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Working Group

Final Report

DC Networks on the distribution level – New trend or Vision?

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Working Group

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DC Networks on the distribution level – New trend or Vision?

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

The following list contains commonly used abbreviations in this report.

A	Ampere
AC	Alternating Current
AIC	Active Infeed Converters
BESS	Battery Energy Storage System
CB	Circuit Breaker
CBA	Controlled Before-After Study
CEI	Customer-End Inverters
CIGRE	International Council on Large Electric Systems
CIRED	International Conference on Electricity Distribution
CTL	Cascaded Two-Level
DAB	Dual-Active-Bridge
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
DPCR	Distribution Price Control Review
DSO	Distribution System Operator
DTC	Direct Torque Control
E.DSO	European Distribution System Operators
EMC	Electromagnetic Compatibility
e-mobility	Electric Mobility
EnR	European Energy Network
ENTSO-E	European Network of Transmission System Operators for Electricity
EVA	Enhanced Voltage Assessment
FCL	Fault Current Limiter
FPL	Flexible Power Link
GaN	Gallium Nitride
GOOSE	Generic Object-Oriented Substation Event
HCB	Hybrid Circuit Breaker
HVDC	High-Voltage Direct Current
ICT	Information and Communications Technology
IEA	International Energy Agency
IGBT	Insulated-Gate Bipolar Transistor
MCCB	Molded Case Circuit Breakers
KPI	Key Performance Indicator
LCN	Low Carbon Networks
LCC	Line-Commutated Converter
LVDC	Low-Voltage Direct Current

MCB	Mechanical Circuit Breaker
MCCB	Moulded Case Circuit Breaker
MMC	Modular Multi-Level
MVDC	Medium-Voltage Direct Current
NIC	Network Innovation Competition
NOP	Normal Open Point
OEM	Original Equipment Manufacturer
P	Active Power
PCC	Point of Common Coupling
PECS	Power Electronic Converter Systems
PET	Power Electronic Transformer
PWM	Pulse Width Modulation
Q	Reactive Power
RMS	The effective value of a varying voltage or current
RTO	Research and Technology Organisation
S	Apparent Power
SCADA	Supervisory Control And Data Acquisition
SDRC	Successful Delivery Reward Criteria
SGEM	Smart Grids and Energy Markets
SiC	Silicon carbide
SME	Small and Medium-Sized Enterprises
SOC	State Of Charge
SOG	State Of the Grid
SOH	State Of Health
SSCB	Solid-State Circuit Breaker
SST	Solid State Transformer
STATCOM	STATic synchronous COMpensator
SVO	System Voltage Optimisation
THD	Total Harmonic Distortion
TRL	Technology Readiness Level
TSO	Transmission System Operator
UC	Use Case
UPFC	Unified Power Flow Controller
UPS	Uninterruptable Power Systems
V	Volt
V2G	Vehicle to Grid
VFD	Variable Frequency Drive
VSC	Voltage Source Converter
W	Watt

LIST OF TABLES

LIST OF FIGURES

SUMMARY OF REPORT

"DC networks on Distribution Level – are they a new trend or a Vision?" That is the question that has focused the efforts of the Working Group the last two years, and whose consideration is summarized in this report. This report represents the first phase evaluation of this topic and is focused primarily on medium (MVDC) and low voltage (LVDC) level applications.

DC solutions are already established in specific applications like point-to-point High Voltage DC transmission (HVDC) systems, DC grids for public transport like such as city tram or subway, ships and aeroplane board grids, data centres, Uninterruptable Power Supplies (UPS) etc. As the majority of new energy applications including renewables, e-mobility or storage are internally DC based, the prospect of DC or hybrid AC/DC distribution offers connections through DC-DC converters that are more efficient and architecturally simpler. In this sense, they are more than just a Vision. Although any deployment of DC distribution grids on a large scale remains unproven given some missing key technologies still remain in development, several of their outstanding high- level benefits have been identified and demonstrated, including the following:

- Expanding the capacity of power lines and grids to host greater volumes of renewables distributed energy resources, e-mobility and other DC based loads;
- Increased energy supply radius and decreased concerns for power quality;
- Improving the system energy and resources efficiency;
- Enhanced grid resilience and management in case of grid faults; and
- More environmentally friendly and sustainable use of resources in production and operation.

Over the last decade, several early technologies for the realization of DC distribution have been demonstrated in a variety of pilot installations and research platforms across a number of countries. The lessons learned from these early pilots evidence the effective contribution that DC distribution networks can make to grid optimization and stabilization, laying foundations for a net zero carbon energy future. The potential for lowering the cost of the energy transition exists. Therefore, it is entirely feasible for AC and DC grids to coexist within hybrid AC/DC energy systems for future power distribution, both, behind (prosumer) and in front of (utility, energy communities?) the meter.

Despite all the development and euphoria around the DC distribution networks, the majority of technical solutions and devices remain in pilot project stage and the commercial markets are missing. To determine the extent to which and if a large-scale breakthrough of this relatively new technology is reasonable for which distribution grid use-cases, areas (utility, industrial or building/infrastructure) and on which voltage level (low and medium voltages) the following actions and additional investments in this field will be required:

- Essential research questions have to be answered and key technologies as well as techno-economic planning tools to be developed by universities/RTOs in collaboration with OEMs;
- Clear use-cases, exploitation strategies and business models for their products and services have to be formulated by RTOs, OEMs and service providers;
- International standards and regulations have to be defined by standardization bodies and regulation authorities;
- Answers to the long-term impact of DC integration into the public MV and LV networks (in terms of capacity and ease to connect future customers in the surroundings of a DC investment, or capacity to reconfigure the grids at least the same way it is done in AC); and
- Operational safety and experience have to be gained for these systems by distribution grid operators in more pilot projects on a short and mid-term perspective to keep a safe, reliable and trustful future supply system.

Therefore, standardization (LVDC and especially MVDC) is mandatory and one main factor for success. This report also discusses the state of the art of international and European standardization.

The main drivers, needs, use cases, functionalities and technical solutions for DC and hybrid AC/DC distribution grids presented in this report have been derived from detailed analysis of more than fourteen global DC pilot projects. They show the actual state of the art in this rapidly developing field. In addition, these findings are complemented by three surveys based on pre-defined questionnaires for university/RTO, manufacturer and utility area. The last one was handled as positioning document of the participating members/companies of this Working Group. The results were analysed in detail within the working group and as many general conclusions as possible were extracted.

As consequence of European and International climate goals, similar to other Smart Grid studies, nearly all projects are driven by the integration of more renewable and decentralized generation units into the system, accompanied by the integration of electric vehicles and storage units, while maintaining or even improving the quality and reliability of supply. In addition, efficient sector coupling (electricity, gas and heat) and the electrification of the industrial processes to reach the decarbonization goals are identified drivers. To establish open energy markets for private and industrial customers, producers and “prosumers”, including demand side management, is also an important objective. As an example, future energy communities, for which the legal framework is currently being created in Europe, can be stated. Therefore, the expression “DC distribution networks” is in some projects not strictly restricted to grid issues and technology demonstrations themselves, but as well includes “Smart Market” objectives and topics.

Functionalities and use cases following the drivers in the context of current DC grid developments are:

- DC and hybrid AC/DC microgrids operated on and off the AC main grid;
- AC grid support through active AC-DC front end power converters;
- Bidirectional power flow with AC-DC and DC-DC power converters including direct energy recovery for variable speed drives (LVDC factories);
- Fault detection and localisation;
- DC switching and overcurrent limiting;
- Automatic reconfiguration in case of grid faults;
- State estimation and optimal power flow energy service;
- Smart power electronic transformers;
- Refurbishments of last-mile MV/LV AC applications by LVDC;
- Soft-coupled MVAC grids with MVDC links; and
- LVDC homes and buildings, smart lighting and electric vehicle charging infrastructure.

To realize the functionalities, a large number of technical solutions in the field of power converters, control and energy management systems, new grid components like MVDC sensors, DC measurement units and protection equipment based on fast power electronic-based hybrid and solid-state DC breakers (LVDC and MVDC) and planning criteria/tools are being developed. In particular, interoperable devices, control and protection strategies/protocols, reliability and component aging studies and test and validation infrastructure/methods are mandatory for the success of extended DC and hybrid AC/DC distribution grids.

Finally, the work of the last two years shows that many projects all over the world are working on similar challenges and opportunities. This emphasizes the need for organizations like CIRED to bring together all the experts on distribution grids and component development, to enable the share of knowledge and expertise and therefore help to move forward into a smart distribution grid future.

Convener Gerhard Jambrich and members of the Working Group, July 2021

1 INTRODUCTION

1.1 Background and Scope of the Working Group

Background

In the 2015 Paris Agreement, the global community pledged to limit global warming to well below two degrees Celsius and, if possible, to below 1.5 degrees Celsius compared to the pre-industrial level. In Europe, in December 2019, EU leaders committed to the goal of climate neutrality by 2050 and following measures ("Green Deal"). In December 2020, EU leaders agreed to raise the EU's 2030 climate target from the current minimum of 40 to at least 55 percent below 1990 levels. Accordingly, the EU's internal greenhouse gas emissions are to be reduced by at least 55 percent by 2030 compared to 1990. In parallel, from the International Energy Agency (IEA), scenarios of a global growing demand of electrical energy as much as 50% till 2040 were developed based on experts estimates because around 650 million people worldwide still have no access to electricity (see Section 2).

As consequence, since the last decade, the energy supply business in Europe faces enormous changings never seen before as the centre of this transformation. The above-mentioned climate goals will strongly and sustainably influence the energy market especially in Europe, but also abroad during the actual and next decades. In the last years, power grids were in the centre of the integration of decentralized generation with renewable energy sources (wind, photovoltaic, biomass). Recently, also sector coupling concepts like Power to Gas, Power to Heat, Hybrid Power Plants, the electrification of the industrial processes and integration of electric vehicles and storage units gain importance to reach the ambitious climate goals.

When we look at power grids and their transition to Smart Grids, a growing number of sources and consumers of electricity are natively producing or using direct current (DC), for example Renewable Energy Sources such as PV panels and wind turbines, e-mobility solutions, storage units and a majority of new electric appliances from domestic to industrial sectors. At the same time, a lot of progress is reported in terms of high-power electronic components and adapted DC breakers. This paves the way for DC network demonstration projects and raises the question of the place these technological solutions may have in the future.

Scope

The Working Group covers:

- DC components, planning issues, standardization and regulatory framework;
- LV, MV and HV distribution networks (in first phase focused on LV and MV);
- Public networks and industrial, buildings, facilities or other specialized networks; and
- Pilots and use cases.

It investigates:

- Economic and technical analysis of DC compared with AC;
- Present maturity and expected progress of the components capable of setting-up DC networks, in particular conversion, protection and metering components;
- Grid integration of components and solutions like power electronic converters in DC distribution networks by matching components as well as grid planning issues;
- In which distribution network situations DC solutions could be most effective;
- Impact of DC solutions on network architecture;
- AC to DC system converting (for instance to enable greater power transfer);

- Prospects of developing these networks in complementarity with current networks; and
- Standardization and regulatory framework.

Existing demonstration projects are presented in this report including, when available, lessons learned from these projects (Chapter 3). The Working Group analyses what could speed up or restrain the development and the large-scale implementation of such solutions.

The Working Group and so this report strongly focuses on the role of DC and hybrid AC/DC distribution grid aspects and other aspects dealing with smart and efficient applications like Smart Generation (including renewable generation), Smart Consumption (including e-mobility, frequency-controlled heat pumps, etc.) and Smart Storages (including batteries, supercapacitors, etc.) are only considered insofar as they correspond to the main purpose of the Working Group.

From a historical point of view, the idea of DC distribution grids is not new. At the early time of electrification around 1880-1900, the first distribution grids starting in USA were local DC grid islands (ca. 1,5 km diameter) where DC generators were powering mainly public lighting (carbon filament lamps) and at this time only available DC motors for e.g. tooling machines (voltages 110 and 220 Volt). The so-called Edison meters were the first practical (DC) measurement devices for billing of electric energy. For protection against over- and short circuit currents mainly fuses were used. At this time no power electronic based converters to step up and step down the DC voltage and also no DC breakers to switch DC currents were available. With the invention of induction motor and AC power transformer AC grids became dominate till nowadays over the, at that time leading and with lots of patents protected, DC technology. Except for established applications such as point-to-point High Voltage DC transmission (HVDC) systems, DC grids for public transport like city tram or subway, ships and aero plane board grids, data centres or Uninterruptable Power Systems (UPS), DC distribution in extended power grids was no major issue until the last decade.

With the ongoing rapid development of high-power electronic components and adapted DC breakers (LVDC and MVDC) as well as new semiconductor technologies − using wide bandgap materials like SiC and GaN which allow higher switching frequencies, lower on-state and switching losses and smaller converter units − together with the steadily decreasing power converter prices, the biggest disadvantages of DC-technology almost disappeared. With the remaining advantages, a revival of DC and hybrid AC/DC distributions grids seems to be possible as one option for transition into a low carbon and renewable energy future. Therefore, the book of distribution grids cannot be written totally new because AC technology will stay in the coming decades the leading technology, but some chapters could take a turn to more DC and hybrid AC grids in the coming years.

1.2 Structure of the Draft Report

The final report of the Working group consists of three main parts:

The first part (Chapters 2 and 3) describes the main drivers and the actual need as well as concrete use cases for DC distribution grid applications on low-voltage and medium-voltage level. The collection of DC distribution pilot projects all over the world is given in Chapter 3. It shows that many drivers are common, but some differ due to the specific situation in the countries.

The main drivers of DC distribution grids for low voltage and medium voltage level are:

- Integration of renewable energy and distributed energy generation;
- Connection of high numbers of e-vehicles (including V2G-technologies) and other DC based loads;
- Establishing storage units;
- Electrification and decarbonization of industry sector;

- Increase of energy efficiency;
- Establishing new energy markets (e.g. future energy communities) and demand side management
- Increasing reliability; and quality of supply; and
- Reduction of operational and investment costs.

The second part (Chapter 4) gives today's “State of the Art” of technical DC distribution grid components and technologies inclusive challenges and hurdles like needed emerging technologies/key components like MVDC breakers, protection systems, etc.

The third part (Chapter 5) presents the “State of the Art” of standardisation of DC distribution grids. European as well as international attempts on standardisation and some national standardisation activities are covered.

Finally, in Chapter 6 conclusions with open points and challenges for the further is given.

1.3 Procedure of the Working Group

The work of the Working Group started with the collection of significant DC distribution grid pilot projects at low and medium voltage level all over the World. As a result, projects in Europe, Asia and North America were identified. The collection was carried out by summarizing available project descriptions, by contacting responsible persons/companies, literature search and the evaluation of related press articles, respectively. Use-case descriptions and corresponding Key Performance Indicators (KPIs) were analysed and extracted as far as available. Standardized templates like use-case templates/methodology described in IEC 62559-2 are not used (incomplete data), but the structure was taken as guidance. This will be a recommendation for ongoing work.

The result of the collection was a database of about 14 DC distribution grid pilot projects from 7 countries in Europe, East Asia and North America. Many of them are local or national projects, while some are realized with partners across national boundaries or even as EU-wide projects. Figure 1.3-1 gives an overview of the analysed DC distribution grid pilot projects in Chapter 3.

Figure 1.3-1: Analysed LVDC (green marked) and MVDC (yellow marked) distribution grid projects spread over the world.

Although the pilot project collection was done very extensively and accurately with contributions from all members of the Working Group from different countries it is – of course – not "complete" since not all countries were represented in this Working Group. The goal of the data collection was not to achieve a complete database of all projects in the world, which is nearly impossible, since an enormous number of different DC distribution projects are running worldwide with new ones starting every year. The idea was rather to analyse as many projects as possible in order to get an overview of the main goals, themes and objectives covered by the projects.

