Funded by the European Union

Horizon Europe

EUROPEAN COMMISSION

European Climate, Infrastructure and Environment Executive Agency (CINEA)

Grant agreement no. 101136131

SHIFT to Direct Current

Deliverable D1.2
Policies, Regulatory framework, and Market Architecture

Document Details

Due date	31-07-2024
Actual delivery date	
Lead Contractor	FRAUNHOFER
Version	0.3
Prepared by	FRAUNHOFER (Kilian Drexler, Bernd Wunder), APRM (Carlos Castro), CIRCE (Romina Lobera, Mikel Refoyo), EATON (Dimitrios Baros, Oleksij Chumak), EDF (César Slongo), EHPA (Giulia Malafarina), INESC ID (Hugo Morais, Guilherme Paraíso), IST-ID (Lucas Pereira), JJC (Enzo Minazzo), NEXNS (Nicolas Rousselet, Lina Ruiz), PCBD (Janos Lazanyi, Blanka Petrik), SCHND (Ahmad Makkieh, Mathieu Guillot, Jean Wild), TALT (Andrii Chub)
Reviewed by	EDP (Carlos Cardoso), RWTH (Katharina Hetzenecker)
Dissemination Level	Public

Project Contractual Details

Project Title	Shift to Direct Current
Project Acronym	SHIFT2DC
Grant Agreement No.	101136131
Project Start Date	01-12-2023
Project End Date	31-05-2027
Duration	42 months

Document History

Version	Date	Contributor(s)	Description
0.1	04-03-2024	FRAUNHOFER	Table of Contents
0.3	05-07-2024	FRAUNHOFER, APRM, CIRCE, EATON, EDF, EHPA, INESC ID, IST-ID, JJC, NEXNS, PCBD, SCHND	Internal Draft
0.4	19-07-2024	EDP, RWTH	Internal review
1.0	23-07-2024	FRAUNHOFER	Final version

Disclaimer

Acknowledgment

This document is a deliverable of SHIFT2DC project. SHIFT2DC has received funding from the European Union´s Horizon Europe programme under grant agreement no. 101136131.

Funded by
the European Union

Executive Summary

This Shift2DC deliverable provides a comprehensive overview of the standardization of Direct Current (DC) systems, particularly focusing on electrical infrastructure within buildings and local distribution systems that operate within Low Voltage (LV) or Medium Voltage (MV) levels. It concentrates on key standards, regulations, and practices that are shaping the implementation and development of these systems. Excluded from this analysis are traction systems and High Voltage Direct Current (HVDC) distribution systems.

The standardization of electrical infrastructure is primarily done at an international level within the IEC or at a European level by CENELEC or ETSI. The various IEC Technical Committees (TCs) and the main standards currently being worked on regarding DC are introduced in chapter two. With the Current/OS Foundation and the Open DC Alliance (ODCA), two different initiatives have gained broad industry support with Europe, specifying a quasi-standard for low voltage DC installations. Outside of Europe two additional initiatives are identified, EMerge Alliance in the US and DC Power Supply Alliance in Japan. A short overview about LVDC standardization in China is given as well.

The European Commission (EC) has funded several projects related to DC systems, focusing on standardization and regulatory framework of DC systems. These include DC-POWER, READY4DC, DC4EU, PROMOTioN, InterOPERA, HYPERRIDE, DCNextEve, FUNDRES, and EISMEA LVDC.

In terms of national regulations, it is noted that systems may not always be directly transferrable when crossing national borders due to national specifics or peculiarities. As such, all Shift2DC partner countries are examined regarding their own standardization bodies and national regulations.

The specifications of ODCA and Current/OS Foundation are compared and while there are some differences, no real incompatibilities have been identified. The differences lie in the application scenarios the initiatives are primarily targeting (industrial DC grids for ODCA and building grids for the Current/OS foundation) and in the protection systems deviating from those scenarios. One example is the earthing system: In ODCA, the so-called AC-sided earthing is an often used solution which enables the use of cheaper non-isolated AC/DC converters while Current/OS Foundation currently requires a TN earthing system resulting in the need of an isolated AC/DC-converter. Both initiatives are also actively working together to allow easier development of components valid for both systems.

Regarding gaps in the standardization, the main barriers are seen in the area of protection, as well as clear definitions and reference architectures. For the later, both Current/OS Foundation and ODCA could be used but would need to be referenced by standardization documents. In addition to this, there has been no significant standardization activity focusing on cable requirements for LVDC installations to date.

In Chapter three, the different market architectures and additional services that DC grids can supply to the public AC grid are analysed. Generally speaking, all services can be categorized as either system, grid or facility level services.

Table of Contents

List of Figures

List of Tables

Acronym

AC	Alternating Current
ACD	Approved for CD
AIC	Active Infeed Converters
ANSI	American National Standards Institute
CD	Committee draft for comments
CDM	CD to be discussed at meeting
CNMC	National Markets and Competition Commission
CPR	Construction Product Regulation
ČSN	Czech Standards
DC	Direct Current
DSO	Distribution System Operator
ESPR	Eco design for sustainable products
EC	European Commission
EE	Environmental Engineering
EMC	ElectroMagnetic Compatibility
EISMEA	European Innovation Council and SMEs Executive Agency
EU	European Union
EV	Electric Vehicle
GCPC	Grid-Connected Power Converters
HVDC	High Voltage Direct Current
ICT	Information and communications technology
IDAE	Institute for the Diversification and Saving of Energy
IEC	International Electrotechnical Commission
IGBT	Insulated-Gate Bipolar Transistor
ILC	InterLink Converters
JWG	Joint Working Group
LVDC	Low Voltage Direct Current
MITECO	Ministry for the Ecologica Transition and the Demographic Challenge
MSZT	Hungarian Standards Board
MVDC	Medium Voltage Direct Current
NPR	Dutch Practice Recommendation
OCPD	Overcurrent Protection Device
ODCA	Open Direct Current Alliance
OVP	Over-Voltage Protection
OWFs	Offshore Wind Farms
PEI	Prosumer Electrical Installation
PWI	Preliminary Work Item
PV	Photovoltaic
RCBO	Residual current operated circuit-breakers
RCCB	Residual Current Circuit-Breakers
REBT	Low Voltage Electrotechincal Regulation
RES	Renewable Energy Sources
SC	Subcommittee
SCCB	Semiconductor circuit breaker
SELV	Safety Extra Low Voltage
SR	Swiss Regulation
SRD	Systems Reference Deliverable
SyC	System Committee

TC	Technical Committee
TR	Technical Report
WG	Working Group

1 Introduction

1.1 Scope and Objectives

This document is intended to provide a comprehensive overview of the current state of standardization concerning direct current systems, with a primary focus on electrical infrastructure within buildings and localized distribution systems that operate within Low Voltage (LV) or Medium Voltage (MV) ranges. It aims to highlight key standards, regulations, and practices that are shaping the implementation and development of these systems.

Excluded from this analysis are traction systems, such as the high voltage grids used in electric vehicles. Additionally, High Voltage Direct Current (HVDC) distribution systems, which are commonly employed for transnational electrical infrastructure projects, are not covered either. These areas do not align with the objectives of the Shift2DC project and as such are beyond the scope of this deliverable.

1.2 Structure

Standardization of electrical infrastructure is mostly done on an international level within IEC or on an European level by CENELEC or ETSI. As such the different IEC Technical Committees and the main standards that are currently being worked on regarding DC are introduced in chapter two. The Current/OS Foundation and the Open DC Alliance (ODCA) are two different initiatives that have gained large support from the industry specifying quasi-standards for low voltage DC installations. Both are introduced before an overview of different European Union (EU) wide projects is given, which focus on standardization of Direct Current (DC). While the IEC standards apply internationally, there might be some specific interpretations or solutions on a national level. As such, all Shift2DC member nations are evaluated on specific national regulations and standards that might deviate from IEC. Afterwards standardization and DC initiatives outside the EU are analysed. Chapter two is finalized with a comparison of all regulations and initiatives, identification of the main gaps within standardization which result in barriers for the implementation and recommendations towards the standardization groups.

In Chapter three, the different market architectures and grid services that LV or MVDC systems can supply towards the public AC grid are analysed. While this is written with the demonstrators in mind, this chapter is kept on a general level, applicable for multiple applications and not just the specific demo sites.

1.3 Relationship with other deliverables

This deliverable D1.2 is the second technical deliverable in the project, from the second task in Work Package (WP) 1.

The results of this deliverable will be closely related to deliverable D1.3 – Use Case Repository (T1.3) and D1.4 – Specification of DC solutions, tools and devices (T1.4). The analysis conducted in this document will also serve as a basis for the deliverable D5.2 – Standardization and Harmonization activities (T5.2) and D5.4 – DC Roadmap and Business models which are related to the final recommendations of SHIFT2DC project (T5.4).

2 Standardization Framework

2.1 International regulations

In this chapter, we explore standards that are developed and adopted on an international scale through IEC. Initially, the chapter outlines the various technical committees that play a crucial role in the standardization of MVDC and LVDC systems. Subsequently, the focus shifts to two prominent international DC initiatives, Current/OS Foundation and ODCA. Both initiatives have formulated respective technical specifications for DC infrastructure. These specifications are frequently utilized in relevant projects, particularly because there are existing gaps in IEC standardization that have yet to be addressed. Furthermore, the chapter discusses several EU-funded projects that have a significant impact on advancing EU-wide or international standardization efforts aimed at bridging these gaps.

2.1.1 IEC and CIGRE

For DC, **CIGRE** is an important standardization community, mainly for cable standards. According to CIGRE TB 1.82, MVDC power cable applications are expected to grow significantly in coming years, based on national experiences and collected feedback (i.e. ANGLE DC project) (cf. CIGRE TB 793, CIGRE WG C6/B4.37. T). However, most of the proposed MVDC cable test protocol suggest adopting an approach based on either MVAC or HVDC standards and materials (CIGRE TB 852/TB 496). In this context, boundaries need to be defined for MVDC applications (nominal voltage or electric field stress). To ensure the same level of performance, interoperability and reliability as in already existing systems, new standards (or recommendations by international bodies) need to be developed. Additionally, the ageing process in insulation materials, spaces of charges and other concerns under DC stress need to be investigated to define the most relevant guidelines.

Within CIGRE TB 1.82, one focus is on “MVDC Cable System Requirements” [1] and the committee is committed to define recommendations of boundary of HV/MV and AC/DC material at the level where accessories and cable require specific solution. The working group pays particular attention to the system requirements, taking into consideration the following aspects: losses and efficiency, operating conditions, cable ratings, overload capacity, fault current and duration, and fault-clearing strategies. The final report is expected to be published by the end of 2024.

In the **IEC** community, many technical committees (TC), subcommittees (SC) and even a system committee (SyC) are investigating the large domain of DC systems. Table 2-1 summarizes the committees and the different subjects of interest.

Table 2-1 : List of IEC technical committees and the respective subjects of interest

Domain	Committees	Subjects of interest
Use cases	TC 8	System aspects for electrical energy supply
	TC 57	Power systems management and associated information exchange
Installations	TC 13	Electrical energy measurement
	TC 64	Electrical installations and protection against electric shock
Equipment	TC 22	Power electronic systems and equipment
	TC 23	Electrical accessories for AC and DC, for household and similar purposes normally installed by instructed or skilled persons and normally used by ordinary persons
	TC121/SC121A	Low-voltage switchgear and controlgear (to be operated by skilled people)
	TC17	HV switchgear and control gear
Appliance	TC 21	Secondary cells and batteries
	TC 82	Solar photovoltaic energy systems
	TC 69	Electric vehicles
	TC34	Lighting
	TC120	Electrical Energy Storage (EES) System
Material	TC 3, 7, 11, 20	Electric cables
	TC 112	Qualification of electrical insulation materials and systems
Efficiency and safety	TC 59, 61	Performance and safety of household
	TC 77	Electromagnetic compatibility
	TC 95	Protection equipment
	TC 73	Short-circuit current calculation
	TC 99	Insulation co-ordination and system engineering of high voltage electrical power installations above 1,0 kV AC and 1,5 kV DC
Integration	SyC LVDC	Work coordination around LVDC systems

All these different committees are responsible for a set of standards, which cover specific subjects inside a technical domain. The System Committee for LVDC (SyC LVDC) elaborated a roadmap which summarizes the IEC standards associated with the respective technical committees and technical domains. The Standardization map of LVDC 2024 (Figure 2-1) is publicly available and can be consulted at [2].

