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Low Voltage DC

German Standardization Roadmap
Version 2

VDE

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1 PRELIMINARY REMARKS

New and innovative applications in the field of energy supply and electromobility require the development of a constant stream of new solutions for using direct current systems. This also applies for building installations in which, for example, a DC power infrastructure could be installed in addition to the AC mains as a means of reducing losses in individual parts of the grid. And this is where the German Standardization Roadmap comes in: a collaboratively developed document that combines a description of the current state of the art with guidance and requirements.

The Standardization Roadmap covers four major groups. Following an examination of the economic and legal framework it looks at safety, protection concepts and grid structures. It continues with a closer examination of system topologies and use cases, before finishing with a concluding section on equipment and components.

On the basis of the findings made while working on this roadmap, the bodies concerned are urged to check whether their standards already sufficiently address the needs of Low Voltage Direct Current (LVDC), and to plug any identified gaps in a timely manner.

Direct current is increasingly used in many areas where conventional alternating current was previously deployed. Examples include lighting systems, data centres and industrial applications. The voltage levels concerned vary greatly, ranging between 48, 380 and 750 V DC in the examples mentioned above.

The behaviour of DC micro grids is being investigated and evaluated in many private-sector or publicly funded projects. Examples include the DC Industry and DC Protective Devices projects. Such projects are based exclusively on normative specifications and take into account recommendations for action from national and international standardization bodies.

At the same time, however, market trends are also emerging in which safety concepts are completely neglected in some cases in the direct current installations, or in which companies develop their own safety concepts without any normative basis. Therefore, this German Standardization Roadmap recommends that the planned DC system be aligned to the normative principles of electrical safety and fire protection.

A further aspect is the service life and sustainability of electrical installations.

Especially for installations in semi-public or public buildings, direct current installations are currently being designed with safety and control concepts which are based on intelligent controllers. Examples include Power-over-Ethernet (PoE) and parallel bus systems. The latter contain lines for power transmission in parallel to the data and control lines. In this case, the energy flow is only activated when a load is plugged in or switched on. These are often special solutions for which no normative basis is currently available. Standardization ensures long-term compatibility.

Manufacturer-specific devices ("Ethernet switches" with PoE function) are used e.g. for lighting systems that are based on PoE. Data such as that for room temperatures, room occupancy, etc. can be transmitted alongside the power for the lighting. Such solutions contribute to improving the energy audit of buildings and electrical systems.

1.1 Introduction and background

The "Low Voltage DC Standardization Roadmap" is a joint effort by the DKE German Commission for Electrical, Electronic & Information Technologies of DIN and VDE and the experts of the various specialist groups involved in the project.

Our electricity supply system was designed to convey AC from central generation plants to decentralized consumers. Homes and businesses are supplied with electrical energy via high, medium and low voltage lines. Lights, motors, power supply units and other appliances in households and industry are the loads. The existing grid has a hierarchical structure. The grid structure is being changed through the integration of renewable energy sources (wind, solar, biomass) as new infeed sources and locations come online. This is resulting in a heterogeneous grid structure. The consumers and producers of renewable energy are now demanding that this model be rethought.

Much electronic equipment could be powered by DC voltage without any conversion losses. Conversion losses from AC to DC voltage would then be saved, making certain power supply components superfluous and thus reducing investment costs. Not only consumers but also producers would benefit. AC/DC converters could be dispensed with.

A DC system would be highly suitable for power generators such as photovoltaic systems and fuel cells. The energy producers often generate direct current (e.g. photovoltaic, fuel cells). However, this first needs to be converted by an inverter in order to be fed into the AC electrical system of buildings, only then to be converted back to DC, in which form it is suitable for many end uses. Such DC-AC-DC conversions result in significant energy losses and could be reduced in a DC grid.

Microturbines, small hydroelectric power plants and variable-speed wind turbines generate alternating current with a frequency different from that of the grid, and therefore need an AC/DC/AC converter. These producers may also benefit from being linked to a DC system as, here too, it is possible to dispense with the DC/AC converter or replace it with a simpler and more cost-effective AC/DC converter.

Depending on the subnetwork structure, battery or storage systems can also be connected directly to the system with no converter, thereby saving costs and reducing losses.

In a so-called low-voltage direct current grid the alternating current is converted into direct current upon being fed into the DC grid by means of central inverters. This current is then distributed directly to the existing DC components at a certain voltage [1]. This also allows any reactive power in the AC grid to be compensated, thus stabilizing the supply system. This type of converter circuit is also known as an AFE (Active Front End) rectifier. This principle gives rise to the concept of a controlled reactive power source. [2]

1.2 Added value through standards

The German Institute for Standardization (DIN e. V.) puts the value of the business and economic benefits arising from the standard at around EUR 16 billion per year. This is achieved as a result of the multiple effects of using standards. Standards represent an essential tool for avoiding technical barriers to trade. They give companies ready access to world markets. Standards also play a crucial role in the area of product liability. Even in cases where the use of standards is not mandatory, compliance with technical standards is critical for providing manufacturers with proof of exoneration in connection with product liability issues.

Standards provide the basis for making products safe and compatible with health, industrial safety and environmental requirements. They are also the yardsticks for conformity and quality marks, and generally simplify communication between all stakeholders.

By participating in standardization, organizations can help protect their own interests, liaise with other interest groups and improve their competitive edge, because they are present at the point at which the global technical terms are defined.

Standards make products, services, production and work processes safer and better. Standards help make services more efficient by ensuring that they intermesh correctly, and that there is full compatibility between them. European and international standards facilitate the global exchange of goods and services.

Developing standards can help the ecosystem of an emerging technology to solve problems; this, in turn, promotes the successful commercialization of new products. And that is why standards make such a big difference for the success of innovative companies: they create a common framework for innovation and establish the "rules of play". Standards provide the framework by defining common terminology, establish the basic features of a product or service and identify the best practices within the ecosystem for obtaining successful results.

Once these rules are established, the rate of innovation is accelerated and the chances of success increase.

1.3 Motivation and need for action in the area of LVDC

1.3.1 Advantages of AC over DC

High voltage is preferable for the transmission and distribution of electrical energy over long distances, as it allows transport losses to be reduced in contrast to the use of a lower voltage. Up to now, alternating current has been converted using transformers. Historically, this was the main advantage of AC systems [3]. Here, the dimensions - and therefore the cost of materials - depended on the frequency used. Developments in the field of semiconductor technology have now made it possible to generate higher frequency AC voltages easily and highly efficiently. This in turn has reduced the material cost of transformers because they can now be made more compact. In addition, the flow of energy in the grid can be controlled more effectively.

User and component safety is ensured by proven protection concepts and protective devices. Knowledge and experience are obvious advantages of alternating current systems.

1.3.2 Advantages of DC over AC

Distributed energy producers often produce DC or use it in their conversions. Most loads make use of direct voltage for the internal supply of the individual function components, meaning that it is already present in the devices. A DC network does away with the need for the conversion steps from DC to AC and back from AC to DC. This results in lower material costs, and conversion losses are also reduced. Storage and uninterruptible power supplies (UPS) are provided by batteries using direct current. A clear advantage of the DC grid is its genuinely uninterrupted operation. The 5 to 8 ms switching time needed for detecting deviations in phase length, phase angle and the amplitude of bypass and transfer switches is dispensed with.

The integration of DC networks into the AC grid allows simple measures to be taken to reduce repercussions on the AC grid and to compensate for peak loads. This would be more complex in end devices.

Direct current yields energetic advantages, regardless of the type of application. This is because it provides for more efficient use of the existing conductor cross-sections. The current density is evenly distributed across the entire cross-section. Current displacement (skin effect) occurs only when an alternating voltage is applied, leading to a higher near-surface current density [4] [5]. A line that connects two nodes in a network which was previously effectively operated with an alternating voltage of 400 V can reduce its cross-section by a factor of 0.867 using a DC voltage of 400 V DC [6]. In terms of conductor load, DC could therefore easily be transmitted via the existing cables [7]. It is imperative to check whether the insulation and the existing installation technology, such as terminals, protective and switching devices, are suitable for the use of DC.

Another advantage over the AC system is the lack of reactive power, as this creates an additional load and corresponding transmission losses.

1.3.3 AC and DC conversion processes

From AC to DC

AC is converted to DC using a rectifier. Such units are installed in most devices, providing a standard-compliant form of the current consumed by the unit. They are generally fitted in devices in which direct current is required. In the simplest case, a rectifier consists of a diode bridge and a capacitor.

The diodes in the bridge are arranged in such a way that a sinusoidal current is converted to a positive current. The current is then smoothed to constant DC using a suitable filter [9]. The smoothed current can now be used for DC applications.

From DC to AC

To convert direct current into alternating current, the current must first be guided in the positive and then in the negative direction. This can be done using two "switches". One of the switches conducts in one direction when the other is opened, and vice versa. The corresponding frequency of the switching determines the waveform and frequency of the current. It is common to use PWM (pulse width modulation) which is able to produce rectangular pulses of varying width to form a sine wave signal. The faster the commutation, the higher the frequencies of the harmonics, making it easier to filter them. Equally, however, the more frequent the commutation, the higher the commutation losses [8].

DC/DC

In order to convert a DC voltage to a DC voltage at a different level, a possible solution is to redirect the input energy either into magnetic storage units (storage choke or transformer) or storage components with an electric field (capcitor) and then release the energy at a different voltage. The efficiency of such devices is 75 % to 98 % [8] [9]. There are different topologies (such as resonant and multi-phase converters) for DC-DC converters. These are classified according to various criteria and assigned to the three main groups of flow, flyback and resonant converters.

AC/AC

AC voltage is [10] transformed up or down using transformers. Transformer efficiency is approximately 98 %. Some experimental transformers with superconducting windings can achieve efficiency levels of up to 99.9 %. However, this simple solution is only possible if the frequency of the input and output voltage is identical. If a different frequency is required for the output, a DC link is needed to convert the AC voltage first to DC voltage and then into a new AC voltage through modulation [8] [11].

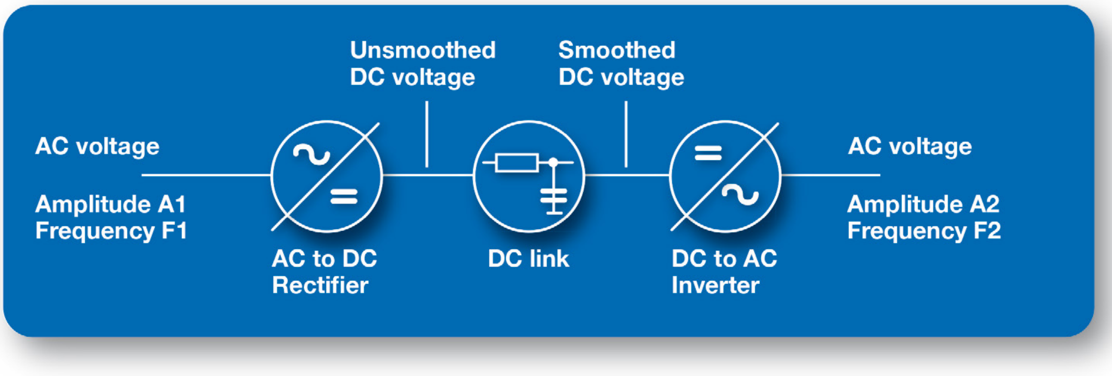


Figure 1 – Structure of a frequency converter

Transformation, rectification and frequency inversion are processes that inevitably involve losses. For example, the input circuits which convert the connected AC voltage for electronic devices account for 40 to 80 % of the power loss, 50 to 95 % of the weight and 50 to 95 % of the volume of the power supply units. Also the AC front end of electronic circuits for controlling electrical drives is responsible for about 50 % of the cost, roughly 50 % of the power loss and more than 65 % of the overall volume of the circuitry [12] [13] [7]. An LVDC grid attempts to circumvent these processes as far as possible in order to provide a more efficient system [15].

2 TERMINOLOGY

2.1 Low Voltage Direct Current

The low voltage range covers DC voltages up to 1500 V. In international standardization this topic is referred to as "Low-Voltage Direct Current (LVDC)".

2.2 Conformity

Conformity is the compliance of a system with the requirements formulated in a specification. The conformity of the interfaces of a system with the corresponding interface specifications represents the precondition for connecting two or more systems via this interface to each other, thereby enabling them to communicate with one another.

Conformity assessment is defined in the international standard DIN EN ISO/IEC 17000 "Conformity assessment   Vocabulary and general principles" as a "demonstration that specified requirements relating to a product, process, system, person or body are fulfilled".

Conformity assessment in Europe has a special meaning: the assessment of products in accordance with the requirements of an EU directive. In accordance with Article 95 of the EC Treaty for the European internal market, EU directives set out minimum safety requirements for numerous products which must be met by the manufacturer.

2.3. Interoperability

Interoperability is a fundamental requirement for the networked components, devices or equipment within a system. It describes the ability of two or more systems to work together to fulfil a task by communicating through their interface. It is therefore scarcely surprising to read in virtually all surveys, studies and market reports that interoperability constitutes an important factor determining the success of new technologies.

The European Telecommunications Standards Institute (ETSI) defines interoperability as the ability of systems, devices, applications or components to work together and to share and use resources and information. An ETSI report distinguishes between different forms of interoperability: protocol interoperability, service interoperability, application interoperability and interoperability from the user perspective.

2.4 Compatibility

Compatibility in technology can mean either
- the interchangeability of components,
- the compatibility of properties or
- the equivalence of properties.

If a (newer) system meets the requirements of another (and possibly exceeds them), this is referred to as backwards (or downwards) compatibility. If an old system fulfils the (basic) requirements of a new one, this is called forward (or upward) compatibility.

An electronic component can be compatible with another with a different name. The components can then be replaced because they have the same characteristics and usually the same or a similar construction.

2.5 Use cases and user stories

User stories are generally text-based descriptions of a cross-domain application told from the perspective of the user. A series of functional use cases can be derived from the user stories. These provide a detailed description of the process from the point of view of the stakeholders and components.

Multiple use cases generally need to be deployed in order to derive a user story. The connection between user stories and use cases can be represented by a mapping table (user story – use case mapping).

3 STANDARDIZATION

Above all else, standards provide a firm basis for technical procurement. They ensure not only interoperability in use, but also protect the environment, equipment and consumers. They provide a future-proof basis for product development and support communication among all participants by ensuring uniform terms and concepts. They define the framework and thus offer a degree of investment security. The development process for standards takes place at various levels (national, European, international) in different organizations. So-called "interested groups" (companies, commercial enterprises, universities, consumers, skilled trades, testing institutes, authorities, insurance companies, etc.) send their experts to working groups in a standardization organization where the standardization work is organized and conducted.

The intention is for standardization to be carried out "openly", ensuring that there is enough space for the development of innovative systems which are distinguishable from those of the competition. Excessively narrow specification could prevent future innovation. Prompt stabilization of the concepts through a consensus and research-based standardization process is also essential for rapid implementation. The ultimate goal is therefore to anchor all the key requirements for uniform technical functioning and applicability in national and international standards.

3.1 Norms

In Germany, a distinction is made between "Normung" and "Standardisierung". "Normung" refers to the scheduled operations and activities for the creation and implementation of regulations used to harmonize products and services.

The purpose of Normung is to avoid technical barriers to use, both nationally and internationally, through harmonization and standardization within the circle of stakeholders, and to promote the exchange of goods and services. Other consequences of Normung are rationalization, compatibility, performance and safety in the use of products and services. Normung is especially applicable if the same or similar items are used in many different contexts in different places by different groups of people. Thus, Normung is understood as planned collaboration with interested parties on the harmonization of material and immaterial objects. The most famous example of successful Normung is the unified paper size DIN A4. Norms define the state-of-the-art in publicly available documents and thus provide non-discriminatory access to knowledge and information for:

- Market establishment for innovative solutions;
- Market development;
- Knowledge transfer;
- Dissemination of best practices;
- Interoperability;
- Reputation transfer to users;
- Confidence in services and products that are created based on the norms.

By definition, Normung must not lead to special advantages for individual players. Its task is to achieve benefits for society as a whole, which is the main difference to consortium-based standardization. In Germany, electrotechnical Normung is conducted in the bodies of the German Commission for Electrical, Electronic & Information Technologies of DIN and VDE (DKE) which develop national norms and represent German interests in the European and international standardization organizations.

In our networked world, if every operator has a secure infrastructure, this also benefits all other operators, as a secure infrastructure cannot be (ab)used for attacking others. This yields positive effects for the whole network. Accordingly, Normung, more than any other instrument, represents an ideal collaborative means of promoting such network effects in a targeted manner and of increasing the overall level of security for the benefit of all concerned.

3.2 Standardization

In its literal meaning standardization denotes the harmonization of goods, services and processes based on a specific pattern of dimensions, types, or procedures. The goal of standardization is to create common parameters such as tools or manufacturing or software components. Standardization, in the German understanding of the term, is therefore technical rulemaking without the compulsory involvement of all stakeholders and without mandatory public participation.

Within the German Normung strategy, the drafting process of specifications or parameters is referred to as "standardization" to distinguish it from full, consensus-based "Normung". For the DKE, standardization represents a means of putting the knowledge and technology transfer between the different stakeholders on an efficient and effective basis, thereby supporting developmental progress. Taking research and development in innovative technology areas as the starting point, new standardization trends need to be identified and addressed. Specifications (guidelines, DIN Specs and VDE application guides) are subsequently developed which in turn are developed into norms in a consensus-based process involving all interested parties and the public. A specification contains the result of standardization work and thereby reflects the state of the art. If a public enquiry procedure has been carried out, it can obtain the status of "generally recognized state of the art".

Table 1 shows the differences between a specification and a norm.

PRINCIPLE	NORM	SPECIFICATION
1. Voluntariness	X	X
2. General public	X	
3. Any person	X	(X)
4. Uniformity and consistency	X	X
5. Relevancy	X	X
6. Consensus	X	(X)
7. State-of-the-art orientation	X	X
8. Economic realities orientation	X	X
9. Public benefit orientation	X	X
10. Internationality	X	
	X Application	(X) Limited application

Table 1 – Comparison of norm and specification characteristics

The term "de-jure standard" in English corresponds to the German term "Norm". In contrast, a "de facto standard" is a result that has not been brought about by at least one national standardization process. Accordingly, the English word "standard" does not represent an accurate translation of the German term "Norm".

"De facto standard" is translated as "Industriestandard", whereas "Standardisierung" is used to denote its creation. In that regard, all standards of industrial interest groups are de facto standards, such as the Bluetooth protocols of Bluetooth SIG or the IrDa protocol of the Infrared Data Association.

3.3 Structure of the standardization landscape

The International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC) and the International Telecommunication Union (ITU) all work to provide consensus-based standards and are the main standardization organizations at the international level. The related standardization organizations at the European and national levels are the European Committee for Standardization (CEN), the German Institute for Standardization (DIN), the European Committee for Electrotechnical Standardization (CENELEC), the European Telecommunications Standards Institute (ETSI) and the German Commission for Electrical, Electronic & Information Technologies of DIN and VDE (DKE) (see Figure 2). The corresponding national standardization organizations are members of ISO, IEC, CEN and CENELEC

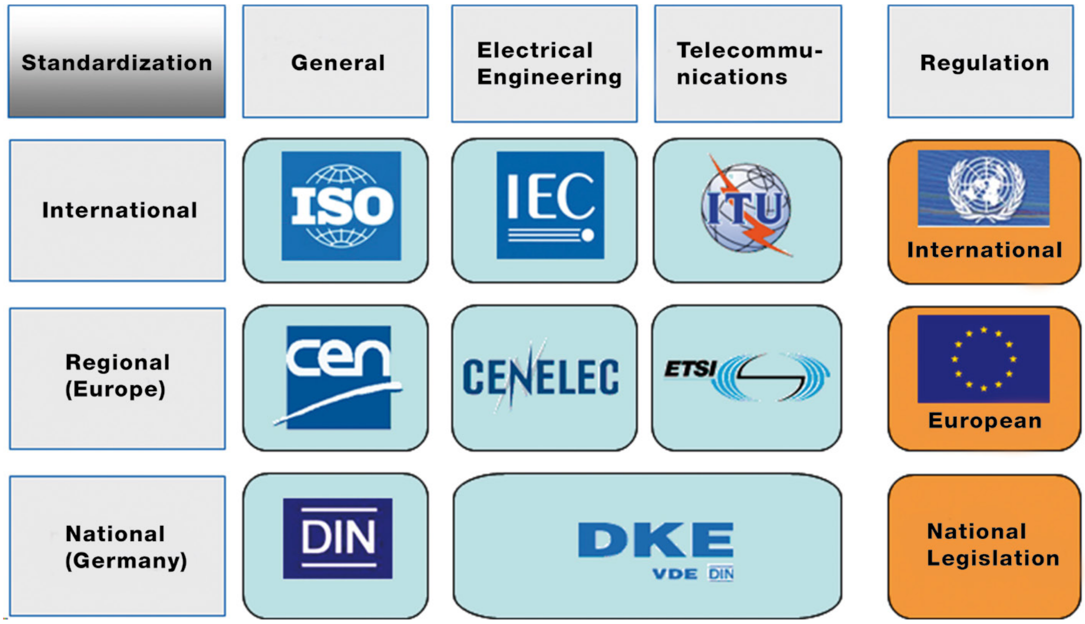


Figure 2 – Overview of the standardization organizations

3.3.1 DIN, CEN and ISO

The DIN German Institute for Standardization offers all interested parties a common platform for elaborating standards and specifications as a service to industry, the state and society. DIN is a private sector organization with the legal status of a charitable body. DIN members include companies, associations, authorities and other industrial, commercial, skilled trade and scientific institutions.

Together with representatives of the interested groups, the main function of DIN is to develop timely, consensus-based standards which meet the needs of the market. DIN is recognized as a national standardization organization by the European and international standardization organizations on the basis of a contract with the Federal Government of Germany.

Today, almost 90 % of DIN's standardization work is European and international. DIN employees organize the entire process of non-electrotechnical standardization at the national level and thus represent Germany at the European and international level via its respective national bodies. The DIN organization represents Germany's standardization interests as a member of CEN and ISO.

3.3.2 DKE, CENELEC and IEC

DKE represents the interests of the electrical engineering, electronics and information technology industry in national and international electrotechnical standardization work and is funded by the VDE. It is responsible for standardization work which is handled by the corresponding national and international organizations (IEC, CENELEC and ETSI). It represents German interests both within CENELEC and the IEC. DKE serves the general public as a modern and non-profit service organization by ensuring the safe and efficient generation, distribution and utilization of electricity.

It is DKE's responsibility to prepare and publish standards in the field of electrical, electronic and information technologies. The results of DKE's electrotechnical standardization work are set down in DIN standards and are accepted as German standards in the DIN set of German standards. Those which contain safety-related stipulations are also included as VDE requirements in the VDE set of regulations.

DKE objectives:

- Safety
  Overall safety for electrotechnical products, installations and their related services, also in the field of occupational safety.
- Compatibility
  System compatibility of products and installations in networked systems and applications.
- Market orientation
  Accelerated market penetration of new technologies through the support of information processes via standards.
- Consensus building
  Bringing together the knowledge and the interests of all relevant parties, building consensus even around controversial technical issues.
- Advocacy
  Representing German interests in the development of international and European standards in order to eliminate obstacles to trade and to open up markets worldwide.
- Quality
  Maintaining a high level of up-to-date rules in a consistent and widely accepted portfolio of standards which are oriented towards market and consumer requirements.
- Conformity assessment
  Worldwide acknowledgement of conformity assessment results.

3.3.3 IEEE USA

The Institute of Electrical and Electronics Engineers (IEEE) is a professional association of engineers in the fields of electrical engineering and information technology. It has more than XX members in over 160 countries. The IEEE was founded in 1963 upon the merging of the two American engineering associations American Institute of Electrical Engineers (AIEE) and Institute of Radio Engineers (IRE). The Institute is divided into ten regions spread all over the world. The work of the member organizations is shared among 300 national groups, which in turn consist of many local associations. In addition, there are numerous "societies" that cover special fields of electrical engineering and information technology. Groups of societies are combined in Technical Councils. The six Technical Councils address broader technical issues. The IEEE specializes not only in publishing technical journals and articles but also in organizing specialist conventions and conferences. It is also renowned for its work in the standardization of technologies, hardware and software, such as in the IEEE 802.11 "Standard for Wireless LAN (WLAN)" and the IEEE 802.16 "Standard for Broadband Wireless Access (WIMAX)".

3.4 National and international activities

The following bodies are currently identifying work areas and coordinating the national and international activities:

- System Committee Low Voltage Direct Current and Low Voltage Direct Current for Electricity Access (SyC LVDC) in the IEC as the successor of the "System Evaluation Group – Low Voltage Direct Current Applications, Distribution and Safety for use in Developed and Developing Economies" (IEC/SEG 4) at the international level for strategic orientation and coordination of the TCs
- IEC/TC 3 "Information structures and elements, identification and marking principles, documentation and graphical symbols" deals with the labelling of systems and equipment
- IEC TC8 WG9 "LVDC distribution"
- IEC/TC 23 "Electrical accessories" on the international level
- IEC/SC 23E "Circuit-breakers and similar equipment for household use" has developed IEC 60898-3 for circuit breakers for pure direct current and has published IEC 60898-3 for RCDs for direct current applications
- IEC/TC 64 "Electrical installations and protection against electric shock"
- IEC/TC 82 "Solar photovoltaic energy systems"
- National mirror committees of the above-mentioned IEC committees within the DKE
- DKE/UK221.6 "Low-voltage direct current distribution networks" as the mirror committee of IEC SyC LVDC and successor of TBINK_LVDC (Technical Advisory Board International and National Coordination) "Low-voltage direct current distribution networks" at the national level
- DKE/AK221.6.1 "Standardization Roadmap" as the successor of TBINK_LVDC_AK_DC prepares the German "Low Voltage DC" Standardization Roadmap
- DKE/AK221.6.2 "LVDC installations"
- The Power Engineering Society of the VDE (ETG) is working on a baseline study of "DC voltage in distribution networks"

3.5 German standardization roadmaps

The existing German standardization roadmaps contain extensive and in certain cases comparable descriptions of the standardization landscape.

3.5.1 German Electromobility Standardization Roadmap 2020

Fossil fuels are an important pillar of the public energy supply. Their availability, for example in the form of fuels for internal combustion engines, is decreasing, resulting in rising prices. In addition, the exhaust gases they produce during combustion have a negative impact on our environment. For this reason, energy needs to be obtained from environment-friendly sources in order to meet the mobility needs of people on a sustainable basis in the future. Therefore, the future of energy supply is one of sustainable energy sources which are available on a permanent and politically reliable basis, and which have a minimum environmental "footprint". By using these sustainable energy sources, electromobility helps lay the groundwork for a future worth living. The establishment of resource-efficient cycles and processes supports long-term progress while maintaining consumers' accustomed levels of comfort.

Ensuring that electricity from renewable energy sources is also readily available for electric vehicles requires adopting a strategic approach to solving the challenges ahead. For electrically driven vehicles, global thinking is currently still primarily a question of technical standards: charging performance, charging plugs and battery capacity. It is functionality, price, environmental awareness and responsibility across national borders that will ultimately determine user acceptance. "Round tables" are needed where participants can jointly develop the technologies and elaborate the standards and specifications which can then be used as the basis for further development. Automobile manufacturers, energy suppliers, network providers and research institutions have long since recognized how closely intertwined their electric mobility network is. The electric car of the future will be integrated as a critical element in the "smart grid". Many new interfaces are opening up and offering opportunities for the further development of existing ones.

Electric vehicles are giving rise to new charging concepts based in particular on the integration of these in the smart home infrastructure. The electric car of the future could be used as an energy storage unit to absorb excess energy, e.g. from the domestic photovoltaic system. The over or under production of electricity could then be compensated in a nationwide smart grid. The networking of ICT systems inside and outside the home is a precondition for this. Local charging stations which can be supplemented by home solar carports and battery storage systems must be integrated in such a smart grid system.

Standardization is of crucial importance in this context as it reinforces the position of the German economy both within Europe and internationally, and offers investment security. Domains such as automotive and electrical engineering/power engineering as well as information and communication technology (ICT) must merge to ensure successful electric mobility and its integration into the smart home infrastructure. The coming together of these formerly separate areas will give rise to new business relationships and areas of value creation.

The German Electromobility Standardization Roadmap 2020

The German Electromobility Standardization Roadmap 2020 was released in 2017 and revises the first version of the German Electromobility Standardization Roadmap published in autumn 2010. It highlights current developments in electric mobility as well as the framework conditions and aligns these with ongoing and necessary standardization activities. The German Electromobility Standardization Roadmap contains the combined knowledge of all those involved in electromobility. Vehicle manufacturers, the electrical industry, energy suppliers/network operators and information network providers were involved in its creation, as were various associations and government bodies. For this reason, the German Electromobility Standardization Roadmap represents the German standardization strategy for this area.

3.5.2 E-Energy/Smart Grid Standardization Roadmap Version 2.0

Reconstructing the German energy supply system without switching it off poses enormous challenges. Fundamental structural changes to the system design have to be made while everything is still running. These challenges involve developing and integrating energy from renewable sources but also restructuring the markets. The smart grid, the combining of power engineering with information and communication technologies (ICT), is pivotal in this restructuring. The energy transition will not happen without development of the power grid and automation of the distribution networks for intelligent synchronization of power generation and consumption. Standardization therefore represents a crucial precondition for the technical realization and for obtaining the investment security required for setting up the smart grid. An important milestone has been passed on the road to creating the smart grid in the publication of the second stage of the German "E-Energy/Smart Grids Standardization Roadmap".

Standardization Roadmap E-Energy/Smart Grids 2.0

The Standardization Roadmap 2.0 not only assumes a pioneering role in the E-Energy / Smart Grid field, it also establishes a new approach to standardization itself by taking the wide range of challenges presented by complex systems in general into account. Of key importance here is the integration of a number of different fields and specialist groups. This is achieved by aligning the activities with the services desired or required by the complex smart grid system. A generic model (Smart Grid Architecture Model – SGAM) is then used to assess the implementation possibilities. The description of the services and the growing amount of detail required in the use cases at the functional, information, communication and component levels have laid the foundations for cooperation between the different standardization bodies involved in reaching the common goal of realizing the desired services and functions.