In addition, three positioning surveys were carried out by the Working Group collecting data within the WG-members and interested worldwide companies and members of European organizations and research networks. Two of them, for manufacturer (Section 4.2) and university/research area (Section 4.1), were based on prepared, anonymized questionnaires on a web-platform, the third one for utility sector was summarized as positioning paper based on potential use-cases (Section 3.3.1 and 3.4.1).

2 MAIN DRIVERS, NEEDS, FOR DC DISTRIBUTION NETWORKS, DEDUCTION OF A VISION/GOAL

Distribution system operators are faced with ever increasing claims for cost efficiency and supply quality requirements. Further, there are new challenges emerging, such as supplying charging stations for electrical vehicles (EV), the integration of distributed power generation and storages, as well as support for demand response. Therefore, a more flexible distribution grid with higher controllability helps to meet the requirements.

DC can improve the grid operation in terms of providing reactive and active power capacity and, voltage controllability. DC solutions can also be economical compared to the AC alternatives in some cases (e.g. a new transformer or cable).

In order to evaluate the need for DC, especially in the prospective electrical grid, the following subchapters analyse the impact of future scenarios and upcoming challenges as a consequence. Based on this, the need for DC in power grids as well as the next generation of power grids and its technical challenges are elaborated.

2.1 Growing Demand of Electrical Power

In order to achieve the goals of the Paris agreement, the ongoing decarbonization of energy generation will make a decisive contribution. To this end, the focus is on further integration renewable energies on the one hand and additional sector integration of the heat and transport sectors in the electrical sector on the other. Hence, the future scenarios and their impact on power grids are examined.

2.1.1 Scenarios for 2040

According to the International Energy Agency (IEA), about 17 percent of the current global demand for energy is met in the form of electricity flowing through our grids [1]. Approximately 37 percent of electrical power is already free from emissions. Around 650 million people worldwide still have no access to electricity. Grid planners will need to account for scenarios with growing demand of electric power while replacing conventional energy sources. Experts believe that energy demand is set to grow by as much as 50 percent by 2040. For this reason, the International Energy Agency (IEA) has developed two possible future scenarios (see Figure 2.1-1).

Overall, current planning figures envisage the emission-free proportion of electrical energy generation growing to between 52 and 79 percent by 2040, with electricity generation rising by one and a half times in total. Measured against today's installed base, this would result in energy from nuclear power growing by 0 to 33 percent, from hydropower by 50 to 75 percent, from wind by 400 to 700 percent, from solar plants by 400 to 700 percent, and from other renewable sources by 100 to 200 percent.

Electricity generation from oil, meanwhile, would virtually disappear and there would be an 80 percent reduction in generation from coal. The amount of energy generated from gas is set to remain stable or grow by up to 50 percent, depending on how things develop. Gas appears the most environmentally sound fossil-based energy source, and the plants that are fired by it have the potential to use gas produced using regenerative methods, allowing them to provide a storage or buffer function.

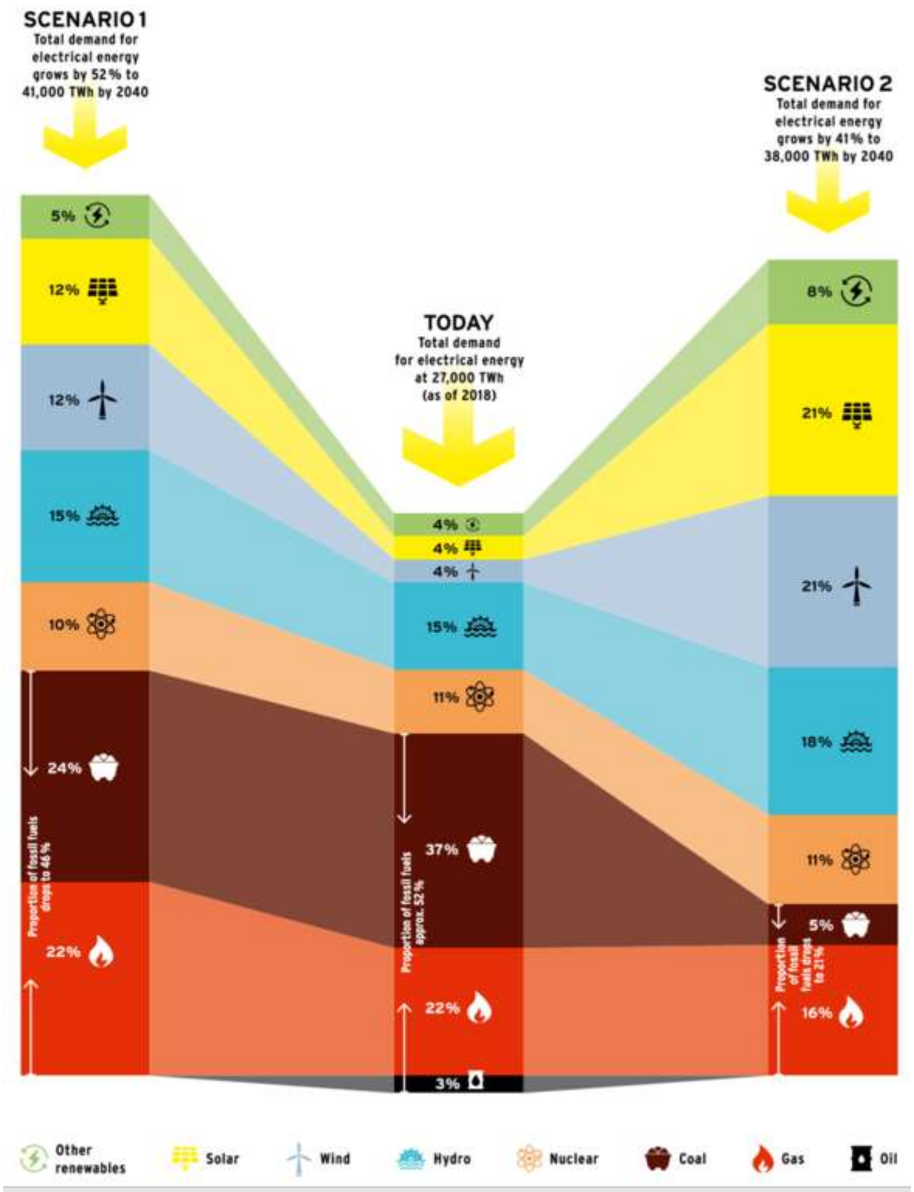


Figure 2.1-1: Two scenarios for electric power by 2040 [2].

The resulting impact on power grids is twofold:

- A structural change from centralized to decentralized provisioning of power; and
- Growth of total power in the grid.

In a more detailed view, power grids will need to change in size, structure and ways to maintain a stable balance of power and stable power flow.

2.1.2 Impact on Power Grids

Future grids will carry more electrical energy as demand continues to rise. In response to our move toward clean forms of energy, the proportion of large-scale power plants (nuclear, coal, and gas) contributing to grids is expected to drop from 70 percent today to between 56 and 32 percent. This means that we will be able to produce 52 to 79 percent of electrical energy without emissions, depending on which 2040 scenario plays out. Solar and wind power will account for the largest energy share, but the amount that these renewable resources are actually able to produce will fluctuate over the course of the year and day to day as local wind, sun, and water conditions change. As many of these plants are also much smaller than their conventional counterparts, the switch to renewable resources is set to have a noticeable impact on grids, which include:

New power control methods

Grid operation will need to adapt to fluctuating electrical energy provision in order to cover demand. Where coal bunkers were once the storage solution of choice, there is now demand for short-term and long-term energy storage methods as a way of regulating the available power balance. The storage technologies with the most focus include power-to-gas plants, pumped-storage power plants, and batteries.

Structural changes in grids

Most renewable sources of energy are installed in locations where the supply of primary energy (wind, sun, biogas, or biomass) is at its most plentiful — not necessarily where demand is highest. Supplies of energy are also becoming increasingly dispersed and renewable plants tend to be smaller than conventional ones. Many producers are shifting away from transmission grids in favour of distribution grids. Due to the fluctuating supply of primary energy, the installed capacity (and therefore the connected load required) in relation to annual energy yield is much higher than it is in conventional power plants. This means that both distribution grids and transmission grids will need to be expanded in many cases.

Growth of power grids

As the world moves toward alternative resources, demand for electrical energy is also expected to rise by 50% worldwide and power grids will be required to transport this additional energy. The capacity needed for transportation will depend on supply and demand over the course of the day. Renewable methods of generating energy create larger fluctuations on the supply side because, due to natural conditions, the operating times of wind power plants are only around 40 percent of conventional plants − and just under 15 percent in the case of solar plants. As a result, much higher capacity levels need to be installed in order to deliver the same amount of energy. Integrating road transportation into the grid also brings new fluctuations on the demand side, which may result in a need to expand the grids, depending on their reserve capacities.

Increased grid flexibility

Grids operate with reserves that they can use in exceptional circumstances and as a backup in the event of problems. As a result of structural changes and increased electricity levels, the capacity of grids will be used more intensively at all voltage levels and, in response, grids will need to be strengthened and provided with relief measures using a more flexible approach to supply and demand.

New technology in power grids

Apart from the production and consumption of energy, a further technological development is taking place in electricity grids. Wind plants, solar plants, electric storage devices, electrolysis plants, charging infrastructures for electric vehicles, and numerous consumers all have one thing in common — they both supply and are operated with direct current (DC).

2.2 Challenges and Future Grid Scenarios in Distribution Grid Operations

There exist several variants and drivers for the distribution grid:

- Variants
    - Difference in size, number, structure, governance;
    - Distribution cost vary greatly;

    - Very few with demand response; and
    - Network indicator of different nature.
- Key driver for changes
    - Network capacity deferral;
    - Local congestion management;
    - Voltage control with renewable; and
    - Loss minimization.

2.2.1 DSO – Current Operation and Future Directions

Some of the recommendation from Council of European Energy Regulator and European DSO on current and future operation of distribution grids are shown below:

- Council of European Energy Regulators on DSO present operation:
    - Run business as expected from network users and other stakeholders;
    - Neutral market facilitator;
    - Public interest, costs and benefits; and
    - Consumers data safety.
- Council of European Energy Regulators on future DSO:
    - Perform flexibility;
    - Exchange network information and co-ordinate with TSOs;
    - DSOs must plan for alternatives to system expansion; and
    - DSOs should be incentivized to consider innovative solutions.
- E.DSO, ENTSO-E on coordination between DSO-TSO:
    - A whole system approach in network planning and investment;
    - Greater coordination in system services, operational and network planning;
    - Exchange of data between network operators to help coordination;
    - Use of flexibility -demand and generation resources; and
    - Fairer cost sharing to avoid reinforcement.
- E.DSO conclusions on Council of European Energy Regulators advice on future DSO:
    - Observability – the intelligent network can provide more data to increase observability;
    - Reduction of losses;
    - System reliability with the help of real-time information;
    - Resilience against cyber-attacks;
    - Optimized and extended life cycle of assets; and
    - Network capacity optimization, lowering connection costs and DSO investments.

2.3 Need for DC in Power Grids

Future grids will be powered to a significant extent by DC-sources. Given the volatile nature of renewable resources, energy storage systems or power-to-gas systems will need to be attached to the grid, which also operate as DC-systems. Electrification of road traffic is adding more DC-systems to the power grid. Industrial machine drives could be easier integrated in a DC power grid via DC/AC inverters and rotating energy directly fed-back to the DC grid (as for example shown in pilot installation DC Industry in section 3.3.2).

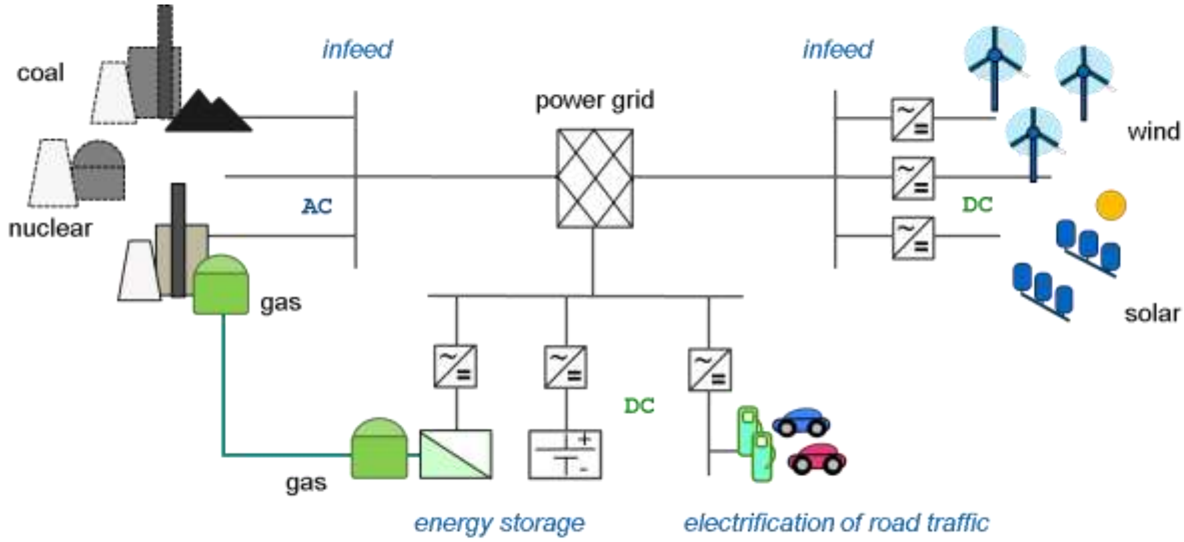


Figure 2.3-1: DC in power grids.

Because of the move toward renewable forms of energy, the installed capacity of direct-current systems in many grids already exceeds that of conventional alternating-current systems (generators, drives, and alternating-current consumers). The use of converters that work with power electronics is set to rise in the future. New equipment with power electronics and new conventional equipment can be used to face the challenging situations presented by operating the grids of the future. Grids are also likely to become more and more automated, while requirements for reliable operation will remain the same.

Another side effect of the further expansion of decentralized renewable energy sources is an increasing short-circuit power in the distribution grids. If the grid topology is switched, for example in an (N-1) case and two sub-networks are connected, the short-circuit power of the interconnected grid can become too large. Based on conventional measures, the separation point will be opened permanently and the (N-1) safety will be restored by additional construction measures within both sub grids. With the help of DC connections, the permanent opening of the separation point can be avoided. By galvanic decoupling of the DC connection, both grids can still be linked without influencing the short-circuit power. additionally, the technical advantage of the DC connection can be used to connect two differently grounded AC grids or two AC grids with different frequencies.

Some major differences between DC used in transmission and distribution systems

The field of DC used for power transmission systems (HVDC) is already structured. HVDC has well-known advantages, and its relevance is now evident in identified cases, mainly point-to-point. For each voltage level, there is a “break-even point” which is the minimum link length from which it is more profitable over the life of the structure to deploy an HVDC link rather than an HVAC conventional link (losses avoided during operation offset additional investment costs). The market and the commercial offer are well structured around known players (American, European and Chinese).

Recent advances in DC disconnection have even allowed the emergence of multi-terminal HVDC systems even if the vast majority of structures remain point-to-point links today.

One of the HVDC solutions specificities: they are always **specific to the project on which they are used.**

For use in medium or low voltage distribution, three major structural differences should be noted for LV/MVDC compared to HVDC:

- The use cases for which the relevance of its use has been demonstrated by global long-term Cost-Benefit Analysis (CBA) studies, compared to conventional AC solutions, have not yet been clearly identified;
- The market and the associated commercial offer are not structured, and the players are emerging with some coming mainly from the world of HVDC and others from the world of conversion for Renewables and / or storage applications; and
- There is a much greater **need for standard solutions that can be selected in short catalogues on the basis of identified criteria** since each MV/LVDC solution needs to fit to a large number of situations.