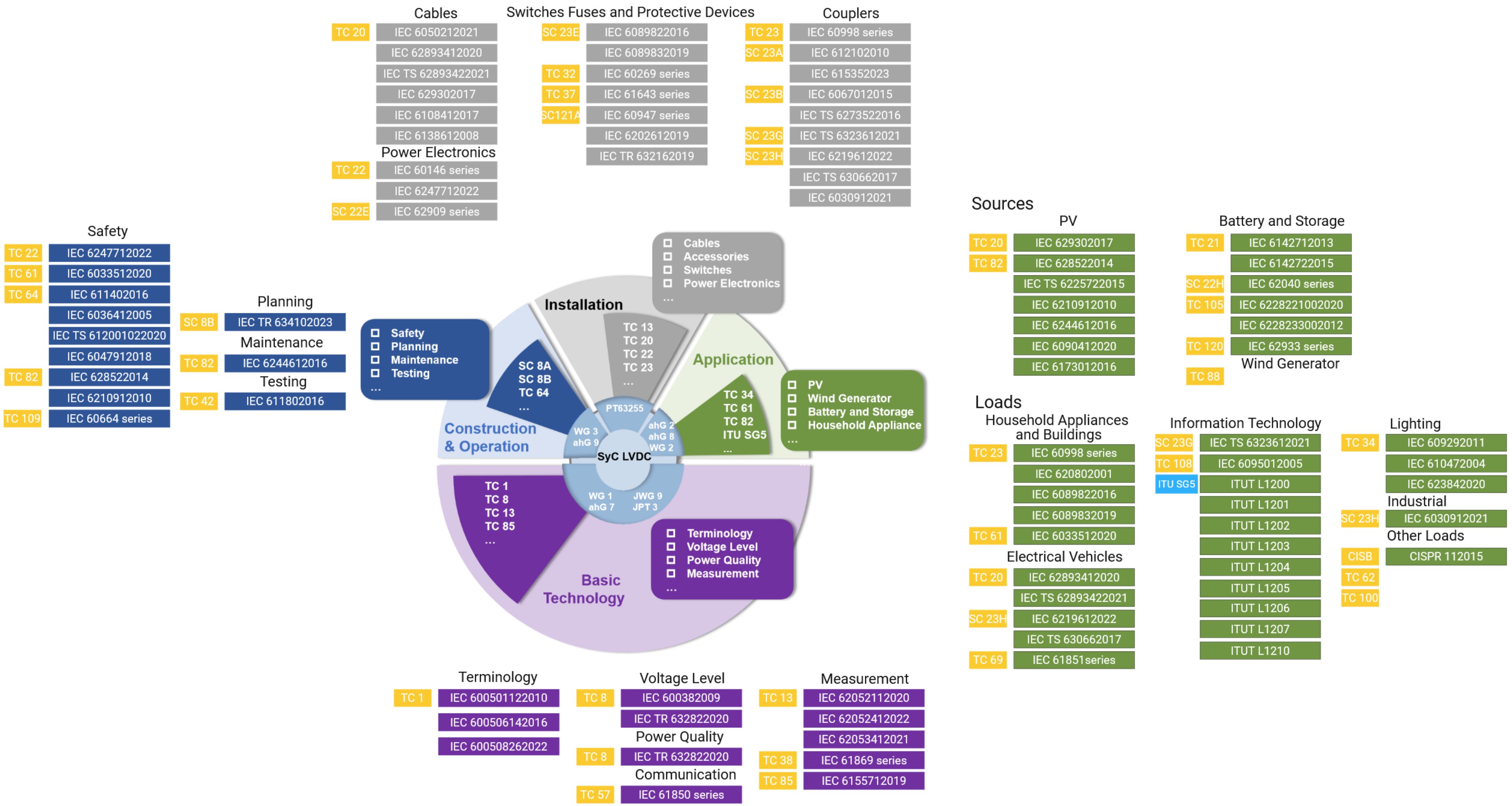

Figure 2-1 : LVDC roadmap of IEC standards map extracted from SysComitee [2] March 22nd, 2024, under revision

Among all these standards, the Shift2DC consortium would like to highlight the following standards and projects that are currently in development or have only recently been published. This is not an exhaustive list of standards applicable for MV or LV DC installations, but more an overview to showcase the gaps identified by IEC standardization bodies that are actively being worked on.

- **IEC 60364-8-82: Low-voltage electrical installations – Part 8-82: Functional aspects - Prosumer's low-voltage electrical installations**
  This standard is covered by the TC64 and has been made public in 2022. It covers low-voltage installations regardless of the current form. As such it is applicable for both AC and DC. IEC 60364-8-82:2022 provides requirements and recommendations that apply to low-voltage electrical installations, both standalone or connected to a distribution network able to operate with local power supplies, and/or with local storage units, and that monitors and controls the energy from the locally connected sources delivering it to current-using equipment, and/or local storage units, and/or distribution networks. Such electrical installations are designated as prosumer's electrical installations (PEIs).
  These requirements and recommendations apply to new installations and modifications of existing installations. This standard also provides requirements and recommendations for the safe, efficient and correct behaviour of these installations when integrated into a smart grid.

  There is an Amendment 1 in the works, covering DC prosumer electrical installation. A first Draft for Comments 64/2668/DC has been circulated in April 2024 to add an Annex to IEC 60364-8-82 Annex F: PEIs with a DC system and distributed sources with isolated interlink converter.

- **IEC TR 63282: LVDC systems - Assessment of standard voltages and power quality requirements**

  JWG 9 of TC8 is responsible for this technical report and is currently working on a second edition with significant changes in comparison to the first edition and an annex for MVDC is added including the description of a MVDC/LVDC distribution system. This second edition is currently in the process of being published.

  The IEC TR 63282 is not a standard in itself, but a technical report and as such is prepared for technical committees working on standards. It collects information and reports experience for the standardization of voltage levels and related aspects (power quality, EMC, measurement, etc.) for LVDC systems (systems with nominal voltage up to and including 1500 V DC).

  Rationale for the proposed voltage values is given. Variation of parameters for the voltage (power quality) for their boundaries are defined. Nevertheless, some of the technical items are not exhaustively explained in this document and some gaps are identified for future work. Attention is paid to the definition of DC voltage.

  The report focuses on LVDC grids in infrastructure or buildings, while the traction system of vehicles is excluded. This document gives technical inputs to TCs in charge of the standardization of different issues and coordinated by SyC LVDC.

- **IEC 63532: InterLink Converters (ILC) - Safety and Performance Requirements**

  This new standard developed by WG12 of TC22 is covering the requirements, guidance, and testing methods dedicated to InterLink Converters for the specific function of interlinking AC power systems to a DC power system.

  This will result in a product specification of the AC/DC converter for non-island LVDC grids. Currently, a committee draft for comments (CD) is being prepared and is expected for end of 2024, while the full publication of the new standard is planned for end of 2026.

- **IEC 62909: Bi-directional grid connected power converters**

  WG8 of TC22 is working on a new edition of IEC 62909-1 (General and safety requirements) and IEC 62909-3 (EMC requirements and test methods). For Part 1, a new edition is currently being worked on, while Part 3 is a completely new addition to the standardization line. In general the IEC 62909 covers aspects of bi-directional grid-connected power converters (GCPC), consisting of a grid-side inverter with two or more types of DC-port interfaces on the application side with system voltages not exceeding 1000 V AC or 1500 V DC. In special cases, a GCPC will have only one DC-port interface, which is connected to a bidirectional energy-storage device.

- **IEC 60898-3: Circuit-breakers for overcurrent protection for household and similar installations - Part 3: Circuit-breakers for DC operation**

  Work on the IEC 60898 is part of SC23 E. It has been published in 2019 already and covers circuit breakers for voltages up to 440 V DC, with a rated current up to 125 A. Applicable short circuit current is also limited to 10000 A. Part 3 specifically covers DC applications. These circuit-breakers are intended for the protection against overcurrents of wiring installations of buildings and similar applications; they are designed for use by uninstructed people and for not being maintained.

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

  Edition 7 of the IEC 60947-1 is currently prepared by SC121A. Currently, it is at the CDM stage and planned publication of the finished standard is December 2025.

  The IEC 60947-1 covers the general aspects of switchgear and controlgear for up to 1500 V DC, (as well as 1000 V AC). General rules and safety requirements, including basic definitions, characteristics, performance requirements but also verification of the characteristics and performance, i.e. the test setup and execution. Other than the higher voltage rating, the main difference to the IEC 60898-3 is that this standard is designed for use by instructed people only. As such this standard covers a different product type.

- **IEC 60947-10: Low-voltage switchgear and controlgear – Part 10: Semiconductor circuit-breakers**

  Part 10 of the 60947 is also in the scope of SC121A. Like the edition 7 of part 1, it is at the CMD stage, and publication is expected in January 2025.

  Part 10 applies to semiconductor circuit-breakers (SCCBs) with a rated voltage of up to 1500 V DC (or 1000 V AC). Since mechanical breaking is complex and costly in DC applications, SCCBs offer a great alternative both from size and cost perspective but have not been covered at all by standardization until now. As such, this is an eagerly anticipated standard for all LVDC applications covered in Shift2DC.

- **IEC 63464-1**: **Protective devices with semiconductor technology for household & similar use – Part 1: Semiconductor residual current circuit-breakers with overcurrent protection (SC-RCBOs)**

  WG12 of SC23E is working on Edition 1 of IEC 63464-1. Publication is planned for June in 2028, as such it is still in its earlier stages.

  According to the scope of the working document 23E/1316/NP circulated in March 2023, this international standard will provide requirements and test set-ups for semiconductor-based residual current operated circuit breakers with integral overcurrent protection (SC-RCBOs) for household and similar uses, for rated voltages not exceeding 440 V AC with rated frequencies of 50 Hz, 60 Hz or 50/60 Hz or 440 V DC, rated currents not exceeding 125 A and rated short-circuit capacity not exceeding 25000 A.

- **IEC 63053-2: Residual current circuit-breakers for household & similar for dc systems – Part 2: Residual current operated circuit breakers without integral overcurrent protection (DC-RCCBs)**

  Another new standard is currently worked on by WG2 of SC 23E with a planned publication date of December 2027, which is currently in the stage of ACD.

  It will cover residual current circuit breakers, specifically for DC based household applications (DC-RCCBs). According to the scope of 23E/1343/NP circulated in December 2023, this document will provide general requirements and tests for residual current operated circuit breakers without integral overcurrent protection for household and similar uses, intended to be used in DC systems (hereafter referred to as DC-RCCBs), for rated operational voltages not exceeding 440 V DC and a rated current not exceeding 125 A, intended principally for protection against shock hazard.

- **PWI 23E-52: Residual current operated circuit-breakers for household and similar uses for dc systems - Part 1: Residual current operated circuit breakers with integral overcurrent protection (DC-RCBOs)**

  This Preliminary Work Item (PWI) is worked on by SC 23E and will give general requirements and tests for residual current operated circuit breakers with integral overcurrent protection for household and similar uses, intended to be used in DC systems for rated operational voltages not exceeding 440 V DC, a rated current not exceeding 125 A and a rated short-circuit capacity not exceeding 10000 A, intended principally for protection against shock hazard.

  PWI 23E-52 is covering "classical" electromechanical DC-RCBO, IEC 63464-1 intend is to describe requirements and test for Semiconductor RCBO. IEC 63053-2 is dealing with another family of residual current device for DC known as DC-RCCB.

- **IEC 61557-12 – Equipment for testing, measuring or monitoring of protective measures – Part 12: Power metering and monitoring devices (PMD)**

  This standard has already been published in 2018 and falls under the responsibility of TC85. It specifies requirements for power metering and monitoring devices (PMD) that measure and monitor the electrical quantities within electrical distribution systems, and optionally other external signals. It covers both AC and DC systems in the low voltage area, fixed or portable, indoor or outdoor usage.

- **IEC TR 63534 ED1 - Integrating distributed PV into LVDC systems and use cases**

  WG7 or SC 8A is responsible for creating this new TR. As it is a technical report and not a standard, it is mostly to be used as a reference document and general guideline, especially for other standardization activities. It is currently at the stage of PCC and the project plan lists a publication date of December 2025.

  Goal of this TR is to develop specifications, standards and reference frameworks to integrate large scale and high penetration of renewable energy via LVDC systems, coordinating control, defining interfaces, fault response and stability issues. This is aimed to guide OEMs and integrators and as such ease installations and provide high quality grid services.

- **IEC TS 63354 ED1 - Guideline for the Planning and Design of DC or Hybrid Microgrids**

  This technical specification is currently being prepared by WG 5 of SC 8B. Since it is currently at the CD stage, the planned publication date of June 2024 is no longer valid, but has not been updated as of the publication date of this document.

  This guideline provides general requirements, technical principles, load and generation forecasting, voltage level selection, topologies, equipment selection, protection system, monitoring and communication, metering, and DER and load connection. It can provide reference for subsequent standards related to DC systems.

- **IEC PT 63317 - LVDC industry applications (SyC LVDC)**

  SyC LVDC is responsible for working on the systems reference deliverable (SRD) 63317. The publication plan is not up to date, since it still shows the planned publication date as May 2024, yet the document is still in the stage 2CD.

  This SRD applies to describe the certain aspects of standardization of LVDC in industrial applications. These industrial applications apply to the secondary economic sector where the processing of resources obtains to the production, distribution and storage of physical goods, especially in a factory or special area. It covers the generation, distribution and consumption of LVDC power at these premises. The SRC 63317 follows the IEC Systems Approach from the domain to the gap analysis and give guidance by describing reference implementation.

  This SRD will provide the main guidelines for all industrial LVDC applications, both for the general public, but also as a reference scenario and design for further standardization. The architecture definition is the foundation so that it will then be possible to specify all the components in accordance with these architecture rules. Both Current/OS Foundation and ODCA specifications are examined within the SyC LVDC.

2.1.2 European Standards

Many IEC standards are adopted unchanged at the EU level as EN standards. Additionally, there are three standardization bodies at the EU level that operate independently and also independently of IEC or ISO standardization: CEN, CENELEC, and ETSI.

- **CEN** (Comité Européen de Normalisation) is responsible for European standards (EN) in all technical fields, except for electrotechnology and telecommunications.
- **CENELEC** (Comité Européen de Normalisation Électrotechnique) includes all the electrotechnical committees of Europe and is responsible for standardization in the field of electrotechnology.
- **ETSI** (European Telecommunications Standards Institute) is responsible for standardization in information and communication technologies.

The most important standards for DC applications, as addressed in Shift2DC, are IEC standards, which are adopted unchanged across Europe as EN standards. However, there are also some standards that have been developed and adopted exclusively by European standardization bodies.

The telecommunications industry can be seen as a pioneer in the field of LVDC grids. Due to the electrical architecture in data centres with in-line UPS systems and DC loads, ETSI published the first version of a standard for DC distribution with up to 400 V as early as 2003. ETSI has also published a standard for earthing systems of DC applications:

- **ETSI EN 300 132-3 – Environmental Engineering (EE); Power supply interface at the input of Information and Communication Technology (ICT) equipment; Part 3: Up to 400 V Direct Current (DC)**

  The main standard defining the 400 V system has been published as Version V2.2.1 in July of 2021. It defines the electrical interface for components to be used with a distribution grid of up to 400 V DC. The standard is written with an architecture in mind which is directly connected to a battery system. Typically, DC installations prefer to connect batteries to the grid only via converter systems and current discussions in the data centre community revolve around higher voltages, especially taking larger systems like hyperscale data centres into consideration. As such, this standard is not seen as the state of the art.

- **ETSI EN 301 605 – Environmental Engineering (EE); Earthing and bonding of 400VDC data and telecom (ICT) equipment**

  Published as version V1.1.1 in January 2013, this standard has not been actively worked on for some time. Yet it still does provide a tremendous reference document and the earthing systems defined in here are used as the basis for those of the system specifications of ODCA or Current/OS Foundation.

