were not affected by them, however. Depending on the nature of the installation, higher-energy current impulses and therefore also higher voltage spikes may also occur. In these cases, It is recommended to install SPDs.

SPDs should be chosen that are able to limit voltages to well below the voltage withstand capability of the device or devices that need protection from expected surge currents. In DC-INDUSTRIE2, the voltage withstand capability is defined as 2 kV. Ideally, the protection level should be set to 80% of the system's voltage withstand capability, which in this case would be 1.6 kV. It is also recommended to make sure that the SPDs and protected devices are suitable for the same power levels, for example by impulse testing the end devices together with an upstream SPD to make sure that the integrated voltage-limiting elements (suppressor diodes, filters, capacitors, or varistors) will not be overloaded and damaged.

12.4.5 Overvoltage Protection Between Active Conductors and Earth

Overvoltages between active conductors and earth are caused by inrush currents, e.g., as a result of switching operations after earth faults or of lightning strikes. In addition to the previously mentioned (8/20) µs impulse for switching operations, an impulse with the form (10/350) µs is used for lightning strikes.

The amplitudes of these transient overvoltages often greatly exceed the maximum impulse voltage of 4 kV set by DC-INDUSTRIE2 (see 12.3.1), which the insulation of a system or devices is designed to withstand. Near or direct lightning strikes in particular can induce voltages between active conductors and ground of between several tens of kV and 100 kV.

SPDs should be selected whose voltage limiting properties are sufficient to keep the protection level L+/- towards PE below the permissible impulse voltage withstand level of 4 kV with the expected surge current impulses. According to HD 60364-5-534:2016, 534.4.4.2, the protection level should be even lower, at no more than 3.2 kV.

82 IEC 61000-4-5, table 1 specifies different surge voltage test levels depending on the installation classes (electrical environment) in Annex C and connection type (internal/external connections). For DC-INDUSTRIE devices, the test level is normally 2 kV (1.2/50) µs.

12.4.6 Selection of Appropriate Overvoltage Protection Devices

SPDs for AC grids, e.g., installed ahead of an AIC, must be tested in accordance with IEC 61643-11. The risk parameters of EN 62305-1 can be applied. SPDs must be selected and installed in accordance with the requirements of HD 60364-5-534. Accordingly, type 1 surge protectors are required for infeed devices at building entrances when an external lightning protection is installed; type 2 surge protectors are required wherever overvoltage conditions may occur, particularly more than 10 m of conductor-length away from the previous SPD (IEC 60364-534.4.9).

The standard covering the selection, installation, and testing of **SPDs for DC grids** is IEC 61643-41. Compliance with the PV dedicated standard IEC 61643-31 in not enough for DC applications. Only the IEC 61643-41 tests the DC disconnection capabilities during short circuit.

Risk parameters and protection according to EN 62305-1 DC grids can in principle also be applied **analogously to AC grids**. However, the SPDs for AC grids cannot be applied to DC grids for the following reasons:

- In DC, there is no zero crossing.

  ⇒ Increased requirements for disconnecting SPDs

  This fact is only fulfilled when the SPD is tested according to IEC 61643-41.

- When using energy storage systems and especially batteries, significantly larger short-circuit currents can occur in DC grids than in AC grids.

  ⇒ Increased requirements regarding the disconnecting behavior of SPDs and their upstream fuses

  This fact is only fulfilled when the SPD is tested according to IEC 61643-41. In addition, the prospective short circuit current of all sources shall be determined and compared with the SPD data sheet. If the real short circuit current exceeds the maximum value of the SPD, a catastrophic failure of the SPD is possible. SPDs with PV certification only (IEC 61643-31) must not be used in DC grids.

On the PV side in photovoltaic systems (PV) feeding into DC systems, selection and installation are carried out in compliance with HD 30364-7-712 or, optionally, according to the application guide for IEC 61643-32. SPDs for the DC PV side must be tested in accordance with EN 61643-31. When connecting PV systems, a type 1, type 2, or combined SPD is required to provide protection from direct and indirect lightning strikes.

The following parameters, among others, need to be considered when selecting DC SPDs:

- The maximum operating voltage of the DC system
- The nominal operating voltage of the DC system
- The minimum and maximum prospective short circuit current at the installation location of the SPD.
- Expected temporary overvoltages (TOVs) in the DC application, caused either by galvanic coupling with an AC system or generated within the DC application
- The expected amplitude of switching overvoltages
- The configuration of the grounding system for the DC grid and the upstream AC grid
- The expected AC/DC voltage between active conductors and ground under normal operating and fault conditions

With devices of protection class I, in the event of an insulation fault the DC fault current predominantly flows to the central grounding point via the green-yellow protective conductor.

12.5 Corrosion and Stray Currents

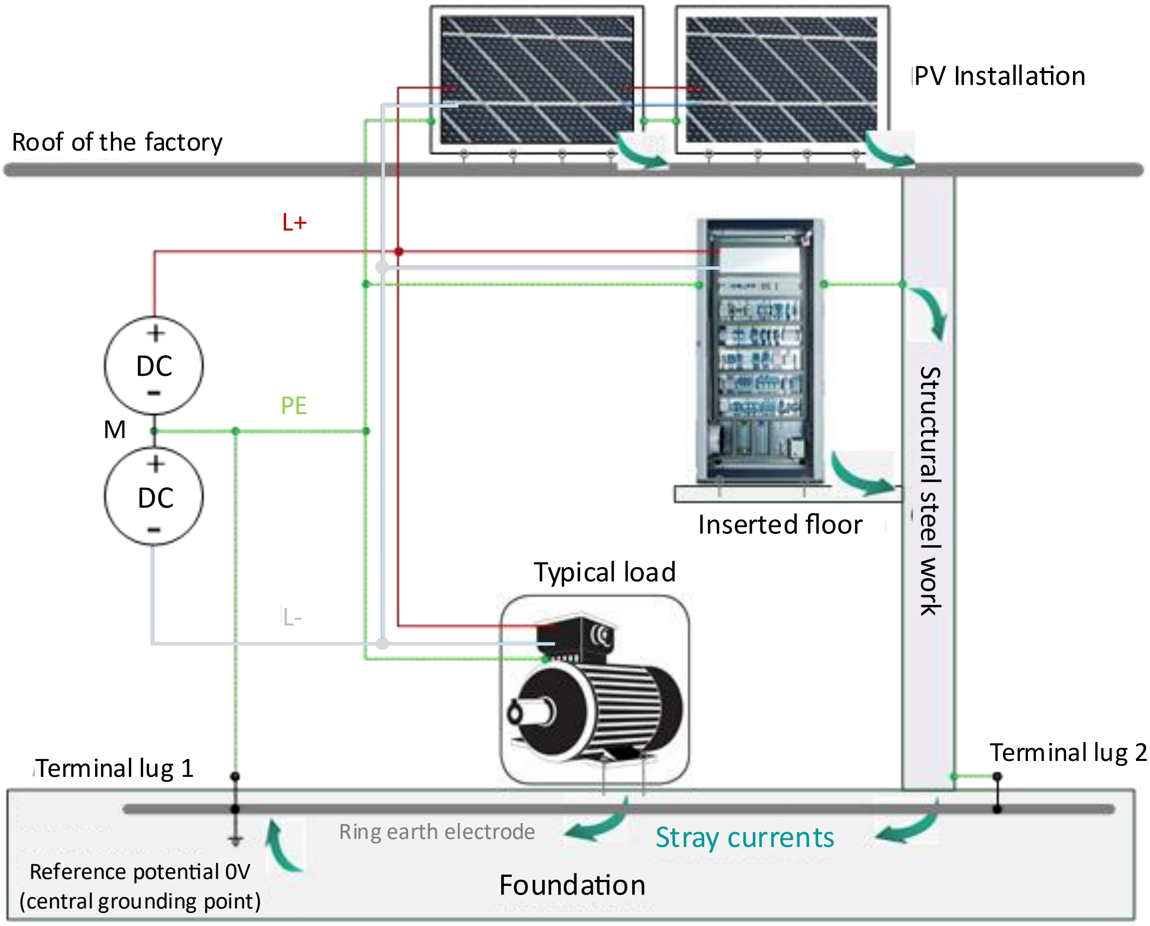

Figure 12.19: Schematic diagram of stray currents in a hard-grounded DC grid

Corrosion is caused by stray currents (also known as parasitic DC currents) at the point where they pass from the metal into an electrolytic medium (concrete / soil) [83]. Electrochemically, this process is known as a partial anodic reaction. For DC stray current corrosion to occur, a material-specific minimum potential difference must be exceeded. EN 50162 specifies a threshold of **200 mV** for steel-reinforced concrete [35.]. Figure 12.19 shows possible stray current paths.

Using Faraday's law, it can be calculated that exposing an electrolyte to a current of 1 A for one year will cause the loss of 9.13 kg of iron. It should be noted that only current flowing electrolytically, for example through concrete, causes loss of material, not current flowing through a metallic ring earth electrode (to take an example). Current flowing through metallic conductors does not change the material.

For example, whether a stray DC current flowing continuously through concrete will have a critical effect on buildings over time depends not only on the magnitude of the current, but also on how it is distributed over multiple metal-concrete contact points. Based on practical experience in railway systems, an electrolytically flowing stray DC current of less than 10 mA per transition point between earth and electrolyte is considered non-critical [36.].

Four different stray current paths and their mechanisms have been studied in DC-INDUSTRIE. They are described in the following sections.

12.5.1 Stray Current Flowing Directly from an Active Conductor into an Electrolytic Medium

An example of this is a PV system for a factory building with DC cables laid directly on the concrete roof.

83 Stray current corrosion is a DC-specific topic since periodic reversal of current flow in AC systems prevents material degradation. Stray current corrosion has been a well-known phenomenon for a long time in DC-powered electric railways and large PV systems.

If, for example, an insulation fault occurs because of an animal chewing on a DC PV cable, resulting in a galvanic connection between the active conductors of the PV system and the production hall's earthing system, the electrolytic stray current will be driven by the full DC voltage of the PV system. This electrolytic stray current is limited only by the electrical conductivity of the concrete roof and the remaining insulation resistance of the damaged cable.

Sustained stray currents of up to 300 mA are generally tolerated in grounded PV systems and do not lead to their shutdown (see IEC 63112).

If currents of this magnitude primarily flow through the concrete roof into metallic earthed structural elements (steel beams), over the building's lifespan non-negligible corrosion can be expected to occur at the transitions between concrete and steel.

Possible preventive measures:

- Galvanic insulation of the PV system and use of insulation monitoring, see IEC 63112, Table 1 and Chapter 5.2
- For a grounded DC grid and connection of the PV system via a non-isolating DC/DC converter, see 8.2 and 8.5.
  - No direct laying of PV cables on an electrolytic medium (concrete roof, earth)
  - Installation of PV cables in metallic cable ducts connected to protective earth
  - Daily checking of insulation resistance when switching on the system[84]

12.5.2 Electrolytically Flowing Stray Current Parallel to the Ring Electrode in a Foundation

Typical factory buildings have a ring earth electrode with several connection points. If a stray current flows through a connection and the ring earth electrode to the central earthing point, the portion of current flowing through the ring earth electrode will not cause any corrosion. However, as the ring earth electrode is based in an electrolytic medium, an additional parallel current path (current divider) can develop and possibly cause corrosion.

German standard DIN 18014:2023 specifies in section 8 that the resistance between any two connection points to the ring earth electrode must not exceed 1 Ω. Lower resistance, though, is beneficial since it makes the detection of earth fault currents easier. The current to exceed the 200 mV corrosion threshold mentioned above (first paragraph of this chapter 12.5) for the maximum permitted resistance of 1 Ω is only 200 mA!

Possible prevention methods:

- Choice of DC-IT earthing type and permanent use of an insulation monitoring system. In the DC-IT system, insulation resistances less than 1600 Ω (at 0.5 A) or even less than 800 Ω (at 1 A) at 800 V would have to occur in order to drive such DC currents in the ring earth electrode. These insulation resistances are much lower than the minimum insulation resistance required in section 8.3.3 (100 Ω/V). Insulation monitoring would therefore detect this fault.
- DC Sector For low ohmic earthed DC systems: Provide residual current monitoring on critical DC sectors, i.e., sectors capable of carrying such high DC fault currents undetected.
- Avoid current flow via ring earth electrodes by connecting all bodies to the PE conductor system, which is insulated from the earth potential and connected directly to the CEP.
- Daily checks of the insulation resistance when starting up the system.

12.5.3 Parasitic, Electrolytically Flowing Stray Currents to Earthed Equipment

With devices of protection class I, in case of insulation failure most of the DC fault current flows via the green-yellow protective conductor to the central earthing point. However, many such devices have direct electrically conductive contact with an electrolytic medium. For example, protective-earthed robot enclosures are directly bolted to the foundation.

Measurements performed in DC-INDUSTRIE test applications have found parasitic earth resistances in the range from 5 kΩ to 7 kΩ between devices of protection class I and the central earthing point. The ratio of the metallic protective conductor current to the parasitic electrolytic stray current was

84 According to EN IEC 63112:2021-05, section 5.2, this is mandatory.

determined to be approximately 10 000 to 1 [85]. In order to exceed the electrolytic DC leakage current value of 10 mA mentioned above from railway technology, DC fault currents of approximately 100 A would have to flow unnoticed for a long time in this case, which is rather unlikely.

Current divider ratios between metallic and electrolytic current, respectively, on equipment of 1 000 to 1 or even smaller would be more critical. Such a low earth resistance with a small current divider ratio is conceivable, for example, if a mounting screw of protection class I equipment comes into direct conductive contact with an unearthed steel mat in the concrete, or if the foundation becomes damp.

Possible countermeasures:

- Choice of a DC IT earthing system. DC fault currents on the order of a few amperes cannot go unnoticed in an insulation-monitored DC IT system.
- For low ohmic earthed DC systems:
  - Initial and possibly periodic determination of parasitic earth resistances in equipment of protection class I that have direct conductive contact with an electrolytic medium, and calculation of the current divider between metallic current flow and electrolytic current flow based on the findings.
  - Differential current monitoring is recommended in critical DC Sectors, in other words sectors that are able to drive high DC fault currents without this being noticed.

12.5.4 Parasitic, Electrolytically Flowing Stray Currents from Neighboring Systems (HVDC, PV Fields)

If HVDC lines or large externally operated PV fields run close to production plants, significant corrosion can occur due to coupling of stray currents from these systems. These effects can take place independently of the earthing concept and independently of the type of power supply (DC or AC).

No in-depth studies have been carried out on these problems since they are not specific to DC industrial plants.

In these cases, general corrosion protection measures such as installing sacrificial anodes can be taken. These are also described in EN 50162.

85 To determine the current ratio, a current of 10 A was applied between the equipment of the system and the central grounding point. The electrolytic stray current was measured using a current clamp with one conductor connected to the 10 A current source and the other to the PE conductor of the equipment (to measure leakage current).

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Annex A Planning and Design of DC Grids

There are some important differences between planning alternating current and direct current systems. When applying AC design rules to a DC system, several aspects need to be taken into account in order to ensure successful operation of the DC grid. These concern the technology itself, specific requirements regarding protective and switching technology, the bidirectional power flow, and the microgrid structure in which loads and energy producers are locally interconnected. Figure A.1 shows a procedural model for structured design and implementation of an industrial DC grid.

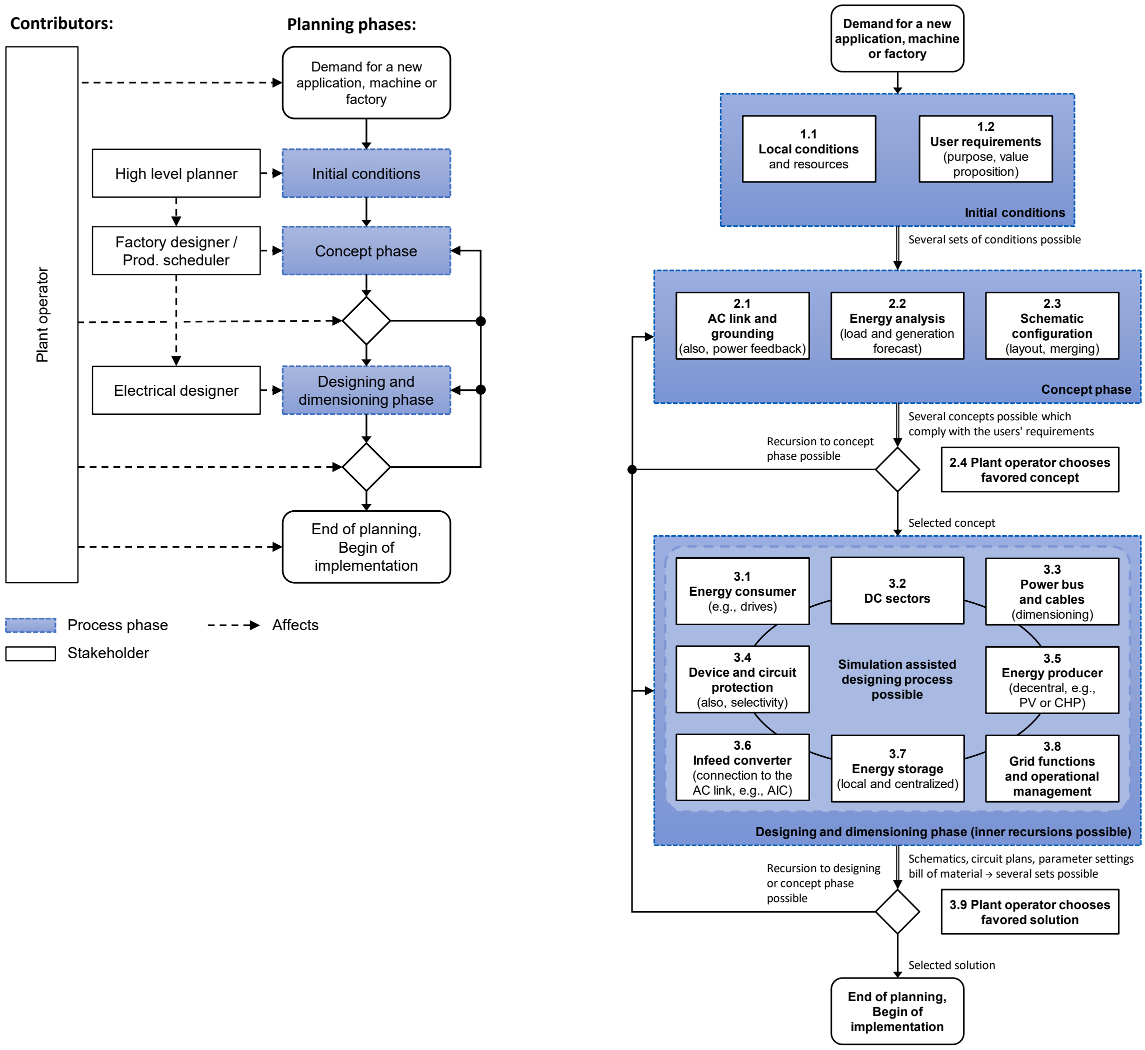

Figure A.1 Flow chart for designing and implementing industrial DC grids

The essential steps are clarification of the initial conditions, creation of an overall concept, and actual design of the DC microgrid with detailed planning and dimensioning. In the design phase, the recommendation is to take an iterative approach in which the interdependence among the individual parts are repeatedly balanced until a consistent overall solution is achieved that meets the previously defined requirements.

Annex B Operation

Operation of a DC system differs in several fundamental respects from running an AC system. This has been visualized here with the aid of flowcharts for different types of processes. Figure B.1 shows two examples.