The processes developed in drawing up the roadmap are already being used today in similarly complex tasks, such as in the fields of E-Mobility, Active Assisted Living (AAL) and Smart Home. Common aspects include the joint development of topics such as definitions of requirements for applications, the reduction of complexity, common understanding and consensus building, and thus the very foundations of standardization. The national and regional regulatory work of defining in some cases highly detailed requirements represent a special task. The roadmap recommends the proven approach of leaving the formulation of the technical details to the established standards bodies. The procedure which is described maintains the basis for consensus building despite a very broad range of interest groups.

The German studies have proved popular at the European and international level, too. The activities for implementing the smart grid standardization mandate M/490 of the European Commission and the activities at IEC level are based on the method described. However, the stakeholders are increasingly dependent on the cooperation of industry, government and the general public to ensure that the complex standardization work bears fruit quickly. The work already initiated must be implemented in greater detail and in the existing bodies. It is also important to observe, to use and to publicize the existing internationally recognized standards in the field of energy, industrial and building automation. Thus, increased participation is necessary at the national and international levels to ensure that Germany can continue to assume and play a strategically pivotal pioneering role in standardization. In the view of the VDE|DKE, German companies should therefore make a greater contribution to German, European and international standardization. This opens up great opportunities both for the companies themselves as well as for Germany as an industrial location.

3.5.3 Smart Home + Building Standardization Roadmap Version 2.0

The German Smart Home + Building Standardization Roadmap – Version 2.0

In the last few years the term "smart home" has come to describe the technologies deployed in residential rooms and buildings in which networked devices and systems help enhance the quality of living, safety and efficient energy use levels. Common alternative names for "smart home" are "Intelligent Living", "eHome" or "Smart Living".

The continuing digitization and networking of nearly all areas of human experience are leading to changes in the home environment which are resulting in turn in new possibilities for living and working. Smart home technology is an integral element in the efforts to create sustainable infrastructure development and to improve the quality of life in the urban environment. This includes such aspects as the economy, the domestic and working environments, the social environment, assisted mobility and interaction with the authorities. Smart home is about integrating and using information and telecommunication technologies in the domestic environment to open up a new world of experience and to make existing entertainment, comfort, energy management, health and safety activities more cost-efficient or convenient.

Those involved in the smart home standardization efforts consist of representatives of academic institutions and industrial companies in the fields of home automation, HVAC, consumer electronics, decentralized energy supply and management and system integrators or providers of security technology. The goal of the consortium is to create and maintain an international series of standards which facilitates the sustainable development of interoperable, safe, mobile and reusable applications and services in the home environment.

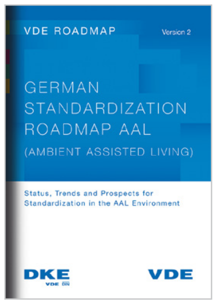
Getting Germany's households and smart home economy into shape for the digital world is the goal of the "Smart Home + Building V 2.0 Standardization Roadmap". The second version picks up the story at a crucial point, as there are already many smart home solutions on the market. However, these are usually optimized for a single application and do not permit an integrated approach. The Standardization Roadmap provides assistance here by paving the way for integrated smart home solutions and helping Germany become the leading smart home market. According to the Standardization Roadmap, "System flexibility, interoperability across system and technology boundaries, information security and data protection are the main requirements to be met by smart home solutions in the future, if it is to enjoy long-term success in the emerging mass market."

The terms smart home, domain and use case are defined in the Smart Home + Building project. Application groups such as energy management, security, entertainment and AAL are identified as domains. Use cases describe players, processes and activities from the perspective of the task, and they abstract technical details.

The main tasks of the DKE are to collect, coordinate and prepare use cases and user stories within the smart home + building environment. A further purpose is to coordinate existing cross-domain work at the national, European and international levels. Technical requirements are derived from the use cases and these are then implemented in standards in the relevant areas. Use cases are therefore used to map processes and implementation plans at an early stage of standardization which can then be implemented systemically.

3.5.4 AAL (Active Assisted Living) Standardization Roadmap Version 2.0

Active Assisted Living (AAL) only established itself a few years ago as a separate area of research and activity, before it was quickly seized upon and developed by numerous national and European players. Characteristic of AAL is high-level interdisciplinarity which gives rise to a large number of partners from different medical, technological, sociological and economic fields. Many specifications exist and are already being applied to individual systems today. However, the mere existence of these specifications is not enough to satisfy the specific requirements of the AAL systems and products. From the wide range of specifications it is necessary to identify and select the ones which are actually system-relevant.



The German AAL Standardization Roadmap – Version 2.0

A prerequisite for the widespread adoption of networked health technologies and assistive technologies is safe, simple and interoperable systems that are of measurable benefit to users. It is important to plug any gaps - especially with regard to the integration and interoperability of the individual systems, but also e.g. with regard to quality assurance and to the training of specialists. Bringing together all the different participants and overcoming the new obstacles by creating new points of contact and interfaces represent challenges. The interface structure between different networks (but also between technical devices and systems) is giving rise to demand for (systematic) standardization in places.

Comprehensive understanding and a general perspective of the various stakeholders must continue to be supported. The German AAL Standardization Roadmap Version 2 promotes a common approach for all those involved in the AAL environment, while also raising awareness of other concerns. Further development of the German AAL Standardization Roadmap is discussed with the relevant bodies, standards committees and other interested expert groups.

The AAL environment is also reflected in the smart home domains. Their infrastructures overlap in some cases. For this reason, there must be close cooperation between these areas. Synergies can be developed with the smart meter and smart home areas through appropriate public relations activities. Assistive technologies are basically technologies which allow users to perform tasks and movements in a simplified way, or autonomously, which would not be possible without such technical support. Sensors installed in the home can record activities and request support as needed. The use of integrated health and smart home technologies offers needs-based assistance and support to people or helps them retain their independence in the home environment. This link between assistive technology and smart home applications lies e.g. in the connection of sensors to entertainment applications (for example via gesture control).

The subsequent inclusion of health care is of high social relevance from the perspective of the individual citizen, as well as from the perspective of the German health economy and leads to greater efficiency and quality of medical care.

AAL is not, however, restricted to the domestic environment; it also includes the environment of those who are still mobile and can leave the home.

3.5.5 Energy Storage Standardization Roadmap

The German government has set ambitious targets for the energy transition: primary energy consumption and the emission of greenhouse gases are to be drastically reduced. The share of renewable energy within the overall amount of energy consumed is to be gradually increased until 2050.

The technologies developed and tested as part of the energy transition are a prerequisite for Germany's future economic success. The factors determining the framework for implementing the energy transition are: safety, economic viability and environmental compatibility.

A central challenge posed by the energy transition is the spatial and temporal balancing of energy supply and demand through the use of large amounts of volatile renewable electricity. Energy storage systems represent a flexibility option which ensures above all that supply and demand are balanced of over time.

The public debate on energy storage often focuses on the storage of electrical energy, e.g. by means of batteries. The standardization roadmap includes all relevant storage technologies for the energy transition. The range extends from thermal, electrochemical (battery) and chemical (e.g. power to gas) through to mechanical storage (e.g. pumped storage plants).

An integrated approach is necessary above all because of the need to link the electricity, heating and mobility sectors. The standardization roadmap presents the current state of standardization in the various sectors and the fields of action which will become necessary in the near future.

DIN, DKE, the Association of German Engineers (VDI) and the German Technical and Scientific Association for Gas and Water (DVGW) have drawn up the standardization roadmap for energy storage in dialogue with experts from the respective committees; the roadmap is updated and reviewed at regular intervals.

4 ECONOMIC AND LEGAL FRAMEWORK

4.1 Market

The importance of DC-based applications such as photovoltaic systems and electromobility is growing as a result of the change in energy policy. At the same time, the rising demand for more and more computing power and memory is increasing the need for DC in computers, servers and devices such as smartphones and tablets. Even parts of the on-board networks of aircraft are based on DC technology.

The market growth is currently difficult to gauge because only niche applications have emerged as yet. However a significant market increase is to be expected in the coming years, especially because future memory technologies will allow considerably more complex DC applications.

One of these niches is data centres: the number of these operating on 380 V DC has increased in recent years.

4.1.1 LVDC as a solution for societal challenges

One of the major challenges facing society is the energy revolution. Decentralized energy supply and storage, which is now already widespread in Germany, may in the future also be realized exclusively with DC in countries such as India and Africa, and possibly also in South America. For economic and geographic reasons this is technically only possible with DC in these countries. However it is also the case in Nordic countries such as parts of Scandinavia because only DC permits longer ranges and higher power using the same cables/lines.

The use of DC power systems is conceivable in many emerging markets. In India, for example, 20 % of the electricity is required for irrigation pumps. These systems are to be converted to decentralized PV-based DC solutions which will then pay for themselves within three years.

4.1.2 The variety of industries and domains in the LVDC market

Which sectors and domains the LVDC market will serve in the future can only be speculated upon at present. However, the first systems and areas are already using direct current systems. Here we examine two domains: mobility and buildings.

In the case of mobility, DC systems are used for the propulsion and control of electric drives for ships, trucks, public transport, aircraft and construction equipment. These are equipped with their own on-board DC systems including drives and automation systems.

The benefits of using direct current systems include:

- Reduction in primary energy consumption;
- Improved dynamics and mobility;
- Easier integration of alternative energy sources;
- Fewer components;
- Significant noise reduction;
- Flexible component placement.

"Buildings" includes all kinds of modern building and the upgrading of existing buildings. Tabelle 2 shows examples of different technologies in buildings that can be realized with DC. The benefits of these technologies and possible applications are also presented.

TECHNOLOGY	ADVANTAGES	APPLICATION AREAS
LED lighting	• Reduction of energy consumption • Reduction of space requirement • Reduction of equipment weight • Flexibility in the placement of components • Integrated digital control e.g. PoE	• Office • Business premises • Data centre/ICT • Home • Residential building • Hospital • Factory • Outdoor lighting
Battery storage systems (e. g. UPS systems)	• Reduction of conversion stages	• Office • Business premises • Data centre/ICT • Residential building • Factory
Integration of renewable energy sources	• Reduction of conversion losses • Optimized use of renewable energy	• Office • Business premises • Data centre/ICT
Power supply for electronic devices	• Higher power transmission with identical cable cross-sections	• Office • Business premises • Data centre/ICT • Home • Hospital
Distribution of DC	• Higher power transmission with identical cable cross-sections • Increasing market penetration of intelligent components thanks to electronic conversion technology	

Table 2 – Applications in buildings

4.2 Legal framework and provisions

4.2.1 Energy Industry Act – EnWG

The German electricity and gas supply legislation was last revised in 2005. The Act, which was initially introduced in 1935, contains basic legal stipulations regarding the supply of grid-based electricity and gas energy to the public which is as efficient, safe and low-cost as possible. In future this is to be based increasingly on renewable energy.

A further function of the Energy Industry Act is to "*Ensure effective and undistorted competition in the supply of electricity and gas and to secure efficient and reliable operation of power grids on a long-term basis*" [14].

In Part 6 "Safety and reliability of energy supply", paragraph 49 regarding the "Requirements of power plants" refers to observance of the generally accepted rules of technology and the technical rules of the Association for Electrical, Electronic & Information Technologies (Verband der Elektrotechnik Elektronik Informationstechnik e.V.).

4.2.2 Low Voltage Connection Ordinance (NAV)

The ordinance on the general conditions for the power connection and its use for low voltage electricity supply contains general provisions e.g. on the grid connection relationship and the connection use relationship, but also stipulations regarding the power connection and the use of the connection. It also covers plant operation and the rights of the grid operator, payment dates, the consequences of infringement and the termination of legal relationships.

Section 7 "Type of grid connection" stipulates 400 V or 230 V as the voltage at the end of the grid connection for three-phase, and 230 V for AC. DC is not mentioned in this context. The type of current can, however, be freely selected.

4.2.3 Low Voltage Directive (LVD)

The directive serves to harmonize the legislation of the Member States concerning the provision of electrical equipment for use within certain voltage limits on the market. It applies to electrical equipment designed for use with nominal voltages of between 75 and 1500 V, direct current. In conjunction with the EMC Directive (see section 4.2.4) it is an important set of rules for the safety of electrically operated equipment.

The new Low Voltage Directive 2014/35/EU was published on 29 March 2014 in the Official Journal of the European Union. A number of changes had to be made to the Low Voltage Directive 2006/95/EC which prompted the European Parliament and European Council to resolve to publish a revised version.

The new Low Voltage Directive therefore means major changes for the market players. The new Low-Voltage Directive must be applied from 20th April 2016.

4.2.4 EMC Directive

The purpose of Directive 2014/30/EC of the European Parliament and the Council, dated 26 February 2014 on the harmonization of the laws of the Member States relating to the electromagnetic compatibility of equipment is to ensure the functioning of the internal market for equipment by stipulating an adequate level of electromagnetic compatibility, and applies for both AC and DC.

4.3 Health and safety (safety requirements, documentation)

Electromobility

Guidelines for electromobility are currently being drafted or are already being applied, especially regarding the production and repair of electric vehicles. DGUV (German Social Accident Insurance) Information 200-005 "Training for work on vehicles with high-voltage systems" (previously: BGI/GUV-I 8686) currently applies for DC, too.

Photovoltaic

The Energy, Textile, Electrical, Media Product professional association (BG ETEM) has developed easy-to-use software that can carry out a risk assessment on photovoltaic and solar installations quickly and easily. This is because the installation, servicing and maintenance of these systems can lead to serious and even fatal accidents, especially falls and electrical accidents. The risk assessment can help employers to take appropriate health and safety measures.

Vehicle batteries

The charging of batteries can be dangerous even at low DC voltage in the event of faults in systems, tools and equipment as well as inappropriate handling. This is because high currents may occur which not only pose a great fire risk, but can also be hazardous to persons. This is described in DGUV Information 209-067 "Charging devices for vehicle batteries" (previously: BGI 5017).

4.4 Insurance industry

The insurance industry, as the main risk carrier, is affected by the application of existing and new technologies at many levels. Here it is especially important to draw the right conclusions from past experience (of damage/injury) with regard to technological safety and to contribute this experience to standardization and therefore to benefit the application of low voltage DC.

This experience and knowledge is passed on through the issue of publications by the German Insurance Association (GDV).

Photovoltaic

The GDV has published the "Photovoltaic Systems" technical guide (VdS 3145) concerning the selection, design, construction and operation of photovoltaic systems. The objective is to minimize property damage and operational interruptions. It addresses fire protection, mechanical, electrical and safety aspects plus the role of fire services in conjunction with photovoltaic systems.

Electromobility

The GDV published "Charging stations for electric road vehicles" (VdS 3471) to provide planners, installers and operators with an overview of the different charging modes for electric road vehicles. It contains information on the different charging options and the different environments in which charging stations are operated.

5 PROTECTION OBJECTIVES AND CONCEPTS

5.1 Safety

The protection objectives and protection concepts are intended to ensure the safety of people, livestock and property with regard to the risks and damage arising from the application of DC that can occur under intended use of electrical equipment or devices.

The following risks should be considered:
- Dangerous electric shocks;
- Excessive temperatures that can potentially cause burns, fires and other harmful effects;
- Overcurrent;
- Undervoltage, overvoltage and electromagnetic influences likely to cause injury or damage;
- Interruption of the power supply;
- Arcing.

5.2 Risk of injury from direct current and protection against electric shock

5.2.1 Introduction

Electrical safety plays an important role in low-voltage, since most devices in this voltage range are operated by untrained persons. In recent years, direct current applications with high operating voltages, and therefore with high contact voltages, have become more commonplace. The development of photovoltaic systems or battery storage units such as those found in electromobility applications means that there are now numerous electrical systems with a rated voltage above the permissible DC contact voltage limit of 120 V. In the supply infrastructure, DC systems have only become established in data centres. Currently, the use of DC power systems is also being considered in commercial buildings.

APPLICATION	RATED VOLTAGE IN VOLTS
Solar-powered garden lights etc.	12
Telecommunications (international, Europe, Germany)	48/60
Level crossing safety devices	36/48
Trams, underground railways, trolley buses	600 or 750
Railway signal technology (Germany)	48/60
Electromobility (present)	48/200-800
Electromobility (future)	up to 1500
Data centres	380
Building infrastructure based on DCC + G Active conductors (+/-)	760
Active conductors to reference conductor (earth)	380
PV systems	24/48/ to 1500
Power supply systems on ships	1000
Emergency power systems and safety power supply	220

Table 3 – Applications and rated voltages

Electric shocks due to direct contact to live conductors and possible electric arcs are the main dangers for humans and livestock. The specific hazards arising from high touch voltages in DC systems have so far not been considered in detail. For this reason VDE/DKE and Forschungs- und Transferzentrum Leipzig e. V. has set up a joint research project with the aim of improving the level of knowledge regarding the effects of direct current on the human body and to test the statements made in standardization.

5.2.2 Effects of electric direct currents on humans

Even low level currents trigger sensitive perception when live parts are touched or released. The change in current is clearly felt at the moment of touching or letting go. But there is also sensitive perception during the current flow itself. The reason for this lies in the stimulation of sensory nerves in the skin. At the point of contact a tingling sensation is perceived that changes to a painful stinging with increasing current (table 4). By comparison: in medicine, the pain-relieving and circulation-promoting effect of direct current has long been used for therapeutic purposes. The dose (current density) is set so that slight, painless tingling is felt. The current density is usually in the range of 0.05 to 0.2 mA/cm^2 [16]. For the palms of the hands (roughly 100 cm^2), this means a current of 5 - 20 mA.

In addition to perception caused by the stimulation of sensory nerves (afferent nerves), there is also irritation of the motor nerves (efferent nerves). In particular, the beginning and the end of the current flow (contact) may cause stimulation of the motor nerves which is transmitted to the muscle. This results in brief muscle contraction only during the change in the current strength. This contraction causes the victim to let go of the point of contact or even to be propelled away from it. This is why there are often also musculoskeletal injuries. This mechanism does not, however, produce a let-go threshold, which must be considered with AC.

CURRENT STRENGTH in mA	SENSATION OF **DC**
up to 2	None
7	Slight tingling
12	Feeling of warmth and increased tingling in the palms of the hands, light pressure in the wrists
21	Strong pressure to stabbing pain in the wrists
27	Tingling in the forearm, pressure pain in the wrists, stabbing pain in wrists, feeling of warmth
32	Strong pressure pain in wrists, tingling down to the elbow
35	Considerable pressure pain in wrists, stabbing pains in the hands
43	Severe pressure pain in wrists, violently tugging and stabbing pain in the hands, cannot be withstood for more than 10 s

Table 4 – Perceptions as described by Osypka [17] of hand-hand current flows, approx. 90 cm^2 contact area.

In a DC accident there is also the risk of ventricular fibrillation. Animal experiments were therefore carried out in the past to determine thresholds. Similar to that of alternating current, the fibrillation threshold for DC has an upper and a lower level. This suggests that direct current will also result in ventricular extrasystoles (VES), favouring recurrence and thus ventricular fibrillation. In addition to the stimulation which occurs when switched on and off, the DC also leads to automatic action of the heart muscle cells [18] during exposure, which leads in turn to the formation of ventricular extrasystoles. The possibility of recurrence as a cause of ventricular fibrillation is raised, meaning that the exposure time and the number of ventricular extrasystoles increase the probability of ventricular fibrillation. Accordingly, the fibrillation threshold decreases with time to a lower level. A comparison of DC and AC fibrillation thresholds reveals that the thresholds are virtually indistinguishable with short flows of current. During longer flows of current, however, the fibrillation threshold for DC however, is higher than that of AC. 2018 sees the start of corresponding supplementary examinations to examine the ventricular fibrillation thresholds.

With longer exposures (when the victim is trapped or stuck, for example) electrochemical effects must also be considered. There may be skin burns at the points of contact. The electric burns at the contact points often differ for this reason. Direct current can also cause the blood cells to dissolve (haemolysis). The haemoglobin which is released can cause kidney damage as a result. The degeneration of the musculature (rhabdomyolysis) can also damage the kidneys through the release of myoglobin into the blood. No thresholds have yet been identified for these electrochemical effects. Long exposure times lasting several minutes are a special case because they only occur when the victim is trapped or unconscious.

5.2.3 Results of the DC-Sich project and areas of further research

Knowledge levels regarding the effects of direct current on humans and animals vary greatly depending on the effect (table 5). While the physiological basis is often known, experimental confirmation is often difficult due to the exacting requirements for animal testing. Deriving meaningful thresholds, however, is not possible without experiments. While perception experiments can easily be performed on test persons, it is not possible to determine fibrillation thresholds on humans.

EFFECT	PHYSIOLOGICAL BASIS KNOWN	EXPERIMENTALLY CONFIRMED	THRESHOLD VALUES EXIST
Perception	√	√ (human)	√
Muscle contraction (cramping, tetanus)	X	X	X
Ventricular fibrillation	√ (incomplete)	√ (animal trials)	√
Electrochemical effects			
Burns	√	√	X
Haemolysis	√	X	X

Table 5 – Overview of scientific knowledge on the effects of direct electrical current

So far, persistent cramping of the muscles has only been observed in a few accidents. The present findings therefore do not permit derivation of a value for a DC let-go threshold. The results of the research show, however, that from a physiological point of view, muscle cramping is also possible with direct current. More research is therefore needed in this area before further statements can be made.

No threshold values are currently available for electro-chemical effects. The necessary experimental investigations are missing in some cases. Although it can be assumed that electrochemical effects only occur with long exposures, threshold values should be derived and documented in the standardization process.

5.3 Overcurrent protection

Protective devices (OCPDs) must be provided to interrupt any overcurrent in the conductors of the circuit before it can cause a hazard due to harmful thermal or mechanical effects on the insulation, connectors, connections or in the surrounding area of the conductors.

The requirements of IEC 60364-4-43 (DIN VDE 0100-430, VDE 0100-430) must be observed.

5.4 Protection against transient overvoltages

According to IEC 60364-4-44 (DIN VDE 0100-443, VDE 0100-443) the protection of persons and facilities from transient overvoltages arising from atmospheric influences or due to switching needs to be assessed and taken into account. The key influencing factors are the location and the availability of facilities. The selection of required surge protective devices (SPDs) is regulated in IEC 60364-5-53 and HD 60364-5-534 (DIN VDE 0100 534, VDE 0100 534). If there is a risk from direct lightning strikes, the lightning protection standards of series IEC 62305 (DIN EN 62305, VDE 0185-305) should also be consulted. With regard to the protection of structures containing electrical and electronic systems, especially when reliable functioning and high security of supply are required, these systems must also be protected from conducted and radiated interference. Disruptions of this kind are caused by the lighting electromagnetic pulse (LEMP) which occurs during direct and indirect lightning strikes. This requirement can be fulfilled by a LEMP protection system in compliance with IEC 62305-4 (DIN EN 62305 4, VDE 0185-305-4). To achieve consistent and efficient surge protection, there must be energetic coordination between the surge protective devices (SPDs) in accordance with IEC 62305-4.

IEC 60364-5-53 and HD 60364-5-534 (DIN VDE 0100-534, VDE 0100-534) contains the requirements for the selection and erection of surge protective devices (SPDs) to limit such transient overvoltages. SPDs limit transient overvoltages in order to meet the insulation coordination requirements under the conditions as set out in IEC 60664-1 (DIN EN 60664-1, VDE 0110 1). IEC 60364-5-53 and HD 60364-5-534 cover transient overvoltages of atmospheric origin and also switching overvoltages generated by equipment within the electrical system itself. In contrast to IEC 60364-4-44 (DIN VDE 0100-443, VDE 0100-443), IEC 60364-5-53 and HD 60364-5-534 explicitly also cover protection from transient overvoltages caused by direct lightning strikes or by lightning strikes in the direct vicinity of a building (or structure) protected by an external lightning protection system. The requirements of IEC 60364-5-53 and HD 60364-5-534 include surge protective devices (SPDs) for alternating current networks. However, where applicable, they can also be applied for the use of surge protective devices (SPDs) in DC networks.

The term TOV (Temporary Over Voltage) is used to describe temporary overvoltages which arise because of faults within the medium-voltage and low-voltage grid. The relevant product and installation standards require SPDs in low-voltage consumer systems to be TOV-resistant. Thus, mentions of temporary overvoltages in the existing standards refer to AC grids. How this works in DC grids, and whether and in what form temporary overvoltages occur in them, need to be verified in detail. Possible examples are the special conditions for the boost charging of battery-fed power supplies (see figure 3, in which the devices connected to the battery must not be affected by the increased charging voltage) or comparable requirements from the United States with respect to power crossing (AC coupling on the DC side in cases of malfunction) in data networks. See also the paragraph on battery-powered DC sources in section 7.3 LVDC generation based on the example of photovoltaics.

DKE VDE DIN
Recommended action

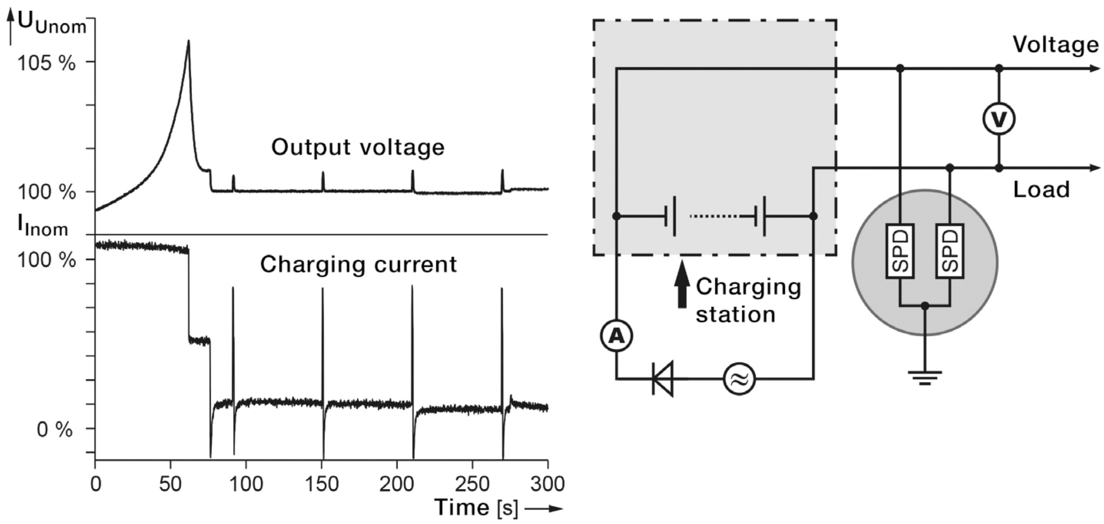


Figure 3 – Boost charging of battery-fed power supplies [19]

5.5 Functional safety at the system level

5.5.1 What is meant by "functional safety"

Supplement 1 (VDE 0803 Supplement 1, see as well IEC/TR 61508-0) to DIN EN 61508 describes "functional safety" in section 3.1:

"We begin with a definition of safety. This is freedom from unreasonable risk of physical injury or harm to the health of people, either directly or indirectly, as a result of damage to goods or the environment.

Functional safety is the part of overall safety which is dependent on a system or equipment providing correct responses to its input conditions.

An overtemperature protection device that uses temperature sensors in the windings of an electric motor to turn off the engine before it can overheat is an example of functional safety. Providing specialized insulation to help a device withstand high temperatures is not an example of functional safety, although it is an example of safety and could protect against exactly the same hazard.

Neither safety nor functional safety can be determined without evaluating the systems as a whole and the environment in which they operate."

5.5.2 The electrical installation system

Wherever low voltage is used there is a danger of people being killed or injured in the event of a fault. To exclude the event of a fault in electrical installations as far as possible, the following measures are deployed depending on the environment/type of installation:
- Basic protection
- Fault protection
- Supplementary protection
- Protective level upgrade

Since there is no separate "Functional Safety" standard for electrical installations, this document uses standards that are thematically related.

5.5.3 Normative references

Important standards in the field of functional safety include:
- IEC 61140 (DIN EN 61140, VDE 0140-1); "Protection against electric shock – Common aspects for installation and equipment ".
- IEC 60364-4-41 and HD 60364-4-41 (DIN VDE 0100-410, VDE 0100-410); " Low-voltage electrical installations – Part 4-41: Protection for safety - Protection against electric shock ";
- ISO 13849-1 (DIN EN ISO 13849-1); " Safety of machinery – Safety-related parts of control systems - Part 1: General principles for design ";
- EN 50495 (DIN EN 50495, VDE 0170-18); "Safety devices required for the safe functioning of equipment with respect to explosion risks; German version ";
- IEC 61508-2 (DIN EN 61508-2, VDE 0803-2); " Functional safety of electrical/electronic/programmable electronic safety-related systems – Part 2: Requirements for electrical/electronic/programmable electronic safety-related systems ".
- IEC/TS 60479-1 (DIN IEC/TS 60479-1, VDE V 0140-479-1); " Effects of current on human beings and livestock – Part 1: General aspects"
- IEC 61557-15 (DIN EN 61557-15, VDE 0413-15); "Electrical safety in low voltage distribution systems up to 1000 V a.c. and 1500 V d.c. – Equipment for testing, measuring or monitoring of protective measures – Part 15: Functional safety requirements for insulation monitoring devices in IT systems and equipment for insulation fault location in IT systems"

Standards are essential in achieving functional safety. A list of the most relevant standards can be found at the IEC website (iec.ch) or in a selection series published by VDE Verlag:

http://www.vde-verlag.de/normen/auswahl-zur-funktionalen-sicherheit.html

Other important IEC standards and VDE standards referenced, for example, in the functional safety standards can be searched for and ordered on the IEC, VDE and Beuth Verlag websites.

http://www.dke.de/de/findenbeziehen/Seiten/findenbeziehen.aspx

Below is a list of information on individual functional safety standards and standardization projects and their respective environments:

- EN 50128 (DIN EN 50128, VDE 0831-128); " Railway applications – Communication, signalling and processing systems – Software for railway control and protection systems"
- EN 61131-6 (DIN EN 61131-6, VDE 0411-506) "Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests" specifies requirements for programmable controllers and their associated peripherals, as defined in DIN EN 61131-1, which are intended to be used as the logic subsystem of an electrical/electronic/programmable electronic (E/E/PE) safety-related system
- Event tree analysis can be used for conducting analyses. This is described in IEC 62502 (DIN EN 62502, VDE 0050-3).
- If a human-machine interface plays a role in maintaining the safety function, IEC 62508 (DIN EN 62508, VDE 0050-2) contains information regarding the design options.
- Supplement 1 to DIN EN 61508 (VDE 0803 Supplement 1 and IEC/TR 61508-0: 2005) introduces the concept of functional safety and provides an overview of the standard series.