2.1.3 European DC Initiatives

In recent years, two major DC initiatives have emerged within the EU: Current/OS Foundation and the Open DC Alliance (ODCA). These initiatives are privately organized and have developed technical specifications for DC installations. Companies, research institutes, and academia can join and participate.

2.1.3.1 Current/OS Foundation

Current/OS Foundation [3] is a non-profit, independent, and open partnership of manufacturers and electricity stakeholders registered in the Netherlands. The foundation counts 46 Partners at the end of June 2024. ABB, Eaton, Schneider Electric, Tridonic and UL Solutions are the board members of the Current/OS Foundation.

Current/OS Foundation provides an evolutive set of rules to ensure interoperability, safety, scalability, effectiveness, and trustfulness of DC Prosumer Electrical Installations (PEI) with distributed sources. These rules define all system aspects for loads, sources, and cables such as voltage levels, protection, earthing, corrosion mitigation etc. in a consistent manner.

These rules define all system's aspects for loads and sources such as voltage levels, protection, earthing, corrosion mitigation etc. in a consistent manner. Current/OS set of rules is open, by nature, to additions by different classifications of products for different use cases.

To ensure the availability of this set of rules to any product manufacturer, the Current/OS Foundation is aiming to ease massive adoption of safe and trustful DC multisource applications in all vertical levels and to avoid fragmentation and confusion on the emerging market.

Under fair, reasonable, and non-discriminatory terms (FRAND) the Current/OS set of electrical rules to the electrical ecosystem are provided with free right of use of IP and clear guidelines on how to manufacture products that work in a Current/OS based DC environment. It also aims to define and operate a certification scheme in respect of scope, competencies, and stakes of all market actors. (Sources and loads manufacturers, design offices and integrators, users, and services providers).

The Current/OS Foundation works to ensure safety and effectiveness of multi sources DC applications, identify the gaps in standards and work them out to reach consensus within contributively people and teams (experts, manufacturers, research institutions). The Current/OS Foundation is a liaison A member of the IEC SyC LVDC.

The Current/OS contribution to the energy transition

The DC installations compliant with Current/OS use the installation voltage as a power management indicator. This voltage can easily be measured at each equipment level and as such reacted accordingly.

The voltage in Current/OS compliant DC systems is not set by a central controller. The voltage is a consequence of the contribution of all sources (that behave like current sources) and the power demand of all loads in the system. All these devices have an embedded behavioural power consumption (or generation) rule to follow called the "droop curve". This droop curve is software defined and can be adjusted at any time.

This being distributed in all equipment, brings multiple advantages.

- **Flexibility:** Current/OS based DC systems have proven a reduction of the peak power demand to the public grid by 66% to 80% [4], [5]. This is a huge advantage when it comes to limiting network congestion. It can also bring massive savings to the grid expansion capacity investment. It can also help to connect more flexible buildings to the same infrastructure.
- **Failure resilience:** If one equipment experiences issues, it does not necessarily affect others, reducing the risk of outages.
- **Scalability:** With a distributed control system based on voltage, adding new equipment is simple, and the system naturally finds a new equilibrium. There's no need, as with a centralized automation system running parallel to the electrical system, to make it evolve in a coordinated way. This relieves a major obstacle experienced by integrators.

Current/OS rules offers the following features:

- **Multi-vendor interoperability:** it defines the applicable voltages and capacitors management at load levels, in order to ensure black start and capacitor pre-charge without protection tripping.
- **Multiple distribution topologies:** as point-to-point energy exchange is far too limited for most applications, the document defines the rules to have distributed sources and loads connected anywhere on the DC bus, multisource power availability and selectivity in case of a fault, and topologies to optimize the number, the size and length of the conductors.
- **Safety on DC distribution:** it defines rules for: protection against overcurrent (overload and short-circuit), protection against thermal effects and burns, protection against overvoltage, protection against arc faults, protection against electric shock and how to prevent corrosion that can damage the building structure in case of current leakage.
- **Easy control:** it defines how to set up a distributed control of power balance and avoid central control through communication and multiple current sensors.
- **Easy design:** it defines rules to simplify as much as possible DC prosumer installation design for any engineering consultant and to make expansions of DC prosumer installation easier in case additional capacity is needed, sources and loads additions are required.
- **Easy installation:** Current/OS rules enable easy installation of safe and reliable DC prosumer installation, provided Current/OS-certified products are used.

- **Easy maintenance:** it defines rules to ensure safe maintenance e.g., zoning concept simplifying risk analysis, simultaneous shut down of sources, Interoperability ensuring simple addition or replacement of sources or loads.

<u>**DC Voltages**</u>

In Current/OS the system voltage U_n can fluctuate within bands according to IEC TR 63282. Inside these bands, the voltage is used as a signal to communicate the power availability to the loads and the sources connected to the grid, to make them react accordingly.

For instance, the so-called 350 V DC "nominal" system will operate normally between 320 V DC and 380 V DC. 250 V DC to 320 V DC will be an emergency band, and 380 V DC to 540 V DC will be an overvoltage band. A representation of the voltage bands is presented in Figure 2-2.

The nominal system voltages U_n supported by Current/OS are 48 V DC, 175 V DC, 350 V DC and 700 V DC in unipolar systems, and 350 /700 V DC and 700 / 1400 V DC in bipolar systems.

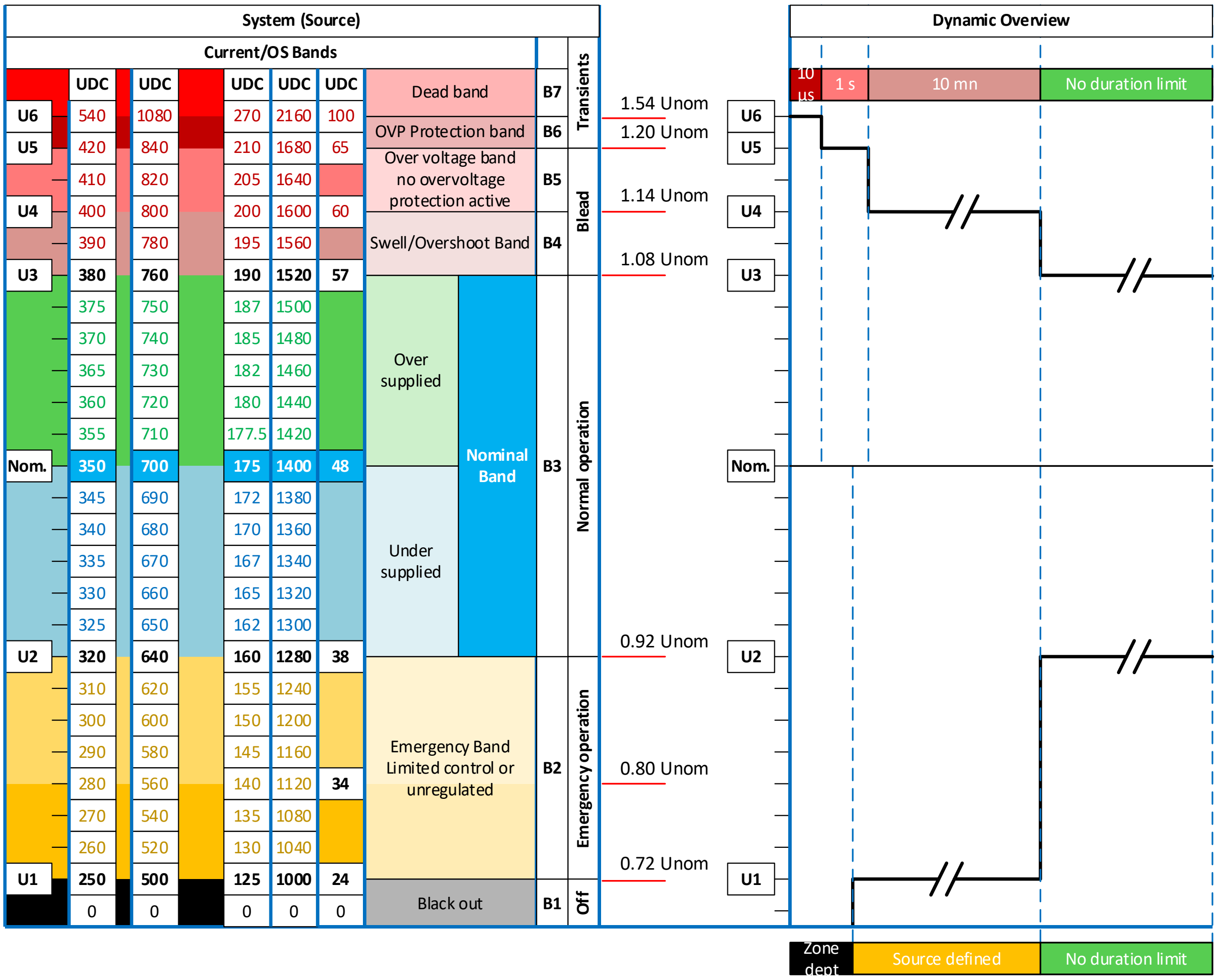

Figure 2-2: Current/OS Foundation DC voltage band

Voltage bands definition and behaviour

All are aligned with future IEC/TR 63282 Ed.2.

- **Nominal band (B3):** the Voltage range in which the system normally operates for unlimited time. Within this band the system operates under droop control.
- **Emergency Band (B2):** The system is in emergency state when the voltage drops below U_2 but not lower than U_1. In this state, the available power from the sources is barely sufficient to keep the system functional. Emergency loads such as emergency lighting can stay active. The system is unbalanced, and action is required. The time the system can stay in this state is limited and depends on the available sources (for example, if storage is part of the system, the system can remain in the emergency state, until the storage is depleted).
- **Blackout Band (B1):** When the voltage drops below U_1, the system is in blackout (or flickering) state. The system cannot operate regularly, and a black start is required to restore normal operation. Sources' undervoltage protection is enabled and flickering may occur.
- **Swell/Overshoot Band (B4):** is the band above the nominal band, where droop control lets the voltage go temporarily above U_3 due to sudden decrease of power consumption within the system. The droop control shall be able to bring the system back in the nominal band in 10 minutes by switching on loads or curtailing power sources. If this is not the case, then all devices must disconnect. All devices connected to the grid shall be fully operating for up to 10 minutes.
- **Overvoltage Band (B5):** When the system is in Over-voltage state (i.e., the voltage is between U_4 and U_5), actions shall be taken (e.g., by disconnecting sources or activating emergency loads in order to dump additional energy) to bring the system back in the nominal band within 1 s and prevent entering the over-voltage protection band (B6).
- **Overvoltage Protection Band (B6):** Finally, in the over-voltage protection band (B6) over-voltage protection devices are activated and the extra energy is dissipated in these devices. This is done to protect components within different devices in the system from excessive over-voltages that they cannot handle. At the end of this band, the over-voltage protections (OVPs) in the system conduct with their maximum capabilities.
- **Dead Band (B7):** The dead band is a prohibited voltage band since permanent equipment damage is very likely. All power sources shall be switched off.

DC Zoning System

To ease design and operation of DC installations, circuits or group of circuits are classified according to the available fault energy and the protection means in 6 DC Zones, labelled as "0", "1", "2.1", "2.2", "3" and "4", described in the following sections. Table 2-2 and Figure 2-3 recaps the main characteristics of the different zones. Different DC Zones are separated by means of current interrupting or current limiting devices, such as circuit breakers or converters.

Table 2-2: Current/OS Foundation DC Zoning System

DC Zone	Main characteristics of the circuits	Main consequences
DC Zone 0	• High short-circuits current source. • No overcurrent protection.	• High fault current • High incident energy in case of arc flash. • Circuits cannot be distributed but must be segregated in panels or in rooms with restricted access.
DC Zone 1	• Most sources have high prospective short-circuit current. • Overcurrent protection devices (OCPD) on the DC bus have breaking time < 50ms (e.g.: EMCBs and fuses). • Multiple sources, all connected to a common distribution board.	• High fault current • High incident energy in case of arc flash. • Circuits should not be distributed but segregated in panels or in spaces with restricted access. • Design cannot be replicated and easily upgraded.
DC Zone 2.1	• Sources cannot deliver a current significantly higher than its nominal current, by design. • OCPD with breaking time < 50ms (e.g.: EMCBs and fuses) on the DC bus. • Energy stored in capacitors is limited to 600 J. • Multiple sources connected to a single distribution board.	• Design of protection only by skilled engineers. • Designs difficult to be replicated and upgraded. • Arc-flash incident energy lower than in DC Zone 1 but requiring assessment. • Limited system availability as selectivity is generally not possible. • Limited design flexibility as sources cannot be distributed. • Suitable for installations with limited complexity.
DC Zone 2.2	• Multiple distributed sources. • Sources (or inductor) that limit the fault current rise and peak. • OCPD with breaking time < 1ms (e.g.: SCHCBs) on the DC bus.	• Capacitor discharge is limited. • Sources can be distributed. • Reduced arc-flash incident energy. • Selectivity is possible but difficult to design. • Designs are replicable, • Design upgrades require care. • Design by skilled design offices. • Suitable for complex installations (after design by skilled engineers). • Additional protection possible with RCD
DC Zone 3	• Multiple distributed sources. • OCPD with breaking time < 10 µs (e.g.: SSCBs) on the DC bus.	• Ultra-limited fault currents on the DC bus • Sources can be distributed. • Incident energy is always very small (<<1.2 cal/cm²). Assessment is typically non required. • Design is limited to nominal currents. Fault calculations is not needed. • Loop or mesh topologies are possible (and easy). • Additional protection possible with RCD

DC Zone	Main characteristics of the circuits	Main consequences
		• Mid-point earthing makes maintenance simpler. • Designs are replicable and upgradable. Calculation of fault energy and current are not needed. • Suitable for complex installations • design at nominal is sufficient, fault conditions design is not needed.
DC Zone 4	Same as DC Zone 3 with Single source	Same as DC Zone 3.