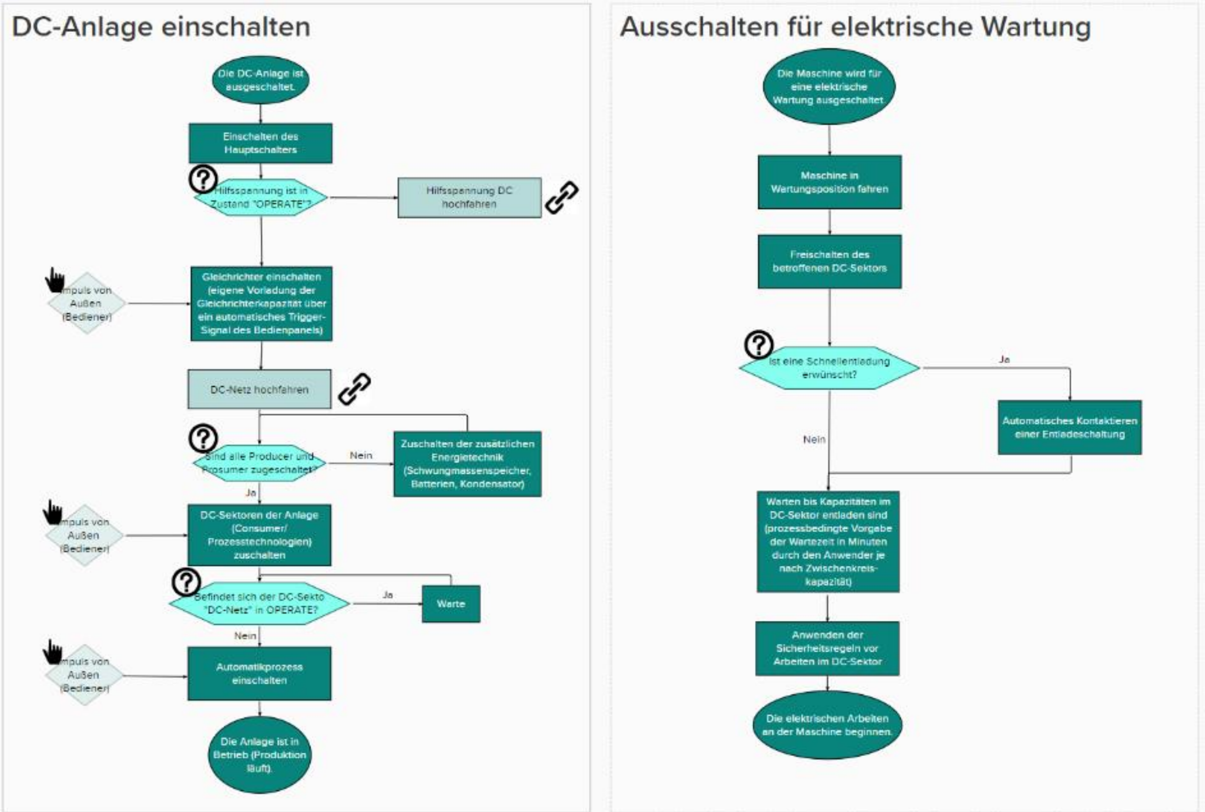

Figure B.1 Flow charts of powering a DC system up and down

Annex C Safety and Personal Protection

C.1 Safety Rules When Dealing with Direct Current

The five safety rules of IEC 60479-1 also apply to DC applications. Table C.1 addresses DC-specific requirements.

Table C.1 Safety rules for DC

Safety rule	Description
Disconnect.	Safe all-pole disconnection of L+ and L-. Disconnection must be performed safely. Disconnecting a DC grid under load can cause arcing and shall therefore be avoided. The absence of a load must be verified, for example using a current meter.
Secure against accidental restart.	To prevent the system from being accidentally powered up, the area in which work is being done must be secured. Keep in mind that DC systems often have multiple power sources.
Make sure that all poles are voltage-free.	It must be verified that no voltage greater than 60 V is present. This is especially important in systems with many sources.
Grounding and short circuits (at > 1 kV only)	This point is normally skipped with low-voltage installations.
Cover or block access to neighboring parts carrying a live voltage.	Avoid touching live components.

C.2 Testing in Systems

Power-up and repeat testing of DC systems is based on the same standards as for AC systems (IEC 60364-6:2016). However, there is a difference in the procedure for measuring loop impedance. A proposal for handling this in DC installations is described in section 12.1.2.2.

Annex D Test Results from DC-INDUSTRIE2

Extensive tests were carried out in the model applications and transfer centers of DC-INDUSTRIE2. This section documents key findings.

D.1 Parallel Connection of Power Supply Units

A series of measurements was carried out at the Lemgo transfer center to investigate parallel connection of active power supply units with common-mode filters. The power supply units used (AIC1: KEB Automation, AIC2: KEBA Industrial Automation) had similar characteristics (two-level topology, space vector modulation without the 3rd harmonic) but were equipped with different common-mode filters. Modulation of the devices was not synchronized. Figure D.1 shows how the power supply units were interconnected.

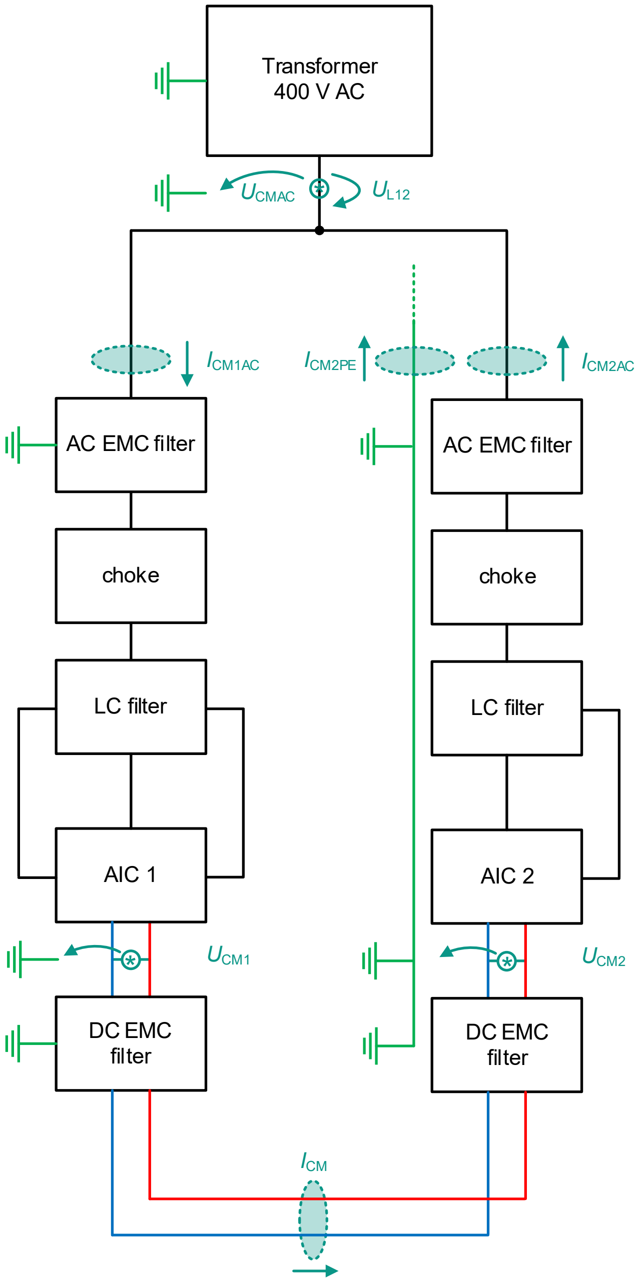

Figure D.1 Test setup for studying parallel connection of active power supply units

During the course of the test series, various parameters were adjusted to study how they influence the common-mode current flowing between power supply units (see Table D.1). Initially the power supply units were directly connected in parallel with identical switching frequencies and without any additional inductances.

Table D.1 Variations of parallel connection of suppliers and their effects

Parameters	Measurements	Results	Comments
Initial situation: operation of both AICs in a typical industrial grid with symmetrical load distribution	I_{CM} = 190 mA	Parallel operation works; moderate common-mode currents flow between the power supply units	-
Variation of common-mode inductance between the supply units 1. Removal of all HF filters 2. Installation of all HF filters (initial situation) 3. Installation of a common- mode choke with four cores and four windings 4. Installation of a common-mode choke with four cores and seven windings	 1. I_{CM} = 5.2 A 2. I_{CM} = 190 mA 3. I_{CM} = 160 mA 4. I_{CM} = 110 mA	Increasing the common-mode inductance between the power supply units reduces the common-mode current.	The common-mode inductances built into the AICs in the form of HF filters significantly reduce the common-mode currents. Increasing the common-mode impedance further only has minimal effects, since the flowing common-mode current mainly comprises frequency components below 1000 Hz.
Operation of both AICs at an artificial grid with large harmonic content: 3rd harmonic: 5%, 0° 5th harmonic: 6%, 0° 7th harmonic: 5%, 0° 9th harmonic: 2%, 0° 11th harmonic: 4%, 180°	I_{CM} = 170 mA	Grid distortions are not critical for parallel connection as long as both AICs are connected to the same grid.	This only applies if the distorted grid voltage has no effect or identical effects on the current controllers of both AICs. If the current controllers both respond differently to the distorted grid voltage, higher circular currents can be expected.
Introduction of an additional Y capacitance (40µF) to the DC grid	I_{CM} = 200 mA	An additional Y capacitance does not cause greater circular currents.	The leakage currents of the two AICs increase, resulting in greater loads on the common-mode chokes and making saturation more probable.
Asymmetrical load distribution 1. AIC 1: 20 kW, AIC 2: 10 kW 2. AIC 1: 10 kW, AIC 2: -10 kW	1. I_{CM} = 600 mA 2. I_{CM} = 1 A	An asymmetric load distribution results in different modulation degrees and therefore to modulating different common-mode voltages while increasing the common-mode circular current. The common-mode current increases with the variation in modulation.	The degree of modulation also depends on the filter design.
Operation of supply units in different grids 1. AIC 1 industrial grid, AIC 2 artifi cial grid w/o distortion°	1. I_{CM} = 460 mA	Operating in different grids with different distortion levels can result in common-mode currents between the	Unless the current controllers are affected by the distorted grid voltage, there should be

Parameters	Measurements	Results	Comments
2. AIC 1 industrial grid, AIC 2 artificial grid with distortion: ■ 3rd harmonic: 5%, 0° ■ 5th harmonic: 6%, 0° ■ 7th harmonic: 5%, 0° ■ 9th harmonic: 2%, 0° ■ 11th harmonic: 4%, 180	2. I_{CM} = 4.6 A	power supply units. The frequency ranges of the common-mode currents match those of the distortion.	no increase in the circular current.

D.2 Droop Curves

This section presents exemplary droop curves (see sections 3.17 and 10.3) for active infeed converters operated in parallel and an AIC with energy storage units. These have been successfully tested in several model installations and transfer centers.

The following studies were carried out in the HOMAG model application to test droop curves and verify stable grid operation. The DC grid is shown in Figure D.2. Areas Q1 and Q2 contained multiple AICs (from KEB and KEBA) that could be operated in parallel, as well as energy storage systems with capacitors (KEBA) and batteries.

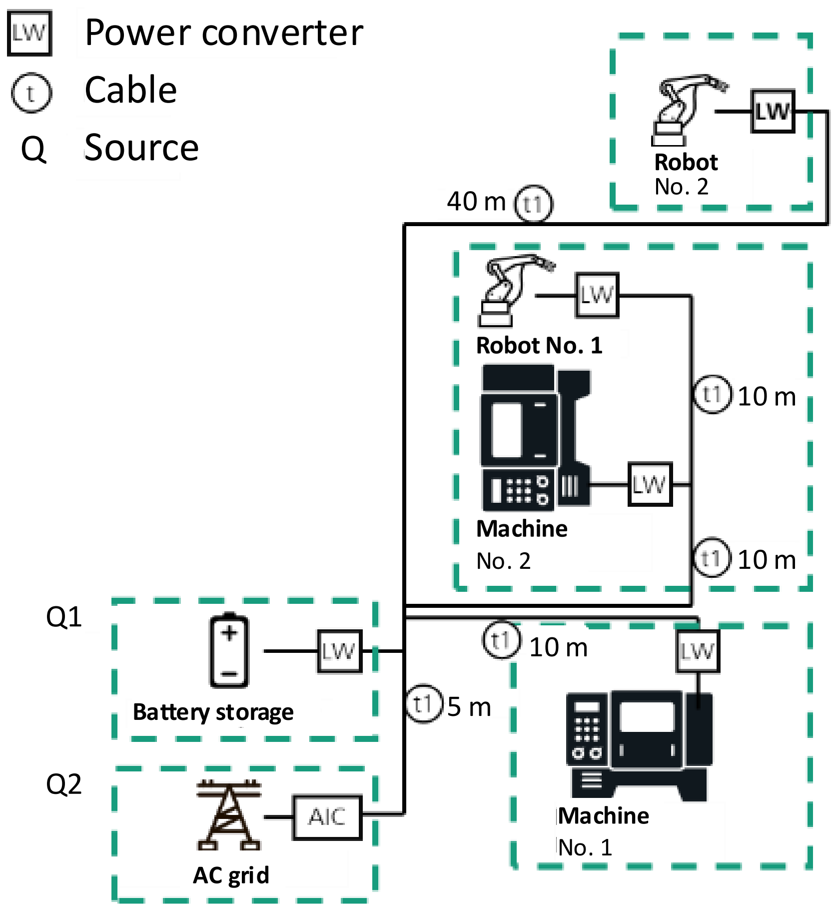

Figure D.2 Overview of the HOMAG model application for testing droop curves

D.2.1 Parallel Operation of Infeed Devices

To enable parallel operation of AICs at an AC-grounded grid, common-mode currents must be limited by meeting the conditions specified in 6.2.4. Appropriate droop curves must also be configured in both AICs.

In the HOMAG model application (and previously in the TH-OWL transfer center), parallel operation of a KEBA AIC with a rated power of 30 kW and a KEB AIC with a rated power of 60 kW was tested. To achieve uniform power distribution, the droop curves were chosen as shown in Figure D.3. In **zone 1**, both devices are suppliers. The same reference point of U_{Q1} = 700 V was selected for both devices, and the slopes $G_{Q1,KEBA}$ = 1 A/V and $G_{Q1,KEB}$ = 2 A/V were chosen corresponding to their rated power levels. In zone 2, neither device fed in or fed back power in order to fully utilize the storage capacity and prevent one device from feeding-in power while the other feeding-back power during idling mode, resulting in inaccurate voltage measurement. In zone 3, both devices fed power back. The same reference point $U_{S1} = 720$ V was chosen for both, and the slopes were determined based on their rated powers as in zone 1.

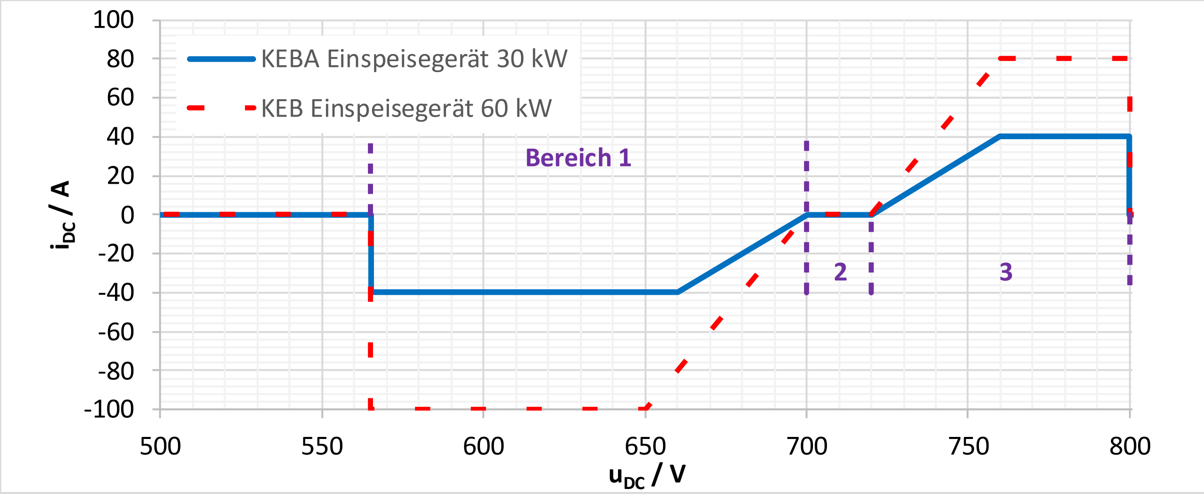

Figure D.3 Droop curves with parallel operation of KEBA and KEB infeed devices

D.2.2 Parallel Operation of an Infeed Device and Energy Storage System

To reduce peak infeed power at HOMAG, an active energy storage system from KEBA was operated in parallel with the KEBA AIC, which has a rated power of 30 kW. The energy storage system consisted of a highly dynamic DC/DC converter with a response time of 1 ms and an energy storage unit with high-performance capacitors. The latter charged and discharged in a controlled manner. The dynamically usable storage capacity was around 6 kJ. The AIC and energy storage system each had an active droop curve. There was no communication between the devices.

Figure D.4 shows the infeed power with and without the energy storage system. It can be clearly seen that the power peaks were reduced from around 38 kW to 26 kW. This corresponds to a reduction of over 30%.

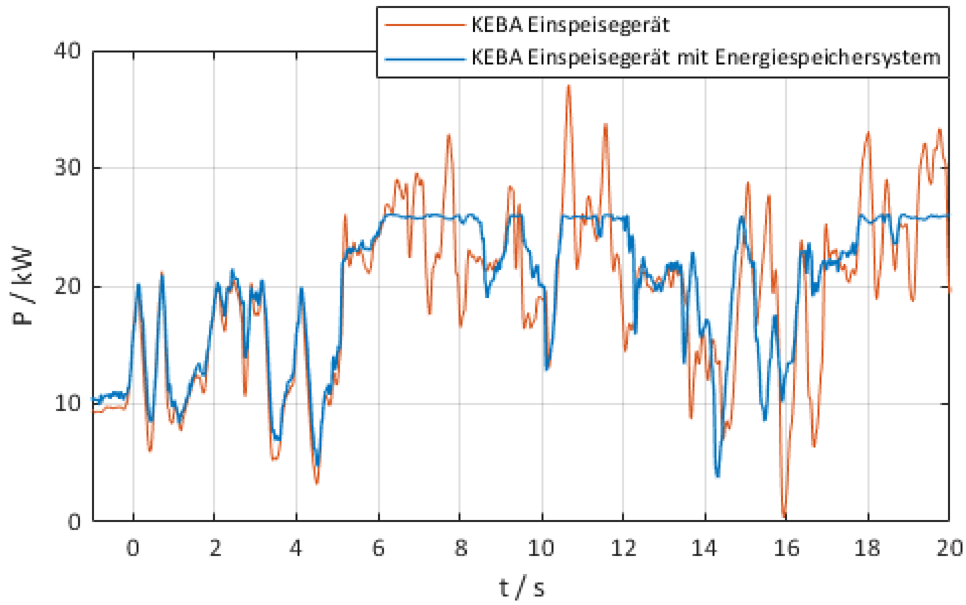

Figure D.4 Power variations of an infeed device with and without peak power reduction

Figure D.5 shows the selected droop curves. The maximum droop curve gain was chosen as G = 2.5 A/V to provide a sufficient margin from the limit of stability; see section 10.4.