5.5.4 Terms used in IEC 61140 (DIN EN 61140, VDE 0140-1)

A whole range of terms are defined in IEC 61140 (DIN EN 61140, VDE 0140-1) to ensure clarity across all categories:

- **Basic protection:** Protection against electric shock under fault-free conditions [SOURCE: IEC 60050-195:1998, 195-06-01]
  NOTE For low voltage plants, systems and equipment, basic protection generally corresponds to protection against direct contact, as covered in IEC 60364-4-41.
- **Fault protection:** Protection against electric shock under single fault conditions [SOURCE: IEC 60050-195:1998/AMD1:2001, 195-06-02]
  NOTE For low voltage plants, systems and equipment, fault protection generally corresponds to protection against indirect contact, as covered in IEC 60364-4-41, especially for faulty basic insulation.
- **Insulation:** Set of properties which characterize the ability of an insulation to provide its function [SOURCE: IEC 60050-151:2001, 151-15-42, modified]
  NOTE Insulation can be a solid, a liquid or a gas (e.g. air) or any combination of these.
- **Basic insulation:** Insulation of hazardous-live-parts which provides basic protection [SOURCE: IEC 60050-195:1998, 195-06-06]
  Note 1 to entry: This concept does not apply to insulation used exclusively for functional purposes.

- **Supplementary insulation:** independent insulation applied in addition to basic insulation, for fault protection [SOURCE: IEC 60050-195:1998, 195-06-07]
- **Double insulation:** insulation comprising both basic insulation and supplementary insulation [SOURCE: IEC 60050-195:1998, 195-06-08]
- **Reinforced insulation:** Insulation of hazardous-live-parts which provides protection against electric shock equivalent to double insulation
  Note 1 to entry: Reinforced insulation may comprise several layers which cannot be tested singly as basic

5.5.5 Additional protection according to IEC 61140, IEC 60364-4-41 and HD 60364-4-41

If the intended use involves an increased risk, e.g. for areas with low-impedance connection between persons with earth potential, the technical committees must consider whether it is necessary to stipulate additional protection. Such additional protection may be provided in the plant, in the system or in the equipment.

In special cases, the consequences of double or even multiple faults should be considered, depending on the assessment of the technical committees.

Risk minimization of electrical installations is shown in Figure 4 based on the HD 60364-4-41 (DIN VDE 0100, VDE 0100) series of standards.

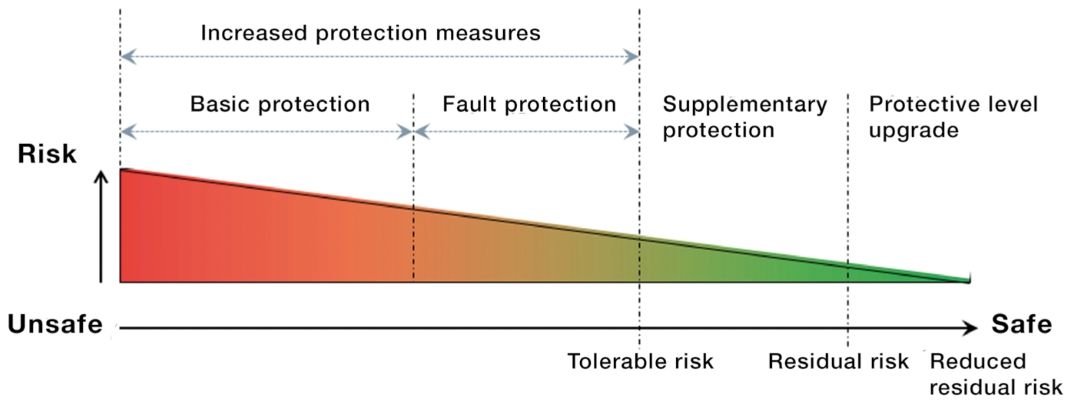


Figure 4 – Risk minimization in electrical installations according to HD 60364-4-41 (DIN VDE 0100, VDE 0100) [20]

Basic protection (protection against direct contact) (see Section 6.1 Basic Protection)

- Basic insulation of live parts
- Protective barriers or enclosures
- Obstacles
- Placing out or arm's reach

Fault protection (indirect contact protection) (see Section 6.2 Fault protection)

- Protective earthing (earthing via protective conductor)
- Protective equipotential bonding of the main earthing bus bar
- Protection by automatic disconnection of supply

Enhanced protective provisions

- Double or reinforced insulation
- Protective separation between circuits
- Safety extra-low voltage through SELV (safety extra low voltage) or PELV (protective extra low voltage)

Additional protection and risk minimization through

- Supplementary protection
  Residual current devices (RCDs)
  Supplementary protection equipotential bonding
- Protective level upgrade
  PRCD (Portable Residual Current Device), IC-CPD (In Cable Control and Protective Device).
  AFFD (Arc Fault Detection Device)
- Preventive measures
  Residual Current Monitors (RCMs)
  Equipment for insulation fault detection (IFLS) in IT systems

5.5.6 Functional safety of electrical installations

The safety level of AC installations is considered below as the basis for obtaining equivalent safety levels for direct current installations.

The corresponding safety integrity level (SIL) is defined for this purpose as follows in EN 50495 (DIN EN 50495, VDE 0170-18) [22]:

"In order to achieve the required safety integrity level, the overall safety lifecycle of the device should be taken into account (EN 61508 1). The required PFD (Probability of Failure on Demand) or PFH (Probability of a dangerous Failure per Hour) are shown in table 6."

SAFETY INTEGRITY LEVEL	LOW DEMAND OPERATION PFD (AVERAGE PROBABILITY THAT A COMPONENT WILL PERFORM ITS DESIGNATED FUNCTION FOLLOWING A DANGEROUS FAILURE)	HIGH OR CONTINUOUS DEMAND OPERATION PFH (PROBABILITY OF DANGEROUS FAILURE PER HOUR)
SIL 4	$\geq 10^{-5}$ to $< 10^{-4}$	$\geq 10^{-9}$ to $< 10^{-8}$
SIL 3	$\geq 10^{-4}$ to $< 10^{-3}$	$\geq 10^{-8}$ to $< 10^{-7}$
SIL 2	$\geq 10^{-3}$ to $< 10^{-2}$	$\geq 10^{-7}$ to $< 10^{-6}$
SIL 1	$\geq 10^{-2}$ to $< 10^{-1}$	$\geq 10^{-6}$ to $< 10^{-5}$

Table 6 – Safety Integrity Level: Failure limits for safety functions

From the perspective of functional safety, today's AC electrical installations, which have been installed and tested according to the IEC 60364 (DIN VDE 0100, VDE 0100) series of standards, are comparable to SIL 3, given that a person or a small number of people can be killed in an electrical accident (derived from DIN EN ISO 13849-1, Annex A).

This theoretically derived value is underpinned by appropriate statistics on electrical accidents in the Federal Republic of Germany. Based on today's accident numbers, the derived practical value of the overall electrical installation system tends towards SIL 4!

5.5.7 Assessment of functional safety based on EN 50495 (DIN EN 50495, VDE 0170-18) for circuit protection devices or protection functions integrated in equipment

The risk assessment is covered in Section 4.1 of EN 50495 (DIN EN 50495, VDE 0170-18) for circuit protection devices or protection functions integrated in equipment [22].

"Therefore, the equipment must be safe in the event of two faults occurring in separate pieces of equipment. If a type of protection is only safe in the case of one fault, the fault tolerance of the equipment can be improved through monitoring with a suitable safety device; or... "

Applied to electric installations this means: there is only a risk of danger if two separate faults occur in the installation (rather than "equipment"), e.g. loss of isolation and failure of the protection device.

Modern protection devices have an HFT (Hardware Failure Tolerance) of 0, i.e. the first failure in the device can compromise the safety function (see table 1 of DIN EN 50495 (VDE 0170-18): 2010-10). This is not a problem, however, because one protection device alone is not allowed as a protective measure. Basic protection is always necessary (e.g. insulation).

Systematic errors must be sufficiently minimized in the electrical installation and the protection devices used.

This can be "proven-in-use" in protective switches for AC, i.e. the use of proven electromechanical protection devices, or systematically developed electronic protection devices with sufficient internal diagnostic capability.

Based on table 2 of DIN EN 61508-2 (VDE 0803-2): 2011-02 for mechanical protection devices, or table 3 for electronic protection devices, SIL 1 is always required for electromechanical protection devices including residual current devices (RCDs), specifically type B (due to sensor redundancy). Fault exclusion is permitted at an extremely low failure rate. This is demonstrated by the durability tests and the returned goods statistics of the manufacturer.

Given that basic protection for the electrical installation is mandatory, the protection device must cover the remaining residual risk. For this, the protection device must have a certain reproducible quality.

Such requirements must also be demanded for DC protection devices, i.e. the product committees should address the topic of SIL and stipulate corresponding normative requirements for the product.

The same principle applies if protective functions are integrated in equipment. DIN EN 61557-15 (VDE 0413-15) can be used for the consideration of DC IT systems (non-earthed power supply) with regard to the functional safety of insulation monitoring devices in IT systems and institution troubleshooting devices in IT systems.

5.6 Arc faults

5.6.1 General

Arc faults cause considerable injury, damage and costs arising from loss of production year after year. Even the very latest switchgear systems cannot completely exclude the risk of arc fault ignition. The most common reasons for this include errors made while working on the switchgear, dirt, foreign objects or animals getting inside the switchgear. Large amounts of energy are released within milliseconds, causing great heat, a pressure wave and toxic gases, similar to the effects of an explosion. There are numerous methods of arc detection, for example:

- Detection of overcurrent associated with arc faults
- Detection of light emitted by the arc fault
- Frequency analyses

The collected data are evaluated and used to initiate different ways of quenching the arc fault, for example:

- Short-circuiting the system, i.e. the current commutes from the arc fault to the low-impedance metallic short circuiting mechanism, the voltage collapses and the arc fault is quenched as a direct result
- Direct control of the circuit-breaker via the shunt release

5.6.2 Arc fault protection systems in power switchgear and controlgear assemblies (PSC assemblies)

Low-voltage power switchgear and controlgear assemblies, commonly referred to as PSC assemblies, are nowadays used in many different ways for switching, protecting and controlling electrical energy. The DIN EN 61439 series of standards contains rules and requirements for the characteristic features of interfaces, operating conditions, design, performance and verification.

Arc faults cannot be completely ruled out within switchgear systems despite the greatest care being taken. In addition to IEC 61439-2 (DIN EN 61439-2), there is also a Guideline which aims to minimize the effects of the faults by addressing the testing and installing of arc fault protection systems for PSC assemblies. Furthermore, the German standardization committees DKE K431 and UK 431.1 are currently developing standards for arc fault detection systems, arc extinguishers and requirements for integrating these devices in switchgear.

All the standards mentioned here apply to both AC and DC systems, but practical solutions for AC operation currently predominate on the market. To protect people from the thermal hazards caused by arc faults, the German ETEM employer's liability insurance association has published an information brochure DGUV-I 203-077 which basically describes the current status of scientific findings on arc faults in AC systems. No studies are currently being carried out into DC arc faults. The results of the ongoing revision will be incorporated into the DGUV-I 203-077 information document.

5.6.3. Danger to persons from electric arc faults and protection from thermal effects

Similar to AC systems, people are particularly at risk from the thermal effect of high-energy DC arc faults (currents in the kA range). Personal protection is particularly necessary during work on installations with the possibility of direct exposure for the person concerned. If stable arc faults form, there is a risk of severe skin burns and eye injury. PPE (personal protective equipment against the thermal hazards of an arc fault) is therefore necessary in addition to technical and organizational measures.

DC systems are currently not explicitly covered in personal protection standards or guidelines. The existing standards for testing (prEN 61482-1-1, DIN IEC 61482-1-1 [59] and IEC 61482-1-2, DIN IEC 61482-1-2 [60]) and on the requirements for protective textiles and clothing (DIN IEC 61482-2[61]) do not differentiate between AC and DC applications, but were developed with the focus on AC systems. The standardized PSA tests are based on AC test circuits.

The direct thermal effects of DC arc faults do not differ fundamentally from those in AC systems. The heating curves and heat flux densities on exposed surfaces (effective energies) have comparable characteristics.

In extensive investigations [62, 63] carried out at the Technical University of Ilmenau with the support of the German employer's liability insurance association ETEM, systematic measurements were carried out on high-energy DC arc faults with the aim of determining characteristic values for DC arc faults, deriving conclusions for the testing and selection of PPE and incorporating the results into standardization. The measurements are used to investigate arc faults in systems powered by DC generators or current converters. Earlier studies also provided information on arc faults in battery circuits ("high-voltage batteries") [64].

In contrast to AC systems, DC systems can produce longer-lasting stable arcs even in the low voltage range. The power converted in the DC arc is mainly determined by the open-circuit voltage, prospective short-circuit current and electrode distance, in analogy to that in AC arc faults. The arc duration (short-circuit duration) is also important for the released arc energy Warc (linear influence). The effective energy Ei0 (energy density on the exposed surface) for the thermal effects of the arc fault depends on the arc energy and the effective distance.

Initial comparative studies, which have not yet been statistically verified, show that the energy levels of DC arc faults under standard box test conditions in accordance with DIN IEC 61482-1-2[60] are comparable with (or covered by) the test energy levels of the AC test arc:

ARC PROTECTION CLASS APC	I_P [KA]	AC TEST CIRCUIT			DC TEST CIRCUIT		
		W_{arc}[kJ]	E_{i0} [kJ/m²]	E_{i0}/W_{arc} [1/m²]	W_{arc}[kJ]	E_{i0} [kJ/m²]	E_{i0}/W_{arc} [1/m²]
1	4	168	146	0.87	175	146	0.83
2	7	320	427	1.33	264	360	1.36

Table 7 – Comparison of the energy levels for standard test conditions according to [60] in the AC and DC test circuit.

Conical electrodes generally have higher effective energy densities in comparison to flat electrodes. Under special conditions, this effective energy density can also be higher than in AC arc faults.

Further investigations are being conducted. Their focus is on the development of personal protection equipment in the event of arc faults. The results will be incorporated into the current revision of DGUV-I 203-077 [65].

5.6.4 Arc faults in low-voltage systems

AFDDs (Arc Fault Detection Device) are defined in standards for AC networks and are available as products. Their functioning and use in AC supply networks are specified in IEC 62606 (DIN EN 62606, VDE 0665-10) and IEC 60364-4-42 (DIN VDE 0100-420).

Residual current protective devices (RCDs) for DC are described in DIN IEC/TS 63053 (VDE V 0640-053).

A product standard for DC arc fault detection devices (AFDDs) for photovoltaic systems is in preparation [66].

Given that such protective switching devices function electronically, a suitable SIL level must be determined for them, although the disconnection function must be performed electromechanically. The safety level of LVDC installations must not be lower than that of modern alternating current installations.

It should also be noted that the thermal effects of the current represent a higher risk for LVDC than for AC. In the case of AC, dangerous arcs can be extinguished by the current zero crossing itself. The risk of electric arcs is significantly higher in DC. Studies conducted by the University of Regensburg show that this is voltage and current-dependent.

Various DC voltages and currents were measured; NYM-J 3x1.5 which is common in Germany was used as the line.

	48 V	120 V	230 V	326 V
1 A	(X)		X	X
1.3 A			X	
1.5 A			X	
2 A			X	
3 A			X	
5 A	X	X	X	X
7.5 A			X	
10 A			X	
16 A	X		X	X

Table 8 – Selection of measurement series for determining AC and DC arc behaviour

The following summary statement was made after evaluation of the measurement series, each consisting of 50 individual measurements per series:

"The measurements obtained have confirmed in full the presumed higher fire risk arising from DC arcs. ... Almost 100 % of the tested samples ignited even at low currents such as 1.3 A. By comparison, the incidence of ignition with AC 1.3A is only about 60 %.

The difference in the ignition times is far greater.

The potential fire risk arising from DC installation technology is therefore estimated to be much higher than that from AC!"[21]

5.6.5 Arcs in electrical installations

These grids place different demands on connectors, switches and cables than conventional AC networks. The absence of zero-crossing, as occurs in an AC mains switch, results in arcing during switching, disconnection or in the event of insulation faults, which puts a considerable strain on and damages the material, ultimately affecting functionality. The physical effect of the arc represents a substantial risk for progressive insulation damage and fires.

DC switching can be mechanical, electronic or hybrid. Recent developments, such as hybrid electromechanical switching elements, represent a promising approach to solving the arcing problem. Depending on the network form selected (IT or TNS), it must be ensured that all current-carrying wires are switched. The IT network, for example, requires all-pole switching.

The availability of detachable connections which can be removed under load if necessary is a key element for the further spread of DC networks in private, public and semi-public buildings. This necessitates basic requirements such as reverse-polarity protection for plugs as well as prevention of risks to people and property during disconnection under load.

DKE VDE DIN
Recommended action

Plugging/unplugging must not pose a hazard. The possibility of arcing in particular must be considered.

5.7 Testing and operation

The requirements for the initial and periodic inspection of electrical equipment are given in IEC 60364-6 (DIN VDE 0100-600, VDE 0100-600) and DIN VDE 0105-100 (VDE 0105-100).

DIN VDE 0100-600 (VDE 0100-600) contains the requirements for the initial inspection of electrical installations in the form of visual inspection, testing and measurement. The initial inspection is performed after the completion of a new system or extensions or modifications to existing facilities.

DIN VDE 0105-100 (VDE 0105-100) contains the requirements for the periodic inspection of electrical equipment to determine whether the system and all associated electrical equipment is in a proper state for operation.

5.8 Disconnection and switching

5.8.1 General

Safe disconnection and switching of direct current must be ensured in order to prevent or eliminate hazards associated with electrical plant or electrically operated equipment and machinery (prHD 60364-4-46, DIN VDE 0100-460). Any disconnection or switching device must meet the relevant requirements of HD 60364-5-53:2015. Every electrical installation must contain devices that allow the active conductors to be disconnected from the power supply. In general, all electrical equipment which require operational switching must include a suitable switch. A switch must be provided for each part of a circuit which is to be switched independently of other system components (DIN VDE 0100-460:2015-11, Section 463.1.1). Manually operated switch-off devices for mechanical maintenance, or control switches for such devices, must be provided (prHD 60364-5-537, E DIN VDE 0100-537:2015-11, Section 537.3.2.3).

Much of the list of products for corresponding applications which comply with HD 60364-5-53:2015 has meanwhile been revised to include DC requirements.

Switchgear for DC is described in the IEC 60947-1 (DIN EN 60947, VDE 0660) series of standards, as well as in DIN VDE 0641-14 and IEC 60898-3 (currently at the draft stage).

5.8.2 Semiconductor elements

Semiconductor elements must not be used as disconnecting devices (VDE 0100-537 (1999-06) section 537.2.1.3; E DIN VDE 0100-460 (2015-11) section 737.2.2).

Switchgear for operational switching can interrupt the current without having to open appropriate isolating section poles (VDE 0100-537 (1999-06) section 537.5.2 E; DIN VDE 0100-460 (2015-11) section 737.3.1.3). Semiconductor switching elements are an example of devices that can interrupt an electrical circuit without opening corresponding isolating section poles. Such semiconductor switching elements only have a switching, but not an isolating function.

5.8.3 Connectors and plug-and-socket devices

Connectors must not generally be used for operational switching (E DIN VDE 0100-537 (2015-11, Appendix A). Connectors are designed and tested according to IEC 61984 and DIN EN 61984, for example. Only connectors with breaking capacity (CBC, connector with breaking capacity according to DIN EN 61984) may be used for disconnection. These are also known as plug-and socket devices. These are designed (and tested accordingly) to be plugged and unplugged under voltage and load. However, suitable test parameters must still be specified for testing in DC applications; the specifications given in IEC 61984 and DIN EN 61984 are not sufficient (see also Section 5.8.4). In the case of connectors without load switching capacity (COC), appropriate measures must be taken to prevent accidental and/or unauthorized opening when installed in accessible areas (E DIN VDE 0100-537:2015-11, Section 537.2.5).

Loads should be connected and disconnected in a current and voltage-free state in DC systems due to the problems of arc quenching (see Section 5.6). Special exceptions can be stipulated separately.

DKE VDE DIN Recommended action

Relevant standards need to be developed for this.

For example, a second edition of DIN EN 61535 (VDE 0606-200) Installation couplers for permanent connection in fixed installations is currently being worked on, which will also describe the application in DC networks. This requires current- and voltage-free plugging and unplugging as well as locking (only releasable with tools) for all plug connections, in order to prevent incorrect operation. Additional marking of the plug connection is recommended for use in DC systems. This revision of the standard is intended to close the gap concerning installation connectors identified in Appendix A of this DC Roadmap.

In power supply systems with only one power source, depending on the design of the system, connectors can be used whose female contacts are protected against physical contact and whose male contacts are not protected (when the connector is open). A mandatory prerequisite for this is that the plug contacts protected against contact are connected to the power source and that risk to persons can be safely ruled out if these contacts are touched (male plug contacts).

DC power supply systems often use more than one energy source. In the case of connectors in the cable path between power sources, energy flow is possible in both directions in normal operation or in the event of a fault. To ensure effective protection against electric shock, both the female and male plug contacts must be protected against contact when such connectors are open.

5.8.4 Reverse polarity protection

Reverse polarity protection can be provided in various forms. A distinction must be made between active and passive systems:

- Mechanically unmistakable plug connection that prevents reverse polarity. A specially designed connector is used here which ensures exactly the same assignment of the pins on the basis of the mechanical design.

Before the plug can be used, the electrician must ensure the correct polarity of the contacts. The reverse polarity protected plug connection can be supplemented by a reverse polarity lock (e.g. diode, active semiconductor component) on the device side, thus ensuring greater reverse polarity protection.

- Use of a passive, electronic reverse polarity protection device. In the simplest case, this can be a diode, combined with a reverse polarity error indicator. A reverse polarity protection device is a simple and reliable method of avoiding reverse polarity.

- Active reverse polarity correction can be used as an addition to a passive, electronic polarity reversal protection device. If the equipment has the wrong polarity, the correct polarity is established internally by using an active electronic changeover switch (semiconductor switching elements). This offers greatest user convenience. In addition, active switching elements provide additional functions, such as delayed switch-on.
- Designs with pilot contact. Here, a pilot contact, connected to the plug contacts before the actual pole contacts, is used to transmit information. The respective polarity can also be checked and contacting of the plugs and socket contacts can be prevented if the polarity is reversed.
- Use of a wireless communication link between plug and socket ("NFC for plugs"). The communication link can be used to transmit data on the consumer's requirements, and on the socket. In addition, the communication link can be used to transmit data on the polarization. Here, a recommendation for action can also be given when the plug is inserted.

In addition to polarity protection, the current must be monitored when the equipment is switched on. Depending on the load behaviour of the equipment, capacitive behaviour (high current during plug insertion) or inductive behaviour (high current during disconnection) may occur. These problems can be eliminated by using an electronic input circuit.

In the case of polarity-independent operation of the load without reverse polarity protection, an electrical device must be incorporated which ensures the correct voltage polarity. This can be achieved e.g. by means of a rectifier built into the device. This can also perform additional functions if active semiconductors are used, e.g. switching of the load to stand-by operation.

5.8.5 Plugs and sockets

Plugs and sockets for DC applications are now available on the market. However, these are only designed for a small number of mating cycles and are not suitable for disconnection/switching under load ($I > 20$ A). The objective should be to define a system with integrated arc suppression, e.g. using semiconductor switches. Alternatively, systems which "communicate" with the corresponding devices would also be conceivable. The "communication" (not necessarily data transmission) could be realized by an additional contact with associated wire. An advantage of such communication would be that the plug or the socket would be dead when nothing is plugged in. This would increase personal protection levels enormously.

Plugs and sockets up to 16 A (EN 60309, IEC 60906-1, DIN VDE 0620-1) can be used in AC applications for disconnection and operational switching (VDE 0100-537 (1999) section 537.5.2 E DIN VDE 0100-460 (2015-11) Appendix A).

However, these versions do not meet the requirements for direct current applications without further measures, as there is always a risk of arcing when plugging and unplugging (see also Section 5.6).

DKE VDE DIN Recommended action

The standards for DC power systems must stipulate the voltage or current above which a mechanical locking device is required for DC plugs.

A distinction must be made between "layman-operable" (reverse polarity protected, disconnection possible under load, without tools, etc.) and "non-layman operable" (e.g. load-free disconnection, with tool, etc.) systems.

Test conditions for the intended operation of DC plugs and DC sockets could be derived, for example, from DIN VDE 0620-1, which only applies to AC applications:

The plug is inserted into and removed from the socket 5,000 times (10,000 strokes) at a frequency of 30 strokes per minute for sockets with a rated current up to and including 16 A and a rated voltage up to and including 250 V;

– 15 strokes per minute for other sockets.

However, further parameters must also be defined for the test, such as the structure of the test circuit (inductive or capacitive, characteristics of the DC voltage source, consideration of any reverse voltages). It must also be determined whether and how any semiconductor and communication systems, either in the connector or elsewhere in the installation (such as in the power supply in the fixed installation or in the load or on both sides), are to be taken into account in the test to reduce the current flow when plugging and unplugging.

5.8.6 DC connectors in data centres and switching centres

Standards on DC plugs and socket outlets for information and communication technology equipment in data centres and exchanges (P DIN IEC/TS 62735-1, VDE V 0620-600-1) are currently being prepared (see also IEC TS 62735-1 (2015-08) and IEC TS 62735-2 (2016-12)).

Proposal: Germany should propose that the IEC converts this TS into an IS for general applications.

IEC TS 62735-1:2015 Edition 1.0 (2015-08-28) Direct current (DC) plugs and socket-outlets for information and communication technology (ICT) equipment installed in data centres and telecom central offices – Part 1: Plug and socket-outlet system for 2.6 kW

IEC TS 62735-2:2016 Edition 1.0 (2016-12-14) Direct current (DC) plugs and socket-outlets for information and communication technology (ICT) equipment installed in data centres and telecom central offices – Part 2: Plug and socket-outlet system for 5.2 kW

Note: The range of application of P DIN IEC/TS 62735-xx, VDE V 0620-600-xx is explicitly limited to DC plug and socket outlets in data centres and exchanges. These standards do not apply to plugs and socket-outlets for domestic use or similar purposes.

Standardized, layman-operable plugs and test conditions are required for direct current.

DKE VDE DIN
Recommended action

5.8.7 Devices for the connection of luminaires

Luminaire connection devices should not be used for operational switching but may be used for disconnection if they meet the requirements of EN 61995-1 (E DIN VDE 0100-460 (2015-11) Annex A).

5.9 Protection against residual and reverse voltages

In the case of automatic switch-off, the "maximum switch-off times" specified in DIN VDE 0100-410 must be observed. Both the actual switching and the reduction of any remaining voltages to a harmless (residual) voltage must take place within the "maximum switch-off times". Further information on "maximum switch-off times" and automatic switch-off in the event of faults can be found in IEC 60364-4-41, HD 60364-4-41 and in DIN EN 0100-410 (2007), Section 411.3.2.

Usually the voltage in switched-off AC circuits drops to a harmless (residual) voltage value without significant delay as soon as the system is switched off.

Especially in DC circuits, it must be expected that, after switching off the supply voltage, the (residual) voltage in the switched off DC circuit will not drop immediately, or only with a delay, to a safe (residual) voltage value. In addition, DC equipment in particular can include energy storage devices (or components) which can lead to reverse voltages.

After automatic switch-off or operational switching, residual and reverse voltages must be prevented as far as possible or limited to a safe level.

Much DC equipment is equipped with capacitors in input, intermediate and/or output circuits. Even after the supply voltage or equipment is switched off, it should be expected that such capacitors - or other energy storage devices - may still be charged or may produce dangerous voltages. Residual or reverse voltages may occur in DC systems depending on the design of the input or output circuit of DC equipment. These voltages can be high enough to produce an electric shock or a dangerous flow of electricity through the body.

To prevent electrical hazards from dangerous voltages, the input or output circuits of DC equipment must be designed in such a way that no dangerous voltages are present or may arise on inputs or outputs after the supply voltage has been switched off.

Input circuits of DC equipment can be equipped with suitable input diodes, for example, to prevent reverse voltages.

Special care must be taken in DC systems in which electrical energy can be fed in by more than one device. Suitable technical circuit measures must be taken in such DC systems, if necessary, to effectively prevent or limit reverse voltages (by power supply equipment).

Reverse voltages can be limited, both in their voltage and duration, by suitable devices. Examples include:

- Discharge devices
- Automatic short-circuiting devices
- Suitable switching and disconnecting devices

5.10 Automatic restarting

Automatic restarting of electric shock protection devices (automatic switch-off) is permitted in systems to which only persons with a background in electrical engineering (EUP, BA4) or qualified electricians (EFK, BA5) have access (DIN VDE 0100-530-2011).

SELV or PELV applications may switch back on again automatically.

5.11 Application of the "Five safety rules" of electrical engineering

5.11.1 General information

Observing the so-called "Five safety rules" is an important basis for safe working on electrical systems. These rules can be found in DIN EN 50110-1 and DIN VDE 0105-100. Most low-voltage power distribution systems are AC, and users have a great deal of experience in consistently applying the "Five safety rules" in AC systems. DC systems have increasingly been installed for newly developed fields of application in recent years. For this reason, reference is also made here to the special features that are important for observing the "Five safety rules" in DC systems.

Almost unnoticed by the general public, DC has successfully been used for many decades in applications such as telecommunications, automation, railway technology and photovoltaics. Extensive practical experience has been gained in these applications, meaning that safe operation is possible - and high availability achievable.