2.4 The Next Generation of Power Grids

The next generation of power grids will need to accommodate a significant amount of DC systems. Today, power converters operate in HVDC links within the power grids. Apart from HVDC, most power converters are attached to the grid at low voltage levels and converted up to medium voltage level by conventional transformers. Access to the grid is granted according to conformance to AC grid codes.

Future power grids may see power converters operating beyond the low voltage level. They may feature potential DC links or DC-distribution in the grid. Hence, power converters may be operating as resources within the grid, rather than an attachment to the grid (Figure 2.4-1). Among the technical questions concerning integration of DC systems are:

- The vertical depth of DC integration: At some point, DC needs to be converted to AC. This point currently resides at the low voltage end but might move up to higher voltage levels; and
- The use of horizontal DC-links: Currently, transmission grids are meshed, and distribution grids still structured according to a power flow from transmission to lower voltage levels. Given the decentralized nature of renewable sources and energy storage systems, it might be more efficient to exchange power in a horizontal way. This would result in a meshed structure of transmission grids while using DC links.

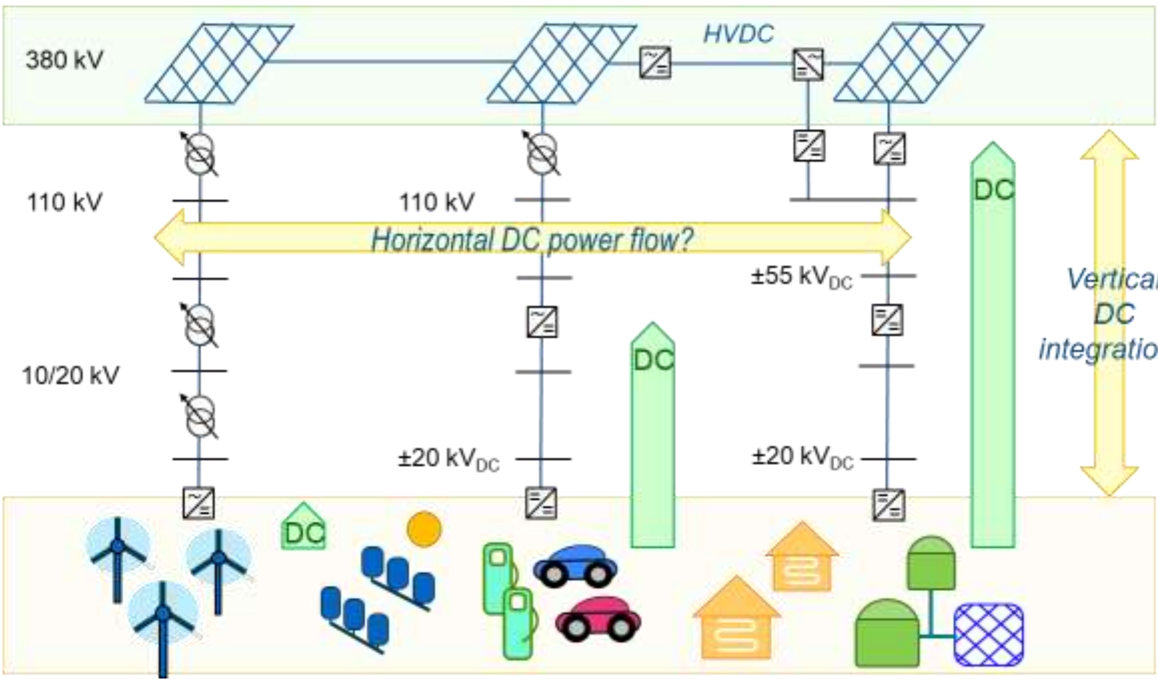


Figure 2.4-1: DC integration into power grids.

DC deployment also starts in industrial power grids. The usage of renewable energy sources in combination of storage systems provides a higher degree of autonomy in industrial grids. In densely populated industrial areas, it may be more efficient to establish DC distribution instead of repeated conversions from DC to AC and back while accumulating converter losses (Figure 2.4-2).

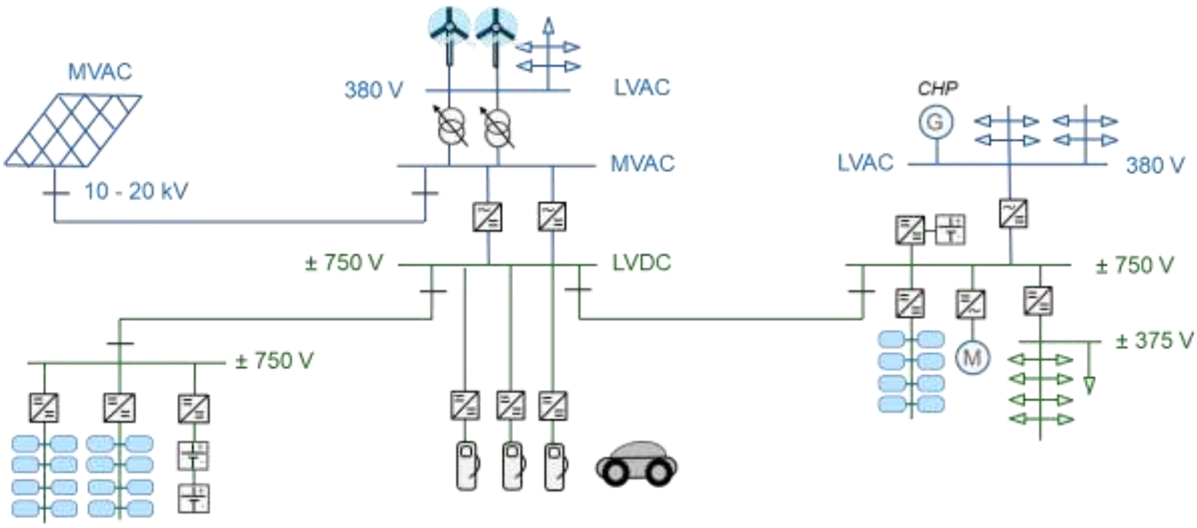


Figure 2.4-2: Industrial power grids.

In such power grids, power converters may take the role of conventional transformers and connect different voltage levels to each other over AC and DC, as well as DC to DC. Whenever power converters operate on both ends of a grid, DC-distribution seems to be the more efficient choice (in terms of cost and power losses). Such an industrial grid adapts to the nature of the systems attached: to AC-systems, it provides AC-connections. To DC-systems, it provides DC-connectivity. Hybrid industrial grids apply in areas with high density of power.

In utility grids, the following use cases apply:

1. DC connection of MV primary feeders (from same or different substations) at normally open locations: This will provide power capacity enhancement of the system. Most likely of back to back structure with or without integration of EV, BESS at the DC bus;
2. DC connection at Primary substation level – This can be between different buses of the same substation or between two substations. This can be back-to-back or point to point in structure. The DC connection between the substation or substation buses can enhance power capacity by using the available transformer head rooms; and
3. The DC grid at MV feeders:

   DC grid connecting primary and secondary substations of different MV feeders can exchange power, use head room in various feeder, provide reliability, integrate EV and BESS Multiport: Multi port connection to MV substation integrating multiple assets e.g. BESS, EV, renewable etc. This can provide grid flexibility, higher utilization of substation capacity and enhance controllability of the connected sources and loads in the multiport device.

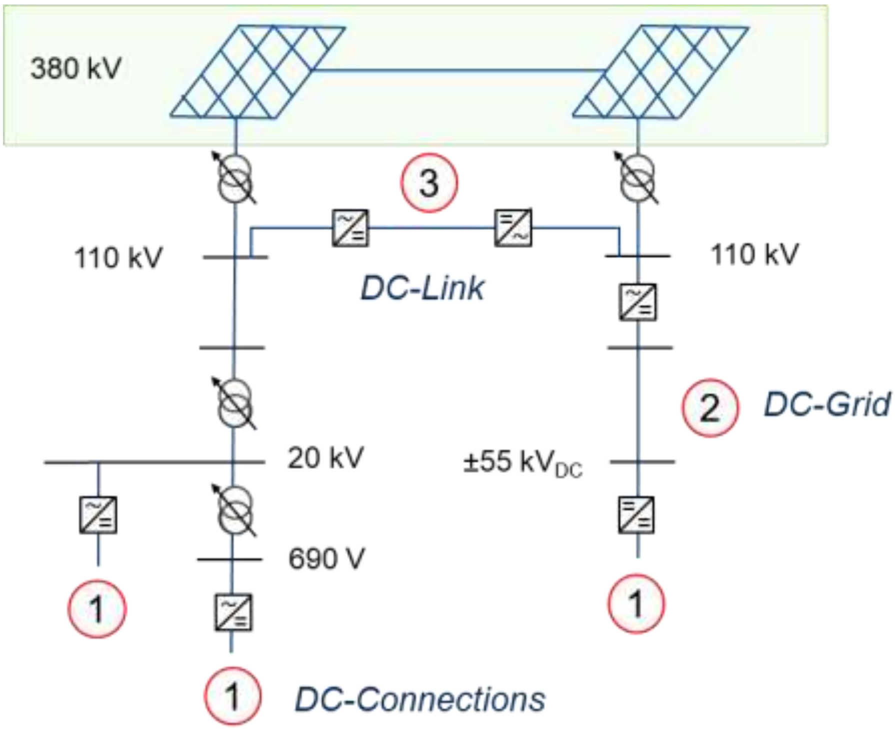


Figure 2.4-3: DC applications in utility grid.

The examples shown represent technical options, which originate from the growing number of DC systems in power grids. Application may look easy, but as the history of power grids shows, there are technical challenges and there is a significant need for standardization to maintain the same level of reliability as in today's power grids.

2.5 Technical Challenges

DC technologies provide comprehensive advantages and new possibilities above AC to meet the challenges of tomorrow. Nevertheless, there are technical challenges mainly reasoned by a lack of experience in both industrial and utility grids, which are discussed in the following subchapters.

2.5.1 Industrial Grids

In industrial applications, DC supply for manufacturing (motor drives) or server farms need an increasing amount of DC power. Other applications with high demand on DC power are fast charging stations for electric vehicles, hydrogen generation, fuel cells and storage systems.

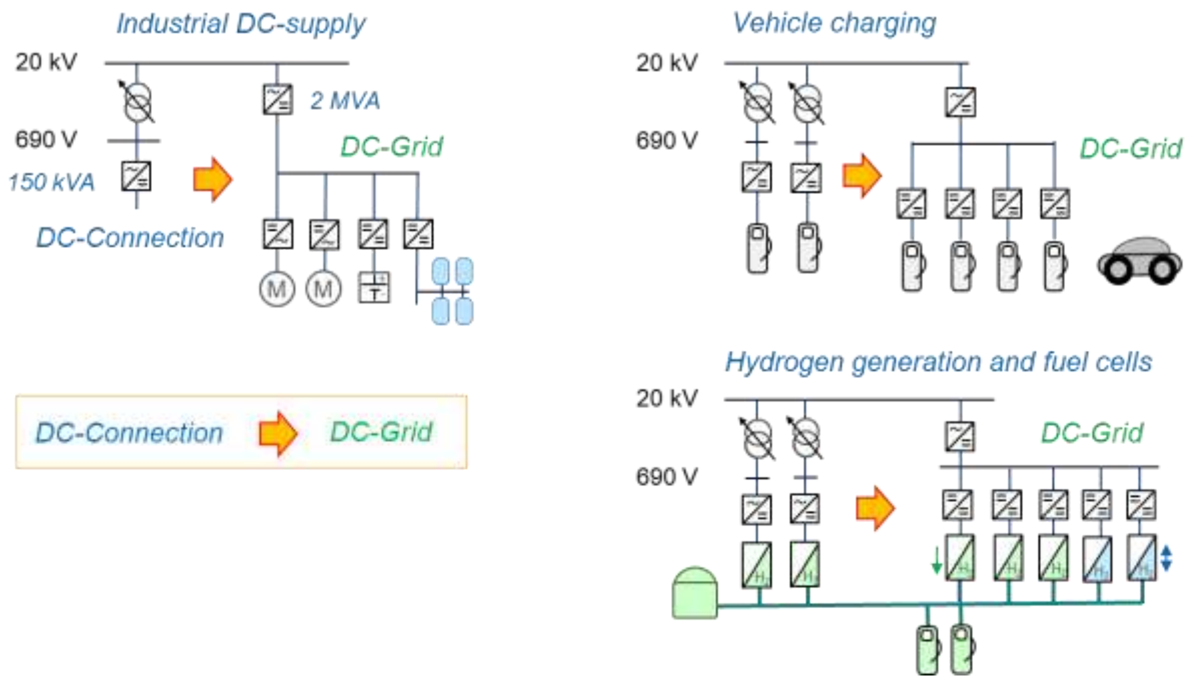


Figure 2.5-1: Example for industrial DC-grids.

Conventional DC connections operating over low voltage AC lines are limited in power to about 150 kW and do not scale up in an efficient way. Moving the AC-converter up to medium voltage level may represent the more efficient approach:

- Higher voltage-level for power transmission (e.g. ±750 V_{DC} instead of 380/√3 V_{AC});
- Higher efficiency of the front-end AC/DC converter (instead of multiple back-end AC-DC converters);
- Lower floor space (AC-DC front-end acting as DC-station with integrated transformer); and
- A cost-effective way to connect DC-systems with low concurrency factors.

The examples illustrate the migration from single DC-connections with limited power move to DC-grids at higher power levels. DC-grids facilitate the integration of DC-systems. The technical challenge is the standardization of DC-grids: While AC-distribution is widely in use, in particular at LV-level, standards on DC-distribution are just emerging.

2.5.2 Utility Grids

In utility grids, connection of DC systems for renewables including storage systems and power-to-gas systems requires AC conversion at some point. Today, AC conversion takes place at low voltage level, so systems interconnect over AC distribution. This may not represent the shortest way for power flow if power from renewable sources needs to be stored before consumption in the grid.

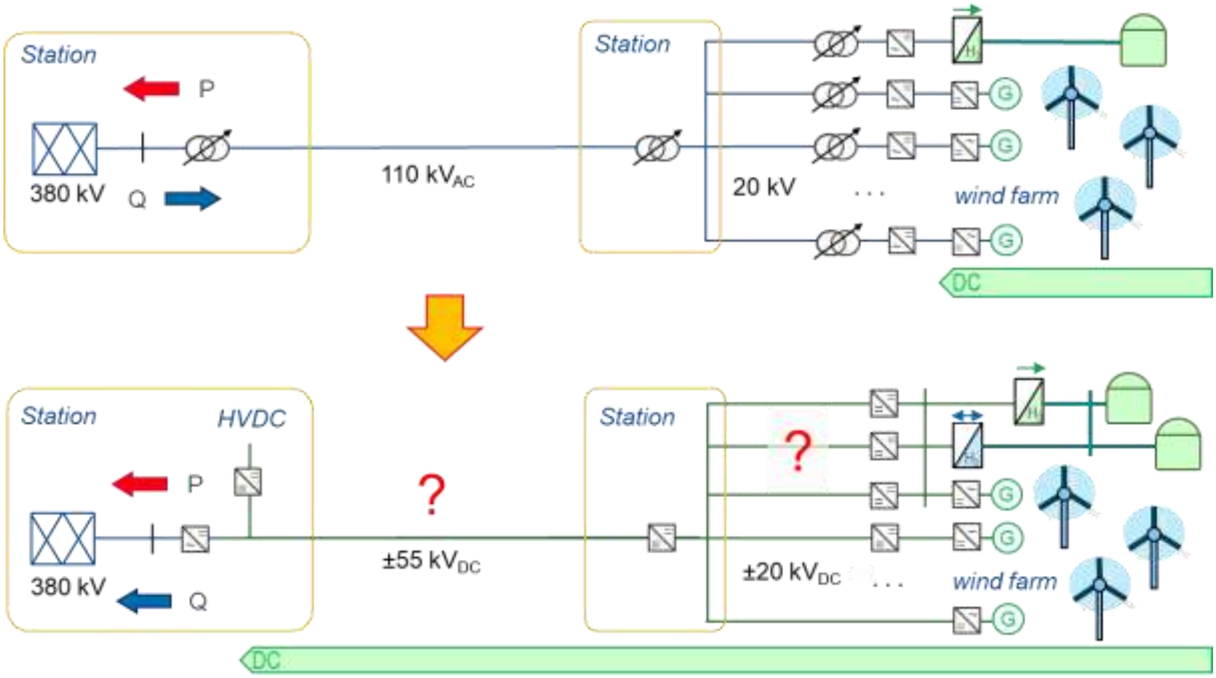


Figure 2.5-2: Connecting DC systems.