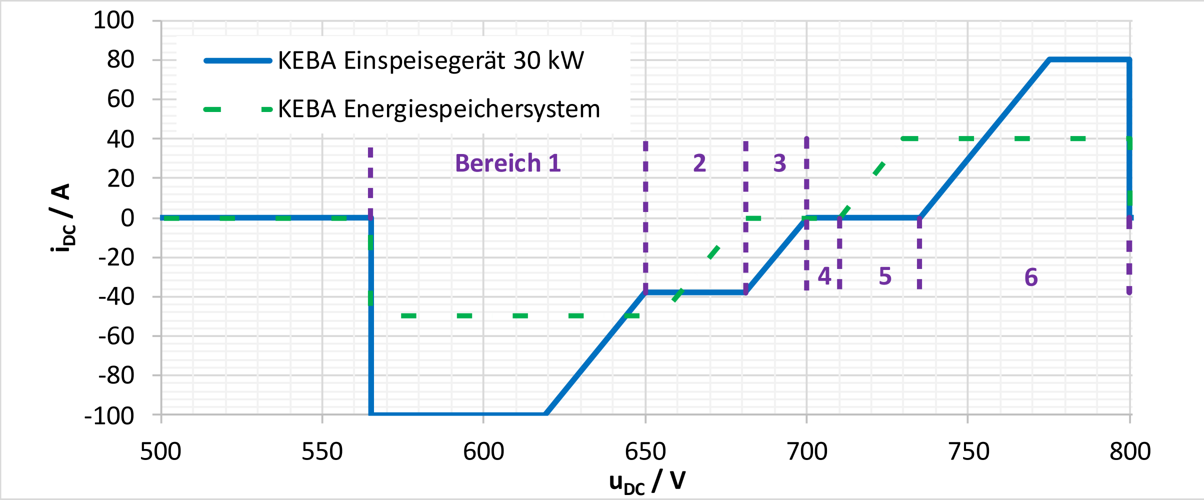

Figure D.5 Droop curves during parallel operation of the KEBA infeed device with the KEBA power storage system for reducing peak loads in the HOMAG model application

In idling mode, the system is in zone 4. If the grid is under load, the AIC supplies power in zone 3 up to the limit of 26 kW. This results in an inflection point at 680 V. In zone 2, the AIC provides a constant current and the peak power level is ensured by the energy storage system. In zone 1, energy is provided by the energy storage system and the AIC. If the energy storage system is completely discharged, only the AIC feeds into the DC grid. In zone 5, the recuperated energy is first absorbed by the energy storage system and only when this is full, or the power that can be fed into the storage system is exceeded is it fed back into the AC grid in zone 6.

Figure D.6 shows the power provided by the AIC and energy storage system. The limitation of infeed power to 26 kW is clearly visible. The graph in the middle shows the corresponding DC voltage, while the bottom graph tracks the charge level of the energy storage system. The control system in the energy storage system keeps the charge level at 95% in idling mode, thus ensuring constant readiness to reduce peak power levels.

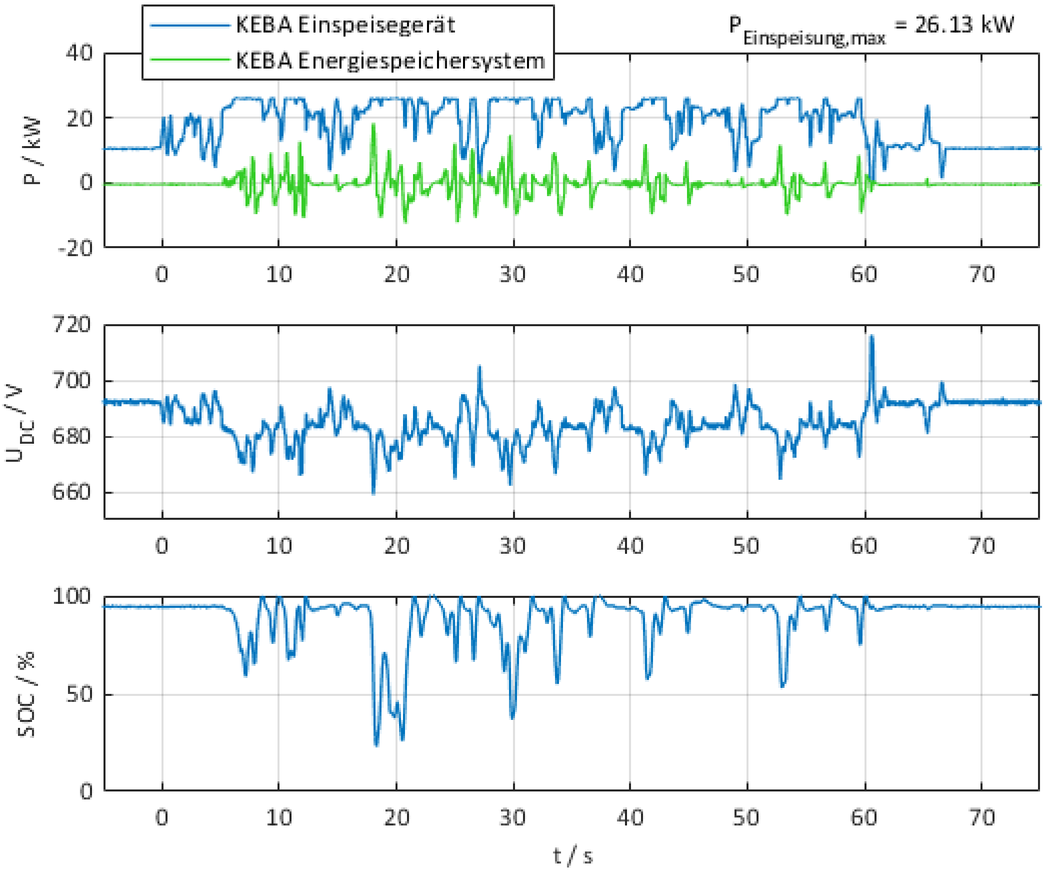

Figure D.6 Power, DC voltage, and state of charge with reduced peak output

The experiments showed that it is feasible to operate the AIC and energy storage system in parallel without communication between them. The fast control system of the energy storage system significantly reduces peak power, and the limited capacity of the storage capacitor is sufficient for meeting the system's requirements.

D.3 Stability of the DC Grid

Two test series were carried out in the Lemgo transfer center to study the grid's stability when grid resonances cause forced oscillations. Resonances corresponding to those of the stimulating source were deliberately introduced into the DC grid. The following were investigated:

- Stimulation by an inverter's switching frequency
- Stimulation by a B6 rectifier

D.3.1 Stimulation by the Switching Frequency of a Power Inverter

The test setup shown in Figure D.7 was used in this case. The film capacitor and leakage inductance of the common-mode choke form a series-resonant circuit with the resonance frequency calculated below. The rectifier was uncoupled from the resonant circuit using a DC choke.

$$f_{res} = \frac{1}{2 \cdot \pi \cdot \sqrt{33\mu\text{H} \cdot 48\mu\text{F}}} = 3999 \text{ Hz}$$

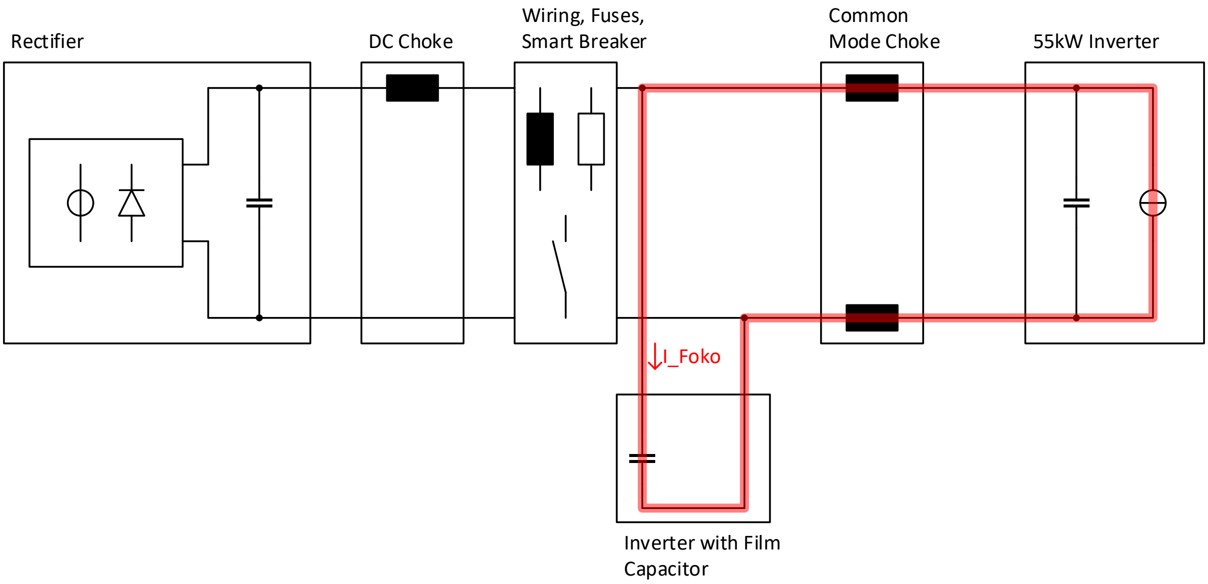

Figure D.7 Alternative setup for studying the resonance point at switching frequency

The resonant circuit is stimulated by switching the inverter at a frequency of 4 kHz. The current I_{Foko} flowing across the film capacitor is used to evaluate the quality of the resonance. The current across the film capacitor without resonance (i.e. without common-mode choke) is used as a reference value for purposes of comparison.

The measurement results in Figure D.8 show that the 4 kHz current flowing through the film capacitor with resonance is only 11% larger than without resonance.

It can be concluded from this that the resonance point is adequately damped and no critical currents flow.

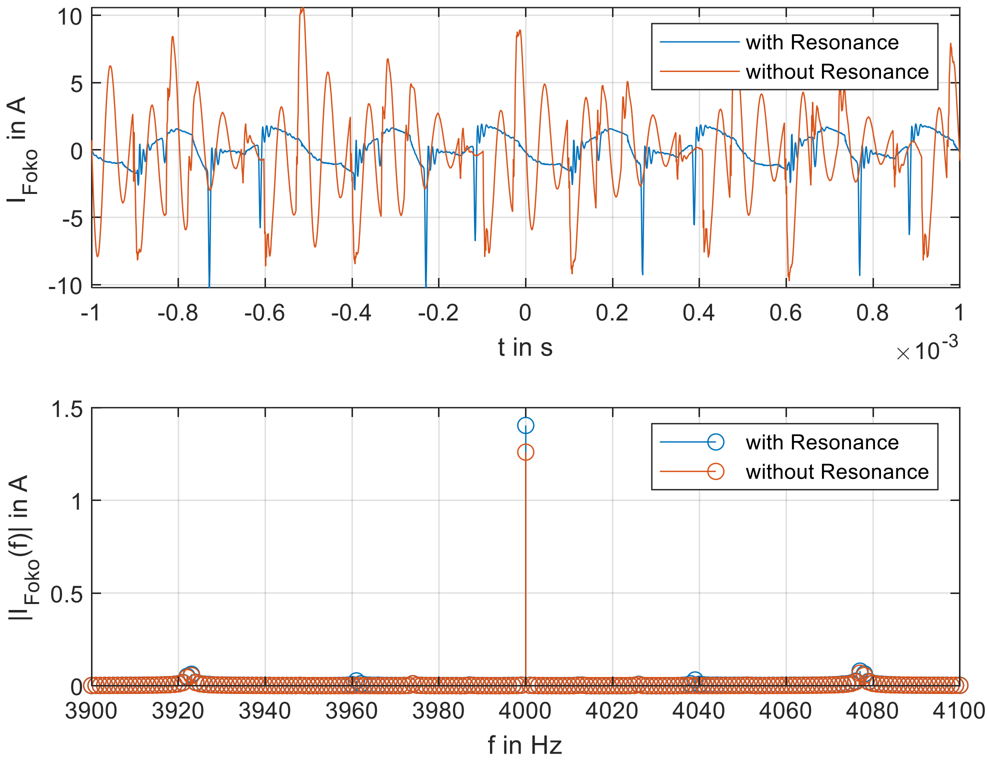

Figure D.8 Current flowing across the film capacitor with and without resonance [86]

D.3.2 300 Hz Stimulation by a B6 Rectifier

The setup from Figure D.9 was used here.

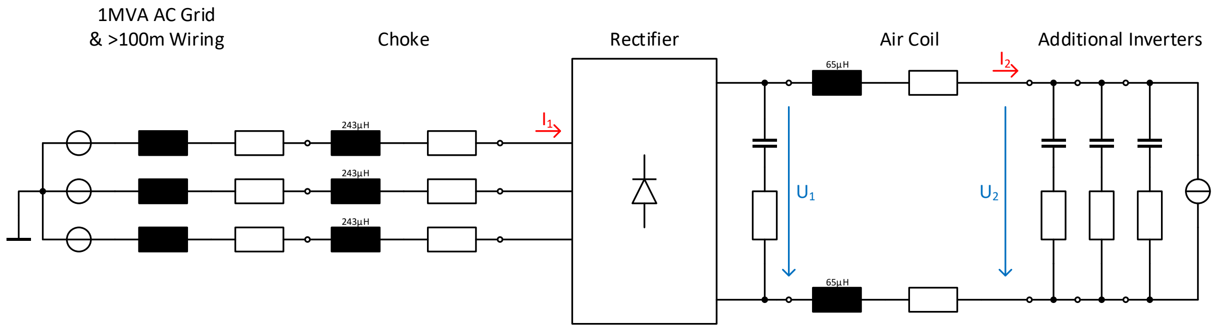

Figure D.9 Alternative circuit setup for studying the 300 Hz resonance point

The line choke, rectifier, air coils, and other converters were appropriately selected to create a resonance point at about 300 Hz. This resonance can be stimulated by the rectifier. For purposes of comparison, the air coil was removed to detune the resonance. The resulting impedance characteristics of the resonant circuits from the perspective of the stimulation source were calculated based on the values of the components (Figure D.10).

86 The high-frequency portions are not present with resonance due to the common-mode choke.

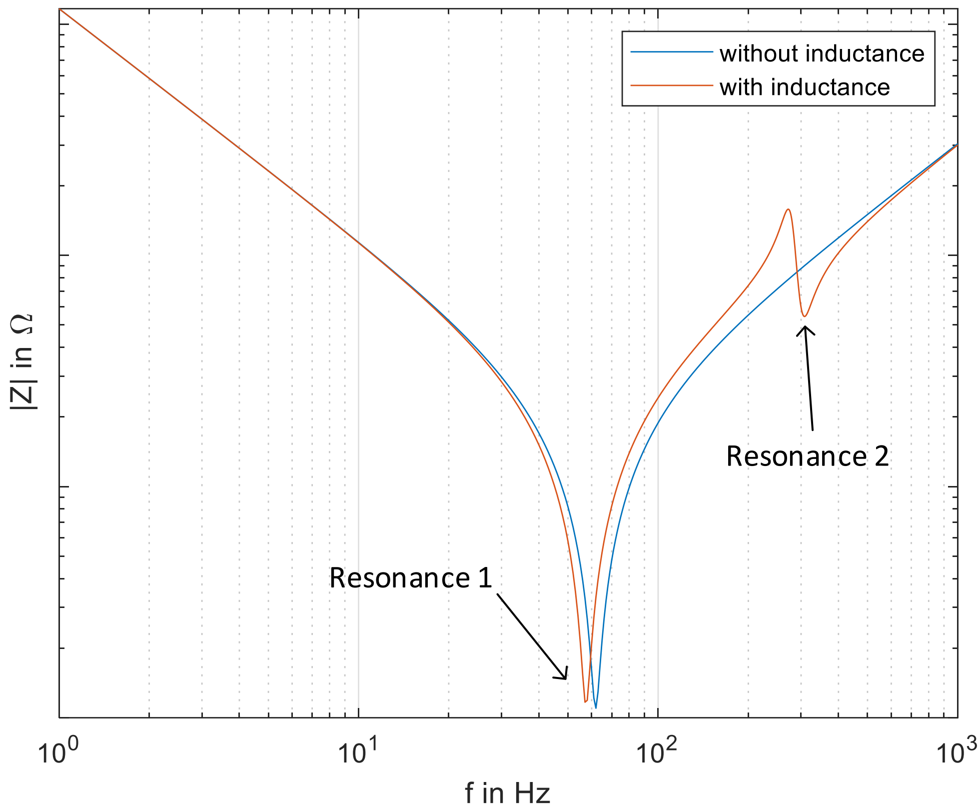

Figure D.10 Calculated impedance as a function of frequency in a setup for studying the 300 Hz resonance point from the perspective of the stimulation source

The current I_2 (see Figure D.9) is used to assess the quality of the resonant circuit. The reference value is the current I_2 in the setup but without the air coils and therefore also without the 300 Hz resonance. Without resonance, the currents and voltages shown in Figure D.11 can be measured while the rectifier is loaded with 30 kW.

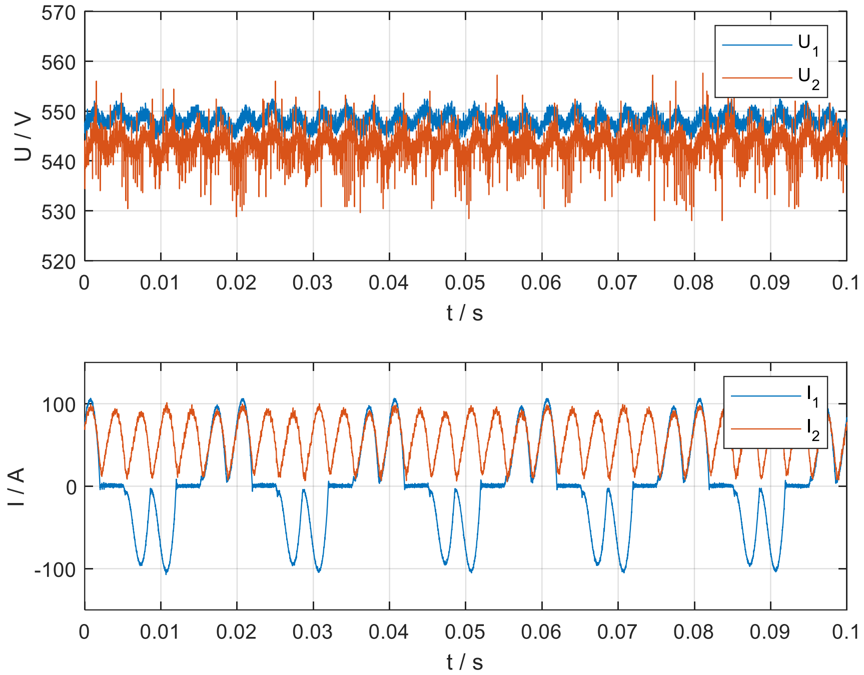

Figure D.11 Current and voltage over time without resonance at 300 Hz

A comparison of Figure D.11 and Figure D.12 reveals that the currents and voltages are significantly higher in the resonance case with an air coil (I_2 is 2.55 times larger than in the case without resonance). The resonance point is therefore weakly damped and can be excited.