In the future, DC is expected to be used increasingly for energy distribution in private homes, in the public sector and in commercial applications. Examples of new fields of application for the effective use of DC include household appliances, lighting equipment, PCs, consumer electronics, but also entire data centres. In many of the newly emerging DC application fields there is little practical experience in their safe operation, or in application of the "Five safety rules".

However, the picture is different for DC pilot systems for new kinds of DC applications. Unfortunately, some new DC systems are designed in a way which prevents correct application of the "Five safety rules". For the safe operation of DC systems and for safe working with DC systems, it is therefore of great importance that DC systems - and also all individual pieces of DC equipment - are designed in such a way that the "Five safety rules" can be applied correctly.

The safety level of new DC pilot systems is often lower than that in AC systems. The reasons for this include a lack of standards (as yet) for the operation of DC systems and DC operating equipment, a lack of operating experience with some types of DC operating equipment, and fundamental differences in the design and operating behaviour of AC and DC systems. There are often considerable differences between AC and DC systems, particularly during switching operations, during the extinguishing of arcs and when operating under short-circuit conditions. These differences can have a major influence on safe system operation.

In many switching devices or surge protection devices present in AC systems, zero crossing of the voltage is used to effectively interrupt operating or short-circuit currents. In AC systems, low-energy arcs often extinguish automatically when the voltage crosses zero. Unfortunately, this is not necessarily the case in DC systems. In DC systems there is no zero crossing of the operating voltage. It is therefore more difficult to interrupt DC currents with electromechanical switchgear or overcurrent protective devices than to interrupt AC currents of comparable amplitude.

In most AC systems, short-circuit currents can be expected that are considerably higher than the respective rated currents. High short-circuit currents enable reliable detection of short-circuits, and comparatively high AC short-circuit currents can be switched off quickly enough for the maximum permissible disconnection times not to be exceeded. In many DC systems, the short-circuit currents are only slightly higher than the nominal currents. With low short-circuit currents, it may be difficult to detect short-circuits reliably and switch them off in time so that the maximum permissible disconnection times are not exceeded.

5.11.2 The five safety rules

Work on electrical systems is required, for example, for maintenance and rebuilding work and to remedy malfunctions and electrical faults. The VDE regulations distinguish between the following methods during work on electrical systems (see DIN EN 50110-1 and DIN VDE 0105-100, Section 6):

- Working on de-energized equipment
- Live-line working
- Working near live parts

The safest working method is "working on de-energized equipment". Here, the "Five safety rules" must be applied consistently (see DIN EN 50110-1 and DIN VDE 0105-100, section 6.2.1):

1. Disconnect from power source
2. Secure against being switched on again
3. Determine absence of voltage
4. Earth and short-circuit
5. Cover or fence off adjacent live parts

All equipment making up an electrical system must be selected and arranged so that the "Five safety rules" can be applied correctly.

In order for work on electrical systems to be planned sensibly and safely, all persons involved in the planning and work must have sufficient knowledge of the structure, function and condition of the system. This is the only way to identify and assess possible dangers and to take appropriate measures to avoid and, if necessary, prevent them.

5.11.3 Disconnect from power source (Rule 1)

Disconnect fully from power source

All parts of an electrical system being worked on must be disconnected from all power sources (energy sources). In electrical systems with multiple power sources, each individual feed must always be disconnected separately.

Disconnection is always effected by switching off or disconnecting one or more circuits. During disconnection, disconnection points are formed which are able to withstand the expected voltage differences. Not all equipment which can interrupt a current flow is also suitable for disconnection! Before disconnection can be carried out, equipment which is suitable for disconnection must therefore be identified. All equipment suitable for disconnection is hereinafter referred to as "disconnection devices".

Equipment suitable for disconnection (disconnection device):

- Circuit breakers (with disconnect function, IEC 60947-2, DIN EN 60947-2)
- Mini circuit breakers
- Fuses
- Switch disconnectors (with/without fuses)
- Residual current devices (RCDs)
- Plugs and socket outlets

Circuit diagrams and system documentation are an important source of information for more complex systems (see IEC 60364-5-51, HD 60364-5-51 and VDE 0100-510). They provide information on the type and structure of circuits and serve to identify equipment with protective, disconnection and switching functions.

In AC systems there is often only one feed (energy source). However, some AC systems have several feeds. Examples of AC systems with multiple feeds:

- Multiple transformers/infeeds
- Backup power supplies
- PV inverters (with/without storage battery)
- Ring lines

In DC systems there is often more than one infeed (energy source). Examples of DC systems with multiple infeeds:

- Multiple rectifiers/infeeds
- Multiple voltage transformers
- Batteries
- Chargers

- Backup power supplies
- PV converters (with/without storage battery)
- Ring lines

Converters are used in a variety of designs and internal circuits to connect power supply systems of different frequencies, voltage levels and voltage types. Depending on the design, the energy flow can be in one (→) or in both directions (↔). The following basic configurations are possible in converters for power supply systems:

- AC → AC
- AC ↔ AC
- AC → DC
- AC ↔ DC
- DC → AC
- DC ↔ AC
- DC → DC
- DC ↔ DC

Converters between different power supply systems should always be disconnected on both sides.

AC and DC systems may include energy sources that cannot be switched off or de-energized (e.g. batteries, PV systems, UPS systems) due to their design. In such systems or system components, a separate risk assessment must therefore be carried out before any work is started. In the risk assessment, particular account must be taken of the possible effects of electric arcs and in the stipulation of working methods. For this reason, a combination of the above three working methods (see section 5.11.2) is always used to ensure safe working on electrical systems or on components with energy sources that cannot be switched off.

Switching capacity

The switching capacity of a disconnection device must be high enough to permit safe disconnection - at the currents and voltages that may occur during disconnection.

Unlike in AC systems, there is no zero crossing of the voltage in DC systems. Therefore, the DC breaking capacity of a switching device or overcurrent protective device (circuit breaker, fuse, switch disconnector, etc.) is usually lower than the respective AC breaking capacity. In addition, the DC switching capacity of switching devices can be polarity dependent. The DC switching capacity must be taken into account in particular when selecting switching devices, overcurrent protective devices and other switchgear/protective devices for DC systems.

If a fuse or a fuse disconnector (fuse isolator) is used as a disconnecting device, the risk of arcing must be taken into account during disconnection. This applies in particular when disconnecting (and reconnecting) DC circuits with the aid of fuses and fuse disconnector.

Energized conductors after disconnection

Attention must be paid to equipment which as not got de-energized properly after disconnection from the supply voltage. Energized conductors or energized components must be expected especially in equipment that has capacitors in its input circuits or equipment that can feed back electrical energy.

Electronic equipment is often used in AC and DC systems today, and the input and DC link circuits are usually equipped with capacitors. It must be assumed that such capacitors don't get fully de-energized after disconnection of the equipment from the supply voltage.

Disconnection device with sufficient clearance between contacts

Disconnection means that a sufficient clearance (isolating distance) is created in air (or equivalent insulation) (see DIN EN 0105-100, Section 6.2.2). The clearance distance must be large enough to prevent unintentional flashovers. The clearances and the air and creepage distances required for safe disconnection must be observed when dimensioning isolating distances. For this reason, electromechanical devices are always used for disconnection (e.g. circuit breakers, miniature circuit breakers, (load) disconnectors, fuse disconnectors).

Notes:

- Semiconductor components must not be used as disconnection devices (see prHD 60364-5-537 and E VDE 0100-537 Section 537.2). Switching devices consisting exclusively of semiconductor components are not permitted to be used for disconnecting.
- A hybrid switching device consisting of semiconductor components and isolating distances (with sufficient clearances and creepage distances) may be suitable for disconnection. However, hybrid switching devices are often only able to switch off operating currents. In such cases, at least one additional external overcurrent protective device (OCPD) is required to ensure protection against overcurrents or short-circuit currents.

Manual actuation of the disconnection device

It must be possible to operate a disconnection device manually in low-voltage installations. For this reason, disconnection devices are usually equipped with suitable levers, knobs, buttons or similar.

Distinct switching status of the disconnection device

Disconnection devices must be designed in such a way that switching states can be safely avoided in which the switching element can stick between open and closed.

Each disconnection device must be designed in such a way that the switching state is distinct. For this reason, disconnection devices usually have an actuating device (lever, toggle, buttons, etc.), the position of which indicates the switching status. An actuating device and any additional mechanical indication of the switching status must be designed in such a way that the displayed switching state always corresponds to the actual switching state of the respective disconnection device. An illuminated display alone is therefore generally not suitable for indicating a switching state distinctly. A hybrid switching device (used as a disconnecting device) therefore also requires an actuating device or a mechanical indicator in order to show the switching state distinctly.

5.11.4 Secure against being switched on again (Rule 2)

To ensure that systems on which work is to be carried out remain permanently de-energized during the work, disconnection devices must be secured to prevent them from being switched on again.

Special caution is required for systems or system components with multiple infeeds. This is the case, for example, in ring lines and systems with more than one energy source. The following applies when securing devices against being switched on again: Each individual disconnection device must be secured against being switched back on.

This can be achieved, for example, by mechanically locking an actuating device or by mechanically locking the actuating mechanism. Many disconnection devices can be locked to prevent unintentional switching - for example, they can be secured against actuation with a padlock. If it is not possible to lock an actuator mechanically, a different proven method must be selected to prevent it from being switched back on.

Disconnection devices can, for example, be equipped with an energy storage device (spring assembly, etc.) or with an auxiliary power supply (electricity, compressed air, etc.). In the disconnected state, there should be no energy in the energy storage devices that allows them to switch back on again. Energy storage devices should be deactivated (e.g. release spring assembly). Similarly, any existing auxiliary power supply must be rendered ineffective through suitable measures.

In particular, disconnection devices in medium and high-voltage installations are often operated "remotely". In some cases there are no "local" actuating devices at all. After disconnection, remote actuation must be securely prevented. Operation of remote-controlled disconnection devices with local actuating devices must also be prevented completely after disconnection. All transmission systems or interlocks used for this purpose must be reliable.

Before work can be started on a disconnected electrical system, suitable warning and prohibition signs must be affixed to prevent unauthorized switching operation (see DIN EN ISO 7010). Suitable covers, stickers etc. can also be used for small disconnection devices (e.g. miniature circuit breakers).

If fuse links are used for disconnection, they must be removed from the fuse holder and kept safe for the duration of disconnection. Fuses must be replaced with screw caps, blind inserts or other suitable inserts. Screw caps, blind inserts or other suitable inserts must be designed so that they can only be removed with a special tool (e.g. a wrench).

Energy storage devices (e.g. capacitors, etc.) that can energize equipment even after disconnection for the supply voltage must be discharged and, if necessary, earthed and short-circuited. Only equipment that permits safe discharging may be used for discharging such energy storage devices.

5.11.5 Determine absence of voltage (Rule 3)

In order to ensure safe working, the absence of voltage must be checked at, or as close as possible to, the work place. The voltage tester or measuring instrument used must be suitable for the particular application. Selection criteria include:

- Max. expected voltage
- Required overvoltage category
- Max. expected short-circuit current
- Voltage type/frequency/polarity
- Ambient conditions

Important information:

- IEC 61243-3-compliant (DIN EN 61243-3) two-pole voltage testers can be used to determine the absence of voltage in low-voltage systems.
- If a voltage tester or measuring device is used and if the voltage input of which has a high internal resistance, then capacitive or inductive reactive voltages may be measured and displayed by the measuring device even if the conductors have already been disconnected. Such capacitive or in ductive reactive voltages can be coupled-in via low-energy capacitive or inductive coupling.
- Some voltage testers have a so-called "load connection". A load connection can be used, for example, to suppress capacitive or inductive reactive voltages or to discharge capacitors. The permissible duration of the load connection can be limited by the manufacturer of a voltage tester.
- If a multimeter is used, it must be configured for the corresponding voltage measurement. If the multimeter is erroneously configured for a current measurement, and if it is used in this configuration to determine the absence of voltage, there is an acute risk of accident! Therefore, the use of multimeters is not recommended for determining the absence of voltage in power systems with significant short-circuit currents. Two-pole voltage testers for low-voltage systems (according to IEC 61243-3 or DIN EN 61243-3) are particularly well suited for reliable indication of the voltage state and for determining the absence of voltage.

The absence of voltage may only be determined by qualified electricians or persons given electrical training. The absence of voltage must not be confused with full disconnection!

In systems with capacitors, the respective discharge times of the capacitors should be waited for, before starting to determine the absence of voltage.

Voltage detectors and voltage testing equipment must be checked immediately before use. If possible, they should also be checked after use.

If work is interrupted, the absence of voltage in the work area must be checked again before work is resumed.

In practice, there are many reasons why a device may still be live although it is supposedly disconnected. Possible causes for this include:

- Faulty labelling of disconnection devices (circuit breakers, miniature circuit breakers, fuses, disconnectors, etc.)

- Disconnection device mix-up during disconnection (e.g. wrong miniature circuit breaker selected)
- Work area mix-up
- Faulty circuit diagrams (cable routing, designations, etc.)
- Line mix-up
- Not all energy sources have been disconnected (e.g. backup power supply)
- Unexpected voltages due to incomplete de-energization (e.g. through capacitors, cables)
- Voltage carryovers due to interrupted PEN conductor or unknown cross-connections
- Capacitive or inductive coupled voltages in already disconnected lines

Sometimes it is difficult to identify disconnected cables clearly at the work area. If there is a risk of confusion and a cable that may accidently not be disconnected needs to be "cut", established safety measures must be taken. In the case of cables for which it is impossible to determine the absence of voltage clearly, suitable cable cutting devices or suitable cable spiking devices, for example, can be used.

5.11.6 Earth and short-circuit (Rule 4)

Earthing and short-circuiting are always necessary in high-voltage systems. In low-voltage systems, earthing and short-circuiting can be dispensed with if there is no risk of the corresponding system being switched on unintentionally.

Possible causes for the unintentional "energizing" of disconnected low-voltage lines:
- Electrical/magnetic fields of (high-voltage) overhead lines in the vicinity
- Electrical/magnetic fields of low-voltage lines; when laid in parallel in the immediate vicinity of disconnected low-voltage lines
- Backup power supply systems
- Distributed energy supply systems (PV systems, combined heat and power plants, fuel cells, etc.)

Notes:
- The voltages coupled in by electric/magnetic fields can have different levels at different times.
- In unfavourable cases, the voltages in disconnected cables and lines coupled in by electric/magnetic fields can be so high that the permanently permissible contact voltages (50 V AC, 120 V DC) are exceeded. Appropriate protective measure: earth and short-circuit

For electrically non-insulated low-voltage overhead lines, all active conductors (L1, L2, L3, N), including switching and control wires, must be earthed and short-circuited in the immediate vicinity of the work area.

Earthing and short-circuiting devices must be appropriate for the intended purpose. When working with earthing and short-circuiting devices, ensure that the individual contacts are connected in the specified sequence! Earthing and short-circuiting devices are first connected to earth and only then to the parts to be earthed and short-circuited. To undo this, repeat in the reverse order.

If earthing and short-circuiting are used on a cable run that is interrupted by the work, earthing and short-circuiting are applied to both sides of the break point.

5.11.7 Cover or fence off adjacent live parts (Rule 5)

Work should be avoided in the vicinity of live parts if possible. If live parts cannot be de-energized, which are in potentially dangerous proximity to the working area (approach zone, danger zone), then the respective live parts must be covered or fenced off. The same safety measures must be applied here as for "Work in the vicinity of live parts" (see DIN VDE 0105-100, Section 6.4). Insulating covers must have sufficient mechanical and electrical strength and must be installed carefully to provide effective protection against accidental contact.

Note:
This safety rule may be applied at any time. For example, it may be appropriate to cover or cordon off adjacent live parts before applying any other of the five safety rules.

5.11.8 Standards and regulations

- DIN VDE 0100-510, VDE 0100-510 (2014-10): Electrical installations of buildings – Part 5-51: Selection and erection of electrical equipment – Common rules; see as well IEC 60364-5-51:2005 and HD 60364-5-51
- DIN VDE 0100-537, VDE 0100-537 (2015-11): Low voltage electrical installations – Part 5-53: Selection and erection of electrical equipment – Switchgear and controlgear – Clause 537: Isolation and switching; see as well prHD 60364-5-537
- DIN VDE 0105-100, VDE 0105-100 (2015-10): Operation of electrical installations – Part 100: General requirements; see as well DIN EN 50110-1 and EN 50110-1
- DIN EN 60947-2, VDE 0660-101 (2015-03): Low-voltage switchgear and controlgear – Part 2: Circuit-breakers; see as well IEC 60947-2 and EN 60947-2
- DIN EN 61243-3, VDE 0682-401 (2015-08): Live working – Voltage detectors – Part 3: Two-pole low-voltage type; see as well IEC 61243-3
- DIN EN ISO 7010 (2012-10): Graphical symbols - Safety colours and safety signs - Registered safety signs; see as well ISO 7010

6.1 Basic protection

Basic protection for devices and systems refers to protection in fault-free operation. This involves taking appropriate measures that prevent live parts from being touched in the normal operation of devices or facilities.

Individually appropriate basic protection safeguards are selected depending on the intended use of the device or the system (e.g. industrial or household). The precautions range from basic insulation (most commonly used in devices) through to measures which may only be applied in the commercial sector because they require specialized knowledge or training, such as obstacle-based protection or by placing equipment out of arm's reach.

The basis for the design and selection of the protective measures is laid down in international standards and has been repeatedly updated. These are the basic safety standards of IEC TC 64, IEC 61140, DIN EN 61140 (VDE 0140-1) and IEC 60479-1, -2, parts of which have been adopted in Germany as preliminary standards DIN VDE V 0140-479-X (VDE V 0140-479-X).

For low-voltage installations, the provisions of the DIN VDE 0100 (VDE 0100) and DIN VDE 0100-410 (VDE 0100-410) standards series apply (see as well IEC 60364-4-41:2005 and HD 60364-4-41).

DKE VDE DIN Recommended action

Concrete protection measures are being developed on this basis for devices and systems by different IEC bodies. In the design of DC applications, the specific thresholds for fibrillation must be taken into account which differ from AC applications.

A high level of safety is achieved through the use of suitable protective equipment in addition to purely mechanical safeguards (such as insulation, enclosures, housings). Here, too, the basics are being implemented in the IEC devices committees (IEC/TC 23) and supplemented for the European and national markets to ensure the typically high level of safety in Germany.

6.2 Fault protection

Fault protection for devices and systems refers to the protection measures when a (single) fault occurs. Since protection design is generally based on the assumption of safe shut-down upon the first fault, double or multiple faults are not considered.

An exception here is IT systems (unearthed power supply) in which the residual current is so low in the event of a first fault that automatic shutdown is not required. A prerequisite for this, however, is that these systems are monitored by an insulation monitoring device (IMD) in compliance with IEC 61557-8 and DIN EN 61557-8 (VDE 0413-8) and that the first fault is reported at the appropriate place. They are therefore primarily used in areas in which a first fault shall not trigger a shut-down.

Depending on the use of the device or the system, appropriate safeguards should also be selected for fault protection which then provide comprehensive protection in combination with the basic protection.

The equipment is assigned to protection classes depending on the selection/design of the protection measure (see also IEC 60364-4-41, HD 60364-4-41 and DIN EN 61140 (VDE 0140-1)), i. e., PC I, II, III.

Apart from the limit values for the switch-off conditions, the same considerations apply as for AC. The required switch-off times are also stipulated for DC in DIN VDE 0100-410 (VDE 0100-410).

Some standards for protection devices for DC applications are already available, or have been initiated by the IEC. IEC 60898-3 for circuit breakers for pure DC is being developed currently by IEC/SC 23E. Product standards for residual current protective devices (RCDs) for DC applications are also being prepared.

The standards for the use of insulation monitoring devices in DC systems are described in IEC 61557-8 and DIN EN 61557-8 (VDE 0413-8) and for insulation fault location in DC IT systems in IEC 61557-9 and DIN EN 61557 9 (VDE 0413-9).

Fuses for DC systems which are compliant with IEC/EN 60269-2/-3/-4/-6 (or DIN EN 60269-6 (VDE 0636-X)) are already available.

6.3 Supplementary protection (e.g. from direct contact) to the same level as AC only up to 200 V DC to earth

Supplementary protection refers to a protection measure in a system that is selected in addition to the basic protection and fault protection. This is a protection measure against electric shock.

IEC/TC 64 and IEC/TC 23 "Electrical accessories" joined forces to conduct studies to determine the voltage level up to which DC applications can be assumed to have comparable protection to AC. The ventricular fibrillation thresholds and the availability of protective devices were considered here.

The analysis showed that in DC applications with operating voltages of up to approx. 200 V to earth, a comparable level of protection can be provided as for AC, and also that the corresponding protective devices exist as products (see also section 6.2 Fault protection).

Applications with higher operating voltages require special measures or special installations (low impedance earthed mid-point at 400 V DC, or closed operating environments, etc.) and should not be used by laymen.

6.4 Fire and property protection

Essentially, the measures for basic, fault and additional protection and the protection devices also apply for fire and property protection.

Suitable protection devices have already been developed for the DC side of PV systems.

IEC/TC 82 and IEC/SC 23E have initiated standardization work in this field.

6.5 Protection against thermal effects

The heat produced by electrical equipment must not cause danger to, or have harmful effects on, adjacent solid materials or materials which could be expected in the proximity of these resources. Electrical equipment must not constitute a fire hazard for adjacent materials.

In the case of systems, the provisions of DIN VDE 0100-442 (VDE 0100 420) also apply for DC applications.

IEC/TC 64 is currently completing the hitherto missing section 532 on "Devices for protection against thermal effects" in IEC 60364-5-53 (DIN VDE 0100-530 (VDE 0100-530)) "Selection and erection of protective devices". This does not contain requirements for DC applications at present.

Electrical work is performed every day worldwide. The risk of arc faults being triggered by technical defects, human errors, dirt or foreign objects in the system cannot be excluded. The specialist employees concerned are particularly at risk from burns, as temperatures of over 10,000° C can be generated in the field of the arc. The main sources of thermal protection are technical systems and arc-fault certified personal protective equipment.

This consists of:
- Electrician's helmet with visor
- Protective gloves
- Protective suit

Under the respective applicable Labour Protection Acts and the Ordinances on Industrial Safety, employers must include protection against arc faults in their risk assessment. If there is a potential risk, the employer must provide personal protective equipment and ensure that this is worn. The personal protective equipment must be tested and approved by an accredited certification body.

Active and passive arc fault protection measures can be carried out to avoid or reduce damage to property and injury to persons. The active measures are aimed at avoiding the causes, while the passive or reactive measures address the generation of the arc fault itself.

In some low-voltage equipment, active arc fault protection measures are therefore already being incorporated which trigger within a matter of milliseconds in the event of a fault. The requirements for such devices are described in DIN VDE 0100-420 (VDE 0100-420). The primary protection objective of such fixed installations is plant protection and the protection of persons in closed systems. To ensure that these objectives are achieved, the energy release of the arc should be limited to values <100 kW for plant protection and to values < 250 kWs for personal protection. The installation of these systems is generally restricted to equipment with high availability requirements, usually in combination with very high short-circuit power levels. With regard to live working maintenance, only a fraction of the systems have an arc fault protection device. Live working, however, is widespread and is particularly carried out in networks which are protected by current-limiting fuses.

People are directly exposed to arc faults in live working situations, such as on low-voltage distribution cabinets. The wearing of personal protective equipment (PPE) is therefore mandatory for live working. Such protective clothing is suitable for reducing the thermal effects of arc faults to such an extent as to prevent 2nd degree burns. According to IEC 61482-1-2, this level of protection can be ensured with a Class 1 PSA up to an arc energy of 158 kJ, and with Class 2 up to 318 kJ. DGUV Information 203-077 provides help in assessing the thermal hazards caused by arc faults and selecting personal protective equipment. In order to achieve a drastic reduction in the thermal effects and in particular the further effects of the arc, attention is drawn to the possibility of the additional use of a mobile short-circuiting device during live working to optimize personal protection.

6.6 Corrosion protection

General requirements are contained in EN 50162 and DIN EN 50162 (VDE 0150) "Protection against corrosion by stray current from direct current systems".

Stray current corrosion can occur on the outside of underground facilities or on the inside of equipment containing electrolyte solutions, such as water pipes near insulating joints or high-resistance pipe connections.

Stray currents can also have other effects, such as overheating. DC-powered systems which can cause current flows in the ground or in any other electrolyte solution, either intentionally or unintentionally include:

- DC-powered railways; (including DC-powered vehicles powered by overhead line or bus bar)
- Trolley bus systems (see figure 5)
- DC power systems
- DC-powered systems at industrial sites
- DC communication and information systems
- Cathodic corrosion protection systems
- High-voltage direct current transmission systems (HVDC)
- Shore-side electricity for ships
- DC-powered signalling systems for railways

The following earthing solutions are common for DC systems:

- Negative pole earthed
- Positive pole earthed
- Neutral conductor earthing
- Isolated operation

In the case of DC conductors with a positive charge (in relation to earth potential), insulation leakage current or leakage current to earth can lead to electrochemical corrosion (oxidation) of conductor material. The higher the (leakage) current from a positively charged conductor to earth, the higher the tendency to electrochemical corrosion.

Progressive conductor corrosion can lead to a significant reduction in the effective conductor cross-section of positively charged conductors. In power engineering DC systems with significant load currents, possible additional heating or even overheating of current-carrying conductors must be expected if the cross-section of conductors is reduced due to corrosion.

To prevent conductor corrosion and leakage current-related corrosion on other conductive parts, DC power supply systems should always be designed to prevent impermissibly high (leakage) current to earth or stray current. Low-impedance earthed DC power supply systems should therefore only be connected to earth at a single point and the protective conductor of a DC power supply system should not carry any significant (leakage) current.

Stray currents and corrosion caused by stray currents can occur in so-called "combined conductors".

Combined conductors in power supply systems (see also DIN VDE 0100-100):
- PEN conductor: Protective earthing conductor and neutral conductor
- PEM conductor: Protective earthing conductor and mid-point conductor
- PEL conductor: Protective earthing conductor and line conductor

TN-C systems operated with DC voltage have either a PEM or a PEL conductor. With PEM and PEL conductors, DC stray currents can occur through other conductive parts or through earth. In order to prevent DC stray currents and corrosion caused by stray currents, power supply systems operated with DC voltage should preferably be designed as TN-S or IT systems.

IT power supply systems must always be equipped with insulation monitoring in order to detect earth faults.

In low-impedance earthed DC power supply systems in which an active conductor has a positive voltage to earth, it makes sense to use an insulation or leakage current monitoring device to detect possible conductor corrosion or stray current corrosion.

Example of application:
- To prevent possible conductor corrosion in telecommunications systems operated with direct current, the positive pole is often low-impedance earthed (e.g. 0 V and -48 V). Stray currents are avoided by the TN-S system structure.

EN 50122-2 (VDE 0115-4) sets out the requirements for minimizing stray currents and reducing their impact on railways.

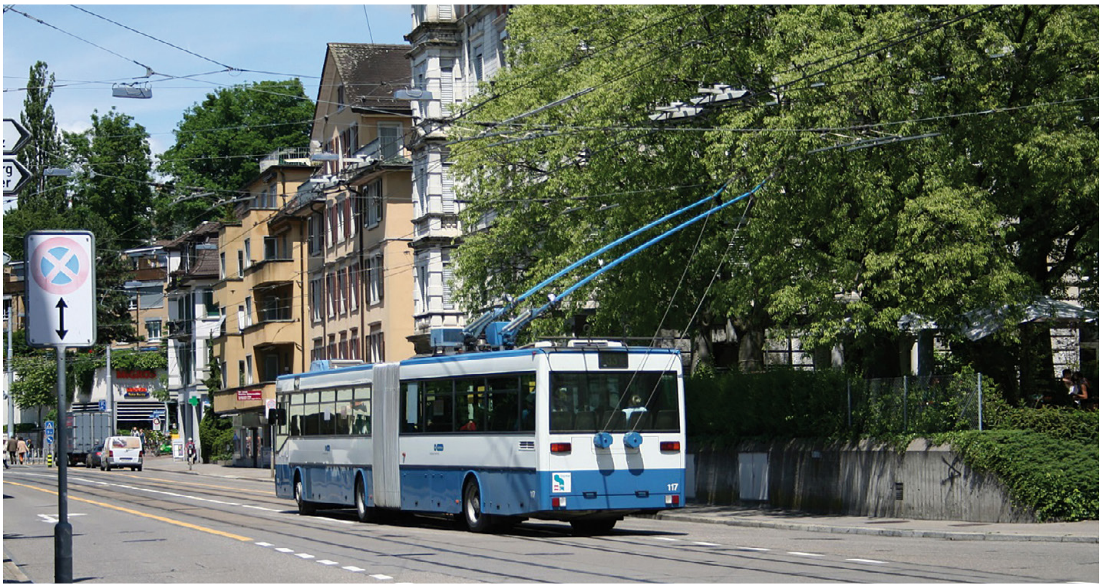


Figure 5 – Trolley bus [23]

Stray current corrosion occurs in DC powered systems. It can be a problem especially in trams and underground railways because in these systems the tracks generally form the 2nd pole and they are not sufficiently insulated from earth. A possible corrosion protection measure is to separate the earthing systems of AC and DC railway systems via spark gaps (see DIN EN 62561-3 (VDE 0185-561-3)) or to use voltage limitation devices according to DIN EN 50526-2 (VDE 0115-525-2).

In the case of overhead line masts and steel tracks on the ground, the corrosion process consists of two partial reactions: the anodic partial reaction of the metal dissolution (oxidation) and the cathodic partial reaction of oxygen reduction.

The anodic and cathodic partial reactions can be represented and corrosion processes or potential dependencies identified with the aid of so-called current-voltage curves.