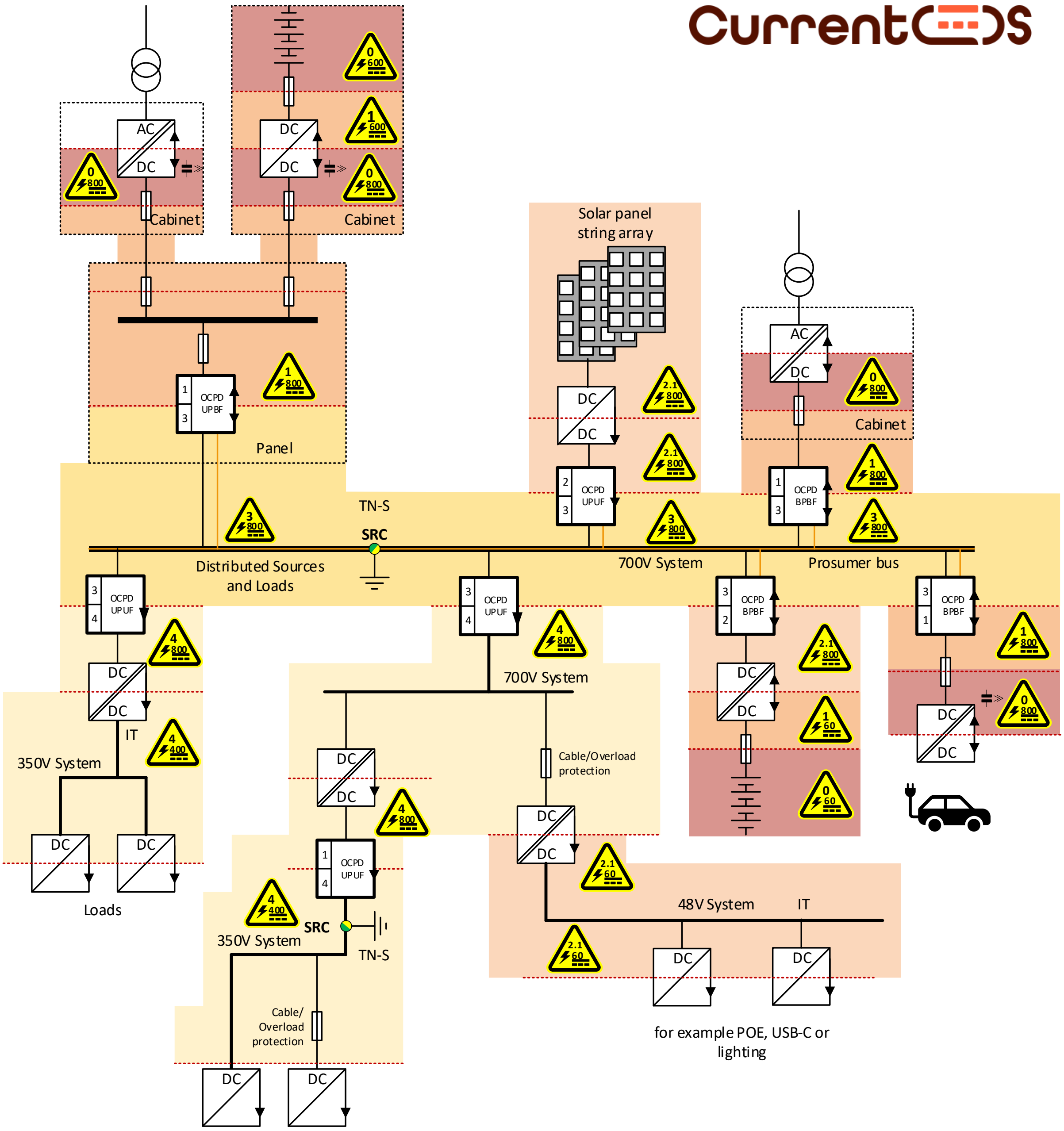

Figure 2-3: Current/OS Foundation DC Zoning System, Zone classification is given by yellow icon in each zone.

IEC 60364 standards apply to all DC Zones. Rules in this document are mainly intended for, but not limited to, DC Zones 2.2, 3 and 4.

Due to the high available fault energy, DC Zones 0 and 1 shall be not distributed in accessible spaces and segregated in restricted areas only accessible to skilled persons.

Current/OS recommends that only DC Zones 2.2, 3 and 4 are distributed, due to the lower fault energies and consequent risks. DC Zone 2.1 can be distributed with the limitations. Different DC Zones are connected by means of devices able to limit the flow of the fault energy from one DC Zone to the other. Different installation rules can apply in the different DC Zones.

System Startup

DC prosumer installations usually include equipment containing capacitors that draw a large in-rush current when powered-on. Without further measures these in-rush currents would trip the protection devices and cause voltage dips or interruptions in weak source applications. Thus, a predefined startup sequence is needed.

In Current/OS, system startup consists of three phases:

- Black start, to pre-charge the capacitance in the DC-bus;
- To pre-charge the stray capacitance of the connection cable between the DC-bus and the equipment;
- To pre-charge the internal capacitance of the equipment.

Startup is typically a hierarchical top-down procedure. A bottom-up procedure can be considered for islanded grids with energy storage in a subcircuit.

System Primary Control

Primary control, or droop control, is a local control loop on the power converters, regulating the current flow according to the voltage level sensed and a droop curve, with the goal of balancing the power input and output in the grid. Primary control has a characteristic time in the order of milliseconds and operates continuously adjusting the setpoint value of the primary control.

A voltage exceeding the middle-band or “nominal” voltage U_n indicates that the system is in “oversupply”. When in this condition, loads shall activate according to priority settings, power shall be stored in batteries, or in thermal storage systems (hot water, fridges and cold rooms, HVAC storage, etc.), or by generating hydrogen.

When voltage is below Un, the system is in “undersupply”. In this condition:

- Loads shall de-activate according to priority settings,
- Electrical storage shall feed power to the grid,
- Thermal storage shall be inactive.

The voltage-dependent behaviour of the equipment is defined by the droop curves below, with the power in the horizontal axis, and the voltage in the vertical axis.

Droop curves allow to effectively manage priority of loads and sources in complex DC systems. Let’s consider a system connected to the AC grid through a bidirectional Interlink converter and including PV generation, battery storage, an EV charger, and a plurality of loads. Figure 2-4 exhibits the droop curves for:

- PV generation (yellow curve),
- Interlink converter connection to the AC grid (red curve);
- Battery storage system (blue curve);
- EV charger (green curve).
- Small load (grey)
- Larger load with linear droop characteristic (orange)

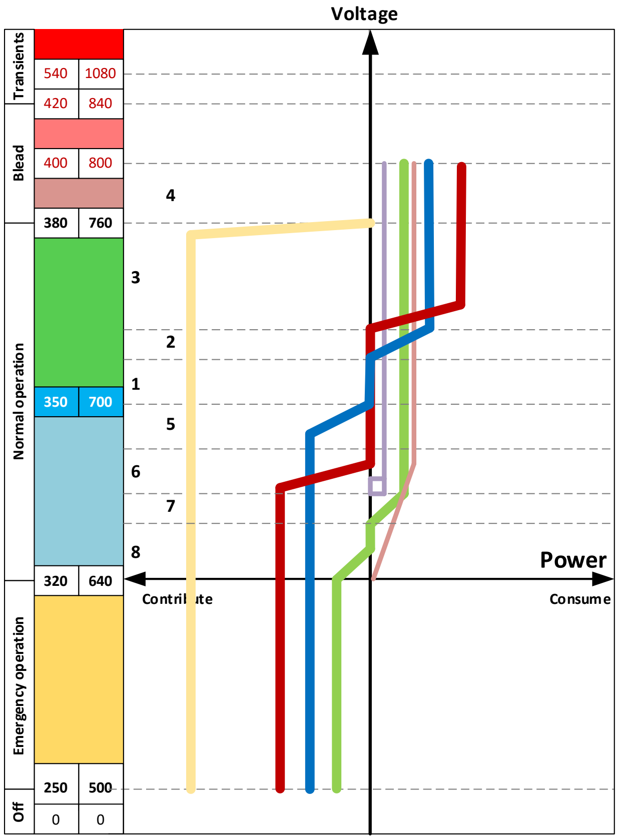

Figure 2-4: Current/OS Foundation DC droop curves

Different situations identified with numbers from 1 to 8 are considered:

1. The power from the PV systems allows to power the loads and to charge the EV. Storage system is not active. No power exchange with the AC grid;
2. The power from the PV systems exceeds the demand from the load and the EV charger. The excess power is used to charge the batteries. No power exchange with the AC grid;
3. Even larger excess power from the PV. Exceeding generation is stored in the batteries and fed back to the AC grid throught the Interlink converter.
4. The system is overpowered. The loads are all active and the EV is charging at nominal power. The storage system plus the export to the AC grid can not absorb the remaining power from the PV. PV production is reduced;
5. The power from the PV systems is not fully sufficient to power the loads and to charge the EV. Storage system contributes to power the system. No power echanges with the AC grid;
6. The power from the PV systems is not sufficient to power the loads and to charge the EV. Storage system contributes to power the system. In addition power is imported from the AC grid;

7. The PV systems production plus the contribution of the storage system plus the power imported from the AC grid is not sufficient to power the (remaining) loads and to charge the EV. EV charging power is reduced;
8. The power fed from the AC grid plus the contribution of the storage system plus the PV systems production is not sufficient to power the (remaining) loads. EV is required to contribute to the system.

Type of system earthing

IEC 60364 defines types of AC earthing system and DC earthing system including criteria for earthing resistance. This document gives some guidelines to select the proper type of system earthing for a hybrid AC and DC application, based on the earthing aspects related to safety for personnel, livestock, and property.

Figure 2-5 exhibits the possible types of connections between AC or DC systems and the consequence on earthing system. The focus of the document is on the DC side because the AC side is well explained in the IEC 60364 series. The Interlink converter needs to be defined in a proper way so that it respects both systems.

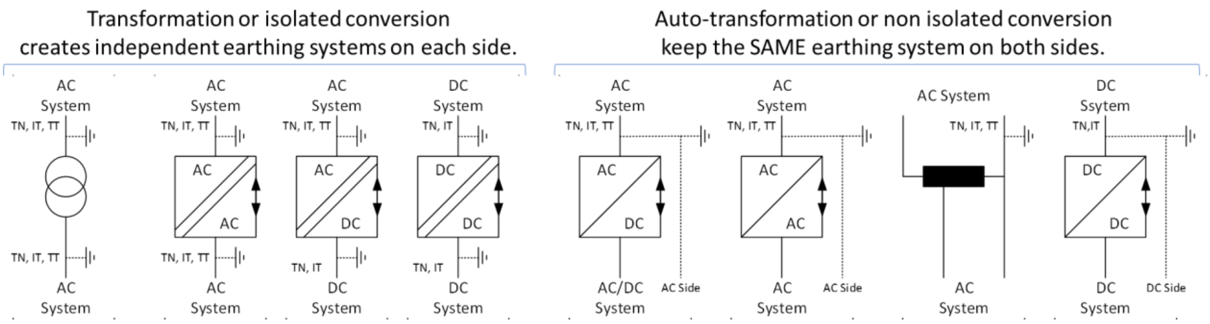

Figure 2-5: Current/OS Foundation Types of connections between AC or DC systems and the consequence on earthing system

TN-S Earthing System

A TN-S earthing system brings many advantages:

- It simplifies electronic protection. Common mode voltages are much reduced as well as hazardous voltage in live areas.
- It helps to improve EMC aspects since electronics inside equipment have the same potential as the enclosure.
- This prevents overvoltage in case of fault, in particular in bipolar systems.
- It is clearer for installers and reduces errors.

Figure 2-6 shows the earthing arrangement for unipolar and bipolar TN-S systems. The recommended type of system earthing system in Current/OS is TN-S according to IEC 60364-1. The mid-pole M shall be connected to earth. The DC grid shall be galvanically isolated from the AC grid.

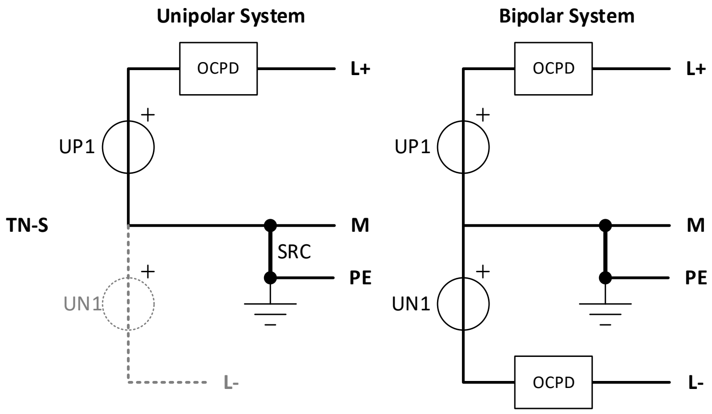

Figure 2-6: Current/OS Foundation DC TN-S earthing system

It is worth mentioning that other type of system earthing such as IT will be elaborated in a future edition of Current/OS System Reference Document.

2.1.3.2 Open Direct Current Alliance (ODCA)

The ODCA [6] is an initiative aimed at promoting the use of DC technology to support and implement the social goal of a resource-saving and CO_2-neutral world. It was founded by the ZVEI[1] along with companies from industry, academia, and research to propel the activities of DC grids forward and bring them to the market.

The ODCA is working towards building a worldwide direct current ecosystem and establishing direct current technology across various applications. The alliance follows on from the successful DC-INDUSTRIE2[2] research project and includes members such as Audi, Siemens, Schneider Electric, Eaton and many others. The use of DC technology offers several benefits, including efficient integration of renewable energy, lower resource consumption, reduced feed-in power, stable grids, and an open system for users.

The ODCA's efforts are significant in achieving climate policy goals, as direct current can contribute to overall energy savings, copper savings for cabling and wiring, and reduction of power-loss in cables. This technology is not only beneficial for the industrial sector but also offers high efficiency gains in the building and mobility sectors.

The system concept of DC-INDUSTRIE2 [5] is going to be used as a base for standardization. The DC-INDUSTRIE2 system concept is a pivotal resource that outlines the framework for an industrial DC grid. This grid has been meticulously developed and tested to ensure efficiency and reliability in the face of the increasing demand for sustainable and integrated manufacturing processes. The DC-INDUSTRIE2 project was supported by the German Federal Ministry for Economic Affairs and Climate Action.