Alternatively, DC-systems could interconnect at low voltage level or at medium voltage level. This way, power flow remains in the DC-domain while the conversion to AC moves further up the power grid. At voltage levels up to 60 kV, medium voltage links could even directly feed into HVDC systems.

Among the potential benefits of DC grids embedded in utility grids are reduction of converter losses, reduction of transmission losses, better control of power flow, and no need for reactive power to maintain voltage levels. At the same time, power converters would become grid resources in much the same way as power transformers: As shown in the figure above, stations now operate DC power converters instead of AC transformers.

The domain of ownership for a grid operator could end at high voltage level (respectively a higher medium voltage level such as ±55 kV$_{DC}$) or at medium voltage level (such as ±20 kV$_{DC}$). In either case, grid codes will be required to specify the rules for operating DC-systems on the grid.

Concerning the grid-side converters, no AC grid codes apply, because they represent grid resources, which the grid operator owns and controls. With less conventional power plants on the grid, it can be expected, that new requirements apply for grid-side power converters, beyond the scope of conventional AC grid codes for renewables on the grid. Most likely, grid-forming features would be among their functional set.

From a technical point of view, moving AC conversion further up into the grid appears to be a reasonable approach, as illustrated in the following figure: Connecting DC systems over DC grids reduces the total number of converters on the way. In particular, when paths are used several times e.g. for intermediate storage of renewable power, direct connection over DC could prove to be much more efficient.

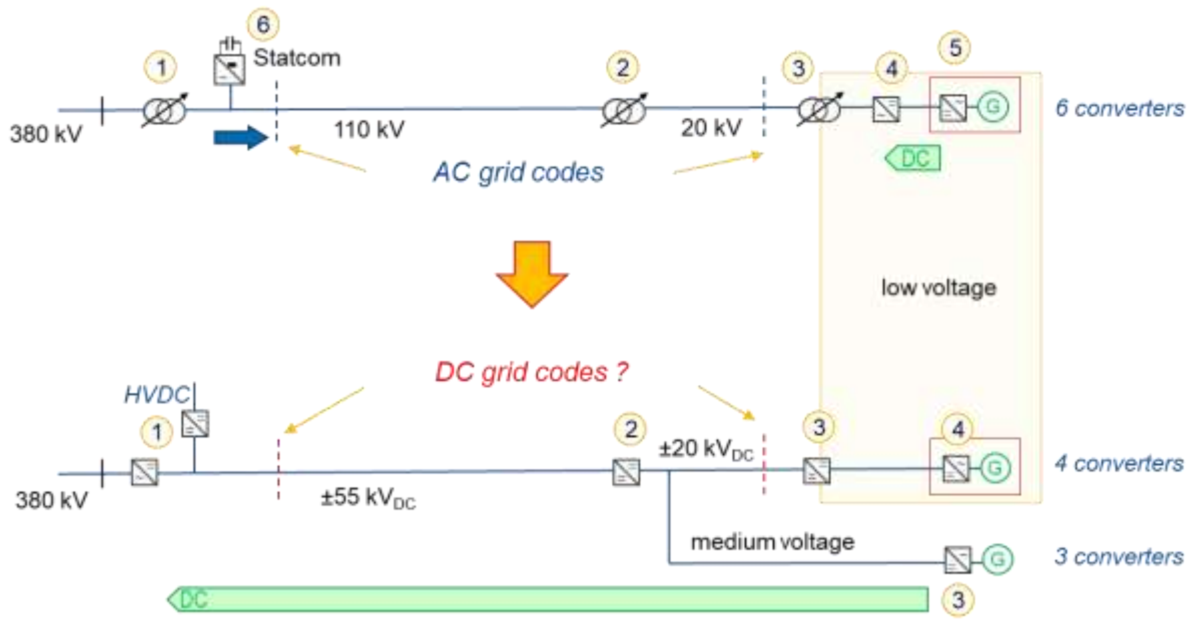


Figure 2.5-3: Technical comparison of AC and DC grid codes.

In summary, there are plenty of issues to be investigated. The current state of the art of DC in distribution grids has DC connections mainly at low voltage level, which are converted to medium voltage by conventional AC-transformers. The better control of power flow has enabled pilot installations for DC-links at medium voltage level. Among the technical issues to be addressed are multi-terminal DC-grids, concepts for operation and protection, and DC grid codes.

While overall efficiency may be a clear benefit, the key requirements for power converters in the distribution grid will be the total cost of ownership over a lifetime of operation and their reliability. Once the key conditions are covered, they may provide new and more flexible ways to operate the grid.

3 USE-CASES AND FUNCTIONALITIES OF DC-DISTRIBUTION NETWORKS

The purpose of this chapter is to summarize applications of DC networks at distribution level, including sample installations and industrial practice. The chapter starts with a comparison of the transfer capacity of DC and AC grids, which represents the key feature of DC systems. Section 3.2 attempts to structure the areas of applications according to a functional view. The main part of chapter 3 is a collection of use cases and solutions, respectively pilot projects worldwide. The collection of use cases and pilot projects differentiates between low voltage applications (in section 3.3) and medium voltage applications (in section 3.4).

3.1 Transfer Capacity of DC-Grids

In power transmission, AC systems utilize 3 wires with a power of

$$P_{1ac} = U_1 I_1 \cos\phi_1 \quad (3.1.1)$$

per wire. U_1 represents the RMS values of the line-to-earth voltage, I_1 represents the RMS-value of the line current, and $\cos(\varphi_1)$ the load factor. In total, the AC-system carries a power of

$$P_{3ac} = 3U_1 I_1 \cos\phi_1 \quad (3.1.2)$$

When operating the same wires on DC, the current needs to be at the same RMS-value as in the case of AC for thermal reasons. Because insulation of an AC system covers the peak voltage, the operating voltage of a corresponding DC system may be fixed to the peak value of the AC voltage ($\widehat{U}_1$), i.e. a factor of $\sqrt{2}$ on the RMS-value:

$$\widehat{U}_1 = \sqrt{2}U_1 \quad (3.1.3)$$

Hence, a DC system may carry a load of

$$P_{1dc} = \sqrt{2}U_1 I_1 \quad (3.1.4)$$

per wire. In total, a two-wire DC-system carries

$$P_{2dc} = 2\sqrt{2}U_1 I_1 \quad (3.1.5)$$

At system level, this leads to the following ratio:

$$\frac{P_{2dc}}{P_{3ac}} = \frac{2\sqrt{2}U_1 I_1 \cos\phi_1}{3U_1 I_1 \cos\phi_1} = \frac{2\sqrt{2}}{3} \approx 1 \quad (3.1.6)$$

Considering the load factor and skin effect, a DC-wire may carry about 150% of the load in comparison to an AC per wire. Hence, the transport capacity of a 2-wire DC system corresponds to a 3-wire AC-system.

In general terms, the following rules apply for DC-systems in comparison to AC-systems:

- A 2-wire DC system has to same power transfer capacity as a 3-wire AC-system;
- Using only 2 wires instead of 3, losses of a DC-system are only 2/3 of an AC-system; and
- A DC system only needs 2/3 of material (e.g. cabling and power converters) of an AC system.

Figure 3.1-1 illustrates the case.

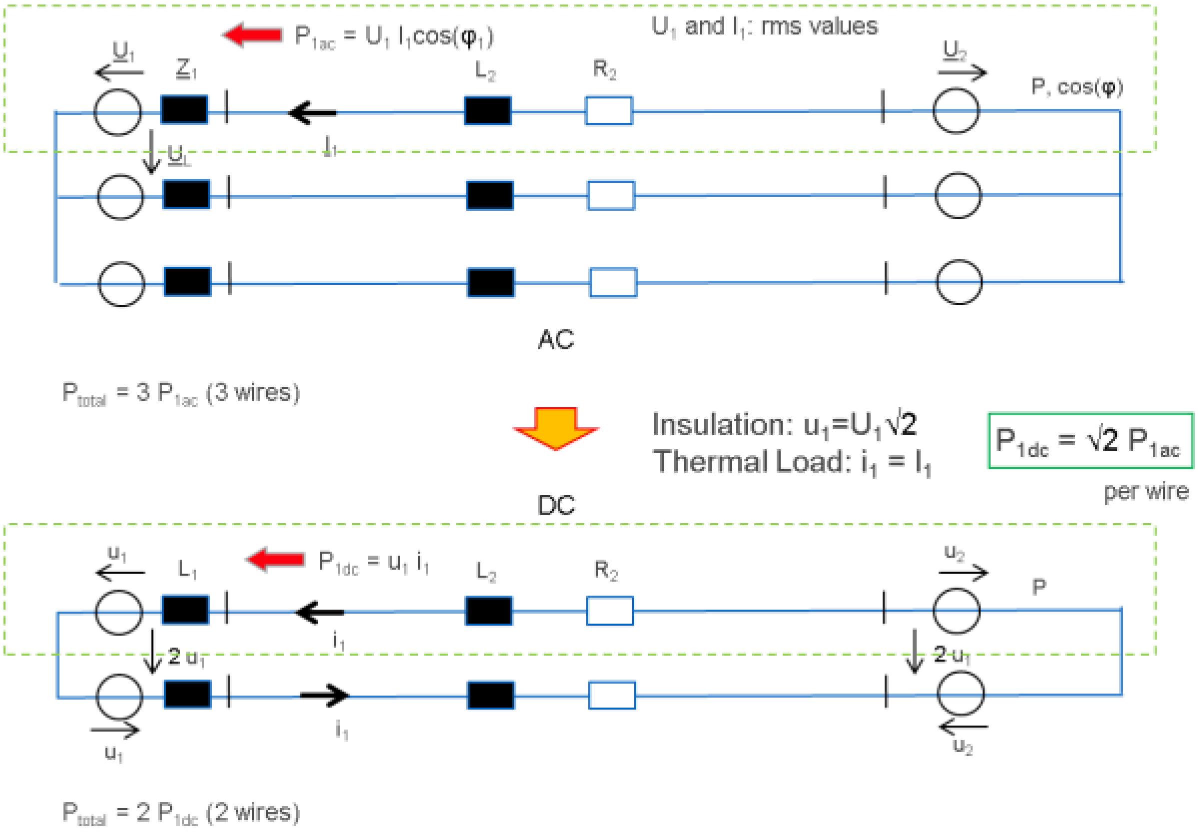


Figure 3.1-1: Comparison of AC and DC transmission.

Depending on the physical properties of cables, DC-systems may actually carry much more load when operated at voltages above the peak value of corresponding AC-systems. This section just intends to compare the basic physical set-up of AC versus DC. For components and technologies, including transfer capabilities, pls. refer to section 4.3 and 4.3.3 (cables and overhead lines).

3.2 DC used in Distribution Systems

Distribution grids handle power supply over multiple voltage levels to traditional AC loads, and increasingly connect DC loads and DC sources. Currently, the conversion from AC to DC takes place at the lowest voltage level. This section summarizes the characteristics and potential benefits of DC applications in distribution grids at low voltage level and medium voltage level.

3.2.1 Low Voltage Applications

In low voltage applications, 4-wire AC systems may carry 2 DC-systems, as illustrated in Figure 3.2-1.

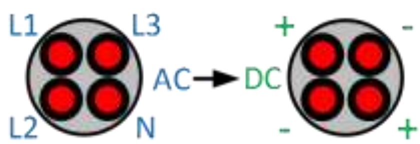


Figure 3.2-1: Use of low voltage AC cables in DC systems.

In this case, an AC cable may carry twice the load when operated in DC at the same RMS-value of the current and at the same AC peak voltage. Many low voltage cables such as 400V are rated for 1 kV [3]. In this case, the DC voltage may be raised to 1 kV, which allows a factor of five in power transmission.

Other options use bipolar systems including a neutral indictor in order to support unsymmetrical systems, which only use one polarity against the neutral conductor. Such DC-systems follow the same concepts as 3-wire AC-systems (with 3 conductors for symmetrical systems), respectively 4-wire AC-systems (with 3 conductors and a neutral one for unsymmetrical systems). DC-systems use 2 phases instead of 3, with opposing phase angles (at 180 degrees). Grounding may follow the same rules as in AC, e.g. TN-C, TN-S, TN-C-S or IT systems.

As a further use case for DC in low voltage level, also DC grid charging infrastructure for electric vehicles may occur in the future. Therefore, a DC microgrid feeding several electric vehicles in a parking ground, e.g. of a larger apartment complex or public parking places. In this case, besides higher transmission capacities, also the lower voltage drop and losses in DC grids can be used to supply in higher distances.

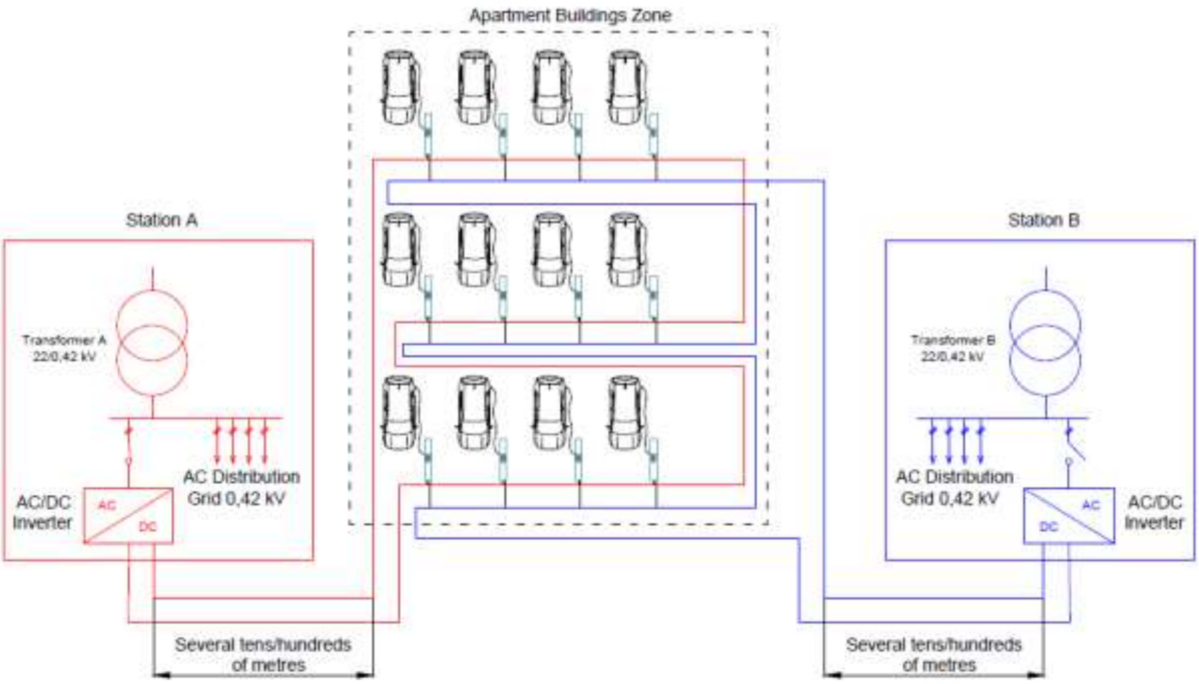


Figure 3.2-2: DC grid charging infrastructure for electric vehicles.