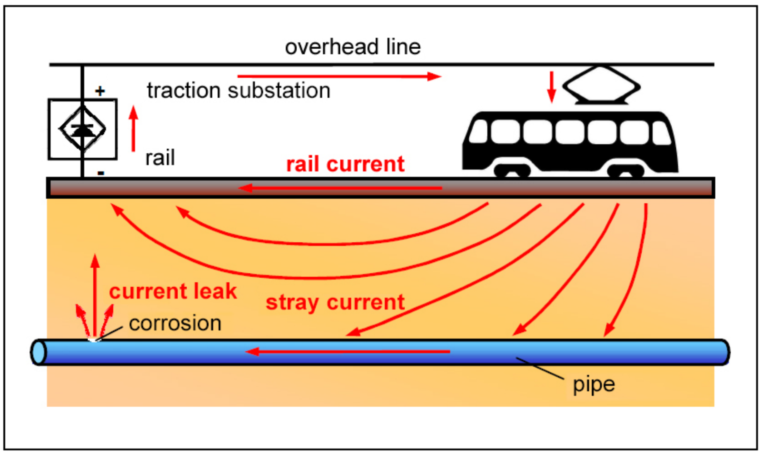


Figure 6 – The risk of stray current corrosion in a DC railway

Further stray current influence occurs in pipes which run underneath DC-powered railways. The rails of such tracks are used to return the operating current, which creates a longitudinal voltage drop at the rails but also in the ground via the track bed. Part of this return current can thus flow through the ground and penetrate the pipeline. Figure 6 shows the risk of stray current corrosion in a DC railway. Increased anodic corrosion occurs if the stray current then exits the pipe again in areas with greater negative potential (e.g. connection of the negative pole of the traction substation to the rails). It is therefore strongly recommended that the positive pole be earthed to reduce corrosion-related damage.

Corrosion due to stray current

The protective current from the external anode beds is greatest in the area of the anode beds and decreases with increasing distance.

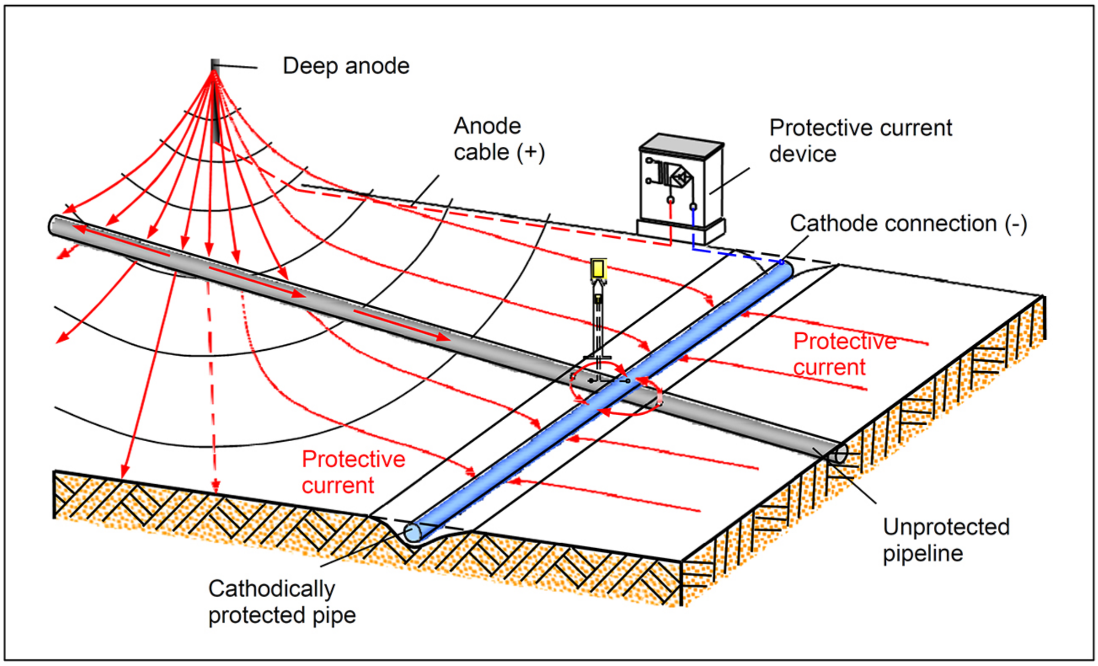


Figure 7 – the voltage curve of an anode bed of a protected pipe

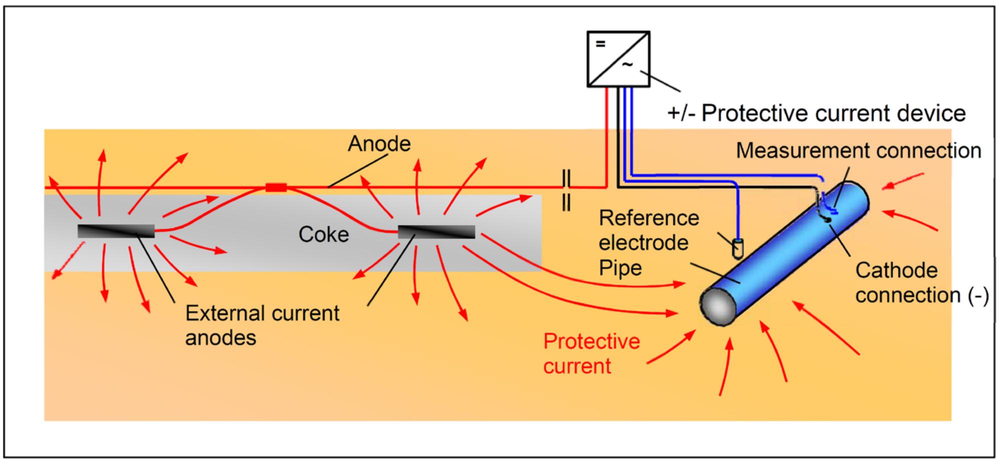


Figure 8 – the protective current

The protective current flows from the anodes via the ground to the critical areas of the pipe, penetrates the damaged areas of the casing and prevents corrosion (see figure 8).

6.7 Lightning and overvoltage protection

The requirements and principles of the currently valid lightning protection standards series IEC 62305-X and DIN EN 62305-X (VDE 0185-305-X) are applicable for the lightning and overvoltage protection of direct current installations, provided they are located in buildings or if the DC cables are fed into physical structures. By contrast, DC power systems which are installed in vehicles are explicitly excluded in the scope of application of the lightning protection standards. The primary parameters of lightning risk contained in IEC 62305-1 and DIN EN 62305-1 (VDE 0185-305-1) therefore also apply for DC applications. The question of whether and in what form lightning and overvoltage protection measures are necessary can be answered by carrying out a risk analysis as described in IEC 62305-2 and DIN EN 62305-2 (VDE 0185-305-2) and the supplements to DIN EN 62305-X (VDE 0185-305-X). Mention should be made here of the decades of experience accrued by the GDV (German Insurance Association) with regard to lightning-related damage to electrical systems. The GDV provides recommendations for the selection of lightning and overvoltage protection for electrical equipment in a wide range of building types and for different types of use in VdS 2010 (Risk-oriented lightning and overvoltage protection). Such recommendations may also be agreed in the insurance contract.

As in alternating current applications, a lightning protection system (LPS = lightning protection system) for DC systems includes the external lightning protection (air-termination system, down conductors, earthing system) and the internal lightning protection (lightning protection equipotential bonding with a system of coordinated surge-protective devices (SPDs), separation distance). In addition to the above-mentioned lightning protection measures, the system's own requirements also need to be taken into account for the use of SPDs in DC systems. In contrast to the previously described lightning protection requirements for AC and DC systems, these systemic specifications of DC SPDs can differ in key respects. Figure 9 shows an overview of the relevant system parameters for DC SPDs. The existing installation regulations for the selection and use of surge protective devices (SPDs), and the product standards for surge protective devices only cover use in AC networks at present. Due to the different system requirements, these cannot be transferred directly to DC applications. The future IEC 61643-41 will describe the special requirements for SPDs in low-voltage DC power supplies. DIN EN 50539-11:2013 12 (VDE 0675-39-11:2013-12) can be used for SPDs designed for use on the DC side of PV systems.

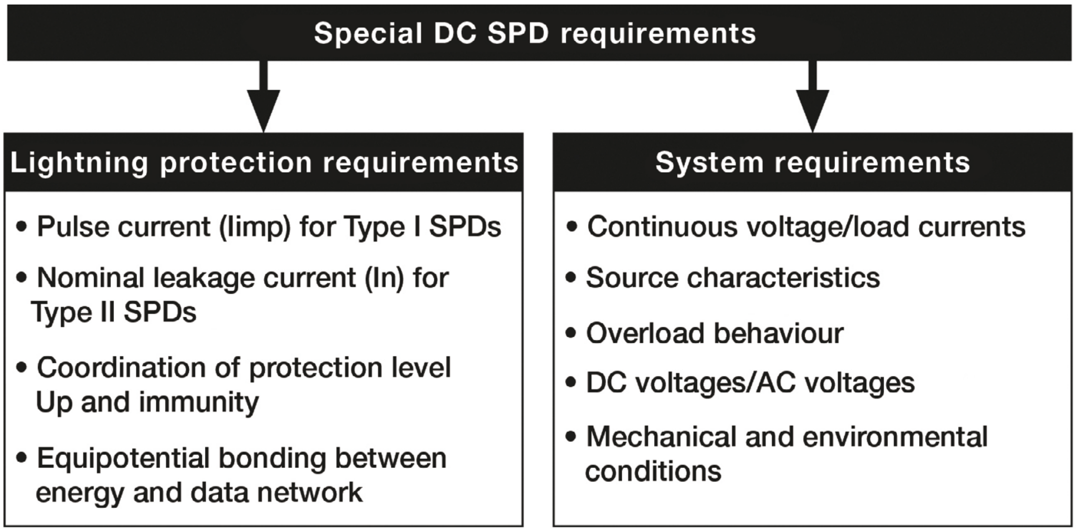


Figure 9 – Overview of requirements for DC SPDs [19]

Appendix E of DIN EN 62305-1 (VDE 0185-305-1) and DIN EN 62305-4 (VDE 0185-305-4) Supplement 1 contains rules for determining the lightning current distribution within a system. The basic principles of lightning current distribution for AC applications described there can also be used as the basis for DC applications.

Figure 10 shows the basic principle of lightning current distribution adjusted for DC applications inside a building with unipolar DC power network and a return cable. Only a single power line, a DC cable, is fed into a building. On its way to earth, lightning current I divides between the earthing system of the building and the DC cable, which is connected via SPDs:

$I_f = k_e \times I$

I_f = component of the lightning current via SPDs into the DC system
I = total lightning current as per LPL
k_e = current division factor

According to the lightning protection standard DIN EN 62305-1: if the supply lines (e. g. electric and telecommunication cables) are not screened and not in metal ducts, each of the n' conductors will conduct the same proportion of the lightning current. If, as a first approximation, it is assumed that the earthing impedance of the power supply system and earthing impedance of the building hit by the lightning are roughly the same and thus half of the lightning current enters the earthing system and half flows into the power supply line, then the current division factor with unshielded cables $k_e = 0.5/n'$ (where n' is the total number of all conductors).

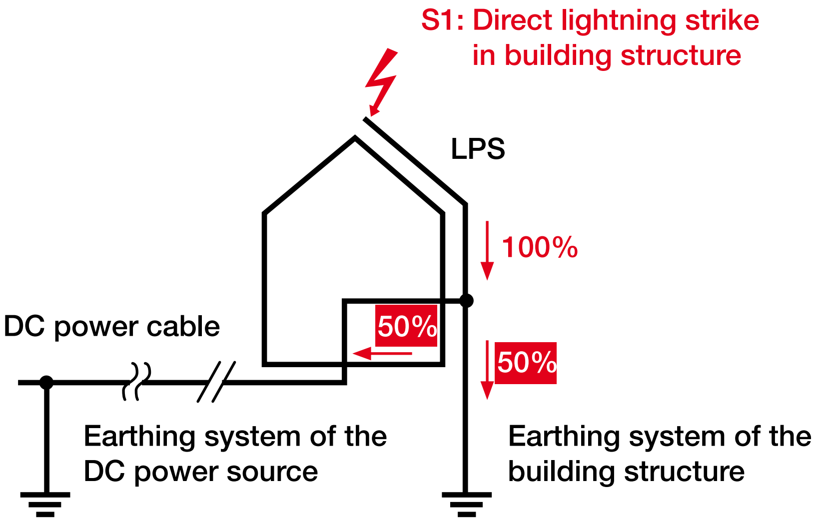


Figure 10 – Example of lightning current distribution according to DIN EN 62305-1 (VDE 0185-305-1), Annex E [19]

In DC systems, the power cables usually have only two (+U, N) or three (+ U, - U, N) individual wires. In contrast to three-phase systems, where the lightning current can divide itself among the three phase wires, or if there is a neutral wire: among four or five single wires. As a result of the lower number of active wires in DC systems compared to three-phase systems, a lightning current of limp = 25 kA 10/350 per protection path can be derived from this simple example for type 1 SPDs in DC systems (for more examples, see table 9).

DESCRIPTION	n‘	I_{imp}
Unipolar DC system with a return cable	2 (+U, N)	25 kA
Bipolar DC system with a return cable	3 (+U, -U, N)	16.7 kA
Unipolar DC system with two return cables	4 (+U, +U, N, N)	12.5 kA

Table 9 – Description of different DC networks [24]

The lightning current distribution in real and in some cases highly complex systems, such as PV roof systems or large PV power plants, may differ dramatically from the simplified approach with only two individual wires.

Basically, the general requirement that the Up protection level of the SPDs should remain beneath the immunity of the equipment to be protected also applies to the overvoltage protection of DC power systems. As in AC systems, a distinction must be made here between protection between the active wires, i.e. in DC applications between the positive and negative wire, and protection between active wires and earth. The selection of the UP for the protection of the active wire to earth can also be based on the rules of insulation coordination in DC systems. The future DIN VDE 0100-443 (VDE 0100 443), based on IEC 60364-4-44/A1 from 2015 will also define overvoltage categories for nominal direct voltage equipment. table 4, which is taken from IEC 60364-4-44/A1 from 2015, describes the overvoltage categories up to and including 1,500 V DC. These rated impulse voltages describe the impulse withstand voltages of equipment between the active wires and earth.

NOMINAL VOLTAGE OF THE INSTALLATION [a] [V]	VOLTAGE LINE TO NEUTRAL DERIVED FROM NOMINAL VOLTAGES A.C. OR D.C. UP TO AND INCLUDING [V]	REQUIRED RATED IMPULSE WITHSTAND VOLTAGE OF EQUIPMENT [c] [kV]			
		Overvoltage category IV (equipment with very high rated impulse voltage)	**Overvoltage category III** (equipment with high rated impulse voltage)	**Overvoltage category II** (equipment with normal rated impulse voltage)	**Overvoltage category I** (equipment with reduced rated impulse voltage)
		For example, energy meter, telecontrol systems	For example, distribution boards, switches socket-outlets	For example, distribution domestic appliances, tools	For example, sensitive electronic equipment
120/208	150	4	2.5	1.5	0.8
230/400 [b, d] 277/480 [b]	300	6	4	2.5	1.5
400/690	600	8	6	4	2.5
1,000	1,000	12	8	6	4
1,500 d.c	1,500 d.c	15	10	8	6

[a] Based on the standard DIN EN 60038 (VDE 0175-1).

[b] This rated impulse withstand voltage applies between the active wires and PE.

[c] In IT systems which are operated at 220-240 V, the line for 230/400 V must be used due to the voltage to earth which arises in a wire during an earth fault.

[d] Recommended values in Annex D of DIN EN 60664.2.1 (VDE 0110-1 Supplement 1): 2011.

Table 10 – Required rated impulse voltage of equipment Uw (Overvoltage categories for DC systems) [24]

Further requirements can be specified in the respective product standards in addition to those contained in IEC 60664-1 and DIN EN 60664-1 (VDE 0110-1). IEC 62109-1 and DIN EN 62109-1 (VDE 0126-14-1) provides specifications for the surge-withstand voltage of inverters for use in photovoltaic energy systems. To coordinate the head protection level with the impulse withstand voltage of PV modules, the impulse withstand voltage of the modules should be taken into account according to DIN EN 61730-2 (VDE 0126-30-2). The different load conditions in DC circuits must also be considered in SPD-tests. These include for example

- overload behavior tests (disconnection test)
- operating duty test of a Type 1 SPD with spark gap

6.8 Conditions for automatic disconnection in case of a fault

The conditions for automatic disconnection in the case of a fault are given in IEC 60364-4-41, HD 60364-4-41DIN and VDE 0100-410 (VDE 0100-410):2007-06 for the automatic disconnection of the power supply also apply for DC applications. The maximum permissible disconnection times depend on the voltage type, voltage level, current system and circuit type (distribution circuit, final circuit).

6.9 Insulation coordination

Air and creepage distances are dimensioned according to the basic standards IEC 60664-1 and DIN EN 60664-1 (VDE 0110-1); the voltage limits 1000 V AC and 1500 V DC apply here. Many product standards are derived from or reference this standard.

A further standard - Safety requirements for electrical equipment for measurement, control, and laboratory use - Part 1: General requirements (IEC 61010-1:2010 + Cor.: 2011); DIN EN 61010-1, also describes the dimensioning of power supply circuits up to 1000 V AC/DC.

6.10 Device coordination / Selective protection / Backup protection

There are no application requirements for device coordination/selective protection/backup protection at present. These are to be drawn up.

DKE VDE DIN Recommended action

6.11 Labelling of systems and equipment

The marking of conductors in DC systems is defined in IEC 60445.

In general, three different scenarios can be distinguished in semi-public buildings, based on the electrical installation or the type of voltage used.

First, there are pure alternating current installations which comply with the latest standards.

Second, a DC voltage network can be used, for example, in installations with high positive (consumption) and negative (recovery) pulsed loads since there is no need to convert DC voltage from/to AC/three-phase current. The associated conversion losses can thus be avoided.

In the third scenario, these forms of voltage exist in parallel. Since an independent electrical distribution system must be used for each type of voltage, two separate electrical distribution systems must be used in hybrid networks, whereas only one electrical distribution system needs to be used for a pure DC power supply or a pure AC power supply of a building (or section).

This can lead to two electrical distribution boards being installed and operated in an installations room. Even for a qualified electrician, it is not immediately apparent what type of installation is involved, either from an external inspection or by opening the switch cabinet. This is because circuit breakers and miniature circuit breakers for "universal current" (AC and DC) have been developed and are now available on the market. Currently there are no exclusively DC cables either, meaning that existing installation cables are used. For example, an NYM cable used in a DC installation cannot be distinguished externally from an AC cable.

Until the labelling of systems, devices and lines has been regulated by standards, the following is recommended: installation rooms in which systems are operated with direct current should have an appropriate sign on the entrance door. The information sign should clearly indicate the voltage level (e.g. Caution 380 V DC).

- The same applies to control cabinets for "mixed installations". It must be clearly identifiable from the exterior whether the respective control cabinets are for direct or alternating current.
- Installation cables should be routed separately in cable shafts or cable ducts. (e.g. AC cable bundle right and DC cable bundle left on the cable tray.)
- The single cables and/or cable bundles should be clearly marked at regular intervals, e.g. using cable label holders. The same applies to the cable ends at the source (control cabinet) and the load (terminal device).

The electrical DC systems as a whole, but also the installation in particular, must be clearly identifiable for external specialists.

6.12 Electromagnetic compatibility (EMC)

Electrical equipment covered by this Standardization Roadmap falls within the scope of the so-called "EMC Directive" of the European Union (Directive 2014/30/EU) on the harmonisation of the laws of the member states relating to electromagnetic compatibility (EMC) and within the scope of national laws derived from this EU-Directive. Some key terms of electromagnetic compatibility are explained in Article 3 of the EMC Directive:

- **Compatibility** – "electromagnetic compatibility" means the ability of equipment to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to other equipment in that environment;
- **Disturbance** – "electromagnetic disturbance" means any electromagnetic phenomenon which may

degrade the performance of equipment; an electromagnetic disturbance may be electromagnetic noise, an unwanted signal or a change in the propagation medium itself;

- **Immunity** – "immunity" means the ability of equipment to perform as intended without degradation in the presence of an electromagnetic disturbance.
- **Environment** – "electromagnetic environment" means all electromagnetic phenomena observable in a given location

Electromagnetic compatibility (EMC) is a key "property" of electrical equipment. The EMC Directive therefore stipulates that:

- Equipment must be designed and manufactured according to the generally recognized rules of technology
- Electromagnetic disturbances (emissions) caused by equipment should not reach a level at which the intended operation of radio and telecommunications equipment or other equipment is not possible
- Equipment must be sufficiently insensitive to the expected electromagnetic interference under normal operating conditions in order to work as intended without unacceptable impairment.

Equipment must therefore be sufficiently immune to disturbances, and the level of disturbances generated by equipment must be so low that other equipment is not disturbed, damaged or restricted in their intended use. In addition, the level of such disturbance must be so low that it causes no unacceptable risks to humans, animals and the environment.

The EMC Directive requires compliance of equipment with harmonized standards:

If a piece of equipment complies with the relevant harmonized standards, it is presumed that it also complies with the basic requirements covered by these harmonized standards. This presumption of conformity is limited to the scope of the harmonized standards and only applies within the basic requirements covered by these harmonized standards.

Harmonized (EMC) standards must be applied for equipment run on DC voltage. If existing harmonized (EMC) standards for equipment powered by direct current cannot be applied, existing harmonized standards (e.g. from the AC power supply) must be amended accordingly, or appropriate new harmonized standards created.

DKE VDE DIN Recommended action

To assess the emitted disturbances and the immunity of electrical equipment, the coupling mechanisms need to be considered via which disturbances can be coupled and emitted:

- Galvanic coupling
- Inductive coupling
- Capacitive coupling
- Wave coupling
- Radiation coupling

The increasing use of sensitive electronic equipment means that special attention must be paid nowadays to the disturbance emission and the immunity of equipment. The proper use of EMC measures is therefore an integral part of the planning and operation of electrical systems. The following EMC measures have been proven in practice to keep the level of disturbance and interference as low as possible:

- Suitable equipment design:
  - Generation of disturbances: Reduction or elimination of the generation and emission of disturbances
  - Immunity: Achieving sufficient immunity
- Shielding of disturbance-generating equipment
- Shielding of sensitive equipment from disturbance
- Shielding of cables and lines
- Filtering
- EMC-compliant design of switch cabinets
- EMC-compliant installation of cables and lines
- EMC-compliant design of potential equalization and earthing systems
- Selection and design of network systems taking electrical disturbance and interference into account
- Compliance with any required distances between cables and lines
- Compliance with any required distances between disturbance-producing and sensitive equipment which is susceptible to disturbance.

The first AC power supply systems were introduced more than a century ago. In the first decades of the "AC" era, linear loads were mainly used which received sinusoidal load currents. For some decades now, non-linear loads have increasingly been used in AC systems which receive non-sinusoidal load currents. Non-sinusoidal load currents are frequently caused by input circuits with power electronic components. These non-sinusoidal load currents are described as "harmonics". Harmonics can lead to the failure or overloading of equipment. Harmonic correction filters/power factor correction (PFC) filters are used to compensate for the negative effects of harmonics. A distinction is made here between:

- Passive harmonic filters (passive PFCs)
- Active harmonic filters (active PFCs)

Because of legislative requirements and harmonized standards, power electronic equipment above a certain power input level is now always equipped with harmonic filters. These harmonic filters require space within equipment housing, and they increase the production costs of the equipment. In addition, both passive and active harmonic filters result in electrical losses. The waste heat produced by electrical losses in harmonic filters must also be removed.

A significant portion of the electrical energy, consumed today in industrial production, is used for the operation of electric motors. The legislation requires high energy efficiency in the operation of electric motors. In order to meet the increased energy efficiency requirements, electric motors are often operated with inverters. Inverters provide an output voltage with variable AC voltage and frequency for variable speed drives. Inverters can be a significant source of interference. This must also be taken into consideration in the use of electric motors in DC power systems. Therefore the basic configuration of inverters is discussed below.

Inverters for the operation of AC motors - connected to single-phase or three-phase AC power supply systems – often consist of the following functional groups:

1. AC input filter (Power Factor Correction)
2. Rectifier circuit (controlled or not controlled)
3. DC link
4. Inverter circuit (e. g. with IGBTs, thyristors, triacs, etc.)
5. AC output filter.

Many electronic loads (including inverters) have a DC link. The direct feed of the DC link circuit from a DC power supply system is expected to yield the following advantages:

- No need for AC input filters (passive power factor correction filters (PFCs))
- Reduced number of components
- Increased energy efficiency

The inverter circuit for the operation of AC motors consists of power semiconductors which can have "conductive" or "non-conductive" operating states. These power semiconductors can be viewed - in simplified terms - as on/off switches that can be operated with a high switching frequency (clock rate). The switching frequencies of inverters for AC motors are normally in the lower kHz range. Higher switching frequencies, up to the MHz range, are common for other applications (inverters for lighting, DC-to-DC converters, etc.). Single-phase and three-phase inverter circuits always take pulsed currents (idealized: square-wave currents) from the DC (indirect) circuit. Pulsed voltage peaks can occur during the switching of power semiconductors in inverter circuits. Inverter circuits consume active power, but at the same time they represent a not-inconsiderable source of interference. The "power and voltage output signal" of inverter circuits (without connected AC filter) is highly non-sinusoidal. Frequencies into the MHz range occur at the output of the inverter circuit depending on the type, as the result of the steep switching edges of the power electronic components.

Inverters usually have an output filter on the output side (in the direction of energy flow). When high-quality output filters are used, it is possible to feed near-sinusoidal voltages and currents via the connecting cable to the motor. An inverter circuit always causes higher-frequency interference which (contrary to the direction of energy flow) propagates towards the power source. In the DC link circuit the amplitude of this interference can be reduced by longitudinal inductors and by capacitors between the active conductors. In the case of inverters for AC power supply systems, this interference caused by inverter circuits is also effectively dampened by rectifier circuits and AC input filters.

To use a power inverter designed for AC power supply systems in DC power supply systems, it is not enough simply to "leave out" the AC input circuitry and the rectifier circuit. An appropriate DC input filter is required.

Inverters for the operation of AC motors in DC power supply systems consist of the following functional groups:

1. DC input filter
2. DC link
3. Inverter circuit (e.g. with IGBTs, thyristors, triacs, etc.)
4. AC output filter.

In the case of DC equipment with capacitors, hazardous voltages may occur even after switching off and after disconnection of the DC equipment. For this reason, DC equipment must be designed in such a way that no hazardous voltages can occur after switching of and disconnection.

DC-powered inverters are already in use for a variety of applications. The operating voltages can range from extra-low voltage up to several kilovolts. For inverters with higher load currents, a higher degree of interference emissions should generally be expected. The operation of inverters run by DC power supply systems (DC/AC converters) is discussed below based on examples.

Examples of DC/AC converters

- Example 1:

Electric railways are often operated with voltages between 500 V DC and 3000 V DC. The power consumption of electric traction motor is several hundred kilowatts; the power taken from the overhead lines can exceed a kiloampere. The latest generation of traction motors is equipped with inverters that cause significant interference in the high-frequency range of the spectrum. This high-frequency interference is emitted by traction systems and partly fed galvanically into the DC power supply system. The overhead wire and the tracks act like an aerial. The frequency spectrum of the high-frequency interference caused by traction inverters extends into the low MHz range. This is readily perceptible if you are listening to a car radio, for example, in the vicinity of a tram which is receiving power. There is generally no interference to FM reception. Medium wave reception, however, is normally severely disrupted. MW radio reception no longer plays a significant role in Germany. However, MW radio reception is used intensively in other parts of the world; in some cases increasingly so. There is insufficient damping of the interference caused by traction inverters in many cases, which can lead to dissatisfactory functioning of other electrical equipment.

- Example 2:

PV inverters are another example of a DC/AC converter. The PV modules deliver DC voltage that is then converted into single-phase or three-phase AC voltage. The inverter circuits and AC output filters of PV inverters are designed so that the interference entering the AC power supply system is sufficiently low and so that they meet the requirements of harmonized (EMC) standards. The PV modules are connected on the output side of PV inverters. The input filters of PV inverters are designed so that the interference emitted towards the PV modules is sufficiently low.

- Example 3:

In recent years, electric vehicles have gradually gained in importance. The battery voltage of modern electric cars is several hundred volts DC. The power consumption can significantly exceed 100 kW in some cases and the current consumption from the battery can top 100 A. Modern cars are equipped with bus systems and sensitive electronics. Neither the on-board electronics nor other electrical equipment outside an electric vehicle may be disrupted by the operation of the electric drive - consisting of drive battery, inverter and drive motors. To achieve this goal, the manufacturers of electric cars use low interference power inverters and DC-compatible filter circuits. Electric vehicles also contain extensive shielding.

Recommended action:

- Further research should be conducted into the EMC behaviour of universal and scalable DC power supply systems with a variety of DC power sources and DC loads.
- EMC threshold values must be established for universal and scalable DC power supply systems.
- EMC standards regulating the operation of universal DC power supply systems and the corresponding DC power sources and DC loads need to be amended or created. Corresponding device standards must be also amended or created.
- In order to achieve noticeable savings in terms of space requirements and in regard to the manufacturing costs of DC-compatible devices in a transition from AC to DC, space-saving and low-cost DC filters are required which are suitable for effective use in DC-powered equipment.

6.12.1 Interaction between EMC filters and insulation monitoring devices

When selecting the devices for an IT system with high stray capacitance to earth, it must be ensured that the measuring method of the insulation monitoring device is compliant or suitable for this. Insulation monitoring devices based on the "DC voltage superposition" measuring principle are usually not suitable for such applications.

6.12.2 Interoperability/mutual interference

Causes of interference

Mutual interference may occur if several pieces of electrical equipment are operated together in one network. Types of interference include:

- Functional impairment
- Malfunction
- Damage caused by overvoltages brought about by mutual interference
- Reduced service life due to additional workload

Mutual interference should always be expected in operating statuses during which voltages and currents deviate from the nominal statuses in the respective network. Possible types of interference include:

- Temporary overvoltages/undervoltages
- Transient voltage dips
- Transient overvoltages due to switching operations
- Increased inrush currents
- Overload
- Underload
- Short circuits
- Earth faults
- Low-frequency and high-frequency conducted interference:

    - In AC: synchronous and non-synchronous to the mains frequency
    - In DC: non-synchronous (to mains frequency)
- Harmonics
- Beats
- Resonances

Interference emission and immunity

Many of the above types of interference are familiar from AC networks, and proven methods exist to control mutual interference of AC equipment to ensure satisfactory operation. However, there are also types of interference that can only be controlled by exerting greater effort. Chief among these are low and high frequency interference and also resonances. In order to be able to control the effects of such interference, the following conditions must be fulfilled:

- The emitted interference of equipment must be low enough to prevent any functional impairment or interference of other equipment occurs.
- The interference immunity of equipment must be high enough to prevent the interference emissions expected from other equipment from leading to functional impairment or interference of the respective equipment.