The system concept outlined in the DC-INDUSTRIE2 project includes LVDC installations applicable to various sectors. The open electric power supply system championed by this concept is not only poised for rapid implementation but also stands out for its high energy efficiency. This system is particularly accommodating to renewable energy sources, facilitating their easy integration into existing

[1] https://www.zvei.org/en/
[2] https://odca.zvei.org/resources/publications/dc-industrie2-project-presentation

infrastructures. A typical DC-INDUSTRIE grid includes multiple DC sectors, power management for stability, bidirectional energy flows, and defined voltage ranges.

<u>Description of an Industrial DC Grid</u>

The "DC-INDUSTRIE2" system concept encapsulates the strategic framework for deploying an industrial DC grid, tailored to bolster the integration of renewable energy and elevate energy efficiency within industrial environments. The concept is grounded in the recognition of DC's escalating significance in industrial power consumption, particularly for electric motors and renewable power generation like solar and wind energy. The DC-INDUSTRIE projects are at the forefront of this transition, aiming to render industrial production more adaptable, intelligent, and energy-conserving.

The DC grid is conceived as an open, low-voltage system, scalable to suit a range of industrial facility sizes, and permits the incorporation of various power suppliers and consumers. It is structured to support bidirectional energy flows and operates within defined voltage ranges. The document delineates the grid's components, including Active Infeed Converters (AICs), Smart Breakers, and DC Sectors, which are clusters of DC devices managed as units. The grid management is integrated into a hierarchical control process within industrial production, encompassing energy management, source management, and power flow management. This ensures optimized power flows and increased utilization of locally generated power. The grid can adopt either a bus or ring structure, with the latter providing continued power supply even if an individual line is interrupted, underscoring the grid's resilience and reliability.

<u>Components of an Industrial DC Grid</u>

The "DC-INDUSTRIE2" system concept provides a comprehensive overview of the operational aspects and components of an industrial DC grid. It highlights the dual operational modes of the DC grid: firstly, the emission of heat into a district heating network, which showcases the grid's ability to contribute to heating solutions; and secondly, the feeding of excess power back into the grid, which demonstrates the grid's efficiency and sustainability. Energy storage systems are underscored for their critical role in maintaining the DC grid's voltage stability during AC power failures and in reducing load peaks, thus ensuring a reliable power supply.

The functions of smart breakers are also detailed, which are essential for the safe operation of the DC grid. These breakers provide reliable isolation in case of faults, facilitate maintenance operations, and have pre-charging capabilities to prepare the grid for smooth startups. Additionally, the research projects examined various insulation materials for DC cables, assessing their durability and performance under accelerated aging conditions. This is crucial for ensuring the longevity and safety of the grid's infrastructure. The serviceability of the AC grid is further discussed, particularly how Active Interface Converters (AICs) can enhance the AC grid by injecting reactive power and compensating for harmonics. Lastly, it outlines considerations for key components such as DC link capacitors and the inductance of supply cables, which are vital in distributed power generation systems, ensuring efficient energy transfer and grid stability.

<u>Voltage Values and Voltage Bands</u>

Regarding the voltage values and voltage bands, the DC-INDUSTRIE2 project serves as a comprehensive guide for the design and operation of an industrial DC grid, focusing on maintaining voltage stability, protecting components, and ensuring efficient energy distribution. It highlights the importance of managing voltage fluctuations and provides a clear set of guidelines for the safe operation of the grid. In more details:

- **Voltage Values and Bands:** The DC grid operates within a voltage range rather than at a fixed voltage, allowing for load flow control using characteristic-based regulation. Two nominal voltage bands are identified: 650 V and 540 V, which are based on the globally widespread AC grids and commonly used components.
- **Component Operating Ranges:** Components within the DC grid, such as active infeed converters (AICs), uncontrolled feeders, loads, and converters for storage or solar infeed, have specific operating ranges. Smart breakers provide protection within certain voltage bands and disconnect the DC sector if voltage exceeds or drops below set values.
- **Nominal Voltage:** The DC grid's nominal voltage is set to 650 V for regulated power supplies and unregulated power supplies of at least 480 V AC. For uncontrolled power supplies connected to a 400 V AC grid, the nominal voltage is 540 V.
- **Voltage Bands and Limit Values:** The document defines several voltage bands, from the blackout band (less than 400 V) to the forbidden band (damage to devices is very likely), and specifies the conditions under which devices should operate or disconnect to protect the grid and connected equipment.
- **Rate of Voltage Change:** The document discusses the impact of load changes on voltage and the potential for premature aging of components like electrolytic capacitors. It suggests that voltage swings should be limited to avoid negative impacts on the lifespan of these components.
- **Protection from Overcharging:** The DC grid is protected from overcharging through actions defined by grid management, such as reducing infeed, increasing consumption of controllable loads, and hardware-based protective measures like varistors and circuit breakers.

<u>**Types of system earthing**</u>

The DC-INDUSTRIE2 projects provides an in-depth analysis of system earthing for direct current (DC) systems, discussing various earthing methods and their implications for system configuration and voltage symmetrisation. Below are some key points:

- **Earthing Methods:** The project compares different earthing methods for DC systems, such as "earthing via the AC grid," "DC midpoint earthing," and "DC IT earthing." Each method has distinct impacts on the system's configuration and the symmetrisation of voltages.
- **Operation Under Different Earthing Conditions:** Procedures for the continued operation of DC systems under various earthing conditions are outlined. The importance of insulation resistance monitoring and protective device triggering is emphasized, along with the creation of temporary earthing solutions like midpoint replicas during isolated operation.
- **Interconnection of Earthing Electrodes:** The project highlights the need for interconnecting earthing electrodes in distributed DC systems to ensure proper voltage stress management.
- **Voltage Stress Management:** Managing voltage stress on components, especially motors, is a critical aspect discussed in the document, ensuring the longevity and reliability of the DC system.

<u>**Pre-charging and Discharging the DC grid and its components**</u>

The DC-INDUSTRIE2 projects provides a comprehensive set of guidelines and technical specifications for managing the pre-charging and discharging processes within a DC grid, emphasizing the importance of controlled voltage and current levels to maintain grid stability and component safety. It serves as a critical resource for engineers and technicians working with DC grids in industrial settings. In more details:

- **Pre-Charging the DC Grid:** The DC-INDUSTRIE2 projects outlines the sequential pre-charging process across different levels of the DC grid to limit inrush currents and prevent triggering protective devices. This involves Smart Breakers and monitoring voltage at various points.
- **Voltage Thresholds and Timing:** Specific voltage thresholds and timing for pre-charging are suggested, such as a lower voltage threshold of 520 V to initiate pre-charging and a differential voltage of 15 V at the end of pre-charging. The timing sequence includes a waiting time of 5 seconds before starting pre-charging and a maximum duration of 4 seconds for the pre-charging process.
- **Pre-Charging Current Limitation:** The project discusses limiting the pre-charging current through a resistor, with a relative charging current defined based on the rated current. It also addresses the impact of consumers drawing power during pre-charging and how to manage the stationary voltage difference that results.
- **Connecting Additional Power Infeed Devices:** It details the steps to connect additional power infeed devices to the DC grid, ensuring voltage matching and limiting charging currents to prevent damage or overcurrent conditions.
- **Discharging the DC Grid:** Discharging procedures are described to ensure safety when the grid or components need to be powered down. The project report specifies that the maximum voltage across devices should drop below 60 V within five seconds after disconnection, with a maximum discharge time of five minutes.
- **Implementing Pre-Charging:** Various methods for implementing pre-charging in Smart Breakers are presented, including using resistors, buck converters, and Insulated-Gate Bipolar Transistor (IGBTs) with chokes.
- **Pre-Charging Topologies:** Different topology versions for pre-charging in a DC sector are distinguished, each with its own method of triggering and managing the pre-charging process.

<u>**Grid Control and stability**</u>

Grid control and stability in DC-INDUSTRIE grids are maintained by managing power flow at various levels, which can range from simple DC grids with uncontrolled rectifiers to complex grids with multiple AICs, power generators, and energy storage units. The control is achieved through hierarchical power flow management, including source and energy management that adjust droop curves based on local values like voltage and current, state of charge of energy storage systems, external parameters, and power costs. Additionally, the stability is ensured by having sufficiently large capacitances in grid components to dampen resonance points and prevent critical resonance currents.

The different stages of power flow management in a DC grid are as follows:

1. **Basic Configuration**: Completely decentralized management without central coordination or droop curves, where each device applies its own control strategy.
2. **Decentral Group Control**: Decentralized management with droop curves but no communication between devices.
3. **Extended Group Control**: Decentralized management with droop curves and communication between devices.
4. **Central Grid Control**: Values are assigned to all active components by a central grid manager for coordinated control.

Electromagnetic Compatibility (EMC) and AC components in a DC Grid

Within the scope of DC-INDUSTRIE2 project, the topic of EMC and the presence of AC components in a DC grid are of critical significance. Ensuring compliance with EMC standards is crucial to avoid electromagnetic disturbances that could affect system stability.

In the realm of DC grids, the absence of standardized limit values and testing regulations for emissions presents a significant challenge. This lack of standardization can lead to inconsistencies and potential inefficiencies in the implementation and operation of DC systems. Furthermore, the use of pulse width modulation is known to generate pulsed currents that contain spectral components, which can affect the performance and reliability of these systems. Electrolytic capacitors play a pivotal role in the stability of DC systems, as they are required to endure the stress of AC voltage components. Ensuring the longevity and effectiveness of these capacitors is essential for the smooth functioning of DC grids.

Additionally, high-frequency leakage currents, which can arise within these systems, necessitate a low-impedance path for their return to avoid disruptions. Lastly, the symmetrical design of filter elements and components is of utmost importance. Such a design is instrumental in diminishing interference within the DC grid, thereby enhancing its overall efficiency and reducing the likelihood of operational disturbances. Together, these insights underscore the need for careful consideration of technical specifications and design principles in the development and regulation of DC grids.

Protection and Safety

The DC-INDUSTRIE2 project is at the forefront of advancing safety measures within industrial DC grids. The project underscores the critical role of fast-acting protective devices to mitigate the adverse effects of short circuits and ground faults. These incidents can cause significant damage to the infrastructure, hence the necessity for immediate response mechanisms.

Protective Devices and Fault Management

To safeguard the integrity of DC grids, the deployment of hybrid breakers, semiconductor circuit breakers, and DC fuses is paramount. These components are engineered to respond swiftly and effectively, curtailing the progression of electrical faults. Hybrid breakers, in particular, combine the rapid response of solid-state devices with the physical disconnection capabilities of mechanical switches, offering a robust solution for fault management.

Selectivity and Shock Prevention

The concept of selectivity plays a vital role in fault isolation within the grid. It ensures that only the affected segment is disconnected, maintaining the overall continuity of the grid. Additionally, protection against electric shocks is a key consideration, necessitating measures that shield personnel from potential hazards associated with DC systems.

Overvoltage and Corrosion Control

Overvoltage protection is another crucial aspect of DC grid safety. It involves the implementation of devices designed to limit voltage spikes, thereby protecting sensitive equipment. Moreover, the project addresses the need to counteract corrosion caused by stray currents, which can lead to the deterioration of metallic components.

Behavioral Analysis During Faults

A deep understanding of the behavior of DC grids during faults is essential for the development of effective protective measures. This knowledge enables the design of systems that not only prevent damage but also ensure the safe and reliable operation of the grid. The DC-INDUSTRIE2 project emphasizes the importance of even power distribution to avert overloads and the implementation of comprehensive safety protocols.

In conclusion, the DC-INDUSTRIE2 project highlights the importance of a multi-faceted approach to safety in industrial DC grids. By focusing on fast-acting protective devices, selectivity in fault isolation, shock prevention, overvoltage protection, and corrosion control, the project lays the groundwork for a secure and efficient DC power infrastructure.

2.1.3.3 EU Projects focussing on standardization

The EU has funded several projects related to DC systems encompassing areas such as DC railroads, HVDC distribution networks, offshore wind farms, and power electronics for DC applications however only a few contributed to the standardization of DC implementations. Furthermore only a few tackle the standardization of LVDC grids. Among the various projects, the following specifically focus on the standardization and regulatory framework of DC systems:

- **DC-POWER (Direct Current – Power flows in megawatt-scale Energy Grids)[3]**

The DC-POWER project (see Table 2-3) aims to modernize the electric energy distribution grid by addressing the limitations of the traditional AC-based system. It proposes using a medium voltage DC (MVDC) distribution system called the D3 Bus, which operates at ±1.5 kV. This new system promises to reduce energy losses by over 90%, decrease downtime, lower equipment costs, and save space, while also increasing sustainability. The project includes two pilot demonstrations: one powering an industrial-scale hydrogen electrolyser and another powering a data centre, both supported by solar PV arrays. DC-POWER develops necessary components like DC-DC converters and system protection to validate the D3 Bus, aiming to set the groundwork for standardizing MVDC microgrids, accelerating the adaptation of these types of electricity distribution systems for future energy needs and achieving net-zero targets.

Table 2-3: DC-POWER project information

Start date	1 January 2024
End date	31 December 2027
Funded under	Climate, Energy and Mobility
Total Cost	€ 8 714 871,00
EU contribution	€ 7 136 536,50
Coordinated by	COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES

- **READY4DC (Getting ready for multi-vendor and multi-terminal DC technology)[4]**

The READY4DC project (see Table 2-4), supported by Horizon Europe, focuses on standardizing HVDC technology to enhance the power grid's efficiency and flexibility. By addressing interoperability challenges, particularly in multi-vendor networks, READY4DC aims to facilitate the integration of renewable energy sources like offshore wind. The project established a community of experts and four open-participation working groups to discuss technical and legal implications, producing white papers to build consensus and influence regulatory changes. The ultimate goal of READY4DC project was to develop the first multi-terminal, multi-vendor HVDC grid in Europe, impacting all applications of power electronics-driven grids and paving the way for a future where DC technology is central at every voltage level.