As a consequence, the cable capacities can be used more efficiently while feeding a higher amount of charging stations. Furthermore, DC enables a faster charging process of the vehicles and at the same time reduces the impact on the overlaid AC grid, for example due to asymmetries

3.2.2 Medium Voltage Applications

Medium voltage power distribution normally uses 3-wire systems, either as overhead wires or underground cables. In order to make efficient use of DC, 2 AC systems may be operated as 3 DC systems. Figure 3.2-3 illustrates the concept.

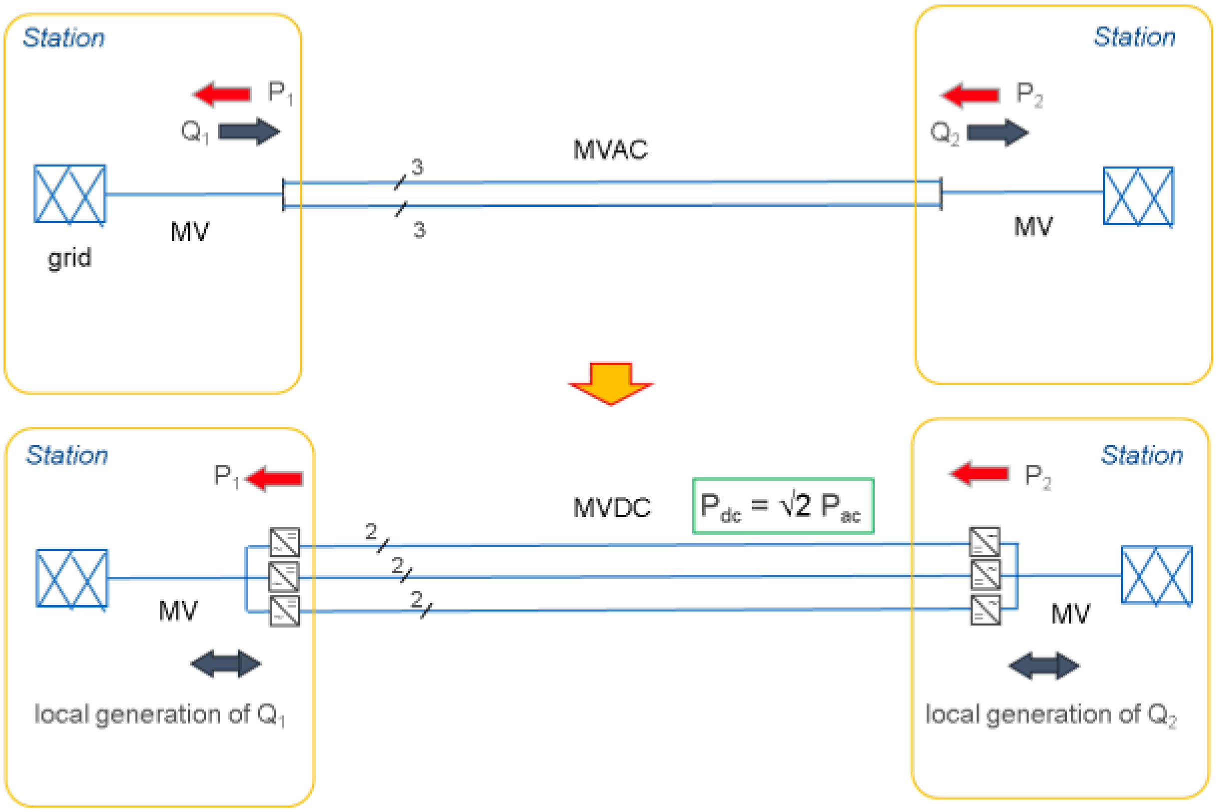


Figure 3.2-3: Use of medium voltage AC cables in DC systems.

Among the benefits of DC operation are:

- More active power (about a factor of 3/2 by using 3 systems instead of 2);
- No reactive power to be carried in the grid (may be generated locally); and
- Controlled load flow and power quality.

Transmission losses are typically the same, because the same number of wires are used. However, in terms of efficiency, the DC case performs better, because it can carry more load with the same losses. If the cable allows increasing the DC voltage, losses in relation to the increased transport capacity become significantly lower. However, the DC case requires the use of power converters that introduce extra losses and costs, which need to be balanced against the capacity benefits.

Functionalities of DC-distribution networks

The DC distribution grid will have similar functions as in AC distribution management system, providing the following distribution grid functions in the distribution management:

- Network Visualization and MVDC: The available measurement at converter terminal can be used as remote measurement for network visualization;
- Fault Management and MVDC: The DC link can help to detect fault with available voltage and current measurement, help to restore the grid quickly and reduce the voltage collapse during the fault;
- Network Maintenance and MVDC: MVDC can participate in switching sequence and change in power output (from MVDC) to offer various optimized system operation during maintenance and normal operation [4];
- Advanced Application and MVDC:

    - Distributed Generation (DG) and MVDC: MVDC can help to reduce such impact of DG with:
        - Controlling voltage;
        - Redirect power flow to enhance feeder power capacity;
        - Integrate DG with multiport converter.
    - Voltage variation and MVDC.
- Network Planning and MVDC: MVDC can participate in centralised, semi centralised or decentralised approaches of voltage variation to:
    - Reduce loss with minimized reactive power flow;
    - Reduce peak power with voltage reduction;
    - Keep voltage in defined limit.

Functionalities of MVDC link

The key functionality of the MVDC link are:

- Control of active and reactive power from operator set point or local measurement based;
- Control of voltage at both terminals from set point, automatic or local measurement based;
- Grid forming control to improve grid strength, stability and reliability;
- Black-start capability;
- Islanding capability with energy storage to supply critical load;
- Active harmonic filtering to improve power quality; and
- Protection coordination with MV network and protection against external/internal faults.

3.2.3 Benefits of DC-Distribution

DC distribution in power grids promises the following benefits:

- Higher Connectivity: More capacity to connect (1) renewable energy sources: solar parks, wind farms and energy storage, (2) carbon emission free loads: charging stations, heat pumps, electrolysis for H2 generation;
- Controlled Load Flow: in increasingly meshed configurations and for grid reinforcements. Power converters allow the dynamic utilization of grid resources; and
- More Transport Capacity for: the integration of traffic and heat into the power grids, the shift to renewable energy sources, the dislocation of power sources and power sinks and the increasingly decentralized supply.

Reactive power supply on AC side: If inverter is adjacent to AC grid or is connecting two AC grids, the power quality in AC grids can be improved. At the same time, the structural change in power grids including decentralisation (renewable power plants replacing conventional power plants) and decarbonisation (electric traffic and heat replacing use of mineral oil) is changing the role of the medium voltage layer from power distribution to power provision and grid operation. The majority of sources and loads representing DC systems driven by power converters, concepts for power controllability, grid structure and protection need to be adapted and technical guidelines produced.

3.3 Low Voltage Use Cases and Applications

This section shows DC applied in practice at low voltage level. The first part (3.3.1) summarizes the general use cases, a second part (3.3.2) has a look at installations world-wide, covering pilot installations, technical prototypes and commercial installations. The order of use cases and pilot installations does not indicate a specific priority or relevance. Use cases and applications are still emerging. The best industrial practice will establish in the coming years together with matching industrial standards.

3.3.1 DC Use Cases Examples for LV Systems

LVDC-UC1: LVDC link for long distance connection of LV customers

Description of the use case

From a MV/LV substation (on the public grid), it could be useful in some cases to create an LVDC feeder to connect a new customer - or a group of customers - particularly far from the substation. In the short term, with the current regulatory context, in order to still connect the customer in LVAC, a DC-AC converter can be used making it a 2-terminal-LVDC link. In the longer term, DC connection to the LV public grid could be proposed by DSO.

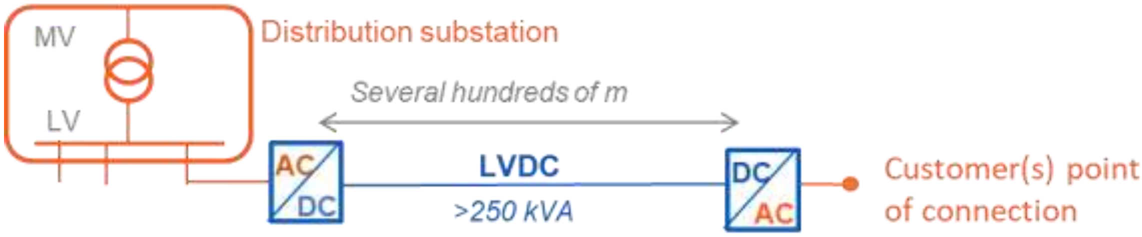


Figure 3.3-1: LVDC link for long distance connection.

Potential advantages of the application

Transit capacity gain by resolution of the voltage constraint: not only the voltage drop is lower (when the DC voltage is at least equivalent to the AC one) but the voltage is either rectified at the end of the link or better controlled at the substation.

Management of LVAC electrical quantities (Q, V_{AC}) at the substation:

- Resolution of voltage constraints at the end of the line/cable; and
- Possibility of ancillary service at the substation.

When to use it?

Mainly as an alternative to an expensive grid reinforcement when the connection of a new LV customer (or several) requires it.

Required equipment

- Around 200-to-1000 kVA LVDC station at MV/LV substation;
- DC link: voltage level and architecture not standardized yet, but voltage levels up to 1500 V are conceivable; and
- Around 200-to-1000 kVA LVDC station at customer point of connection.

To compare with:

- This kind of solution could be compared to:

  - A classic reinforcement of the grid (new MV/LV substation);
  - A solution where a classic LVAC link is used with an AC/DC/AC converter at the customer point of connection.
- A study of the break-even distance of connection from which it becomes profitable using a LVDC link instead of a LVAC one could be useful.

Qualitative assessment of the benefits of the application:

The use of LVDC solutions to connect customers which are either far away or have big power capacity should not be seen as a systematic solution. However, in some specific cases where an expensive grid reinforcement is needed, it should be considered as a potential alternative.

However, using this kind of solutions in the public distribution requires to particularly consider the long-term influence it could have on the grid planning. Indeed, developing DC feeders for customer connection means having DC feeders in the public grid perimeter used for some customers and this has an influence on the long-term on the connection possibilities for future customers of the grid. It also impacts (potentially positively) the way the grid can be reconfigured.

LVDC-UC2: LVAC/LVDC hybrid grids for the integration of high shares of EV/PV

Description of the use case

In the particular context of EV, PV (and storage) development, some high penetration rates could appear in residential areas.

From a MV/LV substation, it could be useful to create a hybrid (AC and DC) feeder with AC double points of connection: AC for classic installations and DC for specific equipment such as EV/PV/BESS.

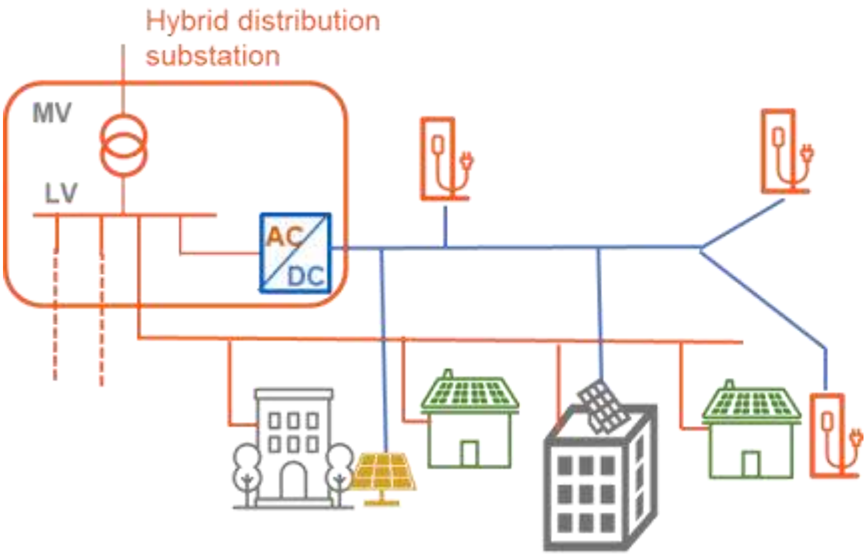


Figure 3.3-2: AC/DC hybrid grid in a residential area with high shares of EV and PV.

Potential advantages of the application:

- Better overall efficiency thanks to the pooling of conversion equipment and the use of DC in distribution;
- Bigger shares of EV/PV integration; and

- Management of LVAC electrical quantities (P, Q, V_{AC}) at the substation and possibility of ancillary service at the substation.

When to use it?

Mainly as an alternative to expensive grid reinforcements when the development of EV and/or PV requires it.

Required equipment

- Around 200-to-1000 kVA LVDC converter at MV/LV substation;
- DC link: voltage level and architecture not standardized yet, voltage level up to 1500 V conceivable; and
- Specific customer points of connection for EV/PV.

To compare with:

- Classic reinforcements of the AC grids; and
- A study of the threshold (in terms of EV/PV development) from which it could be profitable to deploy an LVDC infrastructure for different kinds of grids could be useful.

Qualitative assessment of the benefits of the application

One of the major difficulties related to the development of such a solution is the assessment of the distribution of the extra costs and gains between the DSO, the equipment manufacturers and the owners. Creating a LVDC feeder in the public LV distribution grid means delegating the responsibility of voltage rectification to the DSO (and not in the equipment).

LVDC-UC3: E-mobility charging solutions

Description of the use case

This use case addresses solutions dedicated to e-mobility charging, especially DC charging. Indeed, one of the specificities of EV charging, compared to other uses of electricity, is that it already exists in both AC and DC forms. The converter can therefore be on-board (in the vehicle) or external (in the charging station). Thus, depending on the charging modes, the DC distribution solutions dedicated to recharging electric vehicles have a perimeter that extends either to the stations or to the vehicles themselves.

As EVs need to be able to charge anywhere, an embedded converter will always be needed in the vehicle to be connected to AC grids.

On the short term, DC distribution solutions for EV charging infrastructures seem suitable for the cases where DC charging already exists:

- Fast and ultra-fast charging (22 kW to 350 kW);
- DC vehicle-to-grid; and
- Bus charging stations

This is also the case if existing LVDC-infrastructure in cities can be used, e.g. to charge e-busses on city tram grids overhead-line (converter integrated busses).

On the medium term, this use case also applies to all other EV charging situations and use cases, potentially combined with renewable, storage and/or other DC uses, or even to electrified Sea & River transport where DC distribution solutions can be used to connect charging infrastructure.

In all these situations, the main perimeter that is concerned is the private network of the charging infrastructure operator. The public network is not directly concerned, unless DC connection points to the public grids are proposed by the DSO.

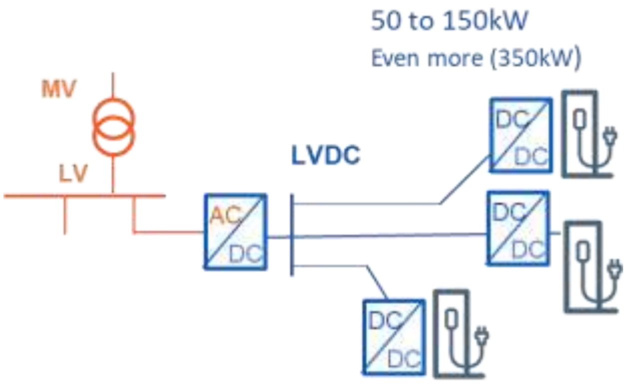


Figure 3.3-3: DC distribution solution for an EV charging infrastructure.