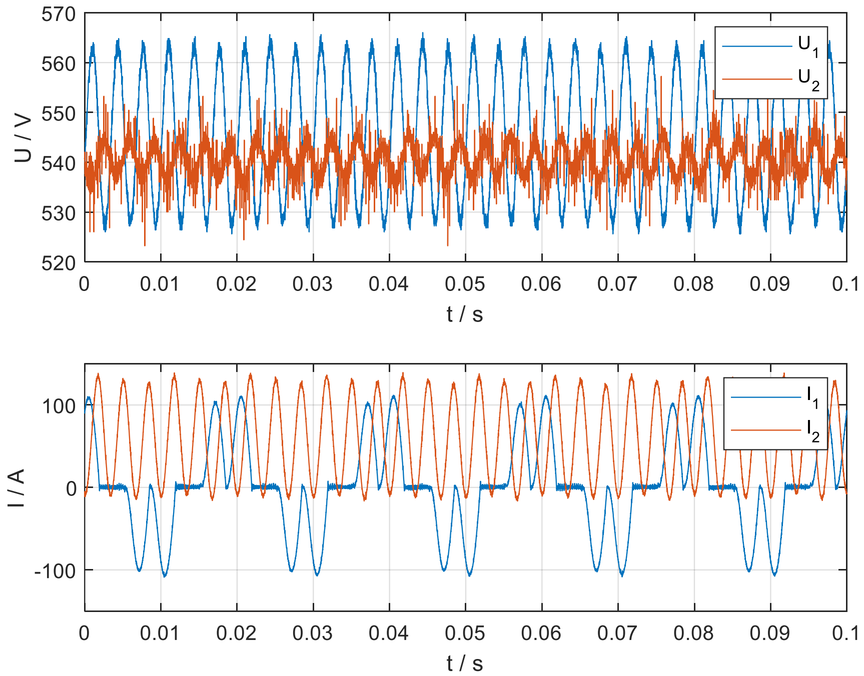

Figure D.12 Current and voltage over time with resonance at 300 Hz

It needs to be checked whether these currents may cause problems depending on how the capacitors in the rectifier are designed. As a rule, the DC grid's capacity is large enough (due to the many installed components) that the capacitors are normally (i.e., without resonance) only subjected to low

300 Hz currents. Consequently, if the 300 Hz currents increase as a result of resonance this will only rarely overload the capacitors.

D.4 Electromagnetic compatibility EMC

D.4.1 Emitted Interference

To validate the electromagnetic concept applied for radiated emissions (section 11.2), comparative measurements were performed of an AC-powered drive and a DC-powered drive with a long power supply cable (15 m) in an open outdoor environment. The studied drive system comprised an AC source (3 phase / 400 V grid, decoupled by an artificial mains networks), a 15 m power supply cable, an uncontrolled B6U rectifier, a drive inverter, an 8.5-meter-long (shielded) motor cable, an asynchronous motor with a flywheel, and various EMI filters. The photograph in Figure D.13 shows the setup.

Figure D.13 Outdoor test setup with long supply cable; the frequency converter is on the left and the power supply on the right

The wooden wall was four meters wide. A cable 15 m long was mounted on it and arranged in three loops. On the left behind the wooden wall was a wooden table on which the inverter was placed. The asynchronous motor was placed behind it. On the right behind the wooden wall was an AC artificial mains networks that supplied the power for the setup. The center of the loop antenna (R&S HFH2-Z2) was about 1.5 m above the grounded floor at the same height as the mounted cable. The EMC test receiver was inside a wooden housing behind the loop antenna and is not visible in this photograph.

The artificial mains network (a Schwarzbeck NSLK 8163) was used to decouple the setup from the AC grid and provide a defined AC grid impedance. It was also placed behind the wooden wall, which is why it cannot be seen in Figure D.13.

A 15m-long standard AC cable (H07RN-F 5x6) was used at the wooden wall and operated with either DC or AC depending on the experiment. At the ends of the cable there were adapters from CE to open cable ends to which the devices were connected.

A standard frequency converter was operated in U/f mode at a switching frequency of 4 kHz. The inverter was connected to an asynchronous motor using an 8.5m-long shielded motor cable. It was possible to power the inverter with either DC or AC current. No EMI filters were installed in it. The output frequency of the inverter remained constant at 20 Hz and was not changed during the experiments.

A total of five variations of the setup were implemented. For each of the five variations, measurements were made at three points of the loop antenna:

- **Point 1**: 0° with respect to the wooden wall (as shown in Figure 2), with the loop antenna parallel to it.
- **Point 2**: 90° with respect to the wooden wall, in other words the antenna was at a right angle to the wooden wall.
- **Point 3**: 0° with respect to the ground, i.e. the central axis of the antenna was vertical.

The magnetic field strength, as the evaluation criterion, was measured from a distance of 10 meters using a loop antenna. Five variants were measured as described in the following subsections.

D.4.1.1 Measurement 1: AC Power Supply Without a Filter

In this measurement, the inverter was powered via its AC terminals. No EMI filters were installed (Figure D.14). As a result, high-frequency capacitive leakage currents flowing from the motor to ground could only return to the inverter via the grid simulator and mounted cable.

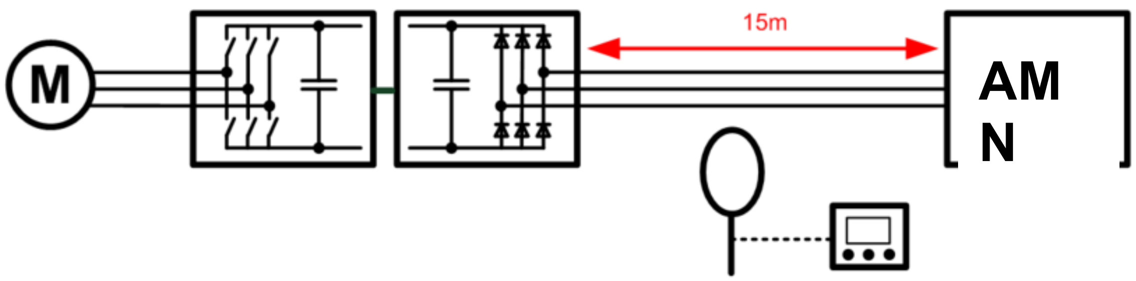

Figure D.14 AC power supply without radio interference filter

D.4.1.2 Measurement 2: AC Power Supply with Filter

This variant corresponds to the approach that is typically taken for AC systems. In contrast to Figure D.14 a typical AC line filter specifically designed for the frequency converter (with a suppression level of C1 @ 50m / C2 @ 100m motor cable) was used.

As a result, the leakage currents could flow back to the inverter via the motor shield, and the mounted power supply cable did not have to carry these high-frequency currents. In this configuration, the measured emission levels were therefore only slightly higher than those in the no-load state.

D.4.1.3 Measurement 3: DC Power Supply without Filter

Like in the variant „AC power supply without filter,” here HF leakage currents could not be directly led back to the inverter and therefore had to flow via the long power supply cable instead. This resulted in high levels of electromagnetic interference (EMI) radiation.

A B6U rectifier without integrated filtration was used to generate the DC voltage.

D.4.1.4 Measurement 4: DC Power Supply with Filters at the Inverter and Rectifier

This variation complies with the system concept, a DC filter was installed at the inverter, a DC filter was placed in front of the rectifier, and an AC filter was positioned after the rectifier (Figure D.15). The two additional filters suppress the emissions generated by the rectifier. In this setup, the HF leakage currents could flow directly from the motor cable shield across Y-capacitors in a DC-HF filter that was integrated directly into the inverter corresponding to the system concept. No significant emissions were therefore expected.

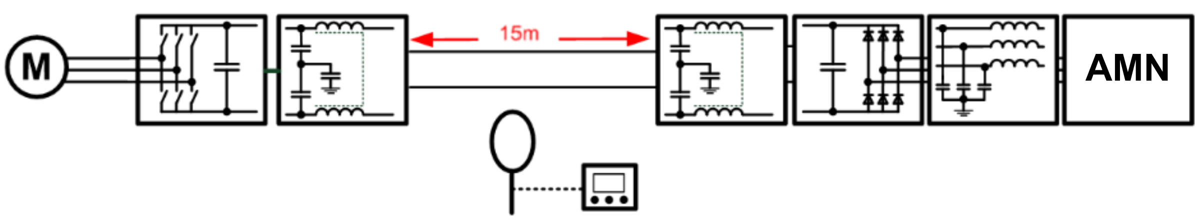

Figure D.15 DC power supply with radio interference filters at the inverter and rectifier

D.4.1.5 Measurement 5: No-Load Measurement

Here the power supply was simply turned off. This variation served as a reference for identifying any external emission sources. By comparing with the other results, it was possible to determine whether any interference was attributable to the system itself.

D.4.1.6 Results of Comparative Measurements

The following measurements have been selected as examples for quantitatively assessing the differences between AC and DC emissions. Across all measurements, the results obtained with the peak detector were consistently about 10 dB higher than those obtained with the average detector. The following graphics therefore only show the peak values.

Figure D.16 compares all peak value measurements made with the antenna at 0° to the wall (position 1), Figure D.17 with the antenna at 90° to the wall (position 2), and Figure D.18 with the antenna parallel to the ground (position 3).

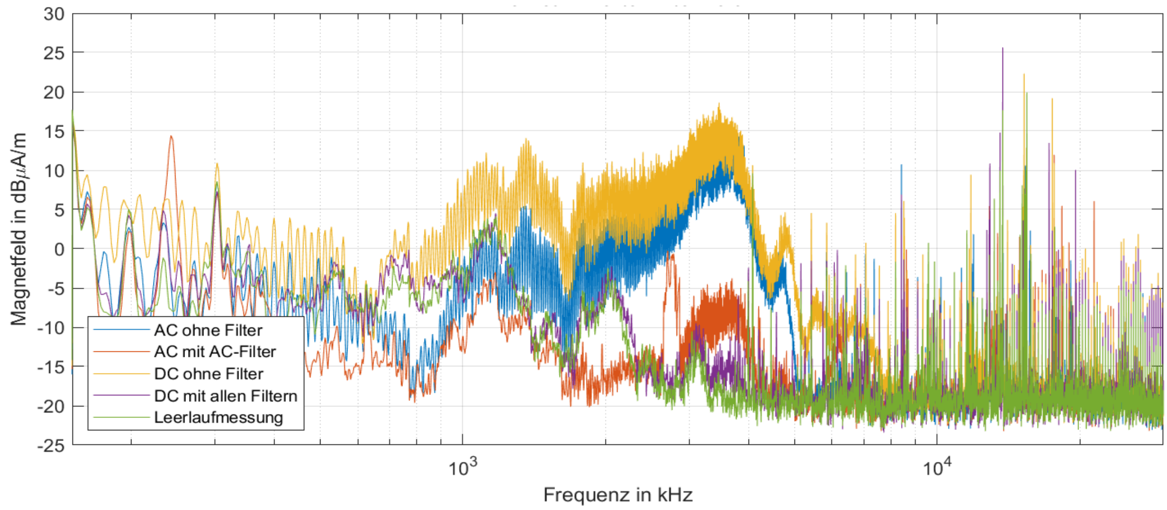

Figure D.16 Comparison of all peak values, antenna 0° to the wall (position 1)

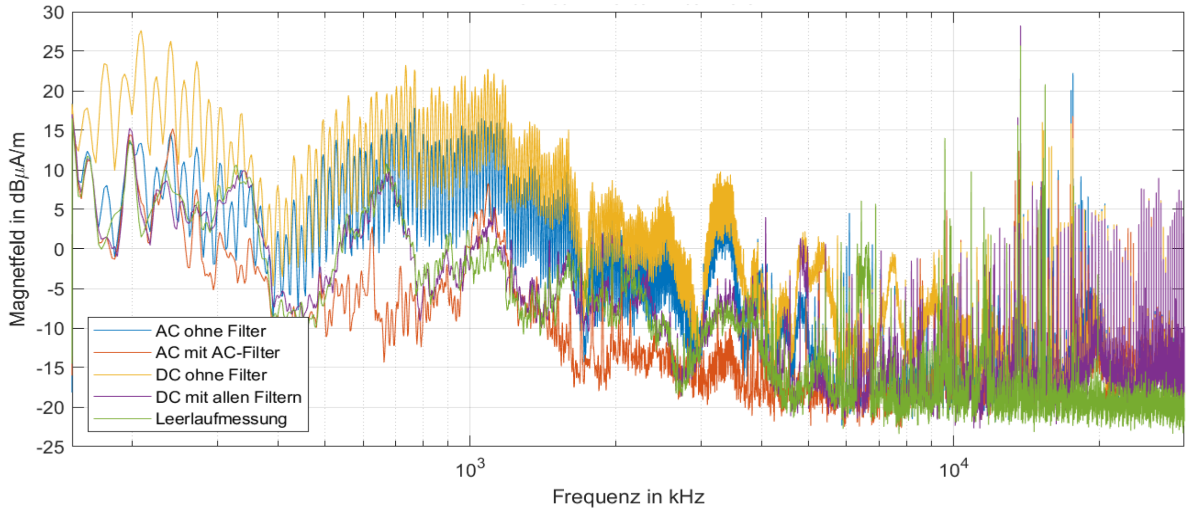

Figure D.17 Comparison of all peak values, antenna 90° to the wall (position 2)

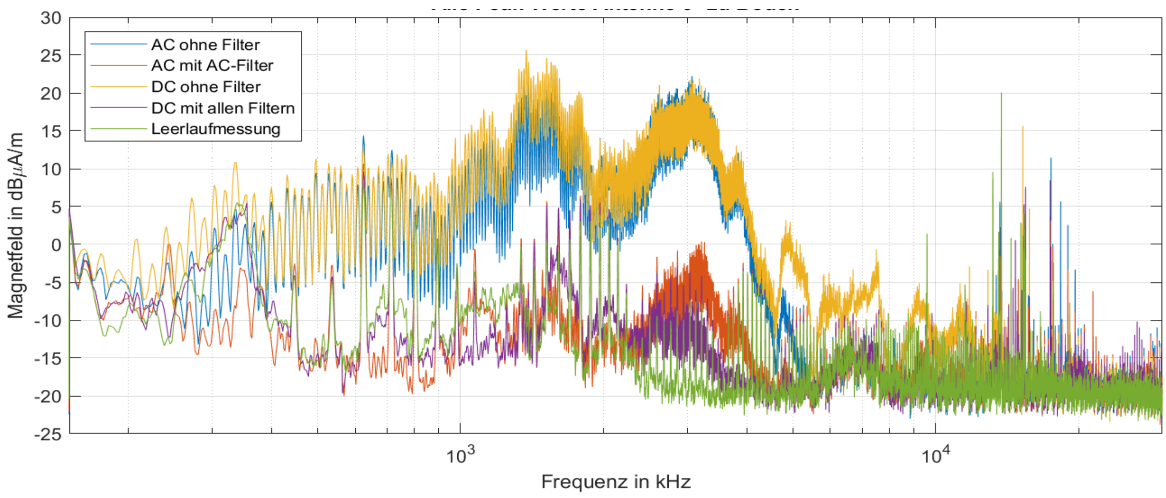

Figure D.18 Comparison of peak values with the antenna parallel to the ground (position 3)

The following conclusions can be drawn:

- Emissions in the variations without filters were consistently higher when powered by DC than by AC. The overall trends and maximum values are very similar, however.
- The measured levels depended greatly on the orientation of the loop antenna toward the wall, especially without filters (yellow and blue).
- At frequencies below 1 MHz, the measurements in Figure D.17 (receiving antenna at right angle to the source and also at right angle to ground) were up to 20 dB higher than in Figure D.18 (antenna parallel to ground).
- In the frequency range of 1-2 MHz, the levels were similarly high with all antenna orientations.
- At frequencies above 9 MHz, all of the measured levels shown in Figure D.16 and Figure D.18
- were in the same range as the no-load measurement. However, Figure D.17 exhibits significant deviations. The increased levels occurred in this orientation for both AC and DC power. At slightly higher frequency resolutions, it can be seen that the local maxima had a frequency spacing of approximately 30 kHz. The cause of these maxima could be, for example, the switch-mode power supply in the inverter. Since the variation of the external filters did not attenuate the power levels, it can be assumed that the radiation occurs directly from the inverter instead via the mounted cable.

The most important finding is:

- With filter elements as described in chapter 11.2, the measured levels do not differ significantly from the no-load measurement with both DC and AC power supply.

It can therefore be concluded that:

- If EMC measures are implemented as shown in Figure 11.5, no shielding of the DC grid cables is required.

D.4.2 Measurements with various artificial mains networks (AMN)

To qualify devices in the frequency-range from 150 kHz to 30 MHz, it is not usual to measure the radiated magnetic field strength. Instead, the disturbance voltage is measured using an artificial mains network. For AC-powered devices, the 50Ω/50µH-AMN described in EN 55016-1-2 is normally used [87]. For DC-powered devices, EN 55011 suggests using a 150 Ω-AMN, which can be used to measure symmetrical, asymmetrical, and unsymmetrical disturbance voltages [88].

87 For limit values, see EN 55011:2016, table 2.

88 For limit values, see EN 55011:2016, table 3.

Figure D.19 compares measurements that were made at standard industrial inverters using both AMN (50 Ω and 150 Ω). Both were supplied with 500 V DC voltage from a laboratory power source. A measurement without EMI filters was also made to demonstrate the filter's effect.

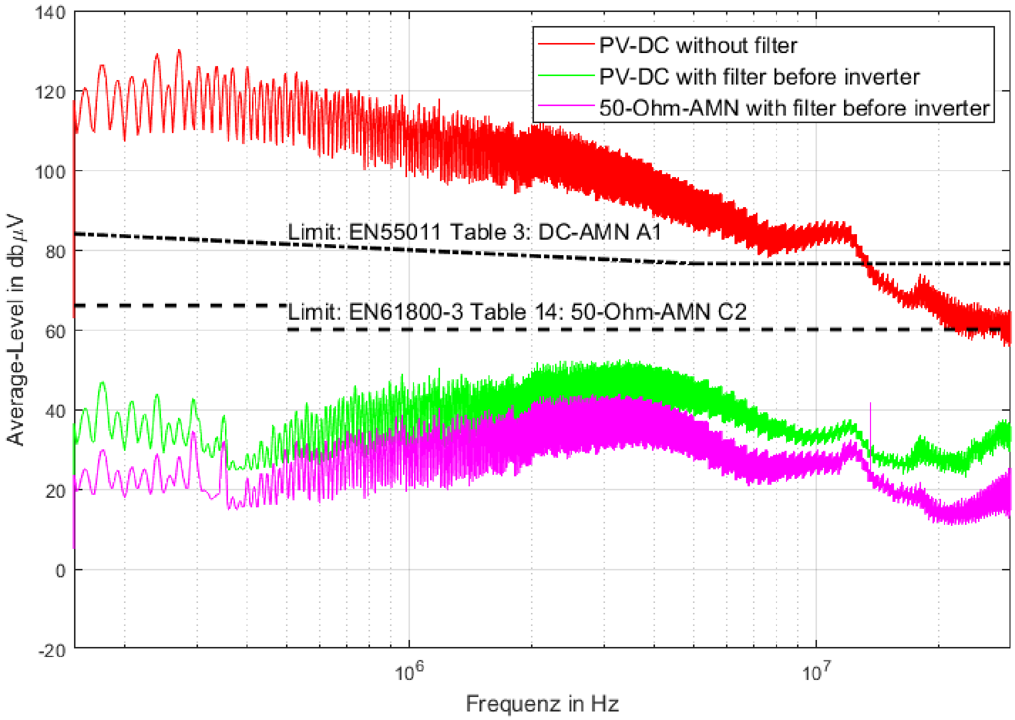

Figure D.19 Comparison of measurements made with two AMN

It can be observed that the green and magenta curves in the graph maintain a nearly constant distance from each other. The measurement values obtained with the DC-AMN are around 10 to 20 dB higher, depending on the frequency range, than those from the 50 Ω grid simulator. Both can therefore be used to assess emitted interference if the limit characteristics are appropriately chosen [89].

Evaluation of the technical specifications of commercially available AMN revealed the following disadvantages:

- Not all 50 Ω AMN are suitable for high DC voltages (> 600 V).
- It can be necessary to install an additional EMC filter between the power supply and the 150 Ω AMN since the grid it has low capacitances against PE (protective earth).