[3] https://www.dcpower.tech/
[4] https://ready4dc.eu/

Table 2-4: READY4DC project information

Start date	1 April 2022
End date	30 November 2023
Funded under	Climate, Energy and Mobility
Total Cost	€ 999 812,50
EU contribution	€ 999 812,50
Coordinated by	RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN

- **DC4EU (DC for European Union)[5]**

The DC4EU project (see Table 2-5), funded by the Horizon Europe Framework Programme, aims to standardize HVDC and DC technologies to help achieve the EU's 2050 climate targets. It supports the European Strategic Energy Technology (SET) Plan Implementation Working Group on HVDC and DC technologies (DC IWG) by engaging stakeholders to create awareness about HVDC and DC technologies, their importance, and regulatory evolution needs. The project aims to: update the implementation plan for HVDC and DC technologies, coordinate national and European research activities, and communicate research and innovation needs of DC technologies to a broad audience. By doing so, DC4EU promotes the wider adoption of HVDC and DC technologies and advances towards climate neutrality.

Table 2-5: DC4EU project information

Start date	1 November 2023
End date	31 October 2026
Funded under	Climate, Energy and Mobility
Total Cost	€ 599 987,80
EU contribution	€ 599 987,80
Coordinated by	KATHOLIEKE UNIVERSITEIT LEUVEN

- **PROMOTioN (Progress on Meshed HVDC Offshore Transmission Networks)[6]**

The Horizon2020 project PROMOTioN (see Table 2-6) tackled the challenges in developing a meshed offshore HVDC transmission network in the North Sea. The project established interoperability between different technologies and concepts by providing technical and operational requirements and standardization methods for HVDC network control, protection, circuit breakers, and gas-insulated substations. It defined common functional requirements for multi-terminal HVDC systems and Offshore Wind Farms (OWFs), researched and compared the performance and interoperability of HVDC network topologies, and developed guidelines and recommendations for technology selection, compatibility, and interoperability on regulatory, technical, and contractual levels. PROMOTioN also developed and validated cost-effective HVDC protection technologies and new types of offshore converters and controllers for wind power integration. It demonstrated different key technologies for meshed HVDC offshore networks, increasing their technology readiness level, and developed a new EU regulatory framework to enhance the economic viability of meshed HVDC projects.

[5] https://itcc.ieee.org/partners/dc4eu-horizon-europe/
[6] https://www.promotion-offshore.net/

Table 2-6: PROMOTioN project information

Start date	1 January 2016
End date	30 September 2020
Funded under	SOCIETAL CHALLENGES - Secure, clean and efficient energy
Total Cost	€ 42 691 662,81
EU contribution	€ 34 480 931,60
Coordinated by	DNV NETHERLANDS BV

- **InterOPERA (Enabling interoperability of multi-vendor HVDC grids)[7]**

The EU-funded Horizon Europe project InterOPERA (see Table 2-7) focuses on defining technical frameworks and standards for electricity transmission, to ensure interoperability between HVDC systems and HVDC components from different suppliers. This project seeks to make future HVDC systems compatible by design, improve grid-forming capabilities, and pave the way for multi-terminal, multi-vendor HVDC projects to integrating renewable energy and accelerating Europe's energy transition. InterOPERA will also provide solutions for multi-vendor project procurement, aligned with current and future regulations and standards, and involve external stakeholders in consultation workshops to enhance the uptake of its results. Recommendations for grid codes and standards will be issued to facilitate the transition.

Table 2-7: InterOPERA project information

Start date	1 January 2023
End date	30 April 2027
Funded under	Climate, Energy and Mobility
Total Cost	€ 69 618 021,38
EU contribution	€ 50 720 449,35
Coordinated by	SUPERGRID INSTITUTE

- **HYPERRIDE (Hybrid Provision of Energy based on Reliability and Resiliency by Integration of Dc Equipment)[8]**

The HYPERRIDE project (see Table 2-8) focuses on implementing DC and hybrid AC and DC grids. It starts by identifying key applications for DC grids, such as local microgrids and congestion relief, and specifies enabling technologies in detail. The project develops grid planning and operation guidelines, optimizes investments with adapted sizing tools, and advances MVDC breakers for grid protection. DC sensors are further developed to enable grid automation, and automation algorithms are validated and demonstrated. The project also addresses cyber security and fault detection, creating solutions to prevent cascading effects and databases for fault prevention. Demonstrations in Germany, Switzerland, and Italy will showcase these technologies and evaluate their benefits, particularly in integrating renewables and electric vehicle charging. HYPERRIDE aims to overcome barriers to new infrastructure concepts in Europe and encourages manufacturers to engage in product development and standardization efforts.

[7] https://interopera.eu/
[8] https://hyperride.eu/

Table 2-8: HYPERRIDE project information

Start date	1 October 2020
End date	31 March 2025
Funded under	SOCIETAL CHALLENGES - Secure, clean and efficient energy
Total Cost	€ 8 233 501,25
EU contribution	€ 6 965 520,50
Coordinated by	AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH

- **DCNextEve (LVDC microgrids for evolved energy communities)[9]**

The DCNextEve (see Table 2-9) main research objectives include developing a comprehensive framework for the design, modelling, and control of clusters of LVDC microgrids, creating and validating models for their typical elements, and optimizing their operation under uncertainty. Additionally, the project aims to implement and test distributed control schemes for these microgrid clusters thus improving the integration of renewable energy sources. Key performance indicators for power quality in LVDC grids were defined and evaluated, with results shared with the IEC's Power Quality Measurement Methods Working Group, contributing to ongoing standardization efforts. This project supports the transition to a smarter, more resilient power grid, benefiting both consumers and prosumers.

Table 2-9: DCNextEve project information

Start date	1 July 2016
End date	15 October 2018
Funded under	EXCELLENT SCIENCE - Marie Skłodowska-Curie Actions
Total Cost	€ 137 422,80
EU contribution	€ 137 422,80
Coordinated by	UNIVERSITATEA POLITEHNICA DIN BUCURESTI

- **FUNDRES (Future Unified DC Railway Electrification System)[10]**

The Shift2Rail funded project FUNDRES (Table 2-10) aims to define a unified DC railway electrification system, focusing on transitioning from 1.5 kVDC or 3 kVDC to 9 kVDC, and implementing the Flexible DC Transmission System to interconnect new DC lines with AC lines using power electronics. It also analyses the integration of a common DC link as an energy hub to collect and distribute electricity from various sources. The project will develop modelling tools and Digital Twins for scenario simulation and performance evaluation. FUNDRES will provide recommendations for the unified DC railway power supply to relevant advisory groups and standardization committees.

[9] https://www.openenergyprojects.ro/
[10] https://fundres-project.eu/

Table 2-10: FUNDRES project information

Start date	1 December 2019
End date	30 November 2021
Funded under	SOCIETAL CHALLENGES - Smart, Green And Integrated Transport
Total Cost	€ 749 540,00
EU contribution	€ 749 540,00
Coordinated by	INSTITUT NATIONAL POLYTECHNIQUE DE TOULOUSE

- **EISMEA LVDC**

The European Commission, via the European Innovation Council and SMEs Executive Agency (EISMEA), finances projects to boost the development and pre-standardisation of innovative subjects in support of the Single Market Programme.
In this context, AFNOR, in collaboration with its partners, is leading a project named Standards4LVDC (see Table 2-11) on the theme of low-voltage direct current. The main aim of this project is to map the existing work on LVDC, which provides a clear overview of the current situation in LVDC standardization, identifying gaps and needs. Additionally, the project exchanges around a proposed scope for a future CENELEC technical body on LVDC, proposing further steps and activities and a preparation of revisions of European standardization deliverables, which support the European Union legislation and policies.

Table 2-11: EISMEA LVDC project information

Start date	1 January 2024
End date	30 December 2024
Funded under	EISMEA agency
Coordinated by	AFNOR (France)

2.2 National regulations – Shift2DC partner countries

Although IEC standards are valid across the EU and are accordingly applied, there are always national specifics or peculiarities, sometimes in conjunction with national legislation. This means that systems are not always directly transferrable when crossing national borders. At the same time, some larger EU member states have their own standardization groups that add additional standards at the national level. For all EU member states represented in the Shift2DC project, these national peculiarities are elaborated and listed, or it is noted if there are no peculiarities and solely IEC standards have to be followed.

To extend the understanding, it is important to recognize that these national variations can affect the implementation and compliance of direct current systems within different EU countries. The Shift2DC project aims to identify and document these variations to facilitate a smoother integration of IEC standards and enhance the interoperability of electrical systems across European borders. This endeavour not only helps in aligning with international norms but also addresses specific local requirements that might otherwise hinder the deployment of standardized technologies.

2.2.1 Germany

German standardization bodies such as DIN, DKE, and VDE generally align with international standards, but they often incorporate national specifics, particularly those dictated by German calibration law (Eichrecht), and they have defined sets of rules and templates for interpreting those international standards. This approach ensures that international guidelines are adapted to suit local requirements and conditions, which can sometimes lead to variations in implementation.

At present, there are no grid codes specifically for DC distribution grids. The existing standards for grid connections are solely focused on AC systems, such as VDE AR4105 and VDE AR4100. These standards provide comprehensive guidelines for the safe and efficient connection of systems to the AC grid.

For the installation of local systems that connect to the AC grid but use DC only locally, the VDE 0100 standard can be applied. This standard is applicable for AC up to 1000 V and DC up to 1500 V, covering standard safety aspects. However, it is worth noting that VDE 0100 has been primarily written with AC systems in mind, which leads to several questionable aspects when applied to DC systems:

- There is an ongoing discussion about reducing turn-off times for higher DC voltages (above 400 V) for the safety measure "automatic turn-off." This discussion stems from the fact that IEC 60479-1 recommends significantly shorter body current durations than VDE 0100-410 currently stipulates.
- The method for measuring fault circuit impedance according to VDE 0100-600 remains unclear, as there are no valid measurement devices available for this purpose.
- There is no standardized method for calculating short circuit protection for DC grids.
- Currently, there is no DC-PEI (Prosumer Electrical Installation), but this will be addressed with Amendment 1 of 60364-8-82.

Furthermore, there is no valid template or set of rules available for insurances and technical inspectors concerning DC grids. The inspection and approval of these systems are heavily dependent on the individual inspector, indicating a need for a uniform methodology.

The German calibration law (Eichrecht) and appropriate meters are not available for DC grids; they are only applicable for DC charging applications. This gap highlights the necessity for further development in this area to ensure accurate and standardized measurements.

To address some of these issues, VDE SPEC 90024 V1.0, "Overview for Installation of DC Low Voltage Systems," is currently under development. This new specification aims to cover several of the aforementioned aspects, providing clearer guidelines and standards for the installation of DC low voltage systems.

2.2.2 France

In France, the institution responsible for the standardization domain is called AFNOR (Association Française de Normalisation). Most French standards are a mirror of IEC standards or follow other international definitions.

French standardization body, AFNOR, follows international standards, but oftentimes with national specifics and defined sets of rules and templates interpreting those international standards.

NF C 15-100 for private distribution:

- NFC 15-100 can be used for installation of local systems, that are connected to the AC grid and utilize DC only locally.

This standard is valid for AC up to 1000 V and DC up to 1500 V and covers standard safety aspects. Yet this standard has been written with AC in mind and is completed by significant number of application guides naturally more developed in AC than in DC, for instance:

- Determination of cross-sectional area of conductors and selection of protective devices practical methods UTE C 15-105
- Determination of the cross-sectional area of conductors and selection of protective devices with calculation software FD C 15-500 (No standardized way for calculation short circuit current for DC grids)
- Connection of electric generators in installations supplied by a public distribution network: UTE C 15-400
- Protection of low-voltage electrical installations against over voltages due to atmospheric discharges and switching Selection and erection of surge protective devices: UTE C 15-443.

Few guides have been published regarding PV and storage but dealing more with AC connection than with DC distribution, for instance:

- Photovoltaic installations without storage and connected to the public distribution network: UTE C 15-712-1
- Photovoltaic installations with energy storage and connected to a public distribution network XP C 15-712-3

Only one document is dedicated to pure DC islanded installation:

- Standalone photovoltaic installations not connected to the public distribution network with battery storage: UTE C 15-712-2

NF C 14-100

- Regarding connexion between the network and the use point, there is the NFC 14 100. This standard defines rules to connect the network to the use point in Low Voltage. Firmly used by DSO Enedis. As previously, the U14 drive the maintenance of this standard.
- Currently grid codes don't exist for DC Distribution grids.

It is possible to conclude that, for the time being, there are no specific standards in the LVDC domain, either for distribution, electrical installations, equipment, or grid codes, since LVDC grids are not yet implemented.

Regarding private electrical installations, the NF C 15-100 standard can be used up to 1500 V, it specifies requirements for unipolar and bipolar distribution systems regarding earthing. It also has some recommendations regarding automatic disconnection time in terms of pole to earth faults and other protection measures to avoid electric shock. However, there are still multiple subjects either not covered by this standard or that need to be modified:

- No definition exists on how to calculate short-circuit currents in LVDC.
- Protection coordination and selectivity concepts are not defined yet.
- Specific earthing and electric shock protection recommendations are also needed.
- The placement of metering devices and specific regulations are absent.

The commission U15 is in charge to maintain this standard. The inputs for their works can be different TCs in the IEC, CENELEC and others.

2.2.3 Portugal

The national standardization body of Portugal is the IPQ - Instituto Português da Qualidade - Portuguese Institute for Quality. The NP (Portuguese standards) are mostly based on IEC or other international standards.

In Portugal, neither DC distribution nor transmission grids have been implemented. However, in the new version of the Portuguese grid distribution regulations, which is currently under revision, will include the requisites for the implementation of HVDCs in Portugal in conformance with the European Union (EU) regulation 2016/1477.

Regarding DC electrical installations, the following national standard must be followed:

- **Low Voltage Electrical Installations Technical Regulations (Portaria 949-A/2006):** This regulation, published by the Portuguese Decree-Law nº226/2005 that establishes the technical and safety conditions for the execution and operation of low voltage electrical installations up to 1000 V AC and 1500 V DC. Although it is more focused on AC systems, some parts may apply to DC installations.