On the longer term, another situation where DC distribution could be used for e-mobility charging concerns the future potential electrified roads. Indeed, for dynamic charging infrastructures on highways or in urban areas, LVDC and MVDC solutions could be used in order to find optimized connection solutions to the grid. The DC solutions could be integrated either only in the private perimeter of the charging system operator or also in the public network perimeter with DC connection points to the grid.

Potential benefits of this use case:

- Pooling of the conversion resulting in:
  - Better overall energy efficiency;
  - Decrease in the overall investment cost;
  - Space saving.
- Control possibilities (U, Q) thanks to converters; and
- Savings on infrastructure and charging solutions

For the last sub-case described:

- Optimal sizing of grid connection and distributed impact; and
- Potential reduction in link losses.

LVDC-UC4: Specific internal LVDC distribution

Description of the use case:

This use case addresses DC solutions for specific installations where only DC end equipment can be found. Several examples can be described;

- Big PV plants (LVDC distribution then potential MVDC inter-array grid);
- Industry 4.0: DC distribution to machine tools using variable speed drives (LVDC distribution); and

- Data centres (LVDC distribution).

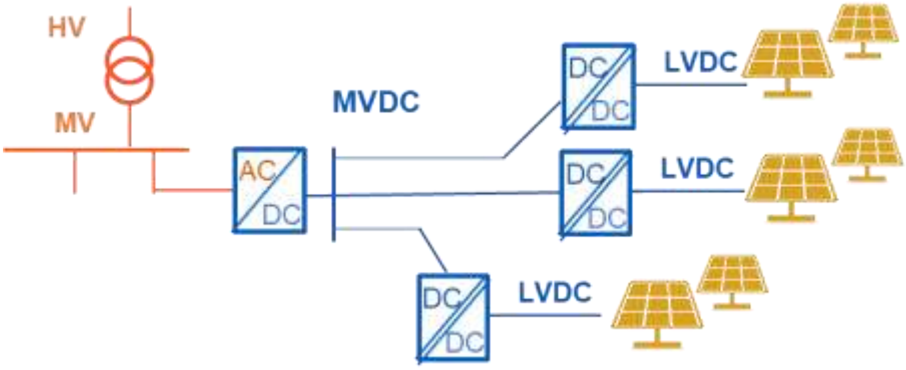


Figure 3.3-4: LVDC and MVDC distribution solutions for specific installations.

In all these situations, the main perimeter that is concerned is the private network of the charging infrastructure operator. The public network is not directly concerned, unless DC connection points to the public grids are proposed by the DSO.

<u>Potential benefits of this use case</u>:

- Pooling of the conversion resulting in:
    - Better overall energy efficiency;
    - Decrease in the overall investment cost;
    - Space saving.
- Control possibilities (U, Q) thanks to converters; and
- End equipment savings.

3.3.2 Solutions and Pilot Projects LVDC

While part 3.3.1 summarizes DC applications in terms of general use cases, the purpose of part 3.3.2 is to show DC applications in practice. This part presents a collection of pilot installations, technical solutions and commercial installations world-wide. The pilot projects are listed in no specific order.

LVDC-Pilot1: LV-Engine project in the United Kingdom [5]

One of the UK Distribution System Operators (DSOs), SP Energy Networks, is carrying out a project, called LV Engine, which aims to trial solid state transformers (SSTs) at 11 kV/0.4 kV substations to deliver hybrid AC/DC networks. This effort will demonstrate number of functionalities as follows:

- Voltage regulation at LV Networks;
- Capacity sharing with other substations;
- Cancelation of LV imbalance load seen by the 11 kV network;
- Reactive power compensation and power factor correction at secondary substations; and
- Provision of LVDC to supply rapid and ultra-rapid EV chargers.

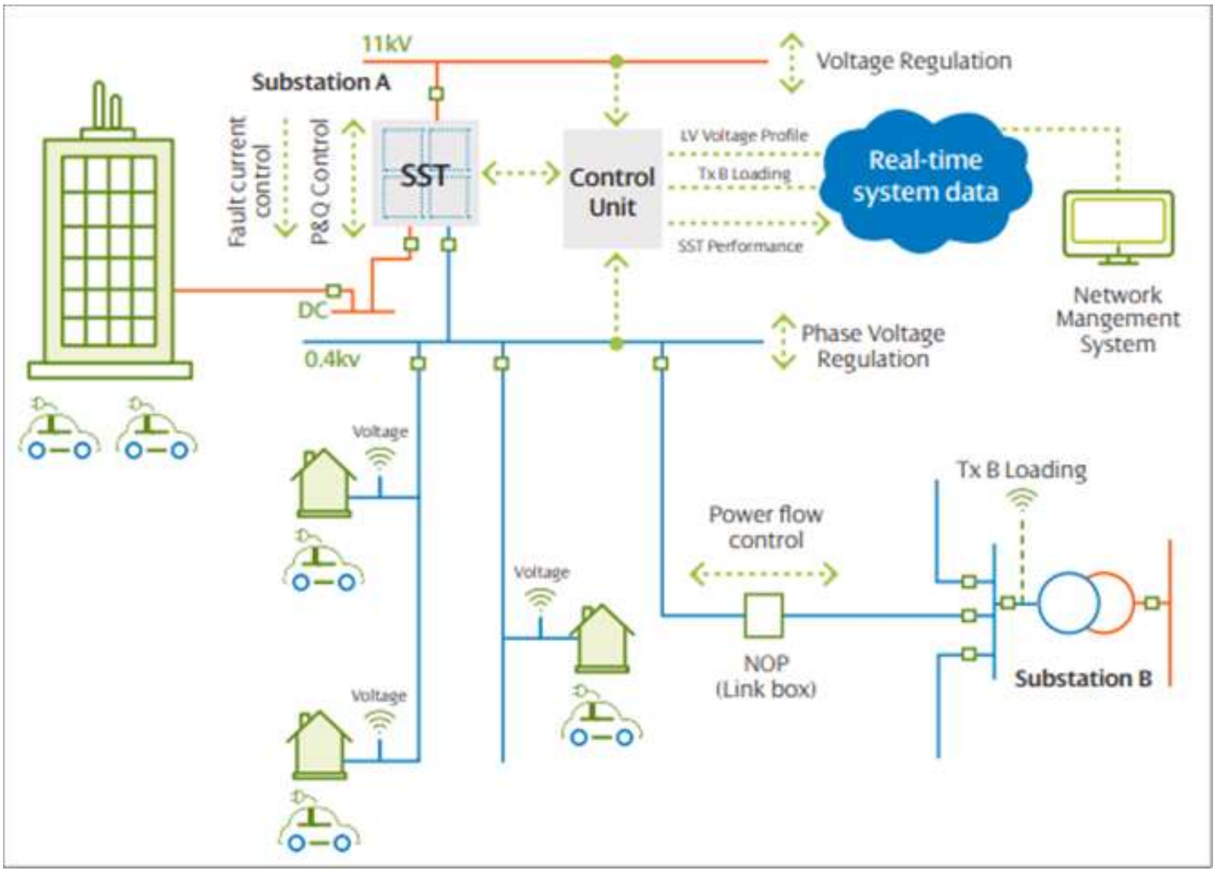


Figure 3.3-5: LV Engine project concept.

The LVDC demonstration is one of the most innovative aspects of the project as it has not been previously trialled by any DSO in the UK. The intention is to not only trial the technology but also develop the requirements for a business as usual solution that can be replicated for future LVDC deployment by a network operator. The main focus of this application is to provide LVDC network for supplying ultra-rapid EV chargers. In this case, a 150 kW EV charger, which is owned by a customer, is supplied by 950 V_{DC} supply (+/- 475 V bipolar) operated by SP Energy Networks. The direct benefit to the customer includes significant reduction in EV charger unit cost, more efficient unit (~2% better efficiency), and better ecological footprint. In summary, the following developments have been carried out in the project:

- SST technology: To deliver the LV Engine functionalities two innovative SST topologies have been developed:
  - Unified Power Flow Controller (UPFC) –This topology uses a modified UPFC topology (for DC supply provision) at the secondary side of conventional transformers (11 kV/0.4 kV). UPFC will be added to the existing distribution transformers to deliver the AC and DC functionalities planned in LV Engine. The aim is to enhance Technology Readiness Level (TRL) of this product from 6 to 9;

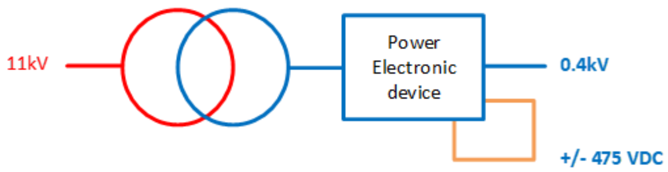


Figure 3.3-6: Modified UPFC topology at the secondary side of conventional transformers.

- Three-stage Solid State Transformer – This design includes a 3 stage conversion SST design using high frequency transformer and a modular design. The aim is to enhance TRL of this product from 5 to 8;

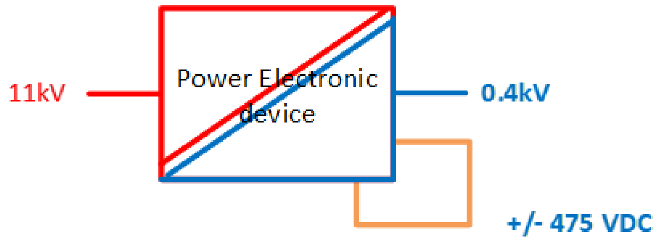


Figure 3.3-7: Three-stage conversion SST design.

- LVDC earthing design: TN-S earthing system has been selected as the most suitable arrangement. Under the UK Electricity, Supply, Quality and Continuity Regulations (2002) (ESQCR), DNOs should provide solid earth at low voltage network owned and operated by them. Also, in order to minimise the risk of stray DC currents in protective earth TN-S earthing was selected as opposed to TN-C or TT earthing; and
- LVDC protection: a protection strategy considering undervoltage shunt release, instead of relying solely on overcurrent protection, has been developed for this application to avoid the need for over-sizing the source converter owned by the DSO. Commercially ready LVDC switchboards are usually complied with IEC 61439-2 whereas the typical LVAC switchboards owned by DSOs should be in compliance with IEC 61439-5. LV Engine project, is designing a DSO approved technical specification which capture relevant requirements in both IEC 61439-5 and IEC 61439-2.

LVDC-Pilot2: DC Distribution projects in South Korea [6]–[12]

The Korea Electric Power (KEPCO) has a DC distribution test center and implements two major LVDC projects. The test center is located at KEPCO's Gochang Power Test Center. It is claimed to be the largest in the world, with 6 km of overhead line and underground cables. The center is equipped with a 500-kW AC-DC power converter, a 2-MW energy storage system (ESS), 250-kW wind turbines, 250-kW photovoltaics (PVs), 50-kW vehicle to grid (V2G), a 100-kW diesel generator, 100-kW cogeneration facilities, 600-kW artificial load, DC home appliances (for example, refrigerators, computers and TVs), high-speed DC circuit breakers and operating systems.

KEPCO currently has two demonstration projects, an LVDC overhead line in the metropolitan city of Gwangju, South Korea, and an LVDC distribution network on the South Korean island of Geochado in the South Sea.

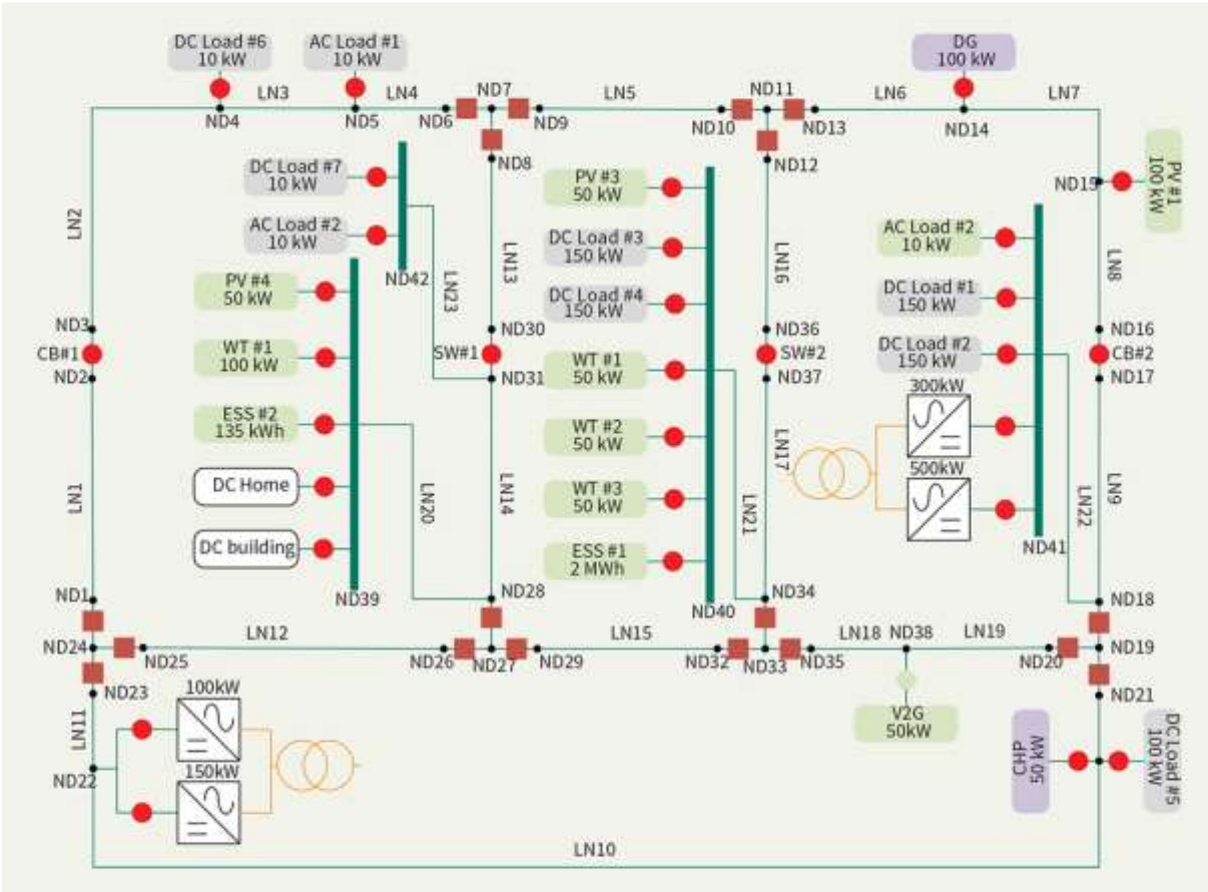


Figure 3.3-8: Single-line diagram of Gochang demonstration site system.