For this reason, we recommend using the 150 Ω-AMN which is established for PV grids.

D.5 AC Voltage Component (Ripple Voltage)

For various reasons e.g. size and cost electrolytic capacitors are typically used in the DC links of drive inverters or power supplies. Due to the ripple current load, these components are subject to significant ageing. Also, when using other capacitor types, such as film capacitors, the amount of ripple current must be known in order to estimate their life expectancy.

Aging of electrolytic capacitors depends mainly on the following factors:

- The ambient temperature
- The applied voltage
- The AC component of the current

89 Limit values: see EN 55011 table 3 for DC grid simulators and IEC 61800-3 table 14, C2 environment for 50 Ω AMN.

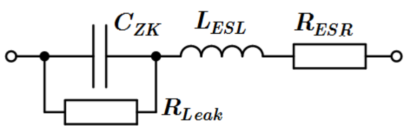

Figure D.20 Simple equivalent circuit of an electrolytic capacitor

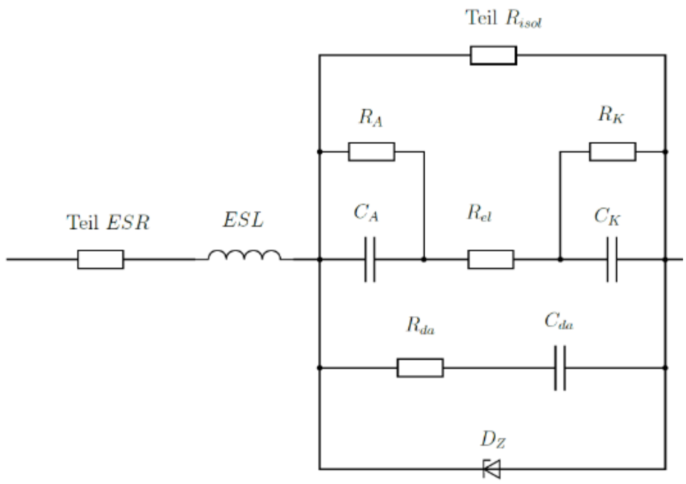

Figure D.21: Extended equivalent circuit of an electrolytic capacitor

Figure D.20 shows a simple equivalent circuit of an electrolytic capacitor, Figure D.21 shows the extended version.

The life expectancy of an electrolytic capacitor can be calculated from the relevant factors, for example using this equation:

$$L_X = L_0 \cdot \underbrace{2^{\frac{T_0 - T_a}{10K}}}_{Temperature} \cdot \underbrace{K_i^{\left(1-\left(\frac{I_a}{I_0}\right)^2\right)\cdot\frac{\Delta T_0}{10K}}}_{RippleCurrent} \cdot \underbrace{\left(\frac{U_0}{U_a}\right)^n}_{Voltage}$$

The individual parameters are listed in Table D.2 below. Detailed calculation instructions, influencing factors, and relevant data can be obtained from the datasheets or capacitor manufacturers.

Table D.2 Parameters for calculating the life expectancy of an electrolytic capacitor

L_X	resulting life expectancy	L_0	nominal life expectancy	K_i	safety factor (2-4)
$\boldsymbol{I_a}$	**actual ripple current**	I_0	nominal ripple current	n	exponent (3-5)
T_a	actual ambient temp.	T_0	nominal temperature	ΔT_0	overtemperature core (≈ 5-10 K)
U_0	rated voltage	U_a	actual voltage		

The factor $\boldsymbol{I_a}$ plays a special role because it cannot be determined by a simple measurement. Because switching devices emit not just a single frequency into the DC grid but also harmonics of it, these must be taken into account as well. The RMS current acts as the load on the capacitor, which includes all ripple components weighted based on their frequency. Mathematically, the following formula can be used to calculate the RMS current of I_a:

$$I_a = \sqrt{\left(\frac{I_1}{F_1}\right)^2 + \left(\frac{I_2}{F_2}\right)^2 + \cdots + \left(\frac{I_n}{F_n}\right)^2}$$

To determine the individual currents corresponding to each frequency, it is necessary to apply a fast Fourier transform (FFT) to the high frequency sampled current signal. The test circuit described in 11.1.3 is simpler to use; its frequency behaviour automatically results in frequency-dependent weighting of the individual ripple current components.

A measurement involving the test circuit of a drive inverter is described here. The setup can involve a load set with two coupled electric motors for setting different operating points on the tested device. As shown in Figure 11.4, the device is powered via an decoupled DC source. The test circuit is integrated parallel to the DC terminals of the device under test, which simulates a grid component with a very small electrolytic capacitance. The power supply of the load drive inverter is independent of the inverter being tested. A corresponding setup is shown in Figure D.22.

The motor assembly shown was used to approach different operating points while the RMS currents emitted by the device under test were recorded by a multimeter integrated in the test circuit. These currents depend on the operating point of the device under test. In Figure D.23 the operating points are defined on the x-axis as a function of speed (degree of modulation) and torque (different colors). The measured ripple current (RMS value) at each operating point can be read on the y-axis. It can be clearly seen that increasing the motor current of the device under test (proportionally to the torque in the case of a synchronous motor) also increases the emitted ripple current. However, the ripple current does not reach its peak at maximum modulation but instead at 60-80% of the rated speed.

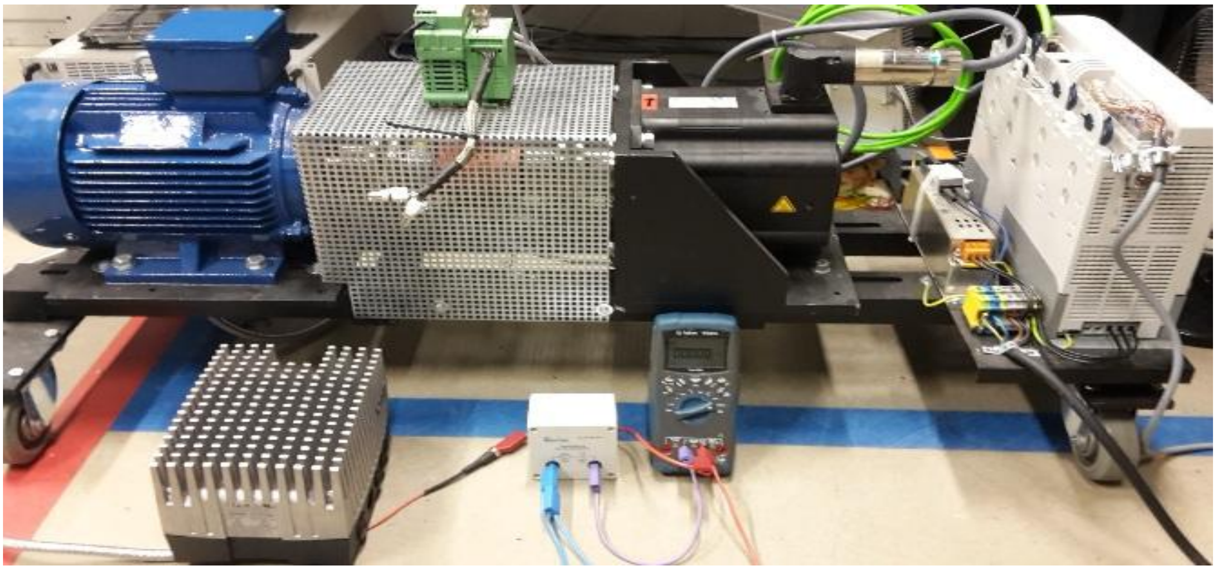

Figure D.22 Photograph of a test setup with power inverter (bottom left), test circuit, and multimeter (front center) and a load set with load drive regulator at the back

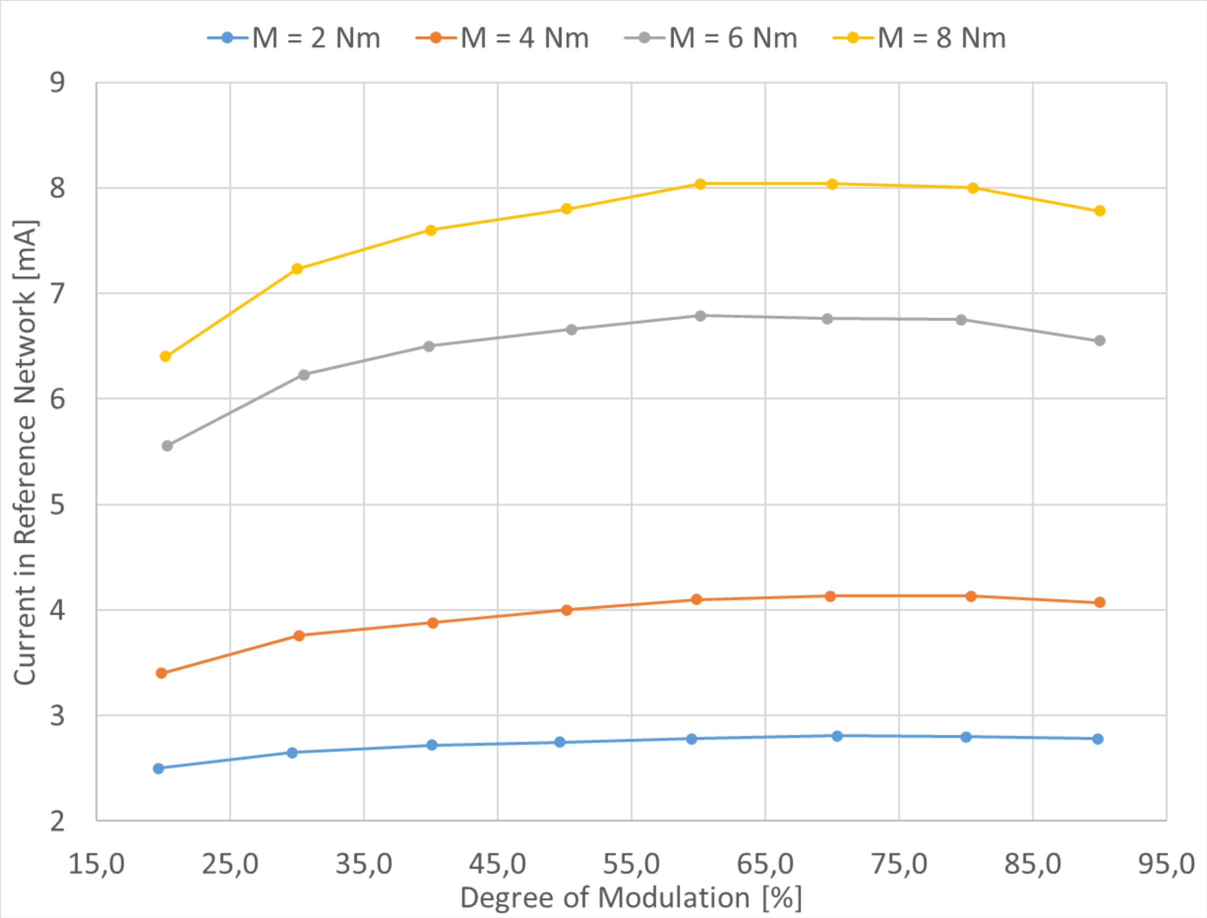

Figure D.23 Ripple current flowing from the device under test into the test circuit while operating a continuously excited synchronous motor.

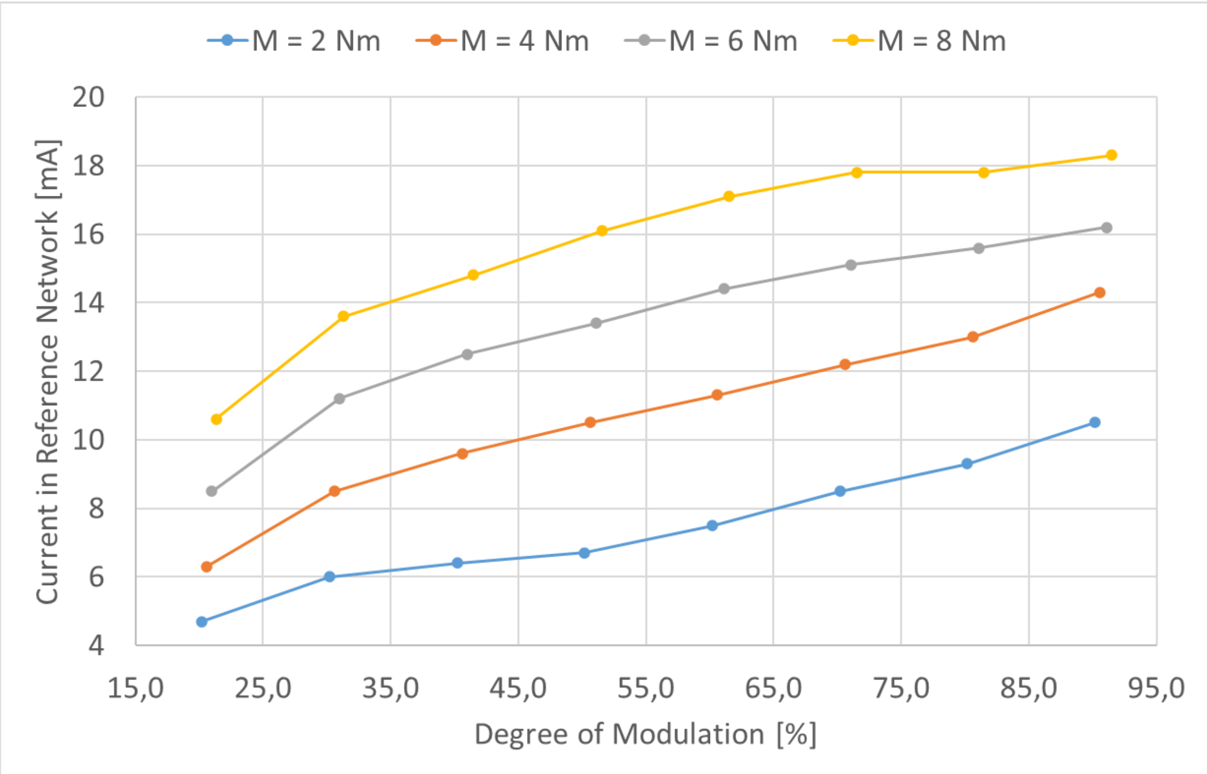

Figure D.24 Ripple current flowing from the device under test into the test circuit while operating an asynchronous motor

Figure D.24 shows the test results for the same device while driving an asynchronous instead of a synchronous motor. Here the maximum emitted ripple current occurs at maximum torque and maximum modulation. Overall, the ripple currents are higher compared to operating a synchronous motor, because here a significantly greater motor current is required to achieve the same torque.

Based on the measurements, it can be concluded that the ripple current depends on the operating point of the drive. The input device should be tested at the most unfavourable operating point. In order to evaluate it should be tested in most unfavorable operating point or through the typical operating cycle.

Two factors thus play major roles in evaluating the stresses resulting from ripple currents, both for individual devices and for devices used in combination:

1. To assess a **system**, it’s necessary to measure the ripple currents throughout an entire machine cycle. Measuring them only at a single point in time may result in an excessively high or low value. The overall load resulting from phases of high and low ripple currents, including recovery and pause times, over the device's lifetime also has to be considered. In a DC grid, the limit of the ripple current is 28 mA (see section 11.1.3).
2. To assess an **individual device**, it is necessary to make measurements at the operating point where the emitted ripple currents are largest. This point does not necessarily correspond to the maximum power level; it can vary depending on the individual components, such as different motors in an otherwise identical drive system. The limit of 40 mA must not be exceeded (see section 11.1.3).

D.6 Leakage Current Measurements

In the DC-INDUSTRIE2 Project, leakage currents were measured in several model applications. With power supplied from an AIC, only high-frequency leakage currents were measured in the range of the switching frequencies, which are no different from those that occur in AC-supplied frequency converters. In the case of power being supplied with a B6 rectifier, a 150 Hz component flowing to ground across EMC capacitors was also measured. Since larger installations also have a larger leakage capacitance, the 150 Hz leakage current must be considered when using a B6 rectifier for the power supply [90].

D.7 Series Arcs

Within the scope of DC-INDUSTRIE2, an appropriate setup was used to carry out series arc fault experiments in both the outgoing line to an individual load in a sub-circuit (see Figure D.25, item A) and the incoming line to an enclosure with the sub-circuits (see Figure D.25, item B). The crank mechanism shown in Figure D.26 was used for these tests. Cables with lengths of 41 m and 241 m with equivalent inductances of about 20 µH and 120 µH, respectively, were used (see Table 6.3 for additional details).

90 150 Hz leakage current can cause saturation of common-mode chokes installed before or after a B6 power supply.

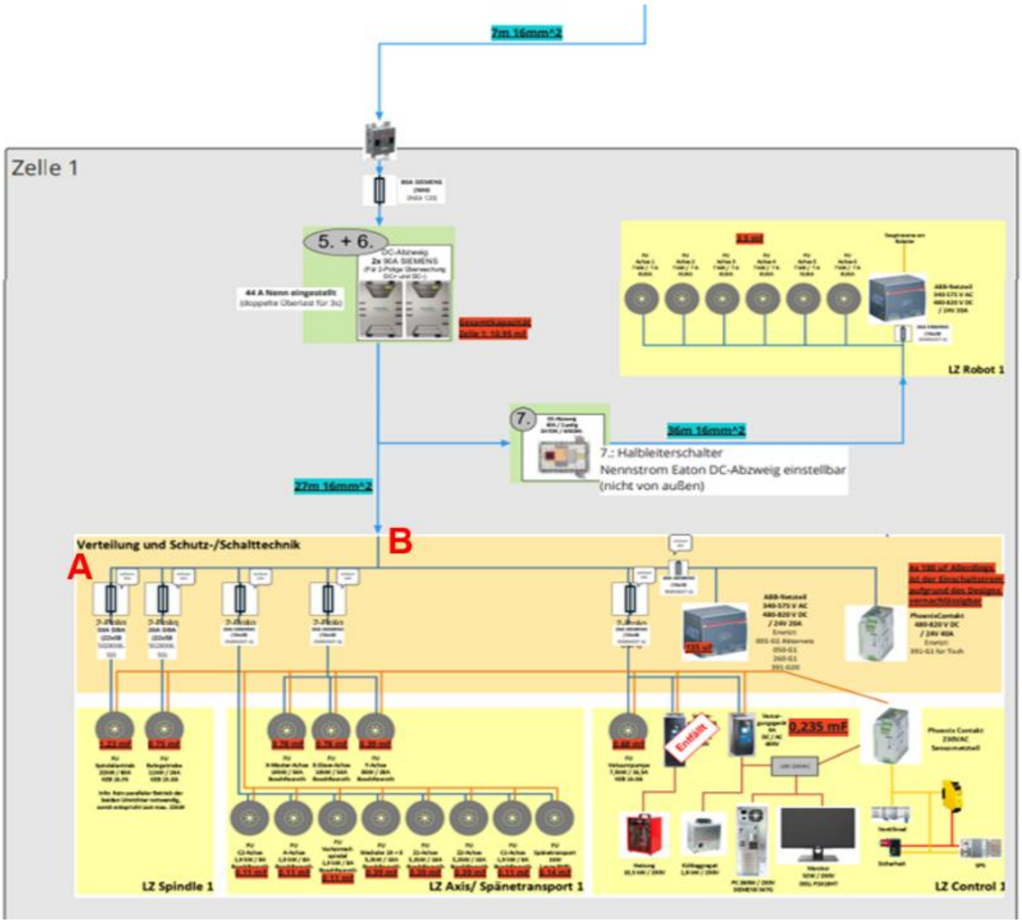

Figure D.25 Test installation for generating series arcs at positions A (within the sub-circuit) and B (infeed to the enclosure)

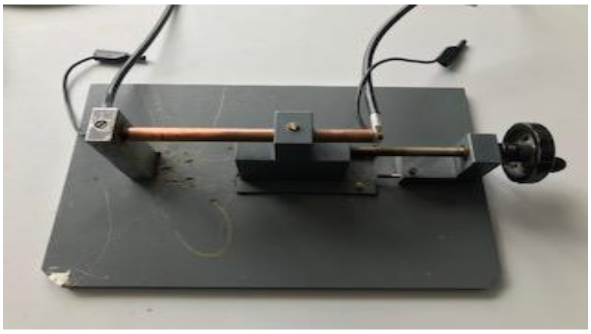

Figure D.26 Crank-operated device for opening contacts (shown here without its protective cover)

The following results were obtained:

- At low initial current values of up to 10 A and a cable length of 41 m, only short-lived arcs that abruptly extinguished were observed.
- With a longer cable (241 meters), an initial current of 22 A, and a constant gap set using the crank (see the photograph at Figure D.26), it was possible to create a stable arc that persisted until the contacts were opened further (see the waveform in Figure D.27). As the inverter capacitors continued discharging and the difference in potential between the open contacts increased, the arc then reignited and in many cases triggered the electronic overcurrent protection device used.