2.2.4 Spain

In Spain, specific standards and specific technical regulations by the IEC are adopted and adapted. The organization responsible for this task is UNE (Spanish Association for Standardization)

On the other hand, the agency responsible for regulating the standards generated by UNE within the electrical framework is the Ministry for the Ecologica Transition and the Demographic Challenge (MITECO), through the Directorate General for Energy Policy and Mines. This Ministry is also responsible for the planning, development and supervision of energy policies. To carry out its work, it relies on other institutions such as the Institute for the Diversification and Saving of Energy (IDAE), especially when analyzing policies related to energy efficiency and renewable energy.

Additionally, Spain also has the National Markets and Competition Commission (CNMC), which is responsible for the supervision and control of energy markets to ensure their proper functioning and competition.

In conclusion, the documents published by UNE, MITECO or CNMC should be consulted regarding regulations related to the electrical system or LVDC systems in particular.

As an example of regulation, there is the Low Voltage Electrotechnical Regulation and supplementary technical instructions (REBT e ITC). Currently, this regulation is under review to adapt to DC installations and to add a new ITC-53 specifically for DC systems installations that are part of a consumer´s installation or a generator connected to the distribution network or the consumer´s internal installation.

Regarding HVDC, the current document to refer is Order TED/749/2020, dated July 16, published in the BOE on August 1, 2020, which establishes the technical requirements for network connection necessary for the implementation of the network connection codes. It mentions as its scope of application high-voltage direct current systems and electrical park modules connected in direct current included within the scope of Regulation (EU) 2016/1447, date August 26, 2016.

For example, the company which controls the electricity transmission network in Spain, REE, bases its own operating procedure “P.O. 12.4” on this regulation. This document is the first that must be complied with in Spain when making a new connection to the electricity transmission system.

2.2.5 Estonia

The Estonian Centre for Standardisation and Accreditation (“Eesti Standardimis- ja Akrediteerimiskeskus MTÜ,” or EVS) is a non-profit association officially recognized by the Government of Estonia as the national standards body. Founded on January 14, 2000, by the Estonian Ministry of Economic Affairs and Communication, the Estonian Chamber of Commerce and Industry, and the Confederation of Estonian Employers and Industry, the EVS plays a pivotal role in Estonia's standardization. An agreement detailing the mutual rights and obligations in organizing standardization activities was concluded between the Government of Estonia and the EVS on April 24, 2000. Standardization in Estonia is regulated by the "Technical Regulations and Standards Act."

Estonian Centre for Standardisation and Accreditation is:

- Full member European Committee for Electrotechnical Standardization CENELEC
- Associate member of the International Electrotechnical Commission IEC
- Full member of the European Committee for Standardization CEN
- Full member of the International Standardization Organization ISO

Employees of the Estonian Centre for Standardization and Accreditation represent Estonian standardisation in CEN Technical Board, CENELEC Technical Board, and CEN-CENELEC Joint Commercial Activities Group.

Currently, Estonia is not part of the key activities on the LVDC ongoing in the IEC, like System Committee on LVDC and subcommittee 121A on Low-voltage switchgear and controlgear. Nonetheless, being the full member of the CENELEC, Estonia automatically adopts all European standards released, including those identical to IEC standards (designated as EN IEC 6XXXX), those based on IEC standards (designated as EN 6XXXX), and those not related to IEC (designated as EN 5XXXX). Also, some standards are being accommodated when local legislation is changed to harmonize them with recently approved European Commission Directives.

The European standards accommodated in Estonia are published at evs.ee website with “EVS-EN” designator.

2.2.6 Netherlands

Royal Netherlands Standardization Institute (NEN) has published the NPR9090 DC installations for low voltage in 2018 with an update in 2022. NPR 9090 is applicable to the design and installation of DC installations for low voltage (up to 1500 V DC) related to the scope of NEN 1010. Combined AC and DC installations are also included in the scope of this NPR as long as galvanic isolation is applied between the AC and DC parts.

NPR9090:2018 Detailed English Scope: (English translation of 2022 is expected in the coming months) This NPR applies to designing and installing DC installations for low voltage (LVDC, to 1 500 V DC) which belong to the scope of NEN 1010. Combined AC and DC installations are also covered by the scope of this NPR, provided that single isolation has been applied between the AC and DC parts of the installations. This means that PV installations with inverters, but without single isolation, are not covered by the scope of this NPR.

This NPR deals with the following focus areas:

- Electrical safety of the installation in relation to people, livestock, and possessions.
- Preventing the occurrence of fire.

- Maintaining the constructional safety of the environment where the installation is located (for example avoiding corrosion problems).

This NPR is a further explanation of NEN 1010:2015 regarding some aspects that play a special role with DC installations. It should be used in conjunction with NEN 1010.

2.2.7 Austria

In Austria, DC installations are covered by standards applied to general electrical distribution, equipment, and systems design:

- ÖVE/ÖNORM E 8001 – older group of standards defining requirements for Low Voltage Installations (up to 1000V AC and 1500 V DC)
- OVE E 8101:2019-01-01 + OVE E 8101/AC1:2020-05-01– guidelines for Low Voltage Installations design (up to 1000V AC and 1500 V DC), in near future it will completely replace previously mentioned ÖVE/ÖNORM E 8001
- Directive 2014/35/EU: Low Voltage Directive: This EU directive sets requirements for electrical equipment operating with a voltage between 50 and 1000 V AC or between 75 and 1500 V DC.

Although the old standards were basically intended for AC, they still cover DC systems as the protection against overcurrent, electric shock, overvoltage, etc. basically the same. However, there many undefined aspects for practical DC installation.

2.2.8 Czech Republic

The Czech Republic does not have dedicated standard for electrical distribution and grid code in DC systems. But DC installation is described in general standards related to the electrical installation in general and particularly in PV installation. The most relevant standards are:

- Directive 2014/35/EU: Low Voltage Directive: This EU directive sets requirements for electrical equipment operating with a voltage between 50 and 1000 V AC or between 75 and 1500 V DC.
- ČSN EN 61140 ED.3 Protection against electric current shock – Common aspects for installation and equipment. This standard is based on EU and IEC standards with the same number EN 61140, IEC 61140.
- ČSN 33 2000-7-712 ED.2 Low voltage electrical installations - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) systems. This standard is based on international standard IEC 60364-7-712.

There are other general standards which can be applied for DC installation and equipment integration: Directive 2014/30/EU - EMC Directive, ČSN EN 61140 ED.3/IEC 61140 - Protection against electric shock, ČSN EN 62305 - Protection against lightning, ČSN EN 50119 – electric traction overhead contact lines.

2.2.9 Hungary

In Hungary, three of the IEC’s previously detailed standards have been implemented. These are:

- **MSZ EN IEC 61936-2:2024:** Power installations exceeding 1 kV AC and 1,5 kV DC. Part 2: DC.
- **MSZ EN 300 132-3:2023:** Environmental Engineering (EE). Power supply interface at the input of Information and Communication Technology (ICT) equipment. Part 3: Up to 400 V Direct Current (DC).

Outside of these, the following standards that contain directives for DC usage have also been adapted in Hungary:

- **MSZ EN 50470-4:2024:** Electricity metering equipment. Part 4: Particular requirements. Static meters for DC active energy (class indexes A, B and C).
- **MSZ EN IEC 63027:2023:** Photovoltaic power systems. DC arc detection and interruption (IEC 63027:2023).

Other partially relevant standards in Hungary are presented in Table 2-12:

Table 2-12: Relevant standards in Hungary

IEC TS 61200-102:2020	Electrical installation guide - Part 102: Application guidelines for low-voltage direct current electrical installations not intended to be connected to a public distribution network
IEC TS 62735-1:2015	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	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
IEC 63318:2022	Specifications for SELV DC systems conforming to the ESMAP multi-tier framework tier 2 and tier 3 requirements for household electricity supply

Other than that, as several IEC standards and directives are under development, it is expected that Hungary will implement them following CENELEC adaptation, as European Standards are mandatorily adapted in Hungary. International regulations not specifically adapted by CENELEC may be implemented if the MSZT (Hungarian Standards Board) deems them particularly relevant, but we do not know of any such plans in the near future.

2.2.10 Switzerland

In Switzerland, DC grids are not yet used. They are still in research and development phase.

Electrical equipment with a nominal voltage between 75 V and 1500 V DC are regulated by the Federal Ordinance on Low-Voltage Installations SR734.27 of 2015. It is based on the Low Voltage Directive 2014/35/EU4 of the European Parliament and Council of 2014.

2.3 Further regulatory landscape

2.3.1 United States

In the United States, there is another DC initiative called EMerge Alliance [8]. Founded in 2008, the declared goal of this non-profit open industry association containing industry, government, and academic member organizations is to promote DC as well as hybrid AC/DC infrastructure for buildings and communities and to develop standards to accelerate the adoption of DC and AC/DC microgrids for commercial, industrial, and residential buildings.

At the standardization level, EMerge Alliance is also developing system standards that describe the electrical infrastructure of microgrids. Similar to Current/OS Foundation or ODCA, this specification does not have a normative character, but it is approached by IEC and ANSI for further relevant work and used by EMerge Alliance members for project implementation. The specification work can be divided into two general areas: microgrids and the connection between multiple such microgrids to form a common large grid. This division is also reflected in the EMerge Alliance committees.

The underlying system approach is based on the application in data centres: a 380 V distribution level is reduced to 24 V for the end application, thus falling into the SELV range. Compared to the younger European DC initiatives, a fixed voltage is used here and not a characteristic curve-based droop control. However, the biggest difference is that the EMerge Alliance also considers hybrid AC/DC grids.

2.3.2 China

Driven by global environmental concerns and aiming for carbon neutrality through renewable energy sources (RES), China is establishing a significant LVDC ecosystem. Supported by substantial investment from the Chinese Energy Foundation, over 20 LVDC demonstrators are currently active in the country.

China is also very active in international standardization boards and technical committees in terms of regulatory development, having also established national standards covering specific aspects of the LVDC domain. In 2020, the latest version of the GB/T 39462 Chinese national standard was introduced, focusing on safety requirements for LVDC. Similarly, in 2022, the T/CABEE-030 standard was released, covering extensive design requirements for DC buildings, including protection equipment, power electronics, and grid management. Among specific aspects covered by these standards, it is possible to find:

- Grid topology
- Voltage levels
- Earthing specifications
- AC/DC Interlink Converter requirements (current limitation and fault ride-through)
- Protection and selectivity

2.3.3 Japan

There is also a DC initiative in Japan: the DC Power Supply Alliance [9]. Founded in 2009, it is older than the two European initiatives, similar to the EMerge Alliance. The primary application area that the DC Power Supply Alliance focuses on is data centres, aiming to improve efficiency, save energy, and protect the environment. However, it is also intended to maintain supply security at schools and public facilities in case of disasters, especially in the field of communication technology. The application area has since been extended to private households, and the system model is also based on this application.

The DC Power Supply Alliance mainly collaborates with Japanese ministries and committees. However, many member companies are also represented in international standardization committees, such as IEEE and IEC, contributing to corresponding standardization work. The system model of the DC Power Supply Alliance consists of three DC levels with different voltage levels, all coupled with the AC grid and with the respective lower DC level. The lowest level, with 5 V or 12 V, is suitable for classic end devices such as mobile phones. The intermediate level, with < 60 V, represents a distribution level safe for uninstructed personnel but can also supply slightly larger devices. The uppermost level, with > 60 V, is for large consumers and serves as a distribution network over greater distances.

2.4 Comparison, Barriers, Recommendations and Conclusion

As outlined in the previous chapters, standardization is almost entirely carried out at an international or at least European level. Moreover, many EU countries do not conduct independent standardization, so no differences in standardization are to be expected across national borders.

Both major DC initiatives, Current/OS Foundation and ODCA, also follow the state of standardization, incorporating valid standards and actively participating in current standardization projects through their members. The biggest differences thus emerge when comparing the specifications of these two initiatives.

The most significant difference arises from their respective original application areas and the resulting approach to specification:

The system concept of ODCA originates, as previously described, from industrial applications, which also gave the name to research projects DC-INDUSTRIE and DC-INDUSTRIE2, among other things, to make braking energy from robots and machines easily reusable. Accordingly, the system design followed more of a bottom-up principle, where the grid was specified starting from the device side. Also, the group of people working on or with the DC grid can be limited to electrically trained personnel in an industrial environment.

In contrast, Current/OS Foundation focuses on building applications, with an emphasis on the simplest and most efficient integration of local PV and battery systems. Accordingly, the system was specified using a top-down approach, and the protection concept was specifically designed for operation by non-electrically trained personnel due to the building environment.

In many technical aspects, both specifications are very similar. For example, both initiatives rely on grid control using droop control, a characteristic-based regulation where the connected converters adjust their grid-side current based on the respective terminal voltage. The voltage ranges of both systems are also fundamentally similar. Current/OS Foundation has the 700 V voltage level, which is found in the ODCA voltage range of 620 V - 750 V. The 350 V voltage level from Current/OS Foundation is not considered relevant for industrial applications by ODCA and is therefore not included in the system concept. However, in initial implementations following the ODCA system concept, there are also outputs with lower voltages (380 V, or even 48 V, for example, to supply hall lighting from the DC grid).

There is a joint working group that is examining the differences between the two system concepts and attempting to achieve the greatest possible compatibility. One of the major points of discussion is seen in the area of protection. As previously described, the intended user groups are different, leading to differences in this aspect. This has consequences not only for the required protective devices but also for fundamental technical design criteria. In particular, the so-called AC-side earthing, a commonly used earthing method in ODCA, should be mentioned, which arises from the usage of non-galvanically isolated AC frontends or passive rectifiers. In Current/OS Foundation, there is a strong preference for galvanically isolated AC frontends, and the use of traditional grounded (TN) grids.

Due to the different application scenarios, however, no incompatibility is seen here, but rather system-dependent differentiations. Especially for device manufacturers, ODCA and Current/OS Foundation do not want to be seen as competing but rather as complementary, and they aim to take advantage of the economy of scale through the expanded user base.

One barrier for the simple and widespread implementation of DC grids is also seen in the area of protection. There is a lack of normative guidelines for the calculation of short-circuit currents, which in turn means that there is currently no standardized method for the coordination of protective elements, especially regarding selectivity. Methods that are standard practice for AC installations and indispensable prerequisites for final acceptance by inspectors, such as measuring fault circuit impedance, are also not yet standardized for DC applications. Lastly, there are no corresponding grid codes for DC grids, which is particularly problematic for DV distribution grids.