Harmonics and beats

In recent years and decades, more and more AC loads have been used, some of which consume highly non-sinusoidal load currents. Non-sinusoidal load currents lead to harmonics in networks and equipment. In the simplest case, the frequency of a harmonic is an integer multiple of the power frequency – the harmonic is therefore synchronous with the power frequency. As a rule, network-synchronous harmonics can easily be controlled using proven measures - such as passive or active harmonic filters.

In AC loads with controlled rectifiers, harmonics can also occur at a frequency which is not an integer multiple of the power frequency, depending on the circuit design and the operating mode of the rectifier. These harmonics are therefore not synchronous with the power frequency. Such non-synchronous harmonics are also called "interharmonics". If a number of devices in a network simultaneously generate non-synchronous harmonics, these non-synchronous oscillations are overlaid over each other. In unfavourable conditions, non-synchronous harmonics can cause so-called beats and lead to malfunctions or even resonances.

By definition, there is no zero crossing of the voltage in DC systems. This means that there is also no power frequency with which the harmonics and interference caused by electronic circuits can be synchronized. Harmonics and higher-frequency interference also occur in DC networks, but without synchronizing at a certain frequency.

Most newly installed DC networks generally use equipment with power electronic input and output circuits:

- Equipment with higher power consumption
    - Typical devices: Frequency inverters etc.
    - Typical clock frequencies: 2...25 kHz
- Equipment with lower power consumption

- Typical devices: Small appliances, notebook power supplies, DC/DC voltage converters for PCB mounting
- Typical clock frequencies: 2...25...1000 kHz; due to technological developments, clock frequencies of several 100 kHz are achieved today – especially in voltage converters for PCB mounting.

Pulse width modulation (PWM) is often used to regulate the power output of power sources and the power consumption of electricity consumers. Conducted interference with frequencies from a few kHz to the low MHz range occurs within power electronic equipment due to the clocking of power electronic components and due to pulse width modulation.

Natural resonance

The typical clock frequencies of power electronic equipment are in the single and multi-digit kHz range. If, for the purposes of simplification, interference caused by switching actions and interference from the AC mains (via rectification) are ignored, conducted interference below 2 kHz is not normally expected in DC grids.

If several infeed DC/DC converters are operated in parallel as current sources in a DC network, the power supplied by DC/DC converters and the DC network voltage may oscillate under unfavourable circumstances. The frequencies of these undesired oscillations (beats) can in some cases be significantly lower than the clock frequencies of the individual converters. Causes of these undesired oscillations include:

- Poor distribution of the supplied power to the different converters – especially in the event of load changes
- Non-synchronized clock frequencies of converters supplying in parallel
- Non-synchronized clock frequencies of DC loads operated in parallel (DC/DC converters, DC/AC converters)

When planning DC systems with several feeds, not only existing DC/DC or AC/DC converters must be taken into account, but also converters which may be added at a later date, such as DC/DC converters for the infeed of energy from PV modules. Converters must therefore be designed and selected in such a way that the power fed into a DC network or the network voltage cannot oscillate during parallel operation.

In a low-voltage AC network that is not equipped with a compensation system, the natural resonant frequency of the network is normally in the range of 50 to 250 kHz. The natural resonant frequency of AC networks with compensation systems can in some cases be significantly lower than 2 kHz – i. e. in a frequency range in which natural resonance can occur due to low-order harmonics.

If natural resonance starts in a power supply grid – e.g. by excitation with harmonics or other higher-frequency oscillations – resonance-induced overvoltages and overcurrents may occur whose instantaneous values can significantly exceed the maximum withstand capacity of typical equipment.

Power-consuming electronic equipment in DC networks is not synchronized by the "power frequency", and non-synchronized line-conducted interference may be overlaid in a DC network. This can generate beats, which can also lead to natural resonance in a DC network.

Natural resonance frequencies in a range between 50 and 250 kHz can be expected in DC networks if there are no significant smoothing capacitors in the network. Practical experience with large-scale DC networks on inland waterway vessels has shown that the natural resonance frequency of a DC network can drop to between 2 and 20 kHz when smoothing capacitors are used – i.e. to a frequency range in which resonance-induced overvoltages and overcurrents are generated, for example, by line-related interference in power electronic equipment. The natural resonance frequency of a DC network can change significantly when DC energy sources and DC loads are switched on or off.

Filters

In order to prevent the propagation of conducted interference that occurs within power electronic equipment and to effectively prevent resonance, all output circuits of power electronic DC power sources and all input circuits of DC power loads must be equipped with suitable DC filters.

Surge protective devices

Audio-frequency interference in the range from 20Hz to 20kHz and high-frequency interference of approx. 10kHz to 30MHz.can lead to undesired leakage currents in voltage-limiting components of surge protective devices (SPDs). Such leakage currents can damage surge protective devices. DC equipment must therefore be designed and selected to prevent inadmissibly high leakage currents from occurring within the surge protective devices used in DC systems.

Carrier frequency systems and Power Line Communication (PLC)

Low-voltage AC systems are nowadays used in various ways to transmit "data" with the aid of carrier frequency systems (see DIN EN 50065-1, VDE 0808-1 (2012-01)). Analogue or digital signals are overlaid over the supply voltage.

The use of carrier frequency systems should also be possible in low-voltage DC systems. Therefore, the equipment in DC systems must be designed in such a way that carrier frequency systems can also be operated without interference in low-voltage DC systems.

Examples of carrier frequency systems:

- Audio frequency ripple control systems
- Electricity meter readers
- Babyphones
- Power line communication (e. g. Ethernet over power line)

Carrier frequency systems in DC networks can also be used for the following applications:

- Charging management of battery sets
- Charging management for individual battery cells
- Load management for AC/DC or DC/DC infeed converters - with multiple infeeds
- Load management for loads - depending on the amount of energy available in the DC network and depending on supply priorities for individual groups of loads
- Central determination of the power consumption of individual equipment - assuming equipment is equipped with appropriate measuring devices and carrier frequency interfaces.

Standardization

Interference emissions caused by harmonics or other disturbances must be controlled by setting suitable limits and staying within them. Harmonics and other interference are not only of relevance for AC networks, they must also be taken into account in DC networks. In contrast to the specifications for interference immunity, there are still considerable "gaps" in energy standards regarding determination of line-conducted interference emission limits in the frequency range between 2 and 150 kHz. The lack of limits in this frequency range are a major reason for the increase currently being observed in functional impairment or malfunctions due to line-conducted interference in AC and DC networks.

IEC standards are being developed at present to determine limits for line-conducted interference emissions in the frequency range between 2 and 150 kHz. Interference in this frequency range is sometimes referred to as "supraharmonic".

The ITU (International Telecommunication Union) recommendations already specify limits for DC power supply outputs in the frequency range from 25 Hz to 150 kHz (see ITU-T K.76).

DIN EN 61800 contains specifications for the maximum permissible interference emissions of variable-speed electrical drives (inverters) and for the required insensitivity to interference; it makes reference to the DIN EN 61000-xx series of standards.

Standards:

- ITU-T K.76 (2008-07): EMC requirements for telecommunication network equipment
- DIN EN 61800-3, VDE 0160-103 (2015-08): Adjustable speed electrical power drive systems – Part 3: EMC requirements and specific test methods (IEC 22G/297A/CD:2015)
- DIN EN 61000-2-2, VDE 0839-2-2 (2003-02): Electromagnetic compatibility (EMC) – Part 2-2: Environment; Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems (IEC 61000-2-2:2002); German version EN 61000-2-2:2002
- DIN EN 61000-4-16, VDE 0847-4-16 (2016-10): Electromagnetic compatibility (EMC) – Part 4-16: Testing and measurement techniques - Test for immunity to conducted, common mode disturbances in the frequency range 0 Hz to 150 kHz (IEC 61000-4-16:2015); German version EN 61000-4-16:2016
- DIN EN 61000-4-17/A2, VDE 0847-4-17/A2 (2009-11): Electromagnetic compatibility (EMC) – Part 4-17: Testing and measurement techniques - Ripple on d.c. input power port immunity test (IEC 61000-4-17:1999/A2:2008); German version EN 61000-4-17:1999/A2:2009
- DIN EN 61000-4-29, VDE 0847-4-29 (2001-10): Electromagnetic compatibility (EMC) – Part 4-29: Testing and measurement techniques; Voltage dips, short interruptions and voltage variations on d.c. input power port immunity tests (IEC 61000-4-29:2000); German version EN 61000-4-29:2000
- DIN EN 50065-1, VDE 0808-1 (2012-01): Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz – Part 1: General requirements, frequency bands and electromagnetic disturbances; German version EN 50065-1:2011

Recommended action

- Rules must be developed for ensuring system EMC in DC networks.
- It must be assessed whether and to what extent the specifications regarding maximum permissible interference emissions and immunity contained in existing standards for AC applications can be applied to DC power supply systems.
- The level of conducted audio and high-frequency interference emitted by DC equipment must be low enough to rule out unacceptably high leakage currents from overvoltage protection devices. Subject to validation, adoption of the standards for AC voltage systems (DIN EN 55013, 55011, 55014, 55015, 55022, ...) should be considered here.
- The equipment in DC systems must be designed in such a way that carrier frequency systems can also be operated in low-voltage DC systems.
- A standard for "Signalling on low-voltage DC electrical networks" must be drafted up (analogous to: DIN EN 50065-1, VDE 0808-1 (2012-01)).

6.12.3 Interoperability in DC networks

If electrical devices are operated on a common mains supply line, this can lead to mutual interference between the devices and impair the functioning of the equipment. This is caused by low and high frequency interference being conducted between pieces of equipment. Excessive interference emissions from equipment and/or excessive sensitivity (low immission resistance) of a piece of equipment can prevent interoperability. Such interaction, which is the basis of interoperability, occurs in both AC and DC networks.

In AC networks, interference can also occur which is caused by rectification of the AC voltage. This low-frequency interference up to a frequency of 2 kHz corresponds to multiples of the network frequency. There are no network frequency-related interference emissions in a DC voltage network, as there is no power transmission based on an AC variable.

Further faults are caused by the inverter and the switching behaviour of the semiconductor switching components used. This causes interference due in part to the clock frequency in the range from a few kHz to approx. 25 kHz. Such high-frequency interference can be eliminated by the use of EMC filters. The same applies to the use of DC/DC converters.

In the medium frequency range, intermodulation products arise from the primary frequency of the output current of the inverter and the network frequency, so-called supraharmonics. These components can be suppressed by suitable modulation methods and a suitable filter design in the DC link. When an inverter is supplied with a DC voltage, only the components of the primary frequency of the inverter output current arise, there are no intermodulation products.

Interoperability can be ensured in a DC network in the same way as in an AC network, provided that existing standards are met.

6.12.4 EMC filters and protective measures

Regardless of the type of network voltage, personal protection and line protection must be guaranteed in an electrical distribution network, in conformity with the applicable normative specifications. Different protective measures can be used depending on the type of network (TT, TN, IT). These are given in IEC 60364-1.

EMC input filters for electrical equipment generally have a characteristic design. A suppression capacitor (X capacitor) is inserted between the input conductors to suppress asymmetrical EMC interference. Symmetrical interference is suppressed by two capacitors mounted between the respective conductors and the earth connection (Y capacitor). Inductive components are also used.

If there is excessive leakage current in the equipment connected to the mains line, the RCD of this mains line may automatically switch off. Leakage currents in a DC voltage network are capacitive leakage currents generated by network ripples and high-frequency components.

The maximum values of the leakage currents should be defined in standards, in analogy to AC.

Recommended action

After a mains line has been switched off in the event of a residual current, a voltage can occur in the relevant mains branch, both in the AC and in the DC voltage network. This occurs, for example, when solar inverters are connected to the relevant mains branch. However, voltages can also occur due to interference suppression capacitors in EMC filters that are not equipped with a discharge resistor. If only loads (of any type) are supplied by a mains line, the energy stored in the filter capacitors can lead to voltage on the mains line. Normative specifications regarding a discharge resistor parallel to the filter capacitor at the input state that this voltage should be discharged. This applies both to DC and AC voltage networks.

In contrast to the household and office applications described, industrial networks or networks in ships may have slightly modified requirements. However, the basic effects are the same.

7 TECHNOLOGIES

7.1 LVDC Topology/Architecture

7.1.1 System definition

Individual DC systems are examined in this section. These are self-contained systems at a particular voltage level (or voltage band). However, they may also be connected to child or parent systems.

7.1.1.1 Network topologies

A number of topologies have been presented so far for DC systems, but not all of these are taken into account in the standards. In addition to island networks that are not connected to the supply grid at all, there are also DC networks that are supplied completely from the public AC grid.

In addition to these two network forms, there are different types of branching, meshing and dynamic switching between ON/OFF grid operation. In these topologies, the network characteristics are mainly determined by the interaction between batteries and the converter systems (e. g. short-circuit current, control and regulation quality, voltage quality), e. g. a DC coupling is increasingly used in PV systems between converter systems (DC-DC converters), battery storage units, chargers and the load.

The CAG1 working group of the IEC SyC LVDC system committee is currently working on various use cases for different new topologies. Examples of existing standards that relate to LVDC topologies are:

- E DIN EN 62040-5-3 (VDE 0558-550-3) Uninterruptible power supply systems (UPS):
- E DIN EN 50171 (VDE 0558-508) Central safety power supply systems.

7.1.1.2 Qualitative requirements (stability, load requirements, ripple, redundancy/availability)

Statements on qualitative requirements regarding the stability, load behaviour, ripple, redundancy and availability of DC networks can be found in various application-specific standards and in in-house specifications from system suppliers. Examples of this in the civil sector include ABD0100 1.8 "Electrical and installation requirements" from AIRBUS, and DIN EN 50155 (VDE 0115-200) "Railway applications - Electronic equipment used on rolling stock". In the military field there are standards such as MIL-STD1275 "Characteristics of 28 Volt DC Electrical Systems in Military Vehicles", VG96916-5 "Electric Systems for Land Vehicles - Part 5: DC networks", MIL-PRF-GCS600A "Characterization of 600V DC Electrical Systems For Military Ground Vehicles" and MIL-STD 704 "Aircraft Electric Power Characteristics".

7.1.2 System boundaries

The transition from a DC system to another network or network level can be effected using DC/DC and DC/AC converters.

7.1.2.1 DC/DC (internal)

DC-DC converter systems are well described in the standards. The following standard in particular is suitable for the low voltage level:

- IEC 61204-6 and DIN EN 61204-6 (VDE 0557-6): Low-voltage power supplies, DC output – Part 6: Requirements for low-voltage power supplies of assessed performance (IEC 61204-6:2000); German version EN 61204-6:2001

Although nominal voltages and voltage bands are presented in the IEC 60038 "IEC Standard Voltages" and DIN EN 60038 (VDE 0175-1) "CENELEC standard voltages" and EN 300 132-3-1 V2.1.1, 2012 standards, the option of concentrating on a smaller number of voltage bands in order to define a development focus needs to be discussed. IEC SEG 4 has identified two particular voltages here (see Section 7.2).

7.1.2.2 DC/AC and AC/DC

Two sets of standards are relevant for conversion from DC to AC and vice versa:

Product standards:

- IEC 60146-X and DIN EN 60146-X (VDE 0558-X) Semiconductor converters
- IEC 62477-X and DIN EN 62477-X (VDE 0558-477) Safety requirements for power electronic converter systems and equipment
- IEC 61800-X and DIN EN 61800-X (VDE 0160-10X) Adjustable speed electrical power drive systems
- IEC 60950-X and DIN EN 60950-X (VDE 0805) Information technology equipment – Safety

Electrical safety standards:

- IEC 60664 and DIN EN 60664 (VDE 0110) Insulation coordination for electrical equipment within low-voltage systems
- IEC 60050 and DIN VDE 0100-200 (VDE 0100-200) Low-voltage installations – Definitions
- IEC IEC 60364-4-41, HD HD 60364-4-41 and DIN VDE 0100-410 (VDE 0100-410) Low-voltage electrical installations – Protection against electric shock
- IEC 60364-5-51:2005, HD 60364-5-51 and DIN VDE 0100-520 (VDE 0100-520) Low-voltage electrical installations – Selection and erection of electrical equipment – Wiring systems
- DIN VDE 0100-530 (VDE 0100-530) Low-voltage electrical installations – Selection and erection of electrical equipment – Switchgear and control gear.

7.1.2.3 Interfaces to loads, storage, sources

Clear interface/transfer point definitions are required to delimit the responsibilities between the various DC network participants.

Participants include:

- Generation, transportation and distribution grids:
  - TSOs (transmission system operators)
  - DSO (distribution system operators)
  - "Generators"
  - "Feeders"
  - "Grid users"
  - "Grid connection users"
- Industry networks:
  - Infrastructure operators for industry
  - Infrastructure operators for ICT => Interfaces to ICT defined e.g. in ETSI EN 300123-2
  - ICT operators (grid providers).
- Commercial
- Households.

7.1.3 Network and earthing systems

The customary earthing systems (TN, TT, IT), described in detail in IEC 60364-1, HD 60364-1 and DIN VDE 0100-100 (VDE 0100-100) and as well in IEC 60364-4-41, HD 60364-4-41 and DIN VDE 0100-410 (VDE 0100-410), can also be used for DC networks.

The requirements for earthing systems, protective conductors and protective bonding conductors are set out in DIN VDE 0100-540 (VDE 0100-540), significant parts of which are also applicable for DC networks.

7.2 Voltage levels (classes)

IEC 60038 and DIN EN 60038 (VDE 0175-1): 2012-04 "CENELEC standard voltages" applie e. g. to DC rail networks (table 2 in the standard) and DC equipment with nominal voltages below DC 750 V (table 6 in the standard).

The IEC "System Evaluation Group - Low Voltage Direct Current Applications, Distribution and Safety for Use in Developed and Developing Economies" (IEC/SEG 4) defines two preferred voltage levels: 48 V and 380 V - one for low and one for higher power levels. This determination is in addition to, and not in contradiction to, the work of the different technical committees.

APPLICATION	VOLTAGE (DC) /V	STANDARD
Cars	12	IEC 60038
HGVs, buses	24	IEC 60038
Cars, HGVs, e-light vehicles, mild hybrids	48	IEC 61851-3 LEVs, ISO 6469-3
ELV (SELV, PELV) limits	120	IEC 61140
Central emergency power supply	220	prEN 50171, DIN EN 50171, EN 50272-X, DIN EN 50272-X
Telecommunications	48	ETSI EN 300 132-3-1 V2.1.1 (2012)
	60	ETSI EN 300 132-2 Annex A
	354, 380	
Electric vehicles (60-800 V)	400	ISO 6469-3, ISO 19295, IEC 60038
Trolley buses	600	EN 50163
Trams	600, 750	EN 50163
Industrial power converters	300-1200	EN 61800-5-1
PV	1500	IEC 60038, , IEC 61727

Table 11 – Examples of standards, applications and voltages used

7.3 LVDC generation based on the example of photovoltaics

In the selection and the design of the SPDs for DC power systems, a number of DC-specific system requirements need to be taken into account in addition to the lightning protection requirements set out in the "Protection against transient overvoltages" and "Lightning and overvoltage protection" sections. The most important difference for all DC applications is the lack of zero crossings of the voltage and the current, in contrast to alternating current systems. Switching is therefore significantly more critical with DC than with AC. There is a considerably higher risk of a standing DC arc occurring. As the result of the different switching conditions in DC circuits, IEC 60947-3 and DIN EN 60947-3 (VDE 0660-107) lists utilization categories for DC switchgear. These are described in the form of corresponding time constants (see table 12).

UTILIZATION	MAKING			BREAKING			TYPICAL APPLICATIONS
	I/I_e	U/U_e	L/R [ms]	I_c/I_e	U_r/U_e	L/R [ms]	
DC-20	X	X	X	X	X	X	Connecting and disconnecting under no-load conditions
DC-21	1.5		1	1.5		1	Switching of resistive load including moderate overloads
DC-22	4	01,05	2.5	4	01,05	2.5	Switching of mixed resistive and inductive loads, including moderate overloads (e. g. shunt motors)
DC-23	4		15	4		15	Switching of highly inductive loads (e. g. series motors)

Table 12 – DC switching categories according to IEC 60947-3, EN 60947-3 and DIN EN 60947-3

As shown in figure 11 , different DC systems have different source characteristics. A conventional DC power source, for example, has a linear response between no-load and short-circuit. A PV generator, by contrast, behaves almost like a constant current source. The special characteristics of the sources should also be taken into consideration with DC applications which use batteries or accumulators for energy storage.

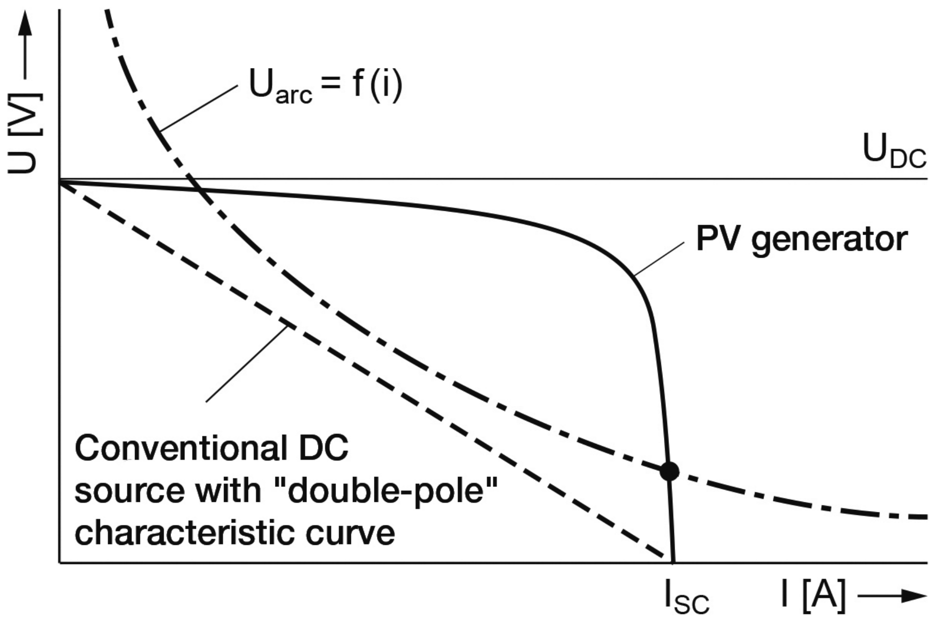


Figure 11 – PV source and conventional DC source [19]

As for AC systems, the maximum open-circuit voltage and the minimum and maximum possible short-circuit current at the place of installation of the surge protective device (SPD) are also principal parameters for surge protective devices (SPDs) in DC applications. Many surge protective devices (SPDs) contain varistors, i.e. voltage-dependent resistors, as protection elements. For open-circuit voltage, the ripple, i.e. the ratio of the mean to the maximum value of the voltage, should therefore also be considered. The ripple is dependent on the type of DC power source. PV generators theoretically deliver a perfect DC voltage, i.e. they have no residual ripple. On the other hand, DC power sources which are fed from bridge connections have varying ripples depending on the type of the bridge connection and possible additional smoothing capacity. Figure 12 shows the DC voltage of a B6-circuit and the arithmetic DC voltage. Providing a DC average is therefore not enough to describe the open-circuit voltage. The maximum peak voltage should also be defined.

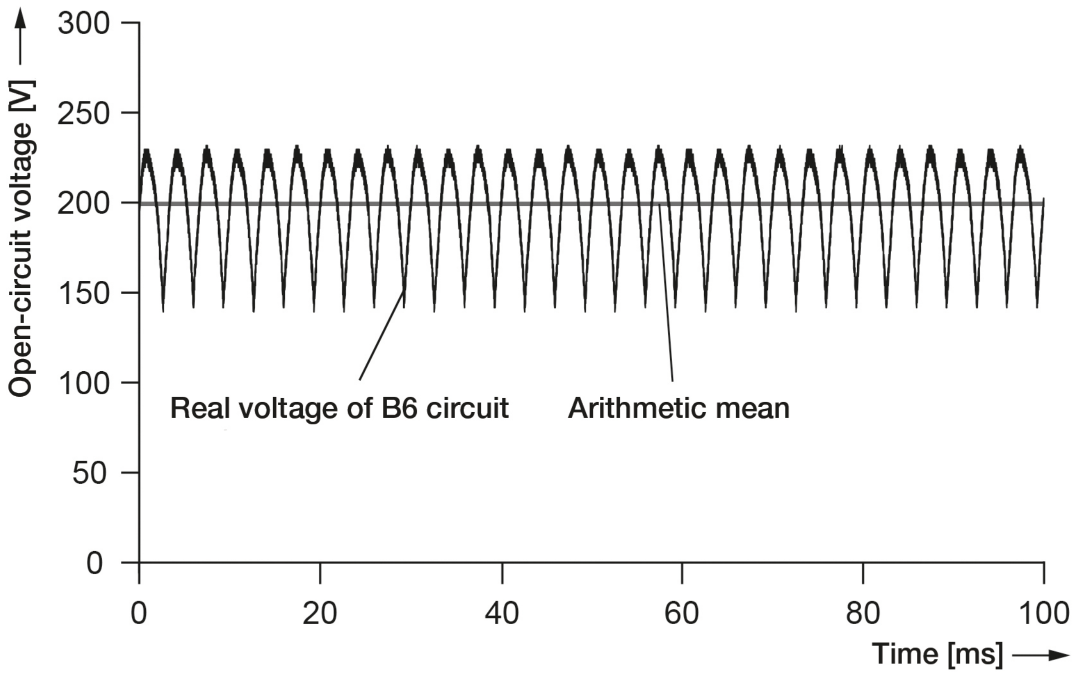


Figure 12 – Real voltage and average in B6 circuit [19]

The "voltage characteristics" in public electricity supply grids are laid down in DIN EN 50160. The previous edition of DIN EN 50160 applies exclusively to the characteristics of the supply voltage at the transfer point to the grid users in public low, medium and high voltage distribution grids under normal operating conditions.

Similar to the existing EN 50160 and DIN EN 50160, the "voltage characteristics" must also be set for DC voltage supply grids. It should be noted that DC loads with controlled power electronic input circuits often take pulsed load currents from DC voltage supply grids. Pulsed, cyclical load currents can cause voltage fluctuations in DC voltage supply grids, the instantaneous frequency (ripple) of which is significantly higher than that of the voltage fluctuations caused e.g. by B6 bridge rectifier circuits. High-frequency fluctuations of the supply voltage (ripples) can cause unwanted leakage currents in surge protective devices (SPDs). To avoid unwanted high frequency leakage currents in voltage-limiting

DKE VDE DIN Recommended action

components in the input circuits of electrical equipment, and also in surge protective devices (SPDs), specifications for maximum ripple must be laid down for DC voltage supply grids depending on the instantaneous frequency of the ripple.

For battery-powered DC sources, as used for example in emergency power supplies, it should also be noted that the boost charge voltage can be well above the nominal system voltage. Comparatively high prospective short-circuit currents can also occur in such DC systems, depending on the internal resistance of the battery used and the external elements.

7.4 Other equipment and components

Various devices and components can be operated at 230 V AC or 220 V DC (with corresponding tolerance bands), if this is documented in the product data sheet. 220 V DC is a nominal voltage for DC emergency and backup power supply systems based on 18 12 V batteries arranged in series. When the AC voltage leaves a given tolerance band in 230 V AC systems due to a fault, selected loads such as emergency lighting can be switched automatically from the AC mains to a separate 220 V DC network. Such DC emergency power supplies may be limited to a part of a building, such as a corridor, or extend over an entire building. This decision is influenced by the power rating, the duration of the emergency power supply, and the number of fire compartments in the building that can be bridged only with special E30-specified power cables [44, 45].

Typical applications of 220 V DC emergency power systems and safety power supplies are lighting systems, production facilities and IT systems. Various standards contain lighting system specifications for switchable operation between 230 V AC and 220 V DC [67, 68, 46, 47,48].

As a rule, these products contain a line filter, rectifiers and a special power factor correction (PFC) unit in the power supply input. In order for this power supply to operate at both 230 V AC and 220 V DC, this must be taken into account by the manufacturer e.g. in the design of the control circuits of the switching power supply.

Combined operation must also be taken into account in the selection of components. Power supplies with thyristor or triac semiconductor components, as used in simple motor controls (e.g. in washing machines), are not suitable for operation with a DC supply voltage.

It should also be noted that devices with switching contacts have a significantly reduced switching capacity, as these are generally not designed for DC.

7.4.1 Cables and wires

This topic is largely covered in DIN VDE 0298-3 (VDE 0298-3) and DIN EN 50565-1 (VDE 0298 565 1). The installation of cables and wiring systems is described in DIN VDE 0100-520 (VDE 0100 520) Low-voltage electrical installations – Part 5-52 "Selection and erection of electrical equipment – Wiring systems".

AC and DC circuits must be carried by separate cables and wires. This is also standard in power circuits and bus applications today. The question is whether it is necessary for the cables of an AC and DC network to have different external colours. Having separate cables allows separate protection of the two voltage distribution systems. The fault scenario in which an AC system and a DC system become galvanically connected during a fault needs to be investigated.

With regard to cables and wires, there are already products on the market which, in contrast to conventional AC power cables, distinguish between L+ and L- or between L and E/M by means of a higher dielectric strength. (600 V AC compared to 1000 V DC)

With regard to the outer sheath colour, there should be clear differentiation from other cables and wires (e.g. by means of colour-coding or similar) in installations.

Recommended action

Nominal voltage

The nominal voltage of an insulated power line is the voltage upon which the electrical properties of the structure and testing are based. The nominal voltage is expressed in the form of two AC voltage values U_0/U in V.