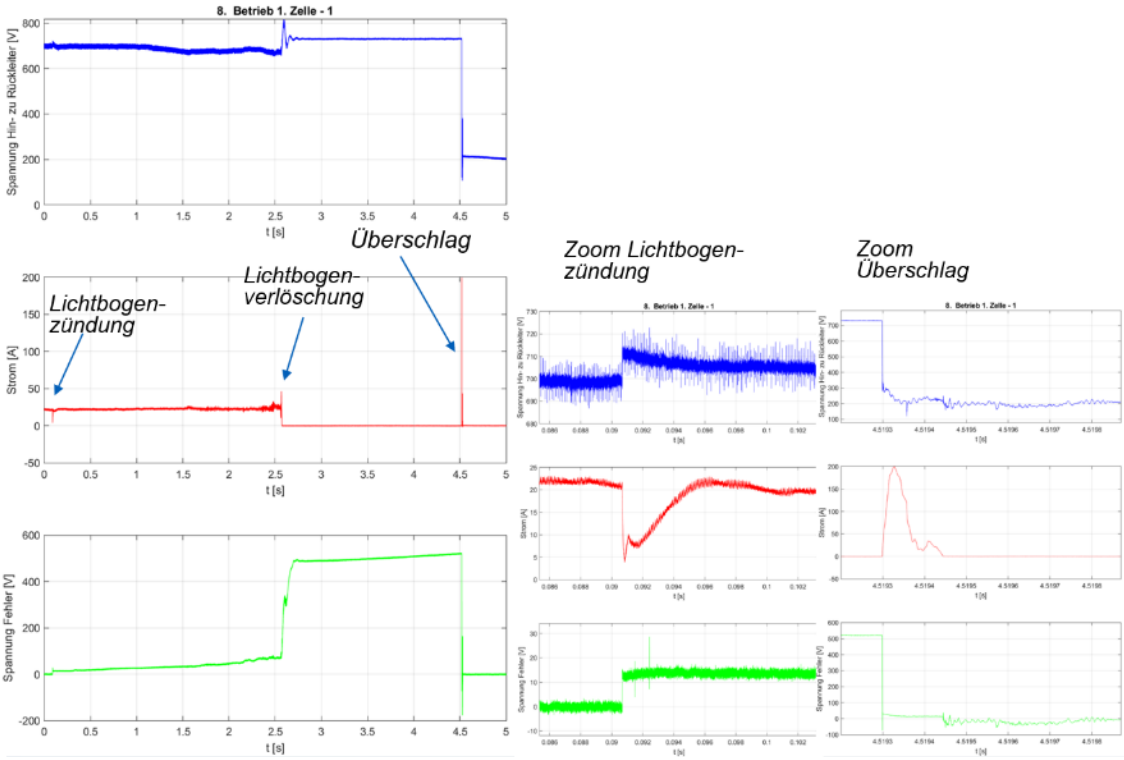

Figure D.27 Stable series arc in a test installation, extinguished by opening the contacts further (blue curve: voltage between line and neutral, red curve: current through the fault location, green curve (only measurable in the experiment): voltage across the fault location)

- With the long 241-meter cable and a lower initial current of about 12 A (as shown in Figure D.28 a stable arc did not immediately form after contact opening. However, if the contact gap was not increased rapidly enough, subsequent arcs occurred as a result of the decreasing voltage because of the inverter capacitor's idle state and the associated increase in potential between the open contacts at the fault location. This can result in repeating sequences of idle modes and arc reignitions (so-called corona discharges). With low positive arc reignition peak currents, however, it is possible for the current to remain above the zero line and produce a stable arc.
- A few times, resonant arc states were observed in the experiments. These can be explained with an arc model with an additional small-signal equivalent inductance and a negative small-signal equivalent resistance of a longer arc column.

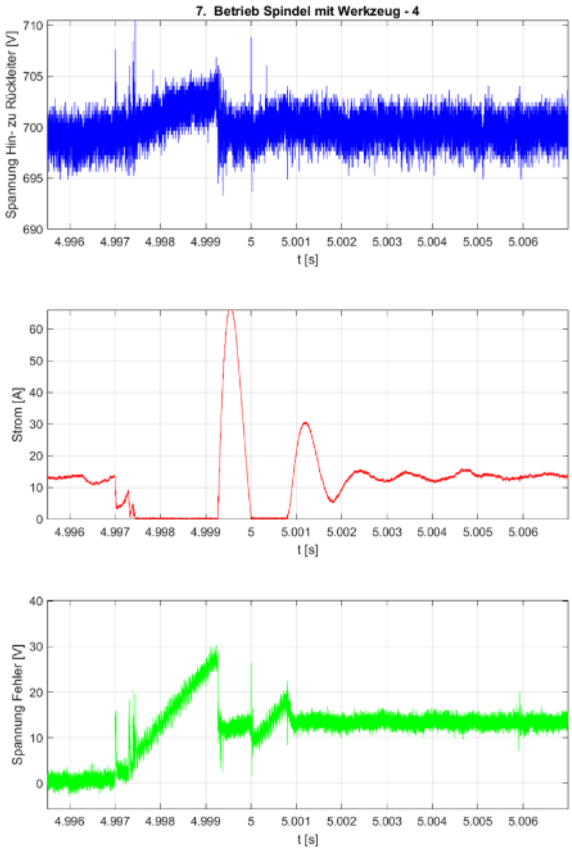

Figure D.28 Arc flashes followed by a stable series arc in a test installation
Blue curve: voltage between line and neutral, red curve: current across the fault location, green curve: (measurable only in the experiment) voltage accross the fault location

D.8 Short Circuits and Selectivity

About three dozen short circuit tests were carried out in the model applications of Homag and BMW and at the transfer center of TH OWL to study short-circuit behavior and selectivity. Different configurations with semiconductor and hybrid breakers as well as fuses were used.

The main findings were:

- All short circuits were detected and reliably separated by the protective devices.
- Selectivity is more challenging in systems with multiple sources than in traditional „top-down" structures.
- Selectivity (see section 3.18) toward parallel sectors improves when storage devices are connected to the DC grid. These devices inject current into the short circuit, thus facilitating activation of the protective device in the faulty sector.
- Semiconductor breakers are best-suited for achieving selectivity, both upstream and toward parallel and neighboring sectors (the topology is shown in Figure 12.12).

By finely adjusting the trip thresholds of the semiconductor breakers, it was even possible to achieve selectivity with only two parallel sectors and the same rated current without connecting any additional storage units to the network (experiments 20 and 21 at TH OWL).

Table D.3 shows an overview of the selectivity of various combinations of protective technologies (semiconductor, hybrid, fuse) in the infeed, at the yellow-highlighted fault location, and in parallel DC sectors, based on measurements performed at the transfer center of TH OWL.

Table D.3 Selectivity with different protection technologies

Infeed	Short circuit	Parallel sectors	If relevant, parallel capacitance at the grid	Result
Hybrid	Semiconductor	-		Selective
Hybrid	Hybrid	1 semiconductor		Nonselective (all sectors and infeed)
Hybrid	Hybrid	1 semiconductor	3.9 mF capacitance at the DC bus	Partially selective (parallel path triggered)
Hybrid	Hybrid	1 fuse	3.9 mF capacitance at the DC bus	Selective
Hybrid	Fuse	2 sectors: semiconductor	3.9 mF capacitance at the DC bus	Partially selective (parallel triggering)
Hybrid	Semiconductor	1 semiconductor (without reverse current detection)		Partially selective (parallel triggering)
Hybrid	Semiconductor	2 sectors: semiconductor (without reverse current detection) and a fuse		Partially selective (parallel triggering of semiconductor)
Hybrid	Semiconductor	3 sectors: 1 semiconductor (with-out reverse current detection) and 2 fuses		Selective
Hybrid	Semiconductor	1 × semiconductor with reverse current detection		Selective
Hybrid	Semiconductor	2 sectors: semiconductor and a fuse		Selective
Hybrid	Semiconductor	1 sector: semiconductor (very sluggish, without reverse current detection)		Selective
Hybrid	Semiconductor (slowest trip curve)	1 sector: semiconductor with re-verse current detection		Selective
Overcurrent device	Semiconductor (slowest trip curve)	1 sector: semiconductor with re-verse current detection		Selective

D.8.1 Selectivity with Semiconductor and Hybrid Breakers

By way of example, Figure D.29 shows the equivalent circuit diagram of test 20 of the TH OWL transfer center, with hybrid breaker Q1 as the infeed breaker for the DC grid and two semiconductor breakers Q12 and Q13, each connected to an inverter with a capacitance of 1.23 mF. The short circuit was created between breaker Q12 and inverter C1. The short circuit was detected and isolated exclusively by breaker Q12, thus ensuring total selectivity.

The prerequisite for this was setting both breakers to almost the same tripping value. Because the fault was rapidly detected and interrupted (within 30 µs), the small portion of the short circuit current supplied by the infeed (only about 5% of the total), which only flows across the breaker of the faulty DC Sector, was sufficient to trigger this breaker (Q12 in Figure D.29) while parallel breaker Q13 remained active to enable continued operation.

Only a small part of the current passed via the infeed breaker (hybrid breaker) Q1, which therefore did not trip.

Figure D.30 shows an example of how current and voltage develop over time during a short-circuit shutdown with semiconductor breakers from Figure D.29. The current in the short circuit sector (red) reaches its maximum after about 35 µs when the semiconductor breaker trips. The voltage in the grid (blue) remains within the permissible range, so operation of other parts of the system is not affected. The neighboring sector (dashed orange line) injects some current into the fault location, but this does not trigger its protective device (also a semiconductor breaker), thus ensuring total selectivity.

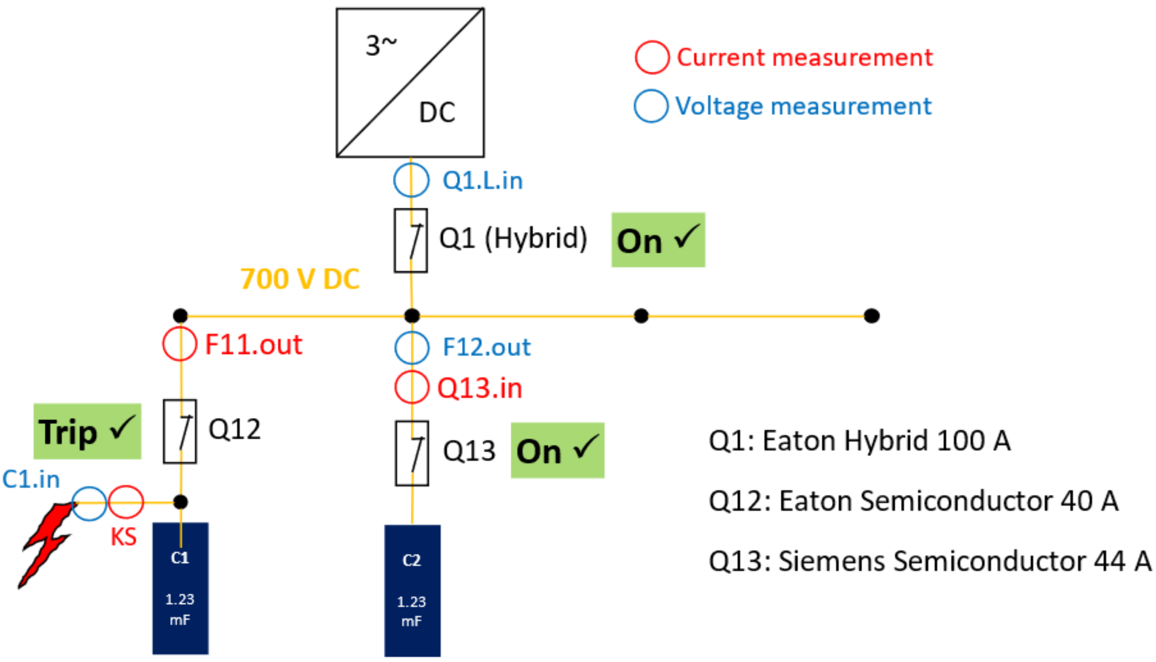

Figure D.29 Selectivity with two semiconductor breakers connected in parallel to the bus

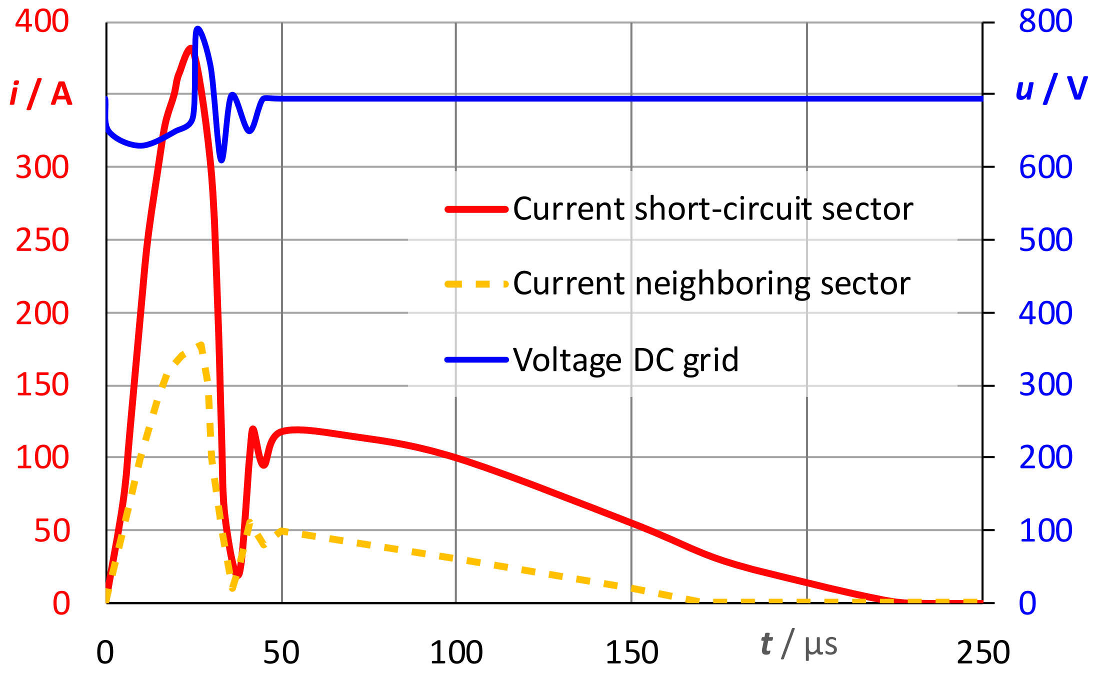

Figure D.30 Traces of current and voltage in a short circuit test with semiconductor breakers (experiment 20 at TH OWL, see also Figure D.29)

D.8.2 Selectivity with Semiconductor and Hybrid Breakers and a Fuse

In these experiments, a large capacitance (3.9 mF) and another DC Sector with a 20 A-fuse were connected to the DC bus parallel to the two semiconductor breakers. Figure D.31 shows the equivalent circuit diagram. The short circuit was induced downstream from fuse F7.

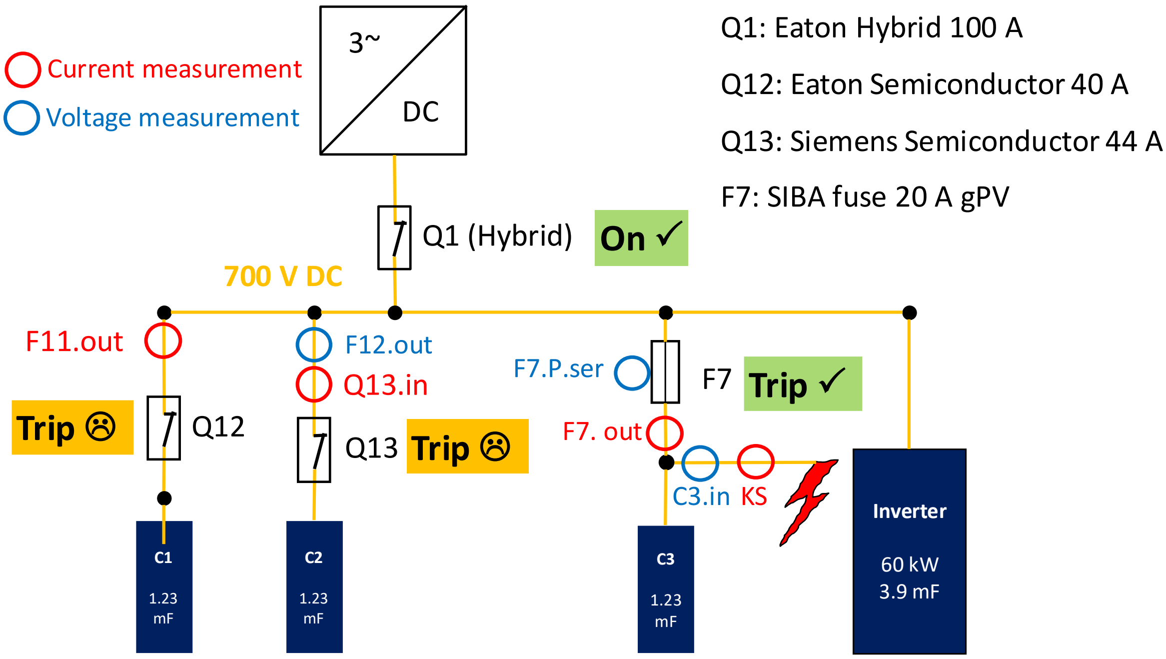

Figure D.31 Selectivity with semiconductor and hybrid breakers and a fuse (experiments 10-12, TH OWL)

In this case, although the 20 A fuse detected and disconnected the short circuit, the contribution of the short circuit current from the parallel-protected sectors with semiconductor breakers of the same capacitance caused these semiconductor breakers Q12 and Q13 to trip before the melting integral of the fuse was reached. As a result, parallel selectivity was not ensured.

Like in the experiment shown in D.29, only a small portion of the current reached the infeed hybrid breaker Q1, which therefore did not trip.

D.9 Ground Fault Experiments

The behavior of an AC-grounded DC grid in response to ground faults was studied in tests at the transfer center of TH OWL (Lemgo) and in the model application at BMW (in Dingolfing). The measurements focused on these aspects:

- Infeed devices: behavior of AICs and protection of freewheeling diodes
- Loop impedance (see also section D.9.2): the influence of AC grid impedance and prospective fault currents

Although conditions differ considerably between TH OWL and BMW in terms of available space and grid power, the basic setups and fault current paths were comparable as shown in Figure D.32.