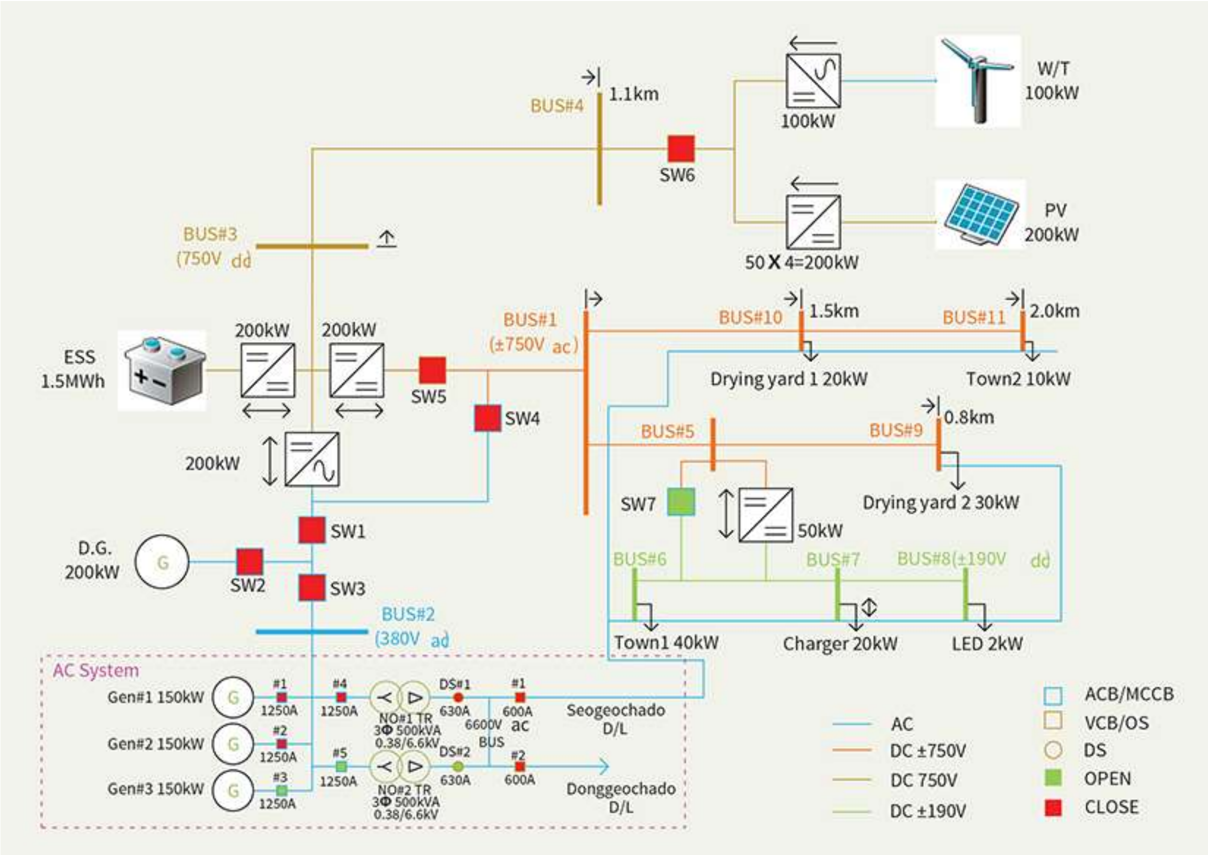


Figure 3.3-9: Island of Seogeochado's dc island distribution diagram.

In Seogeochado, KEPCO constructed a 1500-V_{DC} (±750 V_{DC}) distribution line to replace an existing 6.6-kV_{AC} distribution line. The new DC line connects to the renewable energy sources to supply DC power to residential customers. This LVDC project included the installation of 200-kW solar power, 100-kW wind generation, a 1.5-MWh ESS, DC electric charging points for electric vehicles and a new diesel generator.

LVDC-Pilot3: Suzhou Tongli AC/DC hybrid Project in Jiangsu, China [13], [14]

The AC/DC hybrid project is located in Tongli Suzhou Jiangsu China and sponsored by 2017 National key research and development projects of China. The main stimulation to build this system is:

1. To improve the renewable energy consumption capacity of public power grid. Tongli belongs to the industrial developed towns just along the Yangtze River. Distributed PVs are installed on the roofs of many industrial factories to reduce power consumption which comes up with a lot of overvoltage in PCC and therefore a lot of solar energy should be abandoned;
2. To supply power in high efficiency. With the integration of DC systems, the power efficiency can be improved significantly; and
3. To explore energy transformation technologies.

Tongli has held three international energy reform forums and the first One Belt And One Road energy ministers' meeting, since different power related technologies are implemented here. With AC/DC hybrid system, different kinds of energy can be integrated and transformed more convenient and more stable.

Tongli AC/DC hybrid project contains power electronic transformer (PET), fault current limiter (FCL), DC solid state switch, DC EV charging station, surface PVs on roof/wall/road, super capacitor, and lithium iron phosphate mixed energy storage system. By the end of 2019, the total capacity of the project has reached 4.38

MW in normal operation condition. The capacity of multiple kinds of renewable generators have reached 2.9 MW, together with 2.68 MW of multiple DC loads (e.g. DC data centre, residential quarter, and charging station), 0.97 MW with AC loads and 0.72 MW of energy storage system.

Figure 3.3-10: Suzhou Tongli AC/DC system layout.

All the generators and loads can be integrated by five voltage levels including 10 kV_{AC}, 380 V_{AC}, ±750 V_{DC}, ±375 V_{DC} and 220 V_{DC}, which form one 750 V_{DC} microgrid, one 375V_{DC} microgrid, one 220V_{DC} nanogrid (with a 48 V_{DC} Bus inside) and two 380 V_{AC} Microgrids. Meanwhile, two 3 MVA PETs, two 2.5 MVA VSCs and one bidirectional DC-DC converter are installed together to ensure the convenient and reliable energy transformation among these microgrids/nanogrid. Each microgrid is connected to the public network via at least one PET or VSC, which allows it to have a bidirectional energy exchange with the public network. The topology of Suzhou Tongli AC/DC hybrid system is shown in Figure 3.3-11.

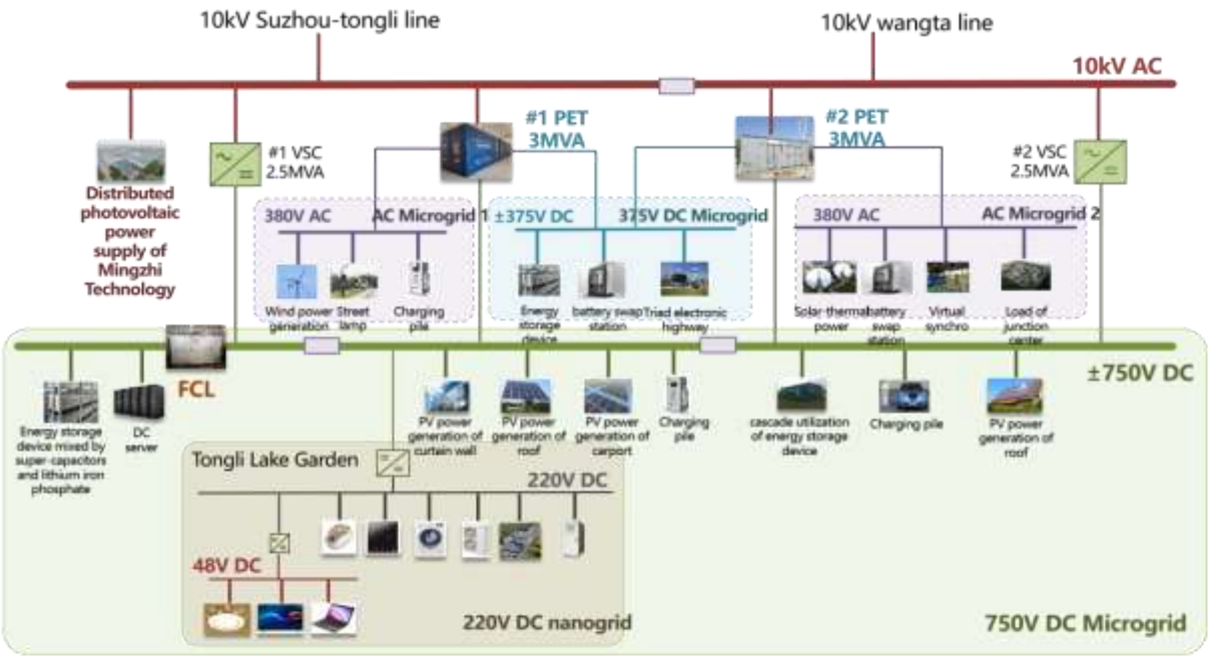


Figure 3.3-11: Suzhou Tongli AC/DC hybrid system topology.

The four most important key operation technologies of the project are:

1. Multi-port high efficiency power electronic transformer technology: Considering multiple kinds of application scenarios, a 3 MVA Silicon-based power electronic transformer (with the efficiency of 96.44%) and a 3*1 MVA Silicon carbide PET (with the efficiency of 98.5%) have been developed. The two types of transformers separately use centralized large capacity and distributed small capacity technology to accommodate different energy dispatch situations, whatever the centralized high density or distributed low density scenario. The high-effective and reliable operation of the park is realized through the coordination of the two transformers;

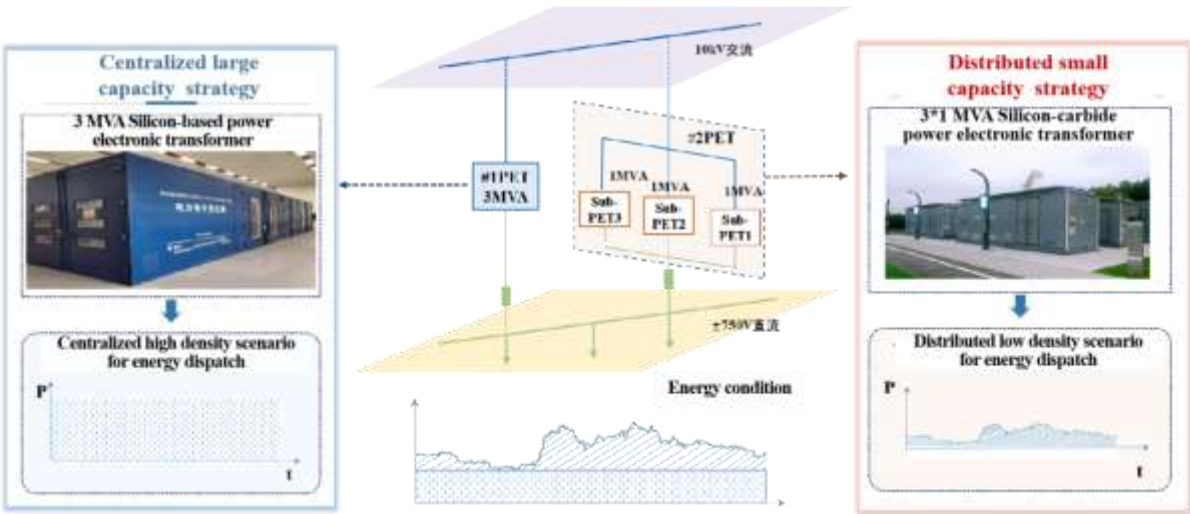


Figure 3.3-12: Multi-port high efficiency PETs cooperation.

2. Multi-boundary protection based on DC grid topology: Aiming at the problems of complex fault mechanism, short fault feature duration and difficult fault location in DC distribution network, multi-boundary protection based on DC grid topology was proposed. GOOSE high-speed real-time communication

technology realizes the rapid identification and precise faults excising, which solves the problem of DC distribution network protection;

3. Impedance-based low frequency oscillation analysis and optimization: It is found that the output equivalent impedance has obvious peaks in the low frequency band, which is easy to interfere with the equivalent input impedance of the load side. The stability margin of the multi-cascade system is improved by parameter optimization, and the oscillation on 750 V_{DC} bus is successfully suppressed;
4. Grounding mode in Tongli demonstration project: In order to solve the problem of current corrosion, Tongli system adopts single point direct grounding. In order to effectively reduce the current existing in the ground wire under unbalanced operation, the N poles are connected with the ground by installing anti-parallel diodes, and the ground wire is grounded directly through only one point.

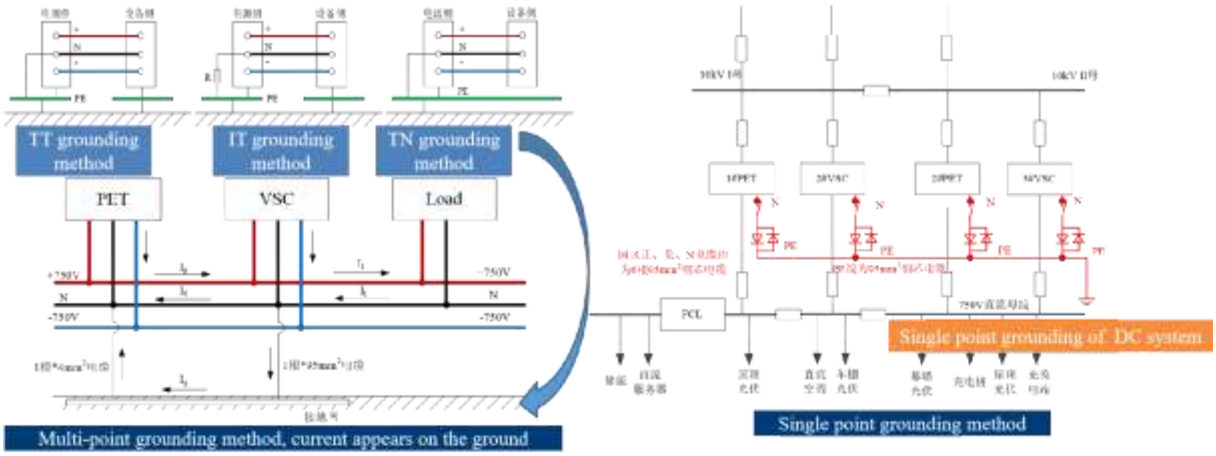


Figure 3.3-13: Grounding Mode of Tongli System.

LVDC-Pilot4: Field test environment for LVDC distribution in Finland [15]–[20]

The introduced LVDC field test environment is a part of the local distribution network owned by a Finnish energy corporation Suur-Savon Sähkö Ltd. (SSS Ltd.) and operated by its subsidiary distribution company Järvi-Suomen Energia Ltd. The platform has been realised in collaboration with LUT University as a part of the Finnish national Smart Grids and Energy Markets (SGEM) research program.

In the utility networks, the LVDC system replaces the present-day 400 V low-voltage AC networks and also lateral parts of the medium voltage network. The opportunity to use up to 1.5 kV_{DC} voltage and power electronic voltage conversions instead of the maximum 1 kV_{AC} voltage and traditional transformers may significantly increase the technical performance of the low voltage distribution. From the DSO perspective, the LVDC technology and the converters in the system:

- Provide means to improve the power quality and supply security experienced by the electricity end-users;
- Improve the economy of the power distribution;
- Provide platform for flexible integration of small-scale renewable generation and energy storages; and
- Form an infrastructure for intelligent network management and electricity market functionalities.

The LVDC system is recommended to be constructed as terrain isolated (IT) underground cabled system due to electric safety reasons. The common LV underground power distribution cables are also rated for DC use. An underground cabled network is less vulnerable to weather phenomena than overhead line network that reduces, for instance, the number of equipment failures due to lightning incidents.