Distribution grids benefit from a higher voltage level and are one of the main applications for MVDC. Yet MVDC is not something that is specified from a standardization point of view. Up to 1500 V DC is considered low voltage and above is regarded as high voltage. HVDC is already widespread in use for transmission systems and as such well examined and standardized. But with the standardization in place at this moment, this would for example result in 3 kV PV installations to be realized with armoured cabling, resulting in a horrific cost efficiency. As such, CIGRE group B1.82 "MVDC Cable requirement" is currently working on a definition, but this needs to be transferred into the IEC standardization as well.

In the context of European strategy for Green Deal, green energy and carbon neutrality in 2050, different regulations are proposed and will concern cables and other installation components:

- ESPR (Eco design for sustainable products)
- CPR revision (Construction product regulation)

When adopted, harmonized technical specifications may, where appropriate for the products they cover, specify that products must be designed, manufactured and packaged in such a way that one or more of the following product-related environments are respected.

It is clearly useful to encourage European countries to take account of the sustainable performance of cables in product standards. In this context, a number of topics could be addressed, such as sustainability, recycled content, recyclability, environmental impact, use of solar energy, waste recycling, etc. This is a strategic European position.

While standardization of DC systems, appliances and applications is currently making a lot of progress, it is mostly done via DC specific standards (a good example here are cables, with the IEC 62930 for photovoltaic (PV) cables or the IEC 62893 for Electric Vehicles (EV) charging cables), or as a general standard but written completely with AC in mind and mostly divide systems by voltage level (<1 kV AC is part of the same family as <1.5 kV DC). A better integration of DC into the main general standards would be beneficial as this would result in a wider range of available devices and components.

Currently, there is a strong tendency to install AC and DC in the same areas (for example, integrating renewable energies in the same building). So, for safety reasons, a major challenge is to clarify the differentiation between AC and DC installation materials and cables to avoid any safety issues that may arise from confusing AC with DC cables like connecting AC appliances to DC lines.

These barriers need to be addressed both in standardization circles and within the two initiatives Current/OS Foundation and ODCA, so that the broader implementation of DC grids, even outside of research projects, can be made easier.

3 Market Architectures

Considering the stakeholders acting in power systems, several services can be delivered by the facilities mainly depending in the existing control systems and in the capability to provide flexibility. To facilitate the classification, services are categorized into:

- **System level services**: Normally managed by TSOs, these services aim to maintain the system's global operation at the required security level. Given that energy trading via bilateral contracts and electricity markets (spot, intraday, real-time) takes place at a national or regional level. Generally, all grid users are eligible to participate in these services, but some capacity limits and time of response are normally imposed. The participation in these services are normally defined by regulation or, more recently, can be procured in specific markets [10].
- In Shift2DC some system level services will be tested namely the black start in Industry demo or the frequency regulation (secondary reserve) in Port Demo.
- **Grid level services** are designed to mitigate constraints that may arise in the transmission and distribution grids. As such, they can be managed and procured by both TSOs and DSOs. However, due to the highly monitored, interconnected, and meshed nature of transmission grids, contrasted with the distribution grids' challenges related to observability, limited connection points, and radial operation, these services are becoming increasingly important in the distribution system. Once coordination between TSOs and DSOs is established, it is generally easier for DSOs to support the needs of TSOs rather than the other way around [11]. This services can be manged directly by the DSO or, in some recent cases, can be negotiated in local markets [12].
- **Facility level services:** In some specific cases, services can be provided to other stakeholders beyond system and grid operators. This is the case of ramping services that can be provided to generators or backup services in an energy community. In that case, the service rules should be established directly between the stakeholders according to the specific needs of the facilities. Aggregators, such as virtual power plants, can have an important role in the coordination of these services.

Concerning the type of "products and services" that can be negotiated, the classification is more complicated due to the diversity of needs of the system. A simple classification can be the following:

- Electricity: Electricity is the main product negotiated between producers and consumers. Nowadays, with new technologies of energy storage and with the increased penetration of distributed generators, the same grid user can sell energy in some periods and buy in others. Considering the use of DC grids, this management becomes even more easy and the installations are more flexible [13]. Analysing the negotiation of electricity in European countries, it is possible to see that most of the electricity is traded in electricity markets or in bi-lateral negotiations.
    - Electricity Markets: Electricity markets are platforms where electricity can be sold and bought according to the rules defined by the market operator, normally in coordination with the national regulators. Although the structure and regulations of these markets differ by country and region, their main goals are to promote competition, ensure a reliable electricity supply, as well as ensuring market transparency and liquidity [14]. These markets function over various timeframes, from

long-term forward markets to near real-time intra-day markets. Nonetheless, the day-ahead market, where electricity is traded for the next day, is the most significant.
  - Bilateral contracts: Bilateral negotiation is a direct agreement between two parties for buying or selling electricity, bypassing the centralized electricity market. The buyer and seller negotiate the terms and conditions, including price, volume, and delivery period. In some cases, these contracts may be indexed to the spot market. However, all contracts, whether established through bilateral negotiation or within electricity markets, must undergo technical validation by the system operators [15].
- Ancillary Services: According to Article 2(48) of Directive (EU) 2019/944 [16], ancillary services refer to a service necessary for the operation of a transmission or distribution system, including balancing and non-frequency ancillary services, but not including congestion management. Non-frequency ancillary service means '*a service used by a transmission system operator or distribution system operator for steady state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability*' [16]. According to the description of the ancillary services, it is possible to see that several "products" can be procured in ancillary services markets. However, the most common in AC grids are the ones related with frequency regulation [15]. Depending on the markets, after the procurement, the services can be activated by activation signals or can be autonomously activated (without activation signal). Nevertheless, the participation on the services should be always monitored. Looking in the characteristics of the DC grids, voltage control services can appear as the most critical ones. However, the existing DC eco-systems are pushing for solutions where these services are shared among all the installed power devices meaning an automatic participation in voltage control [17].
- Flexibility: According to ENTSO-E [18], 'flexibility refers to the ability of the power system to cope with variability and uncertainty in demand, generation and grid availability'. The same reference proposes two types of flexibility namely:
  - Short duration flexibilities (from milliseconds up to a few hours, to balance the system within the day and ensure system stability)
  - Long duration flexibilities (up to several weeks, to compensate for long periods with shortage of wind, solar and hydro generation).

  Nowadays, flexibilities can be procured in markets [16]. According to [19], there are three types of flexibility markets namely.
  - Type 1 is balancing flexibility for the TSO at the transmission system level (these can be classified as ancillary services according to the definition proposed previously).
  - Type 2 is balancing flexibility for the TSO at the distribution system level. Grid users can join these markets after undergoing a pre-qualification process and, in some countries, small-scale flexibility participation is already happening. The involvement of VPPs and flexibility aggregators will be essential in these services.
  - Type 3 is flexibility for the DSO at the distribution system level. These are often referred to as local flexibility markets and are particularly appealing for small resources. However, local flexibility markets are not yet widely implemented in most countries.

Beyond the flexibility negotiated in markets, other type of mechanism can be defined to change the consumption (and production) behaviours. Normally these kinds of mechanism are easier to implement and to engage small grid users. These mechanisms are:

- Variable capacity contracts: The concept of variable capacity contracts is to adjust the maximum power consumption/production of an installation (Port, Buildings, companies, datacentres) during some periods of the day. These services are normally defined in a negotiation between the system operators and the owners of the facilities. After this phase of negotiation, the activation can be performed by the system operator considering a pre-announce period. This requires the existence of an intelligent system allowing the control of the installation to minimize the impact of the power reduction. These contracts can be easily activated through a smart metering infrastructure.
- Implicit demand response (IDR): IDR imposes the involvement of grid users modifying their energy consumption/production profiles in response to price signals without explicit communication or direct control. This approach utilizes technology like smart devices, sensors, and automation systems to adjust energy usage based on predefined criteria or signals from the grid or energy market. A common practice is Time-of-Use (ToU) pricing, where rates fluctuate based on average market prices and are updated every 3, 6, or 12 months [20].
- Explicit demand response (EDR): EDR refers to actions taken by grid users activated by incentives or requests from aggregators or directly by system operators. Considering the configuration of DC grids, where one of the main assets are battery energy storage systems, the participation in EDR can be significative. In the end, the installation can work as microgrids taking advantage of the incentives provided in the EDR service. This scenario will be tested in the case of the Ports where, depending on the demand of the ships, all the demand can be assured by the batteries during some hours.

4 Conclusions

4.1 Summary

This deliverable presents and overview of the current state of standardization regarding LV and MVDC grids and applications as they will be demonstrated within the Shift2DC project. Most standardization is done on an international level within IEC, and while there are some national peculiarities in the standardization and regulation within some EU countries, this should result in better transferability across national borders.

With the system specifications from both ODCA and Current/OS Foundation, two well defined – and in most parts complementary – reference scenarios are presented, which will be the basis for the development of the demonstrators.

The main gaps within the current standardization have been identified, which lie mostly within the protection area as well as clear definitions.

Lastly, the market architectures and grid services that DC systems in general can supply are introduced.

4.2 Next deliverables

This deliverable D1.2 is the basis for other deliverables, mainly D5.2 – Standardization and Harmonization activities (T5.2) and D5.4 – DC Roadmap and Business models (T5.4). In D5.2 the main standardization activities of the project consortium will be documented. As such, identifying the current state and the gaps across not just the different IEC TCs but also across multiple standardization bodies is essential. D5.4 on the other hand will further detail the market and business opportunities. For this exploitation context, the current state of standardization is of utmost importance, since solution not following the standardization roadmap are prone to be obsolete.

5 References

[1] CIGRE MVDC Cable System Requirements, Proposal for the creation of a new working group. [Online]. Accessed: Jul. 23, 2024. Available: https://cigre-usnc.org/wp-content/uploads/2021/12/TOR-WG-B1_82_MVDC-Cable-System-Requirements.pdf

[2] IEC SyC LVDC Roadmap. [Online]. Accessed: Jul. 23, 2024. Available: https://mapping.iec.ch/#/maps/157

[3] Current/OS Foundation Website. [Online]. Accessed: Jul.23, 2024. Available: https://currentos.foundation/

[4] Circl Pavilion Amsterdam. [Online]. Accessed: Jul. 23, 2024. Available: https://www.dc.systems/projects/circl-pavilion-abn-amro

[5] Highway N470. [Online]. Accessed: Jul. 23, 2024. Available: https://www.dc.systems/projects/highway-n470

[6] Open DC Alliance Website. [Online]. Accessed: Jul. 23, 2024. Available: https://odca.zvei.org/

[7] DC-Industrie Systemconcept V3. [Available Online]: https://odca.zvei.org/resources/publications/updated-system-concept-for-dc-industrie2-published

[8] EMerge Alliance Website. [Online]. Accessed: Jul.23, 2024. Available: https://www.emergealliance.org/

[9] DC Power Supply Alliance Website. [Online]. Accessed: Jul.23, 2024. Available: https://ggpah.org/index.html

[10] G. Rancilio, A. Rossi, D. Falabretti, A. Galliani, and M. Merlo, "Ancillary services markets in europe: Evolution and regulatory trade-offs," *Renew. Sustain. Energy Rev.*, vol. 154, p. 111850, Feb. 2022, doi: 10.1016/j.rser.2021.111850.

[11] H. G. Morais Valente, E. Lambert, and J. Cantenot, "Transmission system operator and distribution system operator interaction," in *Local Electricity Markets*, Elsevier, 2021, pp. 107–125. doi: 10.1016/B978-0-12-820074-2.00003-4.

[12] M. Gržanić, T. Capuder, N. Zhang, and W. Huang, "Prosumers as active market participants: A systematic review of evolution of opportunities, models and challenges," *Renew. Sustain. Energy Rev.*, vol. 154, p. 111859, Feb. 2022, doi: 10.1016/j.rser.2021.111859.

[13] H. Huang, M. Zhou, S. Zhang, L. Zhang, G. Li, and Y. Sun, "Exploiting the Operational Flexibility of Wind Integrated Hybrid AC/DC Power Systems," *IEEE Trans. Power Syst.*, vol. 36, no. 1, pp. 818–826, Jan. 2021, doi: 10.1109/TPWRS.2020.3014906.

[14] Z. Jing and Y. Yu, "Spot market design and its influence to the entire electricity market and market regulation," in *2018 International Conference on Power System Technology (POWERCON)*, Guangzhou, China: IEEE, Nov. 2018, pp. 770–775. doi: 10.1109/POWERCON.2018.8602263.

[15] A. Pedro, M. Krutnik, V. M. Yadack, L. Pereira, and H. Morais, "Opportunities and challenges for small-scale flexibility in European electricity markets," *Util. Policy*, vol. 80, p. 101477, Feb. 2023, doi: 10.1016/j.jup.2022.101477.

[16] *Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU*

(recast) (Text with EEA relevance.), vol. 158. 2019. Accessed: Jul. 05, 2024. [Online]. Available: http://data.europa.eu/eli/dir/2019/944/oj/eng

[17] "DC-Systems-White-Paper.pdf." Accessed: Jul. 05, 2024. [Online]. Available: https://www.dc.systems/assets/public/DC-Systems-White-Paper.pdf

[18] "ENTSO-E Vision: A Power System for a Carbon Neutral Europe." Accessed: Jul. 05, 2024. [Online]. Available: https://vision.entsoe.eu/chapters/energy-system-flexibility

[19] X. Jin, Q. Wu, and H. Jia, "Local flexibility markets: Literature review on concepts, models and clearing methods," *Appl. Energy*, vol. 261, p. 114387, Mar. 2020, doi: 10.1016/j.apenergy.2019.114387.

[20] C. P. Guzmán, A. Lekidis, P. Pediaditis, P. M. Carvalho, and H. Morais, "Intelligent Participation of Electric Vehicles in Demand Response Programs," in *2023 International Conference on Smart Energy Systems and Technologies (SEST)*, Mugla, Turkiye: IEEE, Sep. 2023, pp. 1–6. doi: 10.1109/SEST57387.2023.10257505.