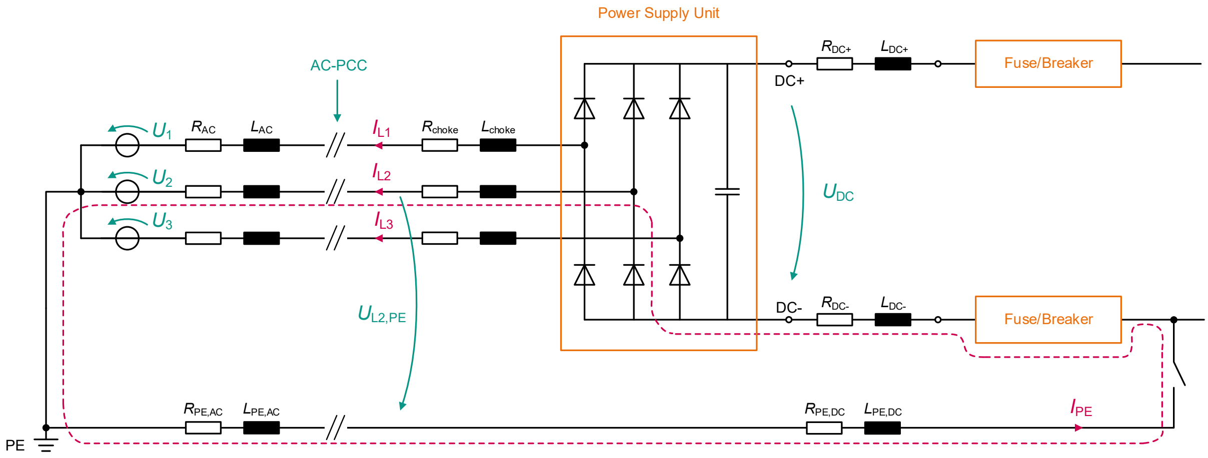

Figure D.32 Equivalent circuit for ground faults in a system grounded on the AC side

The supplying AC grid is modeled using the voltage sources U1, U2, and U3 and the impedances R_{AC} and L_{AC}. These impedances include all line and transformer impedances and describe the system up to the installation's AC grid connection point. If the supply is implemented with multiple interconnected transformers (like at BMW), this parallel connection must also be taken into account in the equivalent impedances.

The interface between the AC and DC networks is implemented with one or more power infeed devices. The behavior of these power infeed devices is explained in detail in section D.9.1.

In addition to the AC-side inductive filter components such as line reactors, DC-side impedances are also added to the fault loop (denoted as R_{DC-} and L_{DC-}). The DC-INDUSTRIE grid is primarily capacitive with little inductance. Pronounced inductances can typically only be expected in the form of current limiting reactors in hybrid breakers (see ch. 10.4.2). In other cases most of the DC-side inductance results from connective components such as cables and busbars. However, these elements also always introduce resistive damping to the system.

The circuit is completed by the impedance at the fault location (not shown in the illustration) and the impedance of the ground connection. The ground impedance is also interconnected and/or distributed and comprises both DC-side and AC-side portions as shown in the diagram.

D.9.1 Behavior and Protection of AICs

The infeed device with corresponding filter components (here R_{choke} and L_{choke}) is located at the system's AC connection point. Due to the functional benefits described earlier (see section 6.2.1), AICs are typically used as infeed devices. In conventional AICs, the operating current normally flows across the active semiconductors (e.g. IGBTs or MOSFETs), but if there is a ground fault it is switched through to the antiparallel freewheeling diodes of the inverter section instead. Whereas the active IGBTs or MOSFETs are quickly turned off (e.g. in response to detection of an overcurrent), the AC grid voltage continues to drive the current against PE across the described freewheeling or body diodes.

Here conventional AICs behave identically to a B6 rectifier. In the case of a single-phase ground fault as shown in Figure D.32, the equivalent circuit diagram can be simplified further to an M3 midpoint rectifier. Only the top or bottom three diodes can carry the fault current I_{PE}, owing to their polarity. In the depicted scenario, when the ground fault occurs the voltage $U_{L2,PE}$ is greater in magnitude than voltages $U_{L1,PE}$ and $U_{L2,PE}$, and the current therefore flows across phase L2.

As described in section 6.2.8.2, the AIC's freewheeling diodes must be protected or disconnected. In these tests carried out at the transfer center of TH OWL and in the model plant at BMW, ground fault tests were performed with both AICs and B6 rectifiers. The results showed that AICs can also be protected with fuses if their melting integrals are matched to the limiting load integral of the freewheeling diodes. If this matching is not feasible, a parallel B6 rectifier can be used to relieve the freewheeling diodes of the AIC during a fault and accept a significant portion of the fault current.

Both methods were exemplarily validated in the measurements. Alternative AIC and filter topologies can increase the cost and/or effort required to provide protection. Ultimately, however, manufacturers of infeed devices are obliged to ensure that the equipment is also protected in the event of a ground fault.

D.9.2 Loop Impedance

Loop impedance, in combination with the driving grid voltage, determines the possible fault current that can flow at a fault location. As already described, it consists of an AC-side and a DC-side component, and the inverter's transfer characteristic also has a (small) influence. The loop impedance can be determined using the method described in section 12.1.2.2.

In the tests carried out in the model plant at BMW, the AC-side grid impedance was both measured and calculated. The calculated impedance was 11.8 mΩ, while the measured impedance was 16 mΩ. This corresponds to prospective fault currents of 19.6 kA (calculated) and 14 kA (measured) for a supply voltage of 230 V (or 400 V phase-to-phase voltage). Although these values differ considerably from one other, they are in a similar order of magnitude. The discrepancies can be due to:

- Failure to insert transition resistances at connection points
- Neglecting the cross impedances when interconnecting the transformers' secondary terminals
- The load state of the transformers when measurements are performed

The time constant (equal to the ratio of inductance to resistance of the impedance (($\tau = L/R$)), was calculated to be 3 ms at the AC grid connection point.

There is also impedance on the DC side, as well as a voltage drop across the feeder. While the AC impedance typically dominates, this portion is also significant in large DC-side installations. This is explained below on the basis of two measurements. Figure D.33 shows a measured ground fault in the BMW plant with an interruption executed by a 160 A gR fuse:

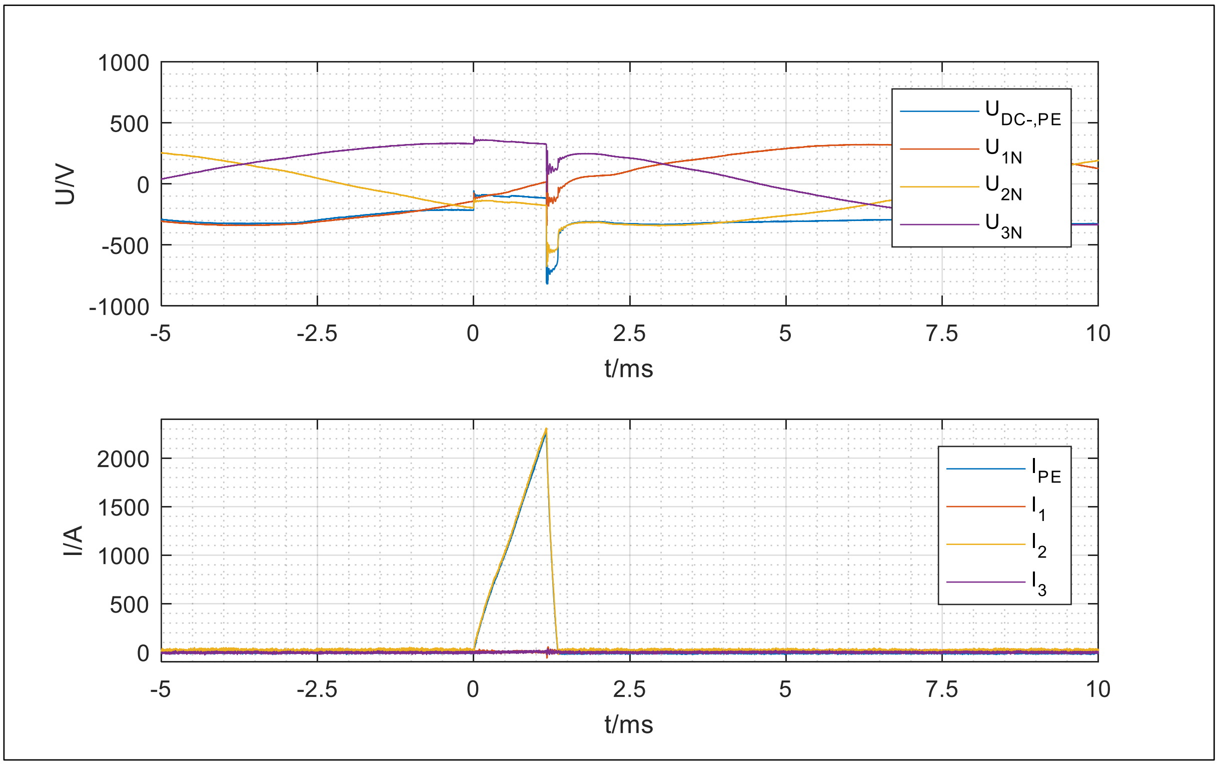

Figure D.33 Measurement 16 at BMW: ground fault with supply via an application cell cluster with 160A gR fuse

Also in this example, it can be seen that the negative phase voltage U_{2N} (yellow) has the largest magnitude at when the ground fault occurs, causing the fault current to flow across phase L2. This is clearly visible in the lower graph: the measured fault current I_{PE} (blue) at the fault location exactly matches current I_2 (yellow) from phase L2. Due to the small size of the protective device in relation to the prospective fault current and the (relatively high) amount of inductance in the AC grid, the current increases almost linearly until disconnection occurs.

In softer grids with higher loop impedances, the increase in current can happen quite differently. When the same system was supplied via a 435-meter-long DC line with a comparable AC network connection topology, the waveforms shown in Figure D.34 were measured.

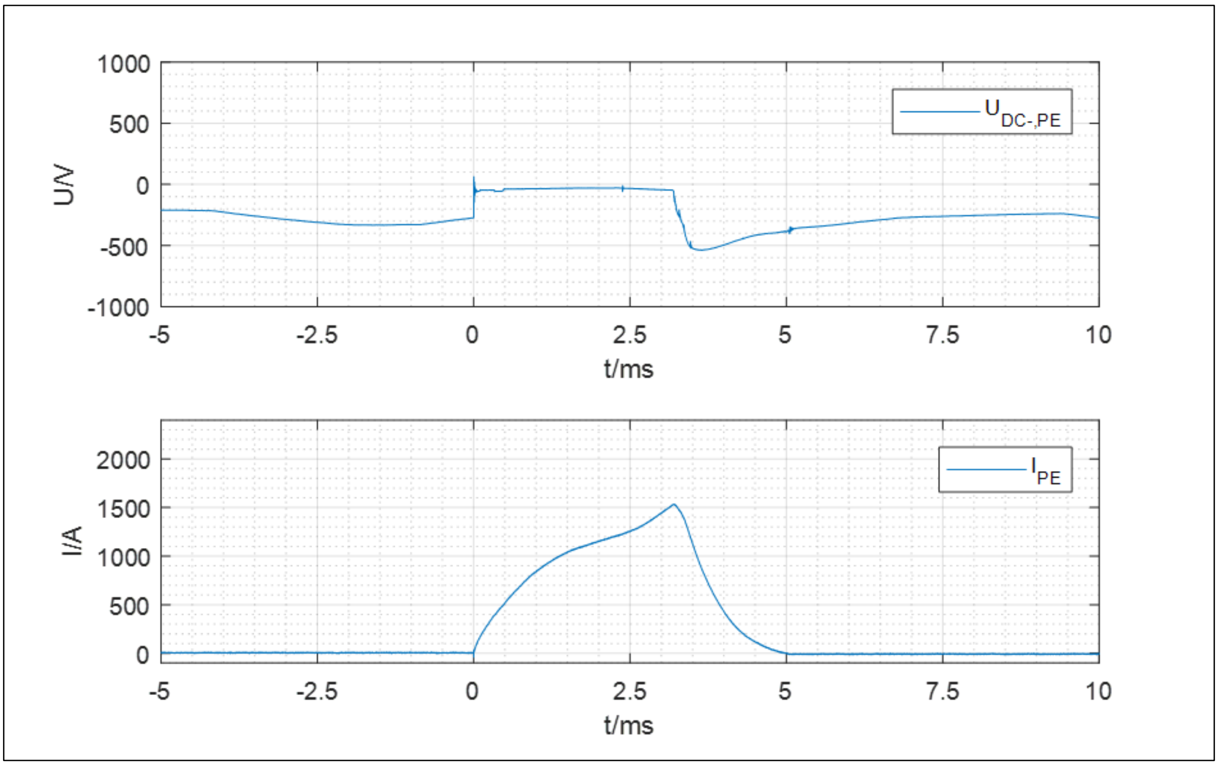

Figure D.34 Measurement 21 at BMW: ground fault when supplying power via a series system cluster with a 100 A-gS fuse

Although the test was carried out with a smaller fuse (100 A), a longer tripping time results because the current increases more slowly. The long line adds high resistance with low inductance to the system. The flattening of the current rise in the time range of about one to two milliseconds is due to the fact that the current commutates to another phase with a larger driving voltage.

Although the tripping time was increased by using a very long line, in this example it is still significantly less than the limit of 400 ms (as shown in Table 12.6) specified by relevant standards. If hybrid or semiconductor breakers are used as overcurrent protection devices instead of fuses, even shorter tripping times can be achieved. These state-of-the-art protective devices respond faster, thus enabling quicker fault detection and isolation to ensure the safety and reliability of the DC-INDUSTRIE grid.

In these tests, all 38 ground faults were successfully detected and cleared within a few milliseconds. The ground fault conditions in the DC grid only differed slightly from the AC grid in terms of loop impedance, which is also why no fundamental DC-specific issues were encountered.

D.9.3 Ground Fault Tests in the DC IT System

In the DC-INDUSTRIE system, the behavior of a DC IT system under ground fault conditions was investigated by conducting tests in the BMW model plant in Dingolfing (see 12.1.2.4). Three ground fault scenarios were intentionally created at different locations, as shown in Figure D.35.

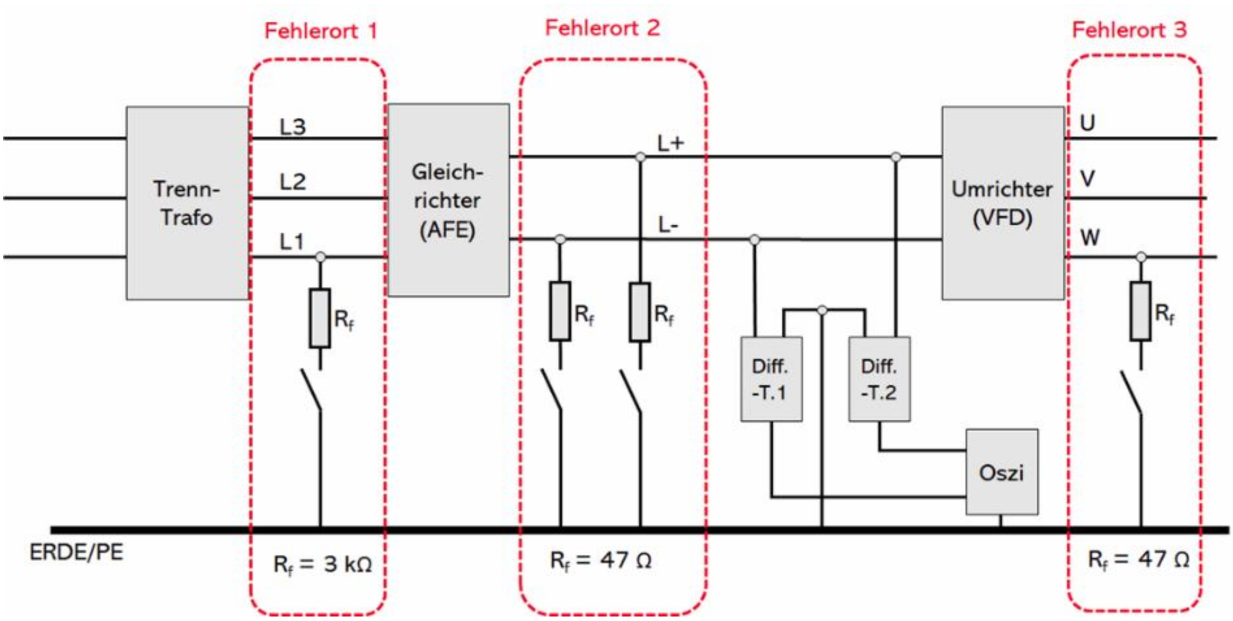

Figure D.35 Measurements at BMW; overview of ground fault tests in a DC IT system [91]

The following boundary conditions were applied:

- Measured conductor-to-ground voltage at both poles
- 650 V nominal
- The following consumers (loads) were operated during the trials:
  - 3 industrial robots
  - 2 lathes
  - Various small drives

Ground faults with 3 kΩ were intentionally induced at location 1 (phase L1 on the AC side). As shown in Figure D.36 this had only a minor impact on the DC voltage. It is expected that at lower resistance values, the effect on the DC grid would be more pronounced. This makes it essential to detect this fault condition, which can be accomplished with typical insulation monitoring devices.

91 Translation: Fehlerort → fault location; Trenntrafo → Isolating transformer; Gleichrichter → inverter; Frequenzumrichter → frequency converter; ERDE → Earth

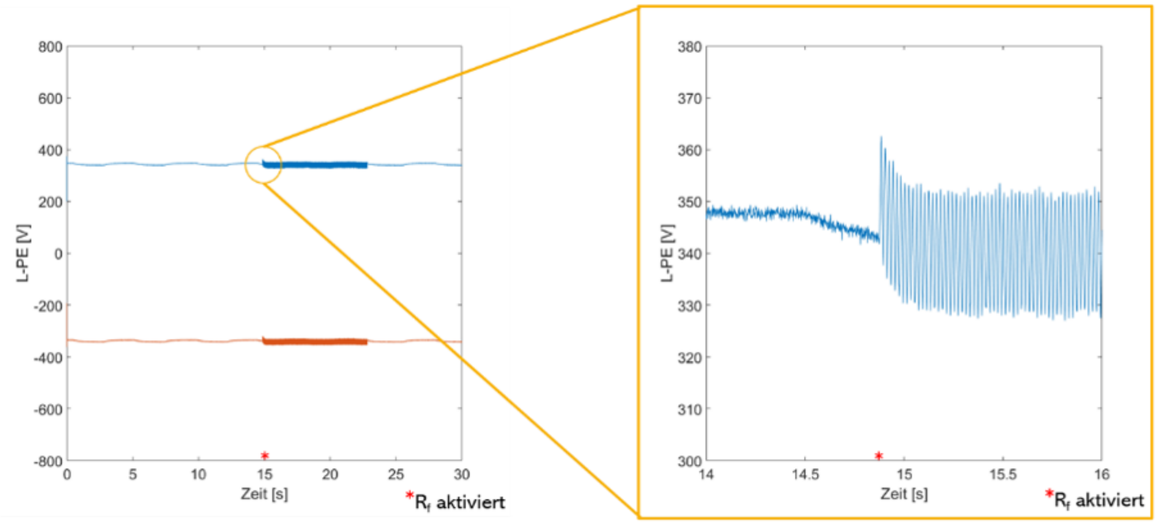

Figure D.36 Voltage of the two active DC conductors to ground with an AC fault at L1 (fault location 1 in Figure D.35), Rf = 3 kΩ, ripple voltage → frequency of 50 Hz, approx. 25 Vpp, 7.6 Vrms

At **fault location 2** (on the DC side), ground faults with 47 Ω were induced. By way of example, Figure D.37 shows the measured voltages between L+ and PE (blue) and L- and PE (orange). As expected, the voltage at L- jumps to the value of the supply voltage (here -650 V), resulting in greater voltage stress for the duration of this ground fault. Even with active drives, the displacement voltage and the detectability of the ground fault have not significantly changed.