U_0 rms value between a line conductor and "earth" (non-insulating environment),

U rms value between 2 line conductors, a multi-core cable or a system of single-core cables.

In an AC system, the nominal voltage of a line must be at least equal to that of the system for which it is used. This condition applies both to the value U_0 and the value U. In a DC voltage system its rated voltage should not be more than 1.5 times the value of the nominal voltage (AC voltage) of the line.

In an AC system, the nominal voltage of a line must be at least equal to that of the system for which it is used. This condition applies both to the U_0 and the U value. The operating voltage of a system may not permanently exceed the nominal voltage of the system. The maximum permanent operating voltage of the cable is shown in table 13. The voltage values for DC are derived from the AC values..

NOMINAL VOLTAGE OF THE WIRE	MAXIMUM CONTINUOUS OPERATING VOLTAGE OF THE WIRE			
	Alternating current	Three-phase current	Direct current	
U_0/U	Conductor - Earth	Conductor - Conductor	Conductor - Earth	Conductor - Conductor
300/300 V	320 V	320 V	410 V	410 V
300/500 V	320 V	550 V	410 V	820 V
450/750 V	480 V	825 V	620 V	1.24 kV
0.6/1 kV	700 V	1.2 kV	0.9 kV	1.8 kV

Table 13 – Maximum voltages for nominal voltage of cabling

Bundling of cables (excerpts from DIN EN 50343 (VDE 0115-130))

If several cables are to be laid in bundles, the following minimum requirements should be taken into account:

- Heat-specific requirements
- EMC requirements
- Different nominal voltages
- Mechanical aspects such as strength and weight of the bundle and available installation space
- If different conductor cross-sections are bundled, the mechanical stresses should be taken into account.

Separation of cables with different nominal voltages for safety reasons

Cables with different nominal voltages must be kept as far apart from each other as possible.

The separation must either be by distance, or by means of insulated or earthed metallic dividing walls (see figure 13). It must be ensured that the insulating partition walls are designed for the maximum expected short-circuit current capability.

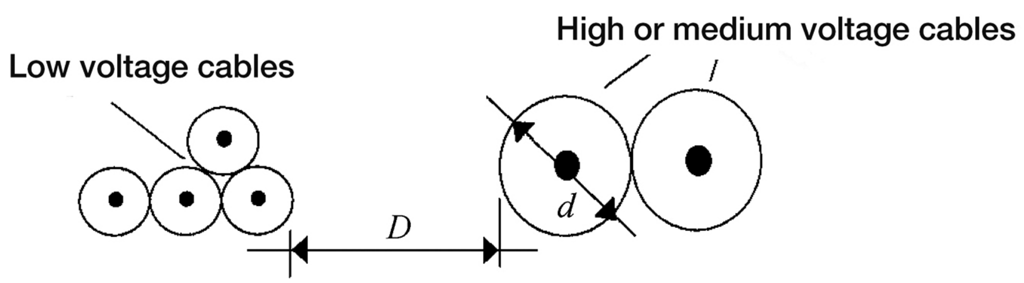
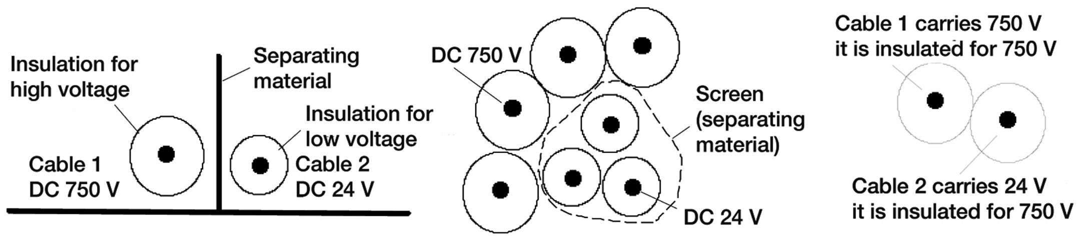


Figure 13 – Separation of cables by distance: D > 2d and D > 0.1 m [27]



a) Separation by a partition b) Separation by a screen c) Separation by insulation

Figure 14 – Examples of separation of cables by separating material or by insulation [27]

7.4.2 Testing and documenting device compatibility for AC/DC

In order to be able to specify products for AC and DC supply voltages, suitable standards and test procedures should be defined in product standards. Examples include [47, 48].

8 REGULATION AND COORDINATION

8.1 Reference field – Smart grid

The change in energy policy is necessitating a change in the energy supply grid towards an intelligent and decentralized energy grid - the Smart Grid. Fluctuations in generation caused by the increasing share of renewable energy in the power grid increase the amount of control required to balance generation and consumption. A special type of regulation is required at the distribution grid level, where much of the renewable energy is connected. A communication infrastructure is required for regulation and coordination of the energy flow in both DC and AC distribution grids.

A Smart Grid Reference Architecture has been developed by the CEN-CENELEC-ETSI Smart Grid Coordination Group. The Smart Grids Architecture Model (SGAM) can be used to represent the necessary communication paths, generation units, transmission routes and business models.

The IEC Strategic Group on Smart Grids (IEC SG3) has been working on the creation of standards for the smart grid since 2008. In its E-Energy / Smart Grids 1.0 and 2.0 Standardization Roadmap the DKE summarizes the trends and prospects of smart grid standardization and cites the following standards as core standards for smart grid communication [28,29,30]:

- IEC/TR 62357-1 "Power systems management and associated information exchange – Part 1: Reference architecture",
- IEC 61970-1, DIN EN 61970-1 "Energy management system application program interface (EMS-API)",
- IEC 61968-X, DIN EN 61968-X "Application integration at electric utilities – System interfaces for distribution management",
- IEC 61850-X, DIN EN 61850-X "Communication networks and systems in substations",
  - IEC 62351-X, DIN EN 62351-X "Power systems management and associated information exchange – Data and communications security".

Further standardization can be found using the following links:

http://www.iec.ch/smartgrid/standards/

http://smartgridstandardsmap.com/

http://www.iec.ch/smartgrid/downloads/sg3_roadmap.pdf

8.2 Control concepts (load flow management, energy management)

There are different requirements with regard to voltage level and quality, depending on the field of application. The network can be supplied by one or a number of inverters, depending on the design of the DC network. The aim is for the power fed into the system to be split based on the nominal power of the respective inverter. This allows equal utilization of the inverters. Various strategies are conceivable for voltage regulation.

The DC voltage droop method is used, for example, wherever there are multiple feed points. The control of the respective inverter must be able to regulate the voltage at the output while ensuring a desirable current/voltage output characteristic. In addition, in the event of a communication failure, each inverter must operate autonomously, thereby ensuring the grid-supporting function of the feeding inverter.

In addition, an overload in a particular supply channel can be detected by the inverter and limited based on a specified characteristic.

The most commonly used droop control method for setting the output voltage of the supplying inverter provides a supply voltage that drops slightly as the supply power increases. This allows other sources to be included in the load supply.

Controllable and adjustable feed-in voltage must be possible at the power output level for virtual impedance. The overlaid control architecture, which is responsible for controlling the entire grid, can only work locally (decentralized control) or with slow communication (distributed control) or with fast communication and central control (centralized control).

Existing standards in this area include [31]
- IEC/TR 62357-1 “Power systems management and associated information exchange – Part 1: Reference architecture”,
- IEC 61970-1, DIN EN 61970-1 "Energy management system application program interface (EMS-API)"
- IEC 61968-X, DIN EN 61968-X "Application integration at electric utilities – System interfaces for distribution management",
- IEC 61850-X, DIN EN 61850-X "Communication networks and systems in substations",
- DIN EN 62351-X "Power systems management and associated information exchange – Data and communications security",
- IEC 62056-X, DIN EN 62056-X (VDE 0418-X) "Electricity metering data exchange – The DLMS/ COSEM ",
- IEC 61508-X, DIN EN 61508-X (VDE 0803-X) "Functional safety of electrical/electronic/programmable electronic safety-related systems".

8.3 System-relevant communication

The scope of communication in an AC smart grid is more extensive than in a simple AC grid. In a smart grid structure with integrated renewable energy generation and local storage, information about the status of the energy storage facilities and generators must be communicated to a central control platform, as must the control signals for regulating the grid. Overall, there is growing demand for communication, including at the lower voltage levels where the scope of communication is also greater.

Depending on the level of growth, a communication infrastructure is also required in DC networks with integrated renewable energy sources and storage facilities. The DC network voltage quality and energy flow control requirements determine not only the control specifications of a network area, but also, as in an AC voltage network, the specifications of the measuring points used to record the status of the energy feed-ins and storage. The size and complexity of a control platform to be implemented for a particular application depend only on the application itself, and not on the type of network, i.e. AC or DC. There are, however, minor differences in the sensors. Accordingly, the local energy and building management control platforms can continue to be used (including their normative functional specifications), however some sensors have to be adapted. This also applies to smart meter gateways, which are currently only available for AC networks. In Germany, the regulatory requirements also need to be considered which derive from the Energy Industry Act, the Protection Profile for a Smart Meter Gateway (German Federal Office for Information Security BSI, BSI-CC-PP-0073) and the Technical Directives (BSI TR-03109) concerning switching access to generation facilities, and possibly also storage and controllable consumption appliances by the grid operator.

Before the system-relevant communication for DC distribution networks can be standardized, the following points need to be clarified:

- Control strategy in the DC distribution grid
- Communication needs for implementation of the control strategy
- Functional safety according to IEC 61508-X, DIN EN 61508-X and DIN EN 61511 (VDE 0810).

8.4 Further communication needs and possibilities

The control communication structures of AC and DC networks are almost identical, although differences can be expected in the parameters used to describe the dynamics. As part of the general digitization and smart grid development it is recommended that a suitable communication structure be provided for DC grids in the standardization process. Applications such as home/building automation, direct marketing and smart metering place further demands on the communication infrastructure and should be taken into account in the context of standardization in the communication concept for distribution grids. The demand for additional standards that specifically address smart grids needs to be clearly identified.

9 APPLICATION FIELDS

9.1 Lighting systems

9.1.1 Introduction

This section provides an overview of lighting systems that use different low-voltage DC power systems, as well as their technical standards. Reasons for using a DC power supply for lighting systems include the greater availability and reliability of a DC power supply in combination with battery storage, the higher performance of cables in DC operation, the simultaneous transmission of electrical power and digital data in a cable, e.g. with power-over-Ethernet, and the direct use of DC from solar power plants with fewer conversion losses. [69]

The normal path for the creation of mandatory standards for DC systems in Europe is based on the "Directive on the harmonization of the laws of the Member States relating to the making available on the market of electrical equipment designed for use within certain voltage limits" [32]. This directive addresses applications with a nominal voltage of between 50 and 1000 V alternating and three-phase voltage and between 75 V and 1500 V DC.

9.1.2 Lighting systems with DC safety extra-low safety voltages

Lighting and 5 V USB

Batteries charged by solar power represent the only way for people with no mains connection to obtain electricity. The main applications of such solar home systems are lighting, as shown in Figure 15 and Figure 16, and the recharging of mobile phones. The LED lamps in these illustrations use a 5 V USB interface to transfer the power to external devices [33]. Such products offer people access to new technologies, as described in the UN Millennium objectives in Section 8F [34]. The USB Implementer Forum has developed standards for this [35].

Figure 15 – Philips LifeLight Plus[36]

Figure 16 – Philips LifeLight Home [36]

12 V DC lighting systems

12V AC and DC supply voltages were originally introduced in vehicles and buildings to power e.g. low-voltage halogen lamps. Today, these voltages are used also for energy-efficient LED lighting. Manufacturer specifications define the applicable AC or DC voltage range [37].

12 V nominal voltage batteries are frequently used in solar-powered street lamps. These lights bring light and safety to areas with no regular electricity networks [38]. In many places, a battery-backed solar power supply enables sustainable and low-maintenance illumination, yet requires lower investment compared to the installation of new power grids (used exclusively for public lighting).

24 V DC lighting systems

The EMerge Alliance partners have developed two standards for 24 V DC and 380 V DC power supplies. The 24 V DC standard for "Occupied Spaces" is based on the limited voltage and power of the "U.S. National Electric Code (NEC)" for safety extra-low voltages in the United States [39.40]. Various lighting products are documented on the websites of the EMerge Alliance that meet the "Occupied Space" standard [41]. These products allow lighting systems to be fitted easily, quickly, safely and flexibly e.g. in suspended ceilings in office buildings.

Lighting systems with 48 V DC Power-over-Ethernet

Electrical devices with up to 100 W power consumption and separate digital communication interfaces can be installed and operated more cheaply using Power-over-Ethernet (PoE) technology than with data lines and separate power cables, which often have to be custom-made. PoE can also be used for smartphone-based personalized light and building climate control.

Companies and partners of the IEEE 802 Standards Project group have developed technical standards for PoE systems which they are currently extending. Examples of these standards include IEEE 802.3af, IEEE 802.3at and IEEE 802.3bt [42, 43].

9.1.3 Low voltage DC lighting systems

Low voltage DC networks in a range from 120 V to 1500 V have two main advantages over AC low voltage 230 V or 400 V systems, for example. Firstly, battery-backed DC voltages provide a high-availability type of power supply which is desirable for critical applications. Secondly, DC supply voltages are used in many variable-speed drives. In braking systems, it is much easier for drives to transfer electrical energy to other drives or loads via common DC networks. Examples include DC networks for railways and industrial systems [70].

216 V DC is a nominal voltage for DC emergency power supply systems based on eighteen 12 V batteries arranged in series. When the AC voltage leaves a given tolerance band in 230 V AC systems due to a fault, selected loads such as emergency lighting can be switched automatically from the AC mains to a separate 216 V DC network. Such DC emergency power supplies may be limited to a part of a building, such as a corridor, or extend over an entire building. The decision on this is influenced by the power rating, the duration of the emergency power supply (battery runtime), and the number of fire compartments in the building that can be bridged only with special E30-specified power cables [44, 45].

Typical applications of 220 V DC emergency power systems are lighting, industrial process control systems and small IT server installations. Various IEC standards contain lighting system specifications for switchable operation between 230 V AC and 220 V DC [46, 47, 48].

350 V DC/380 V DC lighting systems

Data centres and telecommunications systems use uninterruptible power supply systems offering maximum reliability, the battery storage of which has rated voltages of 350 V DC or 380 V DC and the rated power of which extends into the megawatt range. Given that server power supplies also have a 380 V DC internal bus after the mains rectifier and the switching power supply for power factor correction, it was only logical to develop a 380 V DC power supply infrastructure. The European Telecommunications Standards Institute (ETSI) has published a standard for this DC power supply system [49, 50]. The lack of inverters, 50 Hz transformers and power factor correction circuits in 380 V DC systems means that their efficiency is up to 10 % higher than that of conventional data centres with stand-alone AC voltage systems connected to central UPS systems [75].

700 V/760 V DC lighting systems

Industrial low voltage installations with a rated power of more than 2000 W typically take their power from a 400 V three-phase system instead of 230 V AC voltage. A multi-phase system is also an option e.g. for a 760 V direct current system which is implemented as a bipolar ±380 V DC network. High power loads such as drives can be supplied with 760 V DC. Small loads such as computers, industrial control systems and individual lights can be divided into two groups of approximately the same power; half of these are then supplied by +380 V and the other half by -380 V DC. Energy from natural DC sources such as photovoltaic systems can be transmitted with fewer losses to DC loads because there are fewer conversion losses from inverters, transformers and power factor correction circuits [51]. Single and multi-phase AC and DC power systems and their earthing systems are standardized [52].

Lighting systems with very high installed total power can be found, for example, in greenhouses; bipolar DC networks are of interest here. The company DirectCurrent BV has set up a pilot installation in a greenhouse, in which 1000 W lamps are supplied directly with 700 V DC [53].

9.1.4 EMC standards

A set of electromagnetic compatibility (EMC) standards is crucial for the development of robust products and systems. Interestingly, these EMC standards are already formulated such that they can be applied to both AC and DC supply voltages.

IEC 61000-4-5 "Electromagnetic compatibility (EMC) - Part 4-5 Testing and measurement techniques Surge immunity test" defines transient overvoltages and the equipment added to AC or DC supply voltages to test the immunity of products to supply voltage interference. Such transient overvoltages occur during lightning strikes or when currents are switched off suddenly in networks with cable inductance by fuses or circuit breakers.

Many power supplies and ballasts for lighting systems are now constructed as switching power units. The disadvantage of this, however, is that these devices emit both conducted and radiated electromagnetic interference. To limit this interference in AC or DC networks within certain frequency ranges, multiple standards have been developed by the "Comité International Spécial des Perturbations Radioélectriques" (CISPR). These standards have also been adopted in EN standards.

- CISPR 11: "Industrial, scientific and medical equipment – Radio-frequency disturbance characteristics – Limits and methods of measurement";
- CISPR 14-1: "Electromagnetic compatibility – Requirements for household appliances, electric tools and similar apparatus – Part 1: Emission";
- CISPR 15: "Limits and methods of measurement of radio disturbance characteristics of electrical lighting and similar equipment";
- CISPR 22: "Information technology equipment - Radio disturbance characteristics – Limits and methods of measurement".

9.2 Island systems (micro grids)

Micro grids can be designed both as exclusive island (stand-alone) grids or as hybrid grids. Hybrid grids can be grid-connected or operated in island mode. Energy access networks are island grids which are also known as minigrids or village grids. These supply power to remote settlement structures or economic locations such as mine workings.

In its study on AC minigrids the Alliance for Rural Electrification referred to the following standards [58]:

- BWEA "Small Wind turbine Performance and Safety Standards”
- IEC/TS 62257-4 "Recommendations for renewable energy and hybrid systems for rural electrification – Part 4: System selection and design"
- IEC/TS 62257-2 "Recommendations for renewable energy and hybrid systems for rural electrification. From requirements to a range of electrification systems"
- DIN EN 61427-X "Secondary cells and batteries for renewable energy storage – General requirements and methods of test"
- DIN EN 61215 (VDE 0126-31) "Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval"
- DIN EN 61730-X (VDE 0126-30) "Photovoltaic (PV) module safety qualification"
- DIN EN 62124 (VDE 0126-20-1) "Photovoltaic (PV) stand-alone systems – Design verification"
- IEC/TS 62257-3 "Recommendations for renewable energy and hybrid systems for rural electrification. Project development and management"
- IEC/TS 62257-5 "Recommendations for renewable energy and hybrid systems for rural electrification. Protection against electrical hazards"
- IEC/TS 62257-6 "Recommendations for renewable energy and hybrid systems for rural electrification. Acceptance, operation, maintenance and replacement"

The following publication is relevant for the AC section of grid-connected systems:
Greacen, C., R. Engel, and T. Quetchenbach. "A Guidebook on Grid Interconnection and Islanded Operation of Mini–grid Power Systems up to 200 kW." Berkeley: Lawrence Berkeley National Laboratory, 2013.
http://www.schatzlab.org/docs/A_Guidebook_for_Minigrids-SERC_LBNL_March_2013.pdf.

The transferability of these standards to DC needs to be investigated.

DKE VDE DIN
Recommended action

9.3 Energy access networks (Global South)

Special costs and energy efficiency requirements apply for energy access grids. Customer purchasing power in developing countries is often severely restricted, and the available energy sources (mainly kerosene and disposable batteries) are also very expensive.

In its ESMAP programme the World Bank has defined electricity access tiers in order to harmonize minimum standards for electrical energy supply in the development context. Table 14 shows commercial use by small businesses.

			TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Capacity	Electrical	Capacity		Min. 3 W	Min. 50 W	Min. 200 W	MIN. 800 W	MIN. 2 kW
		Energy provided daily		Min. 12 Wh	Min. 200 Wh	Min. 1.0 kWh	Min. 3.4 kWh	Min. 8.2 kWh
		Typical sources		Solar lamp	Home solar system	Generator or minigrid	Generator or grid	Grid
	Non electrical					Some available non-electric energy meets the requirements	Available non-electric energy largely meets requirements	Available non-electric energy meets all requirements
	Both					No relevant application missing solely due to energy bottlenecks		
2. Duration of daily supply	Electrical			Min. 2 hrs	Min. 4 hrs	Min. 50% of work time	Min. 75 % of work time	Min. 95 % of work time
	Non-electric					Some available non-electric energy meets the requirements	Available non-electric energy largely meets requirements	Available non-electric energy meets all requirements
	Both					Longer working times cannot be ruled out due to insufficient energy (capacity or duration)		

Table 14 – Electricity access tiers for commercial use in small businesses [55]

Nearly all current examples of electrification grids are in the SELV field:

- 24 V DC grid devergy (Tanzania)
  http://devergy.com/
- 24 V (48 V India)
  http://meragaopower.com/

However, there are also grids which go beyond this range, sometimes with very unclear rules regarding safety standards (in particular, solid-state fuses):

- 230 V DC SOLAR_IC (Bangladesh)
  http://solar-ic.com/solaricdev/
- 120-250 V DC Schneider Electric
  http://www.schneider-electric.com/products/in/en/8600-access-to-energy-collective-solutions/8610-villaya-collective-solutions/62210-dc-micro-grid/

Other approaches are based on modular, step-by-step development of networks which, starting from home solar systems (10-100 WP solar power, over 4 million of which are currently in use in Bangladesh alone), are increasingly being interconnected and then functioning as a micro grid with or without grid connection.

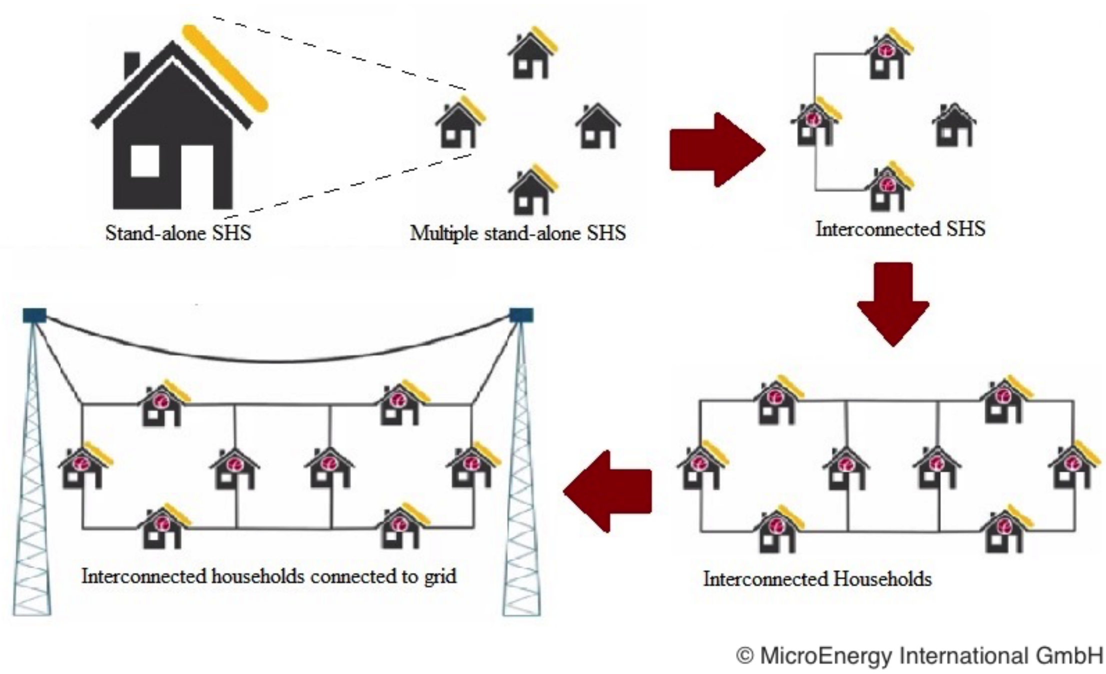


Figure 17 – Modular extensions of DC energy access grids, example shown: swarm electrification [56]

Important existing standards in this area are:

- DIN IEC 62053-41 (VDE 0418-3-41) "Electricity Metering Equipment (DC) - Particular Requirements - Part 41: Static meters for direct current energy"
- DIN VDE 0418-3 (VDE 0418-3) "Specifications for electric integrating meters - Part 3: Direct-current meters"

- DIN EN 62040-4 (VDE 0558-540) "Uninterruptible power systems (UPS) - Environmental aspects"
- DIN EN 61557-10 (VDE 0413-10) "Electrical safety in low voltage distribution systems up to 1 000 V a.c. and 1 500 V d.c. - Equipment for testing, measuring or monitoring of protective measures"
- DIN EN 62040-1 (VDE 0558-510) "Uninterruptible power systems (UPS) - Part 1: General and safety requirements for UPS"
- DIN IEC 62485-1 (VDE 0510-46) "Safety requirements for secondary batteries and battery installations - Part 1: General safety information"
- IEC 62485-2 "Safety requirements for batteries and battery installations - Stationary batteries"
- DIN EN 62040-5-3 (VDE 0558-550-3) "Uninterruptible power systems (UPS) – Part 5-3: Method of specifying the performance and test requirements for d.c. UPS"
- DIN EN 50171 (VDE 0558-508) "Central safety power supply systems"
- DIN EN 62253 (VDE 0126-50) "Photovoltaic pumping systems - Design qualification and performance measurements"

9.4 Mobility/DC-connected charging stations

Existing standards:

- VG 96916 "Electrical systems for land vehicles"
  - Teil 2: "DC 12 V and DC 24 V Networks, basic requirements"
  - Teil 5: "DC networks, technical specification, requirements for electrical systems and compliance tests on system and component level"
  - Teil 20: ""Multi-voltage systems with DC intermediate circuit, design and electrical protection measures, technical specification"
- DIN EN 61557-X (VDE 0413-X) Electrical safety in low voltage distribution systems up to 1000 V a.c. and 1500 V d.c. – Equipment for testing, measuring or monitoring of protective measures
  - Teil 8: "Insulation monitoring devices for IT systems"
  - Teil 9: "Equipment for insulation fault location in IT systems"
- IEC 60092-X Electrical installations in ships
  - Teil 101: "Definitions and general requirements"
  - Teil 202: "System design - Protection"
  - Teil 304: "Semiconductor convertors"
  - Teil 305: "Accumulator (storage) batteries"
  - Teil 501: "Additional requirements for electrical driving systems"
  - Teil 503: "Special features. Special features - AC supply systems with voltages in the range of above 1 kV up to and including 15 kV"
- IEC 62477-1 and DIN EN 62477-1 (VDE 0558-477-1) "Safety requirements for power electronic converter systems and equipment"
- IEC 61000-X and DIN EN 61000-X (VDE 0839) "Electromagnetic compatibility"
- IEC 60664-X and DIN EN 60664-X (VDE 0110) "Insulation coordination for equipment within low-voltage systems"
- IEC 60364-1:2005, HD 60364-1 and DIN VDE 0100-200 (VDE 0100-200) "Low voltage installations – Definitions"
- IEC 60364-4-41, HD 60364-4-41 and DIN VDE 0100-410 (VDE 0100-410) "Low-voltage electrical installations – Protection against electric shock"

- IEC 60364-5-52, HD 60364-5-52 and DIN VDE 0100-520 (VDE 0100-520) "Low-voltage electrical installations – Part 5-52: Selection and erection of electrical equipment – Wiring systems"
- DIN VDE 0100-530 (VDE 0100-530) "Erection of low-voltage installations – Part 530: Selection and erection of electrical equipment – Switchgear and controlgear"
- IEC 60364-7-717, HD 60364-7-717 and DIN VDE 0100-717 (VDE 0100-717) "Low-voltage electrical installations – Part 7-717: Requirements for special installations or locations – Mobile or transportable units"
- ISO 6469 "Electrically propelled road vehicles - Safety specifications"
  - Teil 1: "On-board rechargeable energy storage system (RESS) "
  - Teil 2: "Vehicle operational safety"
  - Teil 3: "Protection of persons against electric shock"
  - Teil 4: "Post crash electrical safety"
- ISO 7637-3 "Road vehicles – Electrical disturbances from conduction and coupling"
  - Part 3: "Electrical transient transmission by capacitive and inductive coupling via lines other than supply lines"
- ISO 16750 "Road vehicles—Environmental conditions and electrical testing for electrical and electronic equipment"
- DIN EN 61851-X (VDE 0122-X) "Electric vehicle conductive charging system – Part 1: General requirements"
  - Part 1: "General requirements"
  - Part 2-1: "Electric vehicle requirements for conductive connection to an a.c./d.c. supply"
  - Part 2-2: "AC electric vehicle charging station"
  - Part 23: "DC electric vehicle charging station"
  - Part 24: "Digital communication between a d.c. EV charging station and an electric vehicle for control of d.c. charging"
- IEC 62196-X and DIN EN 62196-X (VDE 0623-5-X) "Plugs, socket-outlets, vehicle connectors and vehicle inlets – Conductive charging of electric vehicles"
- ISO 23273 "Fuel cell road vehicles - Safety specifications - Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen"

9.5 Photovoltaic (PV)

Potential advantages deriving from the use of PV systems in the home environment in comparison to current AC operation result from the conversion of the building and (possibly also) distribution network to DC. These include, e.g., minimizing conversion losses through the direct use of the generated power. Instead of an inverter, only a DC/DC converter is necessary here, although this itself causes losses. It makes sense either to store any surpluses locally or to feed them into overlaid networks.

In addition, monitoring of the "frequency" variable can be dispensed with. "Energy quantity" and "voltage" still need to be monitored, although no extra effort is required for this.

One problem is the voltage drop during the transmission of higher PV system power levels in the building network at voltages < 50 V. A solution here could be a twin output on the DC/DC converter of the

PV system to ensure a direct network connection for power withdrawal at magnitudes of several kW. However, a similar voltage level to that currently used in AC operation (230 or 400 V) should be maintained.