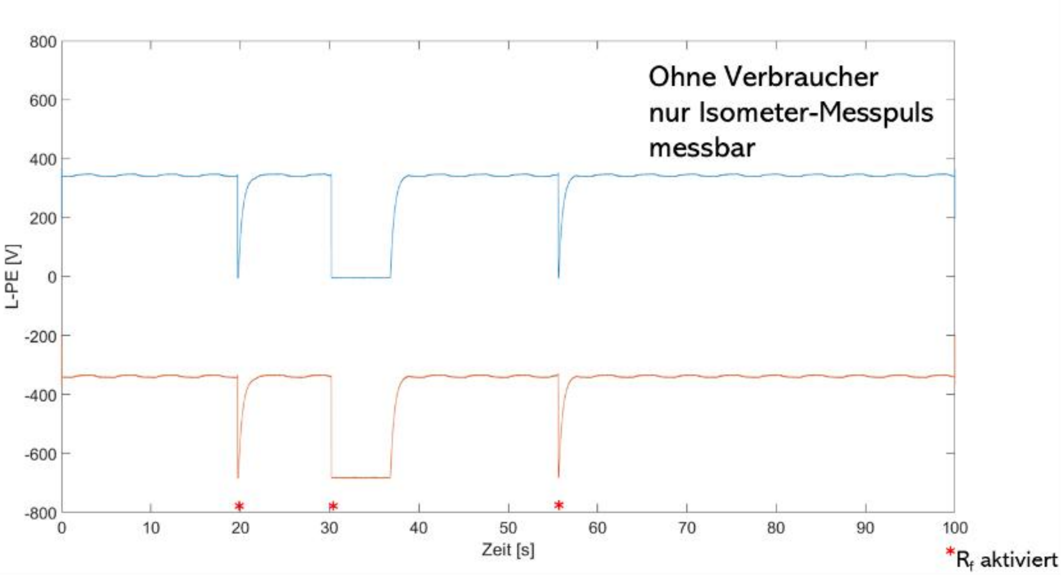

Figure D.37 Voltage of the two active conductors to ground with a fault at L+, Rf = 47 Ω, drive in active.

Ground faults with 47 Ω were induced at **fault location 3** (on the motor side). As can be seen in Figure D.38, this caused the entire DC grid to shift to a higher frequency, which can stress components such as filter capacitors and should therefore be avoided (see chapter 12.1.2.5 for more information).

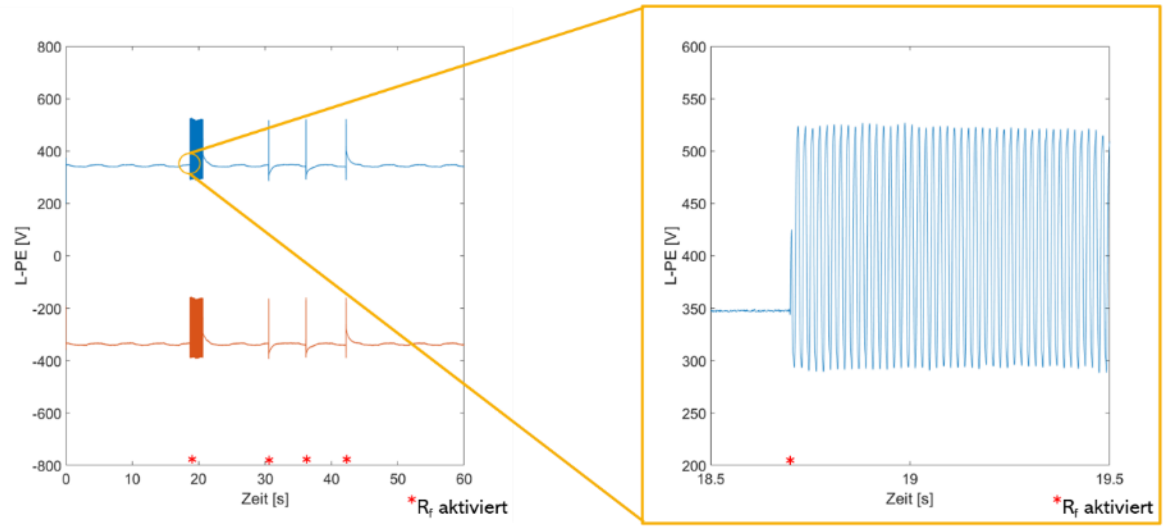

Figure D.38 Voltage of the two active conductors to ground during a fault downstream of the frequency converter (fault location 2 in Figure D.35), Rf = 47 Ω, ripple => frequency of approx. 56 Hz, approx. 230 Vpp, 110 Vrms

D.10 Efficiency Measurement in a HOMAG Model Plant with Three Cells

In-depth efficiency measurements were carried out in the model plant at HOMAG. For this purpose, first the energy of the plant's three production cells was measured in their original AC configuration as shown in Figure D.39. The measured values included the total power supply of all three cells and the consumption of each individual cell. Various configurations were created by varying parameters such as idle load, feed and milling depth.

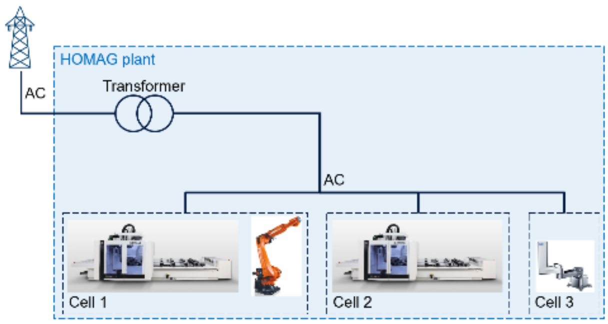

Figure D.39 HOMAG model application with AC power supply

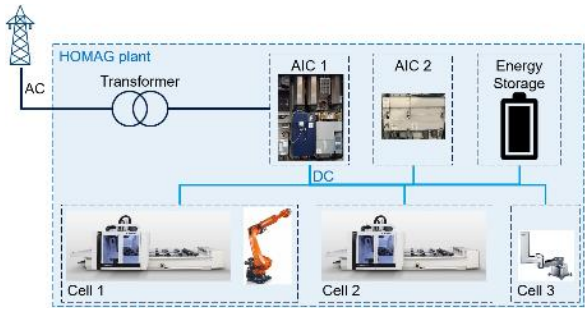

Figure D.40 HOMAG model application connected to the DC grid

After the plant was converted to operate on DC power as shown in Figure D.40, it had two parallel AICs and a rectifier with a DC/DC converter, as well as battery, capacitor, and flywheel energy storage systems. The additional storage and suppliers made it possible to repeat the measurements while varying the machine configuration to a much greater extent. This made it possible to study not only energy efficiency but also other parameters such as peak load reduction. Measurements were performed on the individual cells, at the outputs of the power supplies and at the plant's overall AC supply, enabling more direct comparison between AC and DC.

D.10.1 Use of Braking Energy

The AC configuration included brake resistors, but the available braking energy was not utilized. In Figure D.41 the power profile of the cells in the AC system can be seen at the top and the DC system's power profile with a single power supply and *no* use of energy storage at the bottom. It can be seen that the DC system has a slightly higher base load, but there are also recovery phases (in which the power is below the base load). The slight time shift in the power profiles is due to different milling paths and has no effect on overall power consumption.

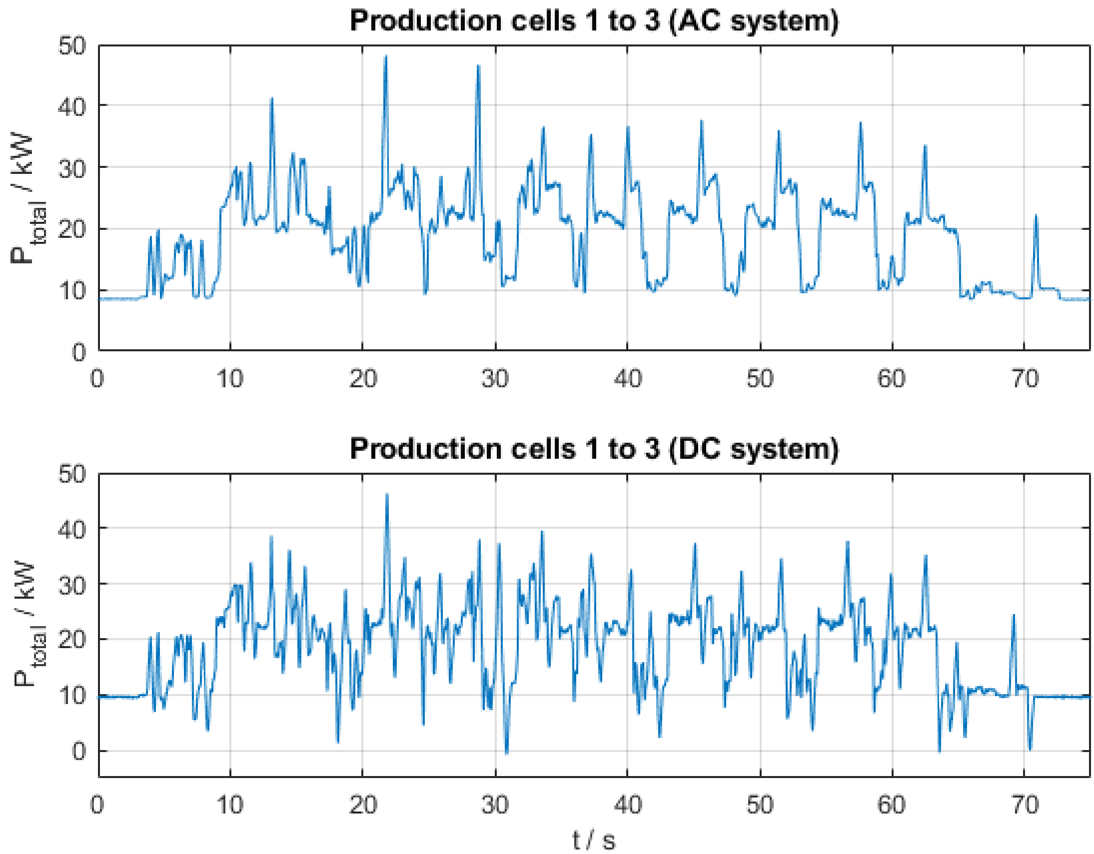

Figure D.41 Power traces at HOMAG connected to the AC grid, AC plant (above), DC plant (below)

Examining this more closely in the case of cell 2 in Figure D.42, for example, the recovery phases are even more pronounced. In the yellow zone (between the base load and 0 W power), some components of cell 2 deliver energy, thus reducing the demand for energy. As a whole, the three cells practically never feed energy back into the overlying AC grid but they do share energy with one another and thus reduce the need to draw power from the AC grid.

This increases the efficiency of cells 1 to 3 by 3.64% (without considering the losses of the energy in-feed device).

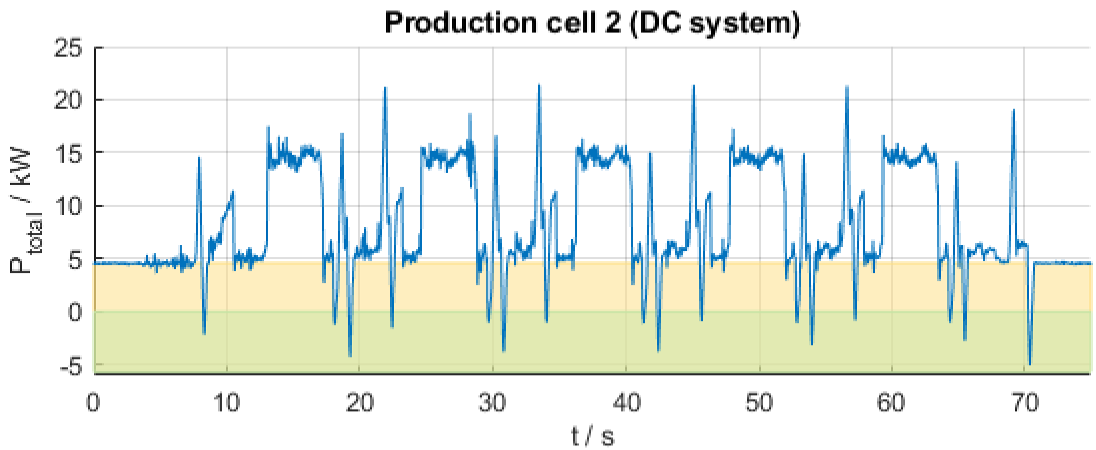

Figure D.42 Traces of power in cell 2 of the HOMAG plant connected to the DC grid without a storage element

D.10.2 Increasing Efficiency by Avoiding Reactive Power

Another effect that helps save energy is the avoidance of reactive power with an active infeed on the AC supply line. During operation of the HOMAG plant on AC power, 19.73 kVar at $\lambda \approx 0.71$ and 200 m of rail or cable were measured. This reactive power induced losses in the supply lines and transformer. But when using DC in conjunction with an active infeed, no reactive power was produced, resulting in an average energy saving of 231 W.

Deducting the additional power consumed by components like AICs and Smart Breakers from these efficiency gains, it turns out that this plant (which had not previously excelled with large efficiency gains) consumes about 1.3% less effective power.

D.10.3 Efficiency Measurement of the HOMAG Handling Cell

In addition to the original plant for the DC project, another subplant at HOMAG with significantly greater potentials (for lifting applications) was analyzed and measured with AC. This plant is used to power the handling and storage of materials. The handling cell shown in Figure D.43 moves wooden panels to and from production cells 1 to 3. In these handling cells, significant losses occur in brake resistors when using a conventional AC power supply. Figure D.44 above shows the power profile of a handling cell. In cyclical operation, the braking chopper causes average losses of 1.24 kW per handling cell (see Figure D.44 below), amounting to 13% of the total power consumed.

In combination with the HOMAG plant shown in Figure D.40, a significant share of this braking energy could be put to use. In an interlinked DC system with two handling cells and the three processing cells, the total active power savings would amount to 5.66%.

Figure D.43 Handling cell at HOMAG with arrows indicating the axes of motion

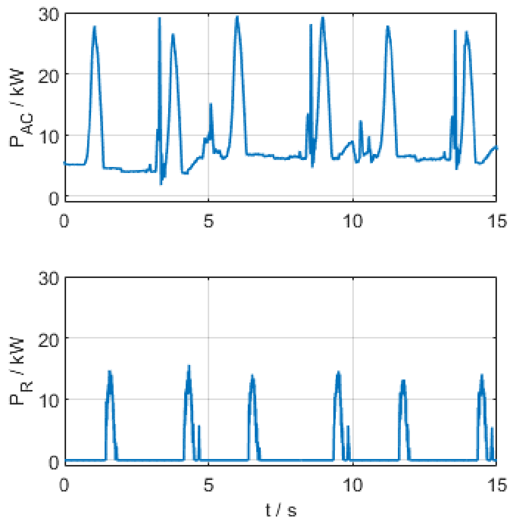

Figure D.44 Power consumption pattern of a handling cell (top) and the braking chopper (bottom)

D.11 Reduction of Peak Loads by Integrating Storage Cells

One major benefit of DC grids is reduction of peak power drawn from the supply grid by installing energy storage systems (see the sketch in Figure D.40). Figure D.45 shows the infeed power profile for the AC grid (gray) and DC grid with storage (green). It can be seen that the peak power has been reduced from 47 kW in the AC grid to 27 kW in the DC grid. **This amounts to a 43% reduction in infeed power.**

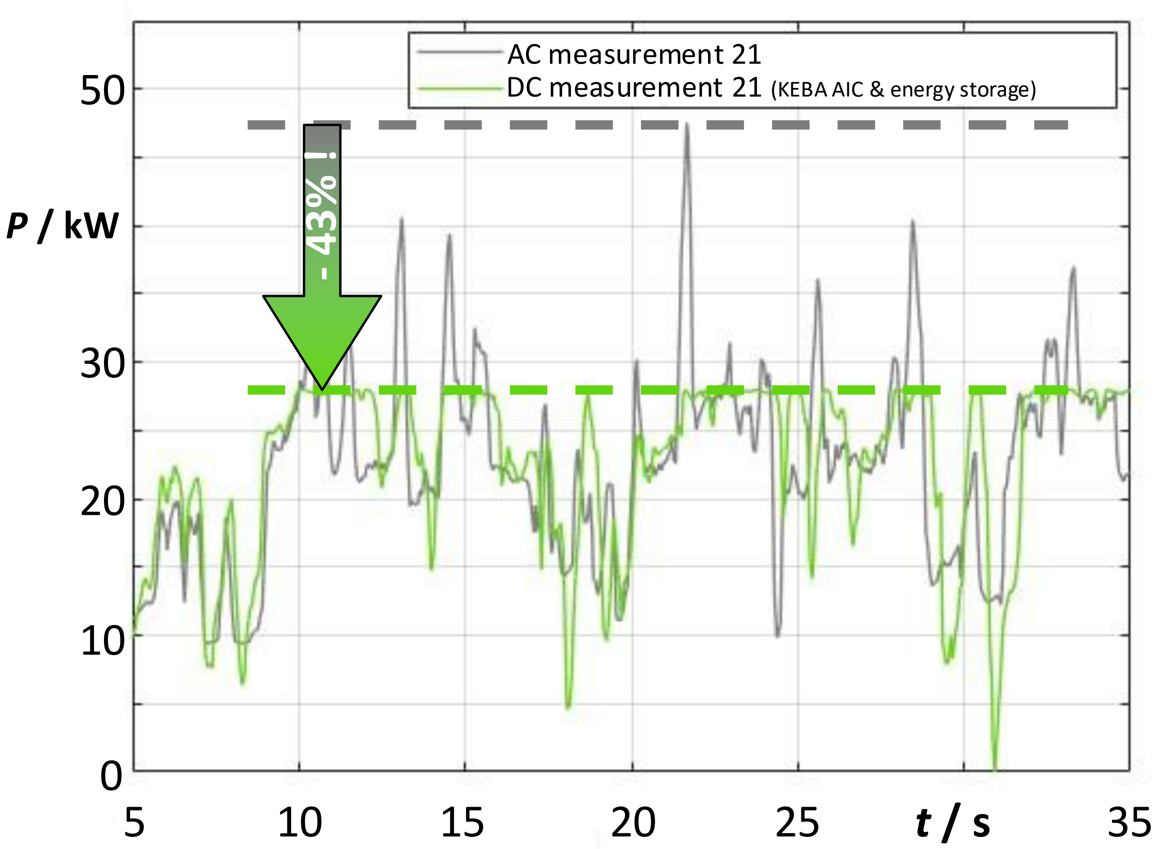

Figure D.45 Comparison of infeed power with AC and DC grids at HOMAG

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The concept was unanimously approved for publication at the DC-INDUSTRIE2 consortium meeting in March 2023.

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- Ostwestfalen-Lippe University of Applied Sciences and Arts in Lemgo, Germany: scientific supervision

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- BLOCK Transformatoren-Elektronik GmbH
- BMW Group
- E-T-A Elektrotechnische Apparate GmbH
- Fraunhofer Institute for Integrated Systems and Device Technology IISB
- Fraunhofer Institute for Manufacturing Engineering and Automation IPAIPA
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F.3 Associated Partners

These companies and institutes contributed as associated partners:

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