This results in the following recommendations based on the existing standards:

- VDE AR N 4105 "Power generation systems connected to the low-voltage distribution network – Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks"
  - Basically still applicable
  - Required power plant characteristics:
    - Short-circuit power (including for protection equipment)
    - Stabilization of the energy balance for the grid → Voltage stabilization must be reassessed to include micro grids
- EN 50160 and DIN EN 50160 "Voltage characteristics of electricity supplied by public distribution networks"
  - Tolerance band (0.4 kV - 10 %) must be maintained
- DIN VDE V 0124-100 "Grid integration of generator plants - Low-voltage - Test requirements for generator units to be connected to and operated in parallel with low-voltage distribution networks"
  - Adaptation to DC grid necessary because some test methods could be dispensed with (e.g. inverters) and others would need to be supplemented (DC/DC converters)
- HD 60364-7-712 and E DIN VDE 0100-712 (VDE 0100-712) "Low-voltage electrical installations – Part 7-712: Requirements for special installations or locations – Photovoltaic (PV) systems". Depending on the target, various fundamental questions arise, such as:
  - Is a change being considered only in the home or also on grid levels 6+7?
  - What nominal voltage is suitable in the home or grid?
  - What is the overriding implementation objective? (general strategy/target).

9.6 Telecommunications operational units

Telecommunications systems have typically been supplied with DC since the introduction of electronic messaging. In Europe, a nominal voltage of 48 V DC has become established, although in Germany the systems were almost exclusively operated on 60 V DC until the advent of the mobile telephone network. (See also ETSI standard ETSI EN 300-132-2)

In telecommunication system operations, high-level energy availability is ensured by central uninterruptible DC voltage systems. Rectifier systems with batteries (generally lead acid batteries) work in parallel standby mode here. This uninterruptible DC voltage supply has proven itself over decades as a reliable form of supply. There are various reasons for preferring this technology to an uninterruptible AC power supply:

- Fewer conversion steps (electronic components in telecommunications systems work on small DC voltage);
  - Higher efficiency
  - Fewer components
- Reduced complexity (distribution and interconnection of networks)
- High availability (no active components between battery and "loads").

However, there is a drawback with the "low" operating voltages used. They require higher current ratings for all components due to the higher current strength. Large cross sections for copper bus bars, cables and wires are used in the systems, for instance.

The constant changes in communications networks and the merging of data processing and storage systems is resulting in the operation of more and more "classic AC loads" (computers/servers) in the same rooms as "classic DC loads". Telecommunication and information technology networks have increasingly merged in this way over the last few years. This trend is set to continue.

DKE VDE DIN Recommended action

It remains to be clarified:
- What type of voltage and what voltage level are optimum for future uninterruptible power supplies?
- Or will it still be necessary to set up multiple networks with different voltages?

9.7 Data centres

The operators of data centres are striving to obtain significant reductions, not only in the investment costs, but also the operating costs. In terms of operating costs, the focus in the past few years has primarily been on efficient UPS systems (online technology) and on air conditioning in general. In addition to the use of indirect and direct free cooling, the supply air temperatures for the IT equipment have gradually been raised. In the 80s and 90s, temperatures of 16° C were regarded as 'normal' in data centres, whereas 24° C and even higher are allowed today. On the assumption that every 1° C increase in temperature results in energy savings of approx. 5 to 7 %, these have represented milestones on the way to achieving "Green IT".

Following years of concentrating on the optimization of air conditioning in data centres, the focus in the last 2 to 3 years has been on the power supply itself. The goal of optimizing the energy supply of data centres while at the same time maintaining or even increasing reliability levels represents a major challenge to both manufacturers and operators.

The change in energy policy in Germany has brought about the resolution of the following measures:
- Nuclear energy to be phased out by end of 2022;
- Increased share of renewable energy sources in gross final energy consumption to 18% by 2020, to 30% by 2030, to 45% by 2040 and to 60% by 2050:
- Share of renewable energy sources in gross electricity consumption to increase to 35 % by 2020, to 50 % by 2030, to 65 % by 2040 and to 80 % by 2050. The most important basis for this is the amendment of the Renewable Energies Act (EEG) which has been in force since January 2012;
- 40% reduction of greenhouse gas emissions by 2020, 55% by 2030 70% by 2040 and 80 to 95% by 2050 (compared to base year 1990);
- 20% reduction of primary energy consumption by 2020, and 50% by 2050;
- 2.1% per year increase in energy productivity in relation to final energy consumption;
- 10% reduction in electricity consumption by 2020, and 25% by 2050 (compared to 2008).

All these measures were resolved after many data centres had already been optimized. The integration of renewable energy in the overall concept of data centres has only been realized in isolated cases up to now. Typically, large photovoltaic farms have been located in the vicinity of data centres to create the visual impression of "Green IT". There is, however, no direct connection between the operation of the data centre and the photovoltaic farm. This kind of "parallel operation" will also change through the reduction of the funding and thus rising investment costs for renewable energy.

Yet one technical solution meets all the political, technical and economic demands of the IT/telecoms industry: direct current!

From today's perspective DC would appear to meet all requirements, as proved by the following arguments:

A major target of using direct current is reaping the benefits of increased availability (reliability) and efficiency. The use of DC does away with the need for elaborate PFC filters (= power factor correction PFC) in power supply units. These filters contain relatively large electrolytic capacitors which can dry out over the years, thereby preventing servers from rebooting. Furthermore, modern switching power supplies generate undesirable (from the perspective of the operator) harmonics in the network which can damage other IT equipment.

In terms of efficiency, the elimination of rectification on the input of an AC power supply reduces total energy consumption.

A further minor side effect is a reduction of the footprint of the power supplies, which in turn yields benefits for the internal ventilation and thus further positive effects.

In terms of the conversion chain, the linking of new, efficient equipment ultimately yields an unsatisfactory overall efficiency level.

These conversion processes, especially within a UPS network, would also be eliminated through the use of direct current and would inevitably lead to a further increase in efficiency.

Ultimately, the use of DC power in data centres would also significantly promote the integration of renewable energies. The latest generation of UPS systems allows direct connection of PV or wind turbines to the UPS facility, which in turn links the generated DC voltage to the battery DC link voltage and adjusts the DC voltage on the output accordingly.

Apart from higher availability and higher operating efficiency, there is another cost reduction aspect for the telecommunications sector. 48 volts DC have been used so far in the telecommunications sector. The consequence of this low voltage is that large electrical outputs require very high currents, which in turn necessitate large cable cross sections. Since copper is very expensive as a raw material, the use of 380V DC in addition to the existing low voltage range could lead to a significant reduction in the cable cross-sections and thus reduce the investment costs for new construction.

9.7.1 Standardization/Planning/Safety

The "First commercial 380 V DC micro grid in Germany" project (see Section 10.4) clearly showed that there are gaps both in the standardization as well as in the products themselves. The following list highlights the main problems/gaps.

Earthing

Recommended action

Can/must AC and DC voltage components be connected directly to an earthing terminal or is it better to keep both separate inside buildings? (Potential differences and voltage overlays as hazards)

Loop impedance

Once a low-voltage system has been installed, the loop impedance should be measured at power frequency to ensure compliance with shutdown conditions. This measurement, as specified in DIN VDE 0100-600 (VDE 0100-600), is required in particular when protection against indirect contact is provided through automatic disconnection by overcurrent protection devices. The measurement results should be recorded in test logs and issued to the operator of the plant. It was not possible to take this measurement because the necessary equipment (measuring instruments) was not available.

Recommended action

Insulation measurement

In Germany, insulation measurements are regulated in "DGUV Regulation 3" (formerly BGV A3). The measurements are taken in individual steps conducted in the following order: protective earth (PE) to neutral (N) and then protective earth to all line conductors (L1, L2, L3). The measurement is taken by briefly feeding a high measuring voltage but with a low-power current source. This prevents the risk of fire. A collapse of the test voltage is then indicative of an insulation fault or flashover. Given that the ETSI standard stipulates that line conductors be directly connected to earth in a TNS network, this measurement is only of limited applicability.

A further disadvantage of insulation measurement, however, is that during retesting, the connected equipment in the system could be damaged by the high test voltage 500 V DC, requiring it to be disconnected. However, this is not possible in 24-hour operation. Potential solutions are provided here by the new standards DIN IEC 60364-6 (VDE 0100-600):2017-06 "Verification" and DIN VDE 0105-100/A1 VDE 0105-100/A1:2017-06 Part 100: General requirements; Amendment A1: Periodic verification. The insulation measurement can be dispensed with if the circuit is permanently monitored by an RCM as described in DIN EN 62020 (VDE 0663), or by an IMD as stipulated in DIN EN 61557-8 (VDE 0413-8). DC-RCMs are not currently standardized. For DC systems, however, DIN EN 62020 (VDE 0663) will need to be revised with regard to DC RCMs.

Recommended action

Personal protection

Data centres can basically be regarded as electrical service rooms, meaning that the use of residual current devices (RCDs) is unnecessary and, for reasons of availability (fault tolerance), also not desirable. Two options are therefore available as preventive protection measures: IT system with insulation monitoring (IMD) or TN-S system with residual current monitoring (RCM).

Some UPS manufacturers already deploy integrated insulation monitoring, but this does not communicate with externally installed insulation monitoring systems e.g. in sub-distribution. It is therefore recommended that insulation monitoring devices compliant with DIN EN 61557-8 (VDE 0413-8) be combined with devices for insulation fault location (IFLS) compliant with DIN EN 61557-9 (VDE 0413-9) that can communicate with each other via appropriate interfaces. An eventual LVDC standard will provide clear targets and define the communication between different manufacturers.

DKE VDE DIN Recommended action

Emergency lighting

In office buildings, emergency lighting is typically activated by undervoltage relays, i.e. the emergency lighting is switched on below a given threshold. There are currently no such undervoltage relays for DC.

Circuit breakers

Currently available circuit breakers are only suitable for up to 250 V DC. The consequence of this is that a double-pole device must be used in a TNS and IT network for 380 V DC or -190/+190 V DC.

9.7.2 Cable/Cable designation

Leaving the idea of only operating new buildings exclusively with direct current to one side, the migration of DC micro grids into existing buildings will play a greater role within the next few years. This will also result in the "mixing" of AC and DC installations. There are currently insufficiently clear requirements regarding which wire and sheath colours the DC power cables should/must have. It would also make sense to be able to distinguish DC power cables visually from AC cables. In the project "The first commercial 380 V DC micro grid in Germany" (see section 10.4) the outputs in the sub-distribution units and also the inputs of the devices were marked: "CAUTION 380 V DC". Standard cables were used which were suitable for 0.6/1 kV nominal voltage. The regulations/standards regarding the nominal voltage should also be clearly defined (dielectric strength).

DKE VDE DIN Recommended action

9.7.3 Connectors/mating cycles

The future standard should make a clear distinction between which connectors which can be operated by laypersons and which by trained professionals, and also between which connectors can be disconnected using tools and which without. The same applies to mating cycles; these differ greatly e.g. in a photovoltaic system and a kitchen appliance or laptop. There is no standard for this in the data centre environment. In the project described in Section 10.4 a plug was used which was designed for up to 20 A and 200 mating cycles with no tools required. The future LVDC standard should provide clear guidelines for this, too.

DKE VDE DIN Recommended action

9.8 Power over Ethernet

Power-over-Ethernet (PoE) has been used in computer networks for small terminal devices (e. g. IP phones, cameras) since around 1999. In recent years, PoE has increasingly been used in smart buildings such as modern office buildings, hotels and hospitals. PoE allows a terminal device to be connected to a data network and simultaneously supplied with electrical power, with the copper in the cable serving a dual function.

PoE is described in the IEEE 802.3-2015 standard, which is currently being extended by IEEE Task Force P802.3bt to include the use of all copper in the network cable, i.e. all four wire pairs [71]. In so-called "4-pair PoE", both wire pair A (RJ45 plug connections 1,2,3,6) and wire pair B (RJ45 plug connections 4,5,7,8) handle both data transmission and power supply.

A PoE system consists of Power Sourcing Equipment (PSE) and Powered Devices (PDs). Each PD is operated on its own network connection of the PSE. PSEs can be PoE midspan devices without any data functionality or PoE switches that serve both as data switches and as power supplies.

There have been three generations of PoE: in IEEE 802.3af the maximum PSE output power per port was 15 W, in IEEE 802.3at it was 30 W and the future "bt" standard includes 90 W.

9.8.1 Power-over-Ethernet power negotiation

The PoE standard defines a negotiation mechanism between PDs and PSEs, consisting of detection and a classification mechanism. This "PoE power negotiation" ensures that only valid PoE PDs are supplied with voltage and that the PSE and PD "agree" on the maximum available power. The negotiation mechanism is independent of the Ethernet functionality. This ensures that a terminal device can be supplied with power before the software is started.

The operating voltage of PoE is between 50 V and 57 V on the PSE side and cannot be adjusted by the negotiation mechanism. The PoE voltage source meets SELV (safety extra-low voltage) requirements. A PD must switch off the load current as soon as the PoE voltage on the PD side drops below 37 V. The voltage levels during the negotiation process are below 20 V.

PDs have special insulation requirements. Electrical contacts which are accessible from the outside must not be galvanically connected to other electrical devices. This effectively prevents earth loops. PSEs are allowed to operate several of their network ports from a single power supply, meaning they are not isolated from each other.

The PoE power transmission can be monitored via the network connection and negotiated parameters can be subsequently changed.

Standard-compliant PSEs have overvoltage and overcurrent shutdown mechanisms. After each shutdown, a new PoE negotiation must be started before PoE voltage can be re-applied. PSEs can also switch off if a PD exceeds the maximum negotiated power. The currents in the network cables are limited in PoE. The maximum current per conductor in the IEEE Std 802.3-2015 standard is 0.3 A. Here a maximum of 2 wire pairs are used. This results in a maximum forward and return current in the cable of 1.2 A. Under no circumstances may PSEs feed more than 100 W into a cable; they thus meet the Limited Power Supply requirements according to [72].

9.8.2 Cabling for Power-over-Ethernet systems

PoE is exceptionally efficient in the transmission of electrical power via network cables [73]. This study investigated the characteristics of "typical" network cabling. The mean losses of 2-pair systems do not exceed 3.4% when CAT5e cables are used, and remain below 2% with CAT6A cables. The results are the same for 4-pair systems up to 51 W. For high-power 4-pair systems (up to 73 W), the losses in CAT5e cables are 4.6% and 2.6% in CAT6A. Higher grade cables should therefore be used for high power levels in order to keep losses to a minimum. Furthermore, the wiring in Ethernet networks is radial, meaning that only the current of a single load has to be transmitted.

Typical network cables are CAT5e cables, consisting of 8 conductors with a 24 AWG cross-section. Two conductors are intertwined to form conductor pairs. The previous standard allowed two pairs of conductors to be used for power transmission. The new "bt" standard will allow the use of all four pairs of conductors in the future. This means that either 50% or 100% of the copper in the cable is also used for power transmission.

Ethernet cables such as Cat5 or Cat6 are typically rated up to temperatures of 60°C. At temperatures above 60°C, the high-frequency characteristics change and data transmission can no longer be guaranteed. Even with conductor bundles, the PoE cabling must not exceed 60°C at any point in the cable.

9.8.3 Connectors for Power-over-Ethernet systems

The typical Ethernet connector is the standardized American RJ45 connector, which is also called the 8P8C modular connector on account of its 8 poles. Although the plug was originally developed for static data cabling, it has a high current carrying capacity of up to 1 A per contact. The contact surfaces of a plugged connection are different from those during the plugging process. This even allows multiple mating cycles under load without deterioration of the contact resistance [74]. This study by Bel Stewart Connector investigated the behaviour of Ethernet connectors under current load. The output during one of the tests was 20 W per contact. Low Level Contact Resistance (LLCR) was measured at the beginning and after 80 cycles. A total of 800 mating cycles were carried out without any major changes in contact quality.

Since PoE negotiates at very low voltages and currents, the contacts are always currentless when plugged in. When a plug is pulled, PoE ensures that the voltage is eliminated from the contacts after a maximum of 300 ms to 400 ms. Open network sockets or disconnected network cables are always de-energized. Only after a valid connection to a PD has been detected and successfully negotiated is the PoE voltage made available.

PROJECT	CONTRIBUTOR	TOPIC	HOMEPAGE
DCSich	DKE, FTZ	Effect of direct current (DC) on the human body in the context of electromobility and the DC supply infrastructure	https://www.dke.de/de/themen/projekte/dc-sicherheit
IsKoNeu	DKE, Bender	Insulation coordination: Environmental aspects in the design of air and creepage distances in new applications	https://www.dke.de/de/themen/projekte/iskoneu
FEN	FEN/RWTH Aachen	Forschungscampus Flexible Elektrische Netze Flexible Electrical Networks (FEN) Research Campus	https://www.fe-naachen.net/
Schaufenster Elektromobilität (Shop window - Electromobility)	BMW, RWE, DB, TU Dresden, ABB	Electromobility connections - DC charging station at the Olympic Park	http://schaufenster-elektromobilitaet.org/de/content/projekte_im_ueberblick/projekt_2568.html
Smart Modular Switchgear (SMS)	TU Braunschweig, funded by BMWi and BMBF	The SMS research project deals with the research and development of switching and protection systems for use in DC networks at different voltage levels.	http://forschung-stromnetze.info/projekte/gleichstromschalter-trennen-lasten/
DCC+G	Siemens etc	DC Components and Grids - DC in buildings	http://www.baulinks.de/webplugin/2012/1328.php4
DC-Industrie	Fraunhofer IISB, Siemens	Demand-oriented distribution of energy within production plants	www.dc-industrie.de
DC protective devices	Fraunhofer IISB	Development of a new, integrated protection concept and new protective devices for future low-voltage DC networks	

Table 15 – DC projects

10.1 DCSich – Effect of direct current (DC) on the human body in the context of electromobility and the DC supply infrastructure

The low voltage range (AC voltages up to 1000 V and DC voltages up to 1500 V) plays a special role in electrical safety because most devices used by lay people are operated in this range. Contact-related electric shock represents the main risk for humans and animals. So-called secondary accidents such as falls are a further cause of accidents. It is generally assumed that DC is less dangerous than AC, at least with regard to the risk of ventricular fibrillation. However, there is evidence of "special effects" in the literature which only occur in DC accidents.

Basic provisions and protection concepts already exist for DC voltages, but there is much less experience in this field than in that of alternating voltage due to the low economic importance of DC voltage in the range of several hundred volts in the last few decades. However, in the next few years, DC voltage applications are expected to gain enormously in significance in power engineering (such as drive technology). Advances in power semiconductors will result in ideas being put into practice that just a few years ago were not yet economically viable. In electromobility, this includes the operation and DC charging of electric vehicles. This concerns in particular the possibility of opening up higher voltage levels (approx. 400 V DC) in vehicles.

The DCSich research project was launched jointly by the DKE and Forschungs- und Transferzentrum Leipzig e.V. and sponsored by the Federal Ministry for Economic Affairs and Energy. The joint project started in August 2012 and was successfully completed in November 2014. Additional professional support was provided by a project-related working group (PBA) consisting e.g. of representatives of trade associations, federations, universities and industry. The objectives of the DCSich project were:

- Improving knowledge about the effects of direct current on the human body
- Drawing up an overview of the possible effects of DC currents, including rating the relevance for the different applications
- Reviewing the statements on the ventricular fibrillation limits for DC and confirming existing or deriving new limit values
- Reviewing the models and typical accident situations through simulations for various applications
- Developing protection concepts for the protection of persons and equipment

Research and simulations were carried out to answer all open questions. New animal testing could be avoided through the evaluation of older experimental investigations.

10.2 IsKoNeu

The increased use of electrical and electronic components in new applications (such as electromobility and photovoltaics) with DC voltages of several 100 V raises new questions regarding insulation coordination, particularly in light of the environmental influences to be considered such as pollution, condensation, etc. It is necessary to examine critically the previous findings regarding the calculation of air and creepage distances for such environments.

On this basis, safety limits should be confirmed or defined and appropriate protection concepts and tests developed. The protection concepts and tests should be incorporated in standards and thus made accessible to the public. It is intended to inform the public and in particular the professional public through appropriate information channels.

The aim of the project is to develop new calculation requirements or to update existing ones. Further objectives include:
- Development of standards and specifications
- Updating of existing publications
- Scientific and informative publications
- Development of training courses and seminars

The project "Insulation coordination: Dimensioning of air and creepage distances under ambient conditions in new applications", funded by the Federal Ministry of Economic Affairs and Energy, was completed and the results summarized in a report. This is available on the DKE homepage.

10.3 Flexible Electrical Networks FEN/RWTH Aachen Research Campus

The Flexible Electrical Networks (FEN) Research Campus is an association of 15 institutes of the RWTH Aachen University and 22 industrial partners from different disciplines. In order to meet the challenges of supplying energy successfully in the future, a high degree of transdisciplinary research and interdisciplinary cooperation is required, as many different disciplines are affected. This transdisciplinary scientific-industrial research is conducted under a single roof at the FEN Research Campus. The joint research of the scientific and industrial partners promotes application-oriented research: research results can quickly be translated into innovative products or services by industrial partners. The Research Campus model is based on the "Research Campus - Public-Private Partnership for Innovation" funding initiative of the Federal Ministry of Education and Research (BMBF), which is aimed at supporting long-term cooperation between science and industry.

The aim of the FEN Research Campus is to conduct research and development into innovative technologies for future electrical networks with a high proportion of renewable and distributed energy sources. The experts at the FEN Research Campus are analyzing how DC technology can be integrated into our future energy supply system. Research in this area includes various fields of research: Network planning and operation, automation and control, standards and norms, cloud platforms for intelligent energy services, power conversion and components as well as non-technical aspects such as social acceptance and biological, ecological, urban development and economic aspects.

The FEN Research Campus is divided into three consortia (low, medium and high voltage).

The consortia are subdivided into "communities" in which the different aspects are explored.

The focus of the research is on optimization of energy supply and distribution at the low voltage level.

Building automation, networking across different domains (electrical/thermal/communication), the use of DC technology and the integration of renewable energy sources are further aspects which are addressed. It also plans to be actively involved in the development of standards for DC voltage systems.

The structure of the Low Voltage Consortium is shown in Figure 18

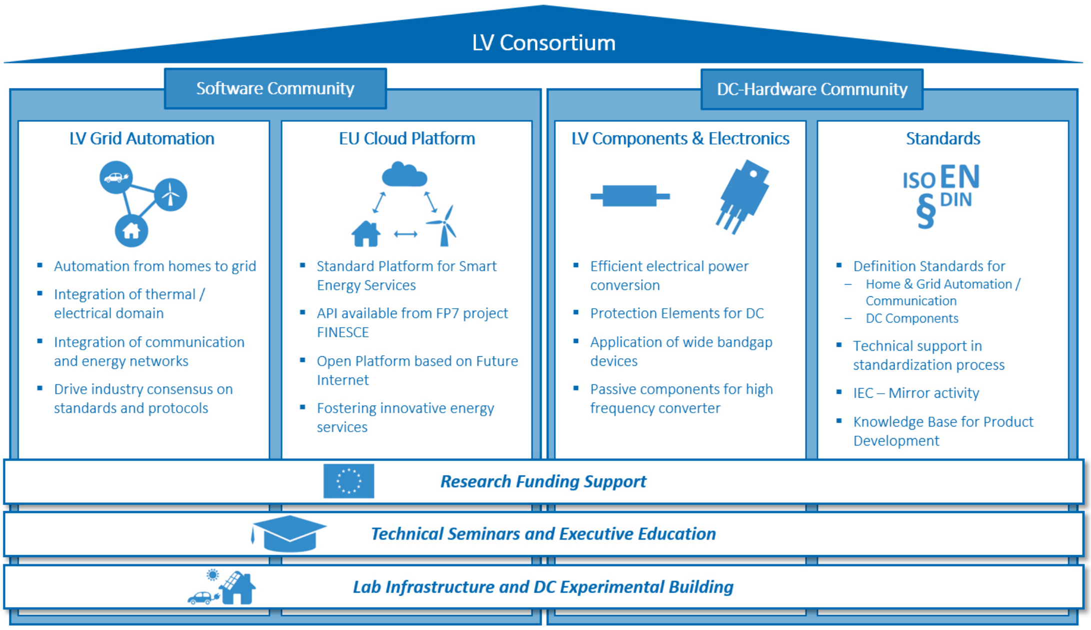


Figure 18 – Structure of the Low Voltage Consortium [58]

The specific topics are complemented by cross-cutting activities which include a laboratory infrastructure and a model DC voltage building.

10.4 The first commercially used 380 V DC network in Germany

Bachmann GmbH & Co. KG in Stuttgart took up the challenge and installed the first commercially used DC micro grid in an office building in Stuttgart. The IT/TC technology, the air conditioning and lighting systems are run directly on 380 V DC.

From the outset, the focus of all activities was on meeting the general requirements for today's data centres and safety in terms of personal protection. At an early stage Bachmann GmbH & Co. KG therefore commissioned a planning office experienced in the field of building and data centre planning which, in close cooperation with the TÜV and VDE organizations, met both of these requirements. It soon emerged that no equivalent standards to those for AC voltage were available, nor were there any products on the market for DC voltage.

Bachmann GmbH & Co. KG based its earthing concept on the ETSI EN 301605 standard which was finally adopted in October 2013.

Taking this standard as its starting point, Bachmann GmbH & Co KG used the DIN VDE 0100 (VDE 0100) series of standards for personal protection as the basis of its work. An example of this is the safe disconnection/interruption of all live cables in the event of a fault.

10.5 DC Industry

DC-INDUSTRIE
ENERGIEWENDE TRIFFT INDUSTRIE 4.0

The aim of the DC Industry ("DC-INDUSTRIE") research project (https://dc-industrie.zvei.org/) is the demand-based distribution of energy within production plants, involving a maximum of energy reuse and a minimum of conversion losses. The idea is to integrate renewable energy sources and energy storage systems simply and flexibly. This significantly increases energy efficiency in production and enables further potential fields beyond the isolated optimization of individual devices to be developed. Energy supplied via the DC network is robust (with regard to fluctuating network quality) and can react flexibly to fluctuating energy supplies. This helps to stabilize the energy grid. Important steps towards achieving this goal include standardized interfaces, increased power density within the electrical drives and the elimination of decentralized AC/DC conversion in the inverters.

10.6 DC protective devices – Development of a new, integrated protection concept and new protective devices for future low-voltage DC networks

Specialized industrial companies and research institutes are working on an intelligent, efficient and comprehensive protection concept for modern DC networks in the three-year "DC Protection Devices" consortium project. E-T-A, ABL, DEHN + SÖHNE, Phoenix Contact, Bender, Bachmann, Fraunhofer IISB and Cluster Leistungselektronik are involved in the ECPE project. It is funded by the Federal Ministry of Economic Affairs and Energy (BMWi).

Reflecting the monopolized radial structures, the grid infrastructure (from the power plant to the consumer) has so far been protected using ever more sensitive and faster triggering protection components. Increasingly, however, consumer-adjacent sources (such as photovoltaic systems and electrical energy storage devices) also require the use of protection devices suitable for direct current. In addition, applications such as energy recovery or island operation are placing completely new demands on protection and switching technology. In contrast to AC technology, there are hardly any uniform standards for the installation and safe operation of DC networks. This is the point at which the project partners come in. Their aim: to develop an efficient and comprehensive protection concept for modern DC networks. Precisely coordinated components for line and overvoltage protection as well as residual current and insulation monitoring are combined to form an intelligent overall protection system that incorporates the latest developments in the fields of power electronics, sensors and communication technology. Intelligent networking and communication between individual protection and switching components ensure maximum failure safety and reliable operation. The main target groups are operators of direct current networks, such as telecommunications companies, computer centres and supermarkets, but increasingly also industrial companies, electricity suppliers, suppliers of photovoltaic systems and electric mobility service providers.

11 LIST OF ABBREVIATIONS

ABBREVIATION/ACRONYM	MEANING
AAL	Active Assisted Living.
AC	Alternating Current
AFDD	Arc Fault Detection Device
AFE	Active Front End
BSI	Bundesamt für Sicherheit in der Informationstechnik (*Federal Office for Security in Information Technology*)
BWEA	British Wind Energy Association
CISPR	Comité International Spécial des Perturbations Radioélectriques
DC	Direct Current
DCC+G	Direct Current Components +Grid
DIN	Deutsches Institut für Normung (*German Institute for Standardization*)
DKE	Deutsche Kommission Elektrotechnik Elektronik Informationstechnik (*German Commission for Electrical Electronic Information Technologies*)
EMC	Electromagnetic Compatibility
EMV	Elektromagnetische Verträglichkeit (Electromagnetic compatibility)
ESMAP	Energy Sector Management Assistance Program
ETSI	European Telecommunications Standards Institute
GdV	Gesamtverband der deutschen Versicherer (*Association of German Insurers*)
HLKK	Heating, ventilation, air conditioning and refrigeration technology
IC-CPD	In Cable Control and Protective Device
IEC	International Electrotechnical Commission
IKT	Informtaions- und Kommunikationstechnologie (Information and Communication Technology)
ISO	International Organization for Standardization
IT	Isole Terre
ITU	International Telecommunication Union
LED	Light Emitting Diode

ABBREVIATION/ACRONYM	MEANING
LEMP	Lightning ElectroMagnetic Pulse
LVDC	Low Voltage Direct Current
MIL-STD	Military Standard
NEC	National Electric Code
PELV	Protective Extra Low Voltage
PFC	Power Factor Correction
PFD	Probability of a Failure on Demand
PFH	Probability of a dangerous Failure per Hour
PoE	Power over Ethernet
PRCD	Portable Residual Current Device
PSA	Persönliche Schutzausrüstung (Personal protection equipment)
PV	Photovoltaic
RCD	Residual Current Device
SC	SubCommittee
SEG	Strategy Evaluation Group
SELV	Safety Extra Low Voltage
SGAM	Smart Grid Architecture Model
SIL	Safety Integrity Level
SK	Schutzklasse (Safety class)
SMS	Smart Modular Switchgear
SPD	Surge Protective Device
SWR	Südwestrundfunk
TBINK	Technical Advisory Board International and National Coordination (TBINK)
TC	Technical Committee

ABBREVIATION/ACRONYM	MEANING
TN	Terre neutre
TOV	Temporary Over Voltage
TT	Terre Terre
UPS	Uninterruptible Power Supply
USB	Universal Serial Bus
USV	Unterbrechungsfreie Stromversorgung (Uninterruptible power supply)
VDE	Verband der Elektrotechnik Elektronik Informationstechnik (*German Association for Electrical, Electronic & Information Technologies*)

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