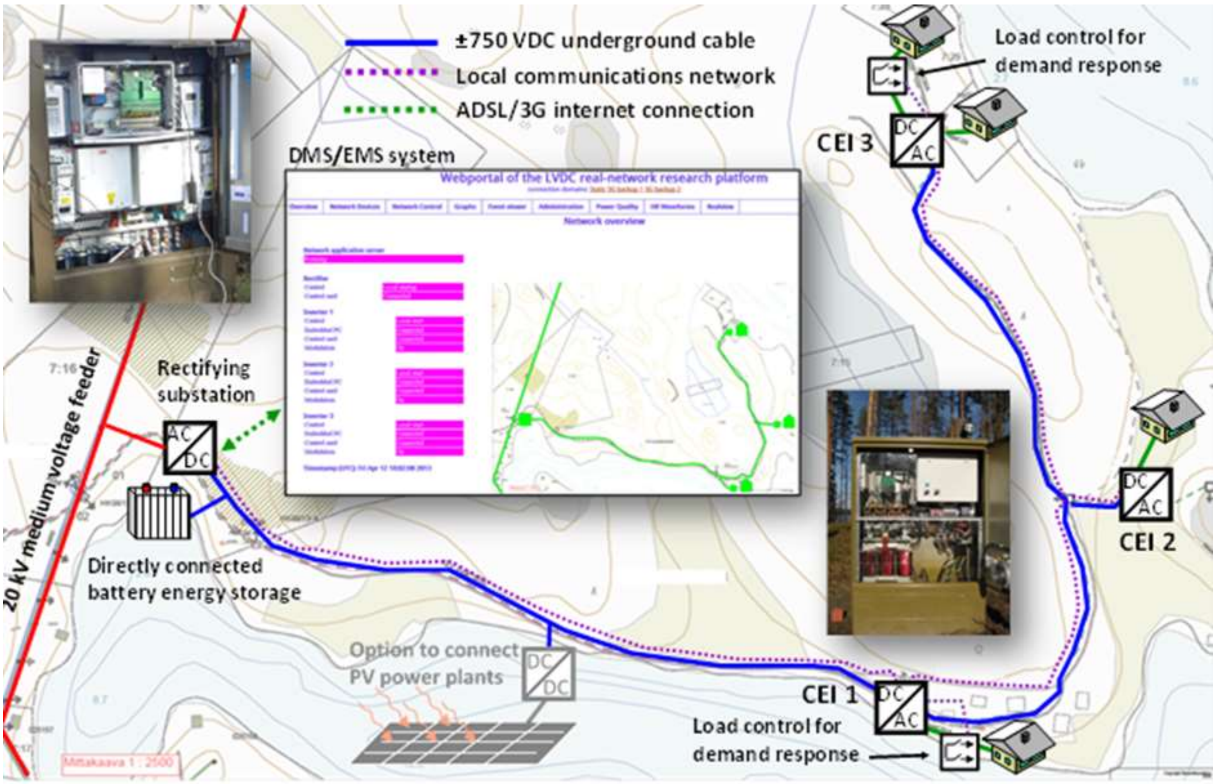


Figure 3.3-14: Main circuit layout of the system.

The main structure of the system follows the basic concept of public LVDC distribution system. The realized LVDC installation comprises of a 100 kVA rectifying substation, a 1.7 km long underground cabled ±750 V_{DC} network and, at the moment, three customer-end inverters (CEI) responsible for providing 230/400 V_{AC} voltage supply for the four end-users (Figure 3.3-14). The setup includes an ICT system for control and supervision of the network and the converters, as well as, a protection system realized based on principles presented in [21]. The system is fed from the 20 kV medium-voltage network through double-tier converter transformer. The LVDC network is realised as unearthed system (IT). The installations are designed according to the national low voltage standard series SFS 6000 based on HD 60364, IEC 60364, IEC 60664. The EN 50160 standard was used as a basis for the voltage quality requirements, but some limit values were altered.

The DC mains have relatively large capacitors that act both as smoothing capacitors and energy storages. The capacitors are divided between the CEIs and the rectifier. All the reactive power demand at customer-end is satisfied by the CEI capacitors; only the active power demand is transmitted through the DC cables. The DC capacitors are dimensioned to store enough energy for short period (~0.5 s) island operation of the system with average load level. This aims on riding through the short un-energized time due to transient MV faults cleared with the high-speed auto-reclosures without interruptions in customers' supply.

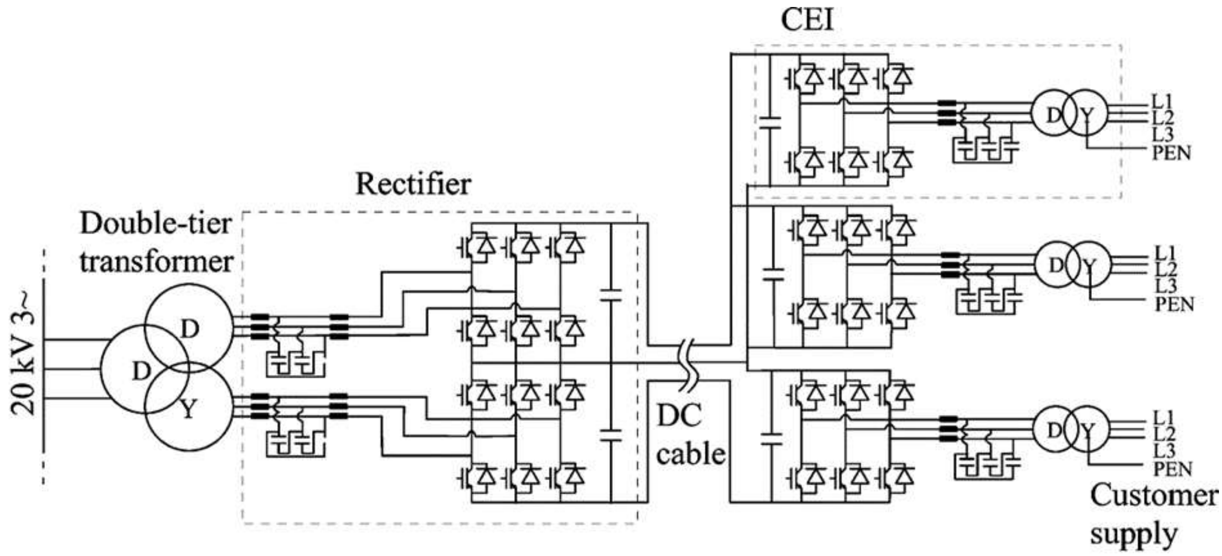


Figure 3.3-15: Simplified main circuit of the LVDC network.

The electric safety is ensured by using both traditional relay protection and protections integrated into the converters as a back-up. The protection system composes of the mains circuit breakers and the insulation monitor relay, located at the rectifier substation, and of the DC circuit breakers located at each CEI. Moulded case circuit breakers with internal overcurrent relays are used. The main breakers are typical $1kV_{AC}$ breakers also familiar from industry. The DC circuit breakers are originally designed for photovoltaic power plants, but due to their high enough DC rating and good breaking capacity they are suitable for power distribution purposes too.

The three-phase CEIs are based on common 330 A RMS IGBT six-pack switch modules that feed the 16 kVA bulky 50 Hz galvanic isolation dry transformers. According to the Finnish LV standardisation the recommended single-phase short circuit current in the customers' connection points should be above 250 A RMS to ensure fast enough operation of the typical fuses and circuit breakers in the in-house networks. The short circuit current in the secondary of the isolation transformers is limited with the inverter control to prevent IGBT faults. Together with the residual current measurement the CEI also acts as back-up protection against faults in end-users' installations.

For the system level control and supervision, each converter has an embedded PC that is connected via optical fibre network to the rectification substation using an IP-based protocol. The rectifier-end PC is the master controller of the whole system. The used ICT system is illustrated in Figure 3.3-16. The communications from to the remote-control web-portal is established either with ADSL connection or with back-up 3G wireless connection. The system can also be connected with a commercial SCADA system.

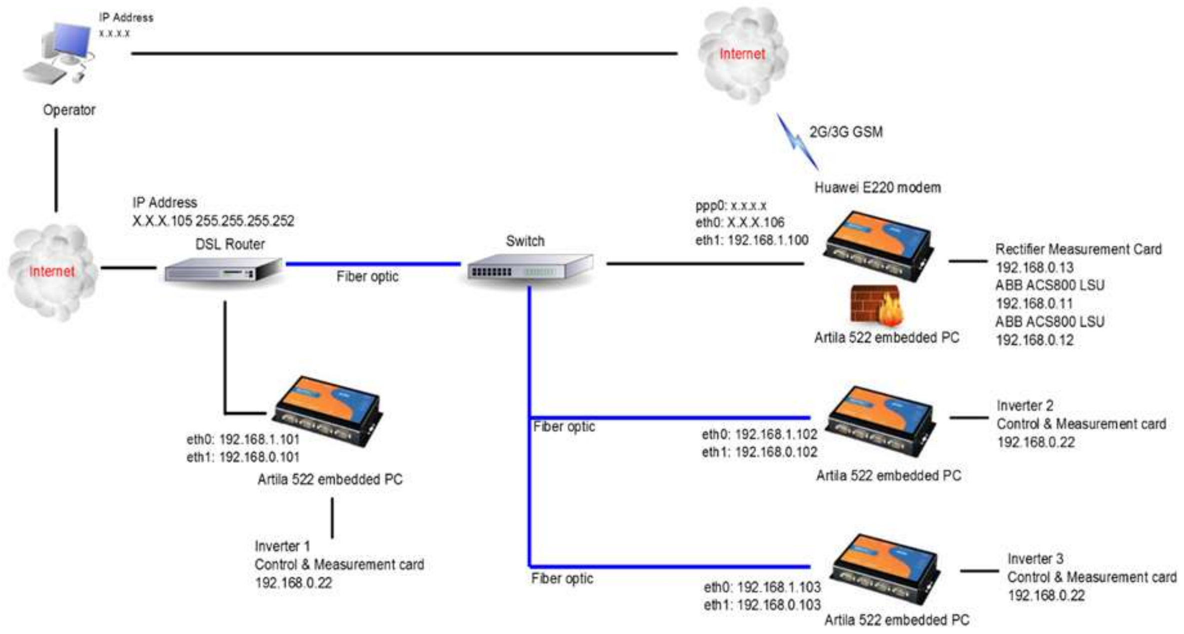


Figure 3.3-16: ICT system for network management.

LVDC-Pilot5: Point-to-point low voltage DC-link in Finland [22]

In Figure 3.3-17 the unipolar point-to-point type of LVDC pilot implementation system is presented, which has been planned in co-operation with Elenia Oy and ABB Oy Drives. Elenia Oy is the second largest DSO in Finland with some 410,000 customers in a 50,000 km2 geographical area. The market share of Elenia Oy is 12% and it has a distribution network of altogether over 65,000 km. Elenia Oy's distribution network consists mainly of sparsely populated areas, so the development of distribution technology is especially important in the rural area networks.

Power electronics enable several new network structures, of which a unipolar point-to-point LVDC system is the easiest option to replace a MV branch by LVDC from the perspective of the DSO. Figure 3.3-17 illustrates the concept of the point-to-point LVDC distribution system.

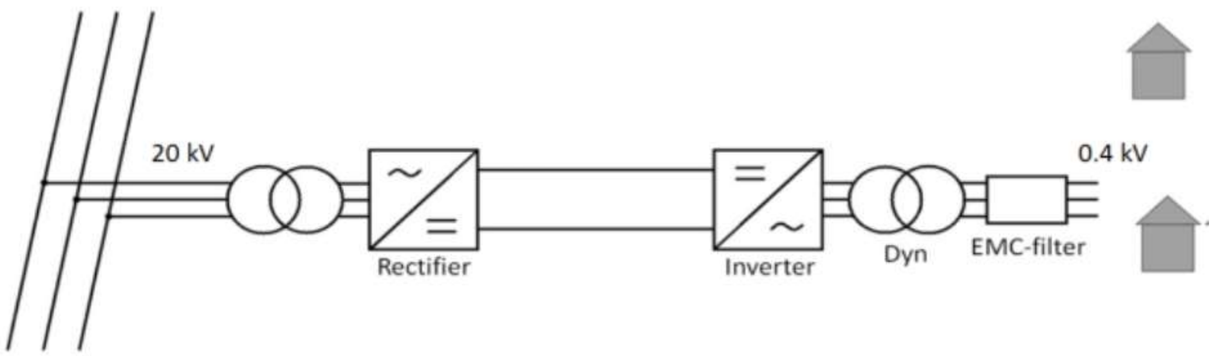


Figure 3.3-17: The point-to-point LVDC distribution system.

The pilot implementation setup is presented in the Figure 3.3-18. The pilot setup is implemented using the usual network components with the exception of a rectifier, an inverter and a DC-cable. Standard 20/0.4 kV distribution transformer supplies the rectifier and the inverter supplies a common low voltage alternating current (LVAC) distribution network with traditional fuse protection.

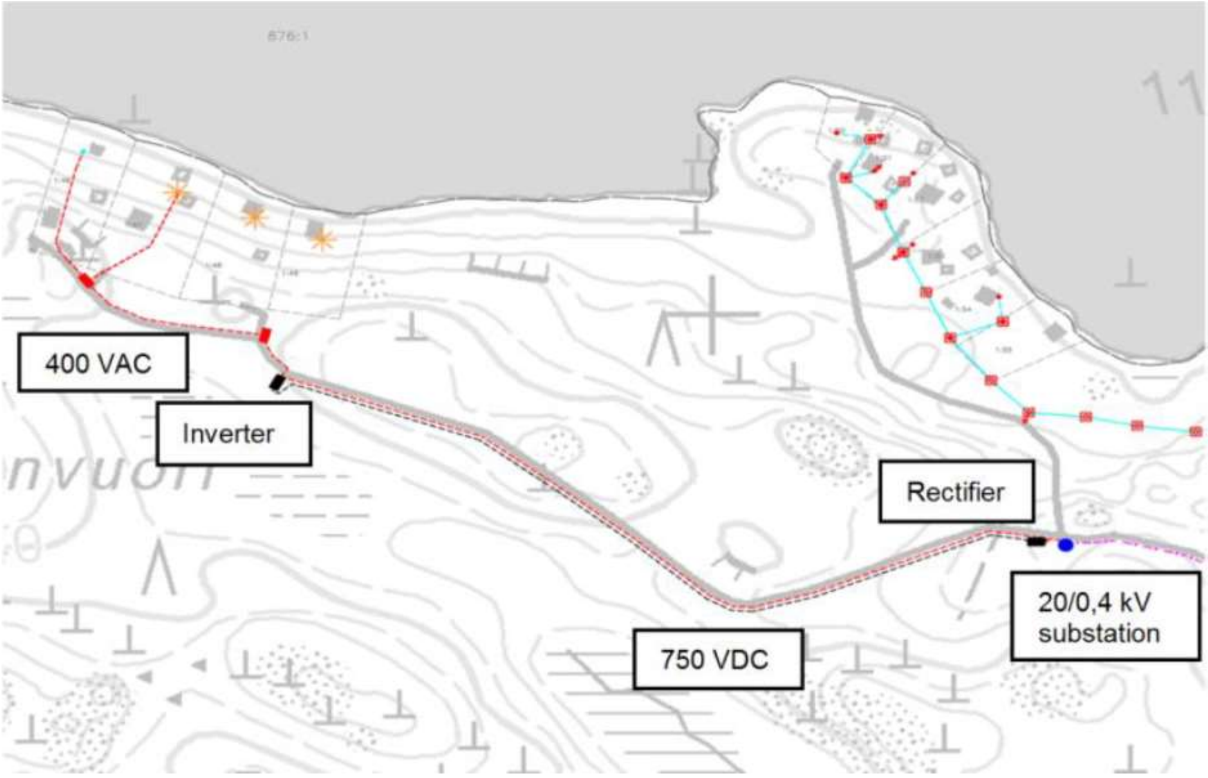


Figure 3.3-18: Field implementation setup of the pilot.

Figure 3.3-18 presents the structure of the pilot setup. Rectifier is a standard ACS800-11 module where only the bidirectional input power stage is used. The DC-voltage is boosted from nominal 570 V_{DC} to 750 V_{DC} to minimize the DC-current and to maximize the available energy in DC-capacitor bank. The cabinet of the inverter consists of a 150 kVA converter module, an output transformer and an additional DC-capacitor bank as energy storage. The output transformer is a normal dry Dyn distribution transformer with a static shield and 460/400 V transformer ratio. The transformer prevents common mode disturbances from spreading to the LVAC network, decreases the conductive emission and makes an earthed star point for the single-phase loads. High frequency conductive emission is limited with an EMC-filter in the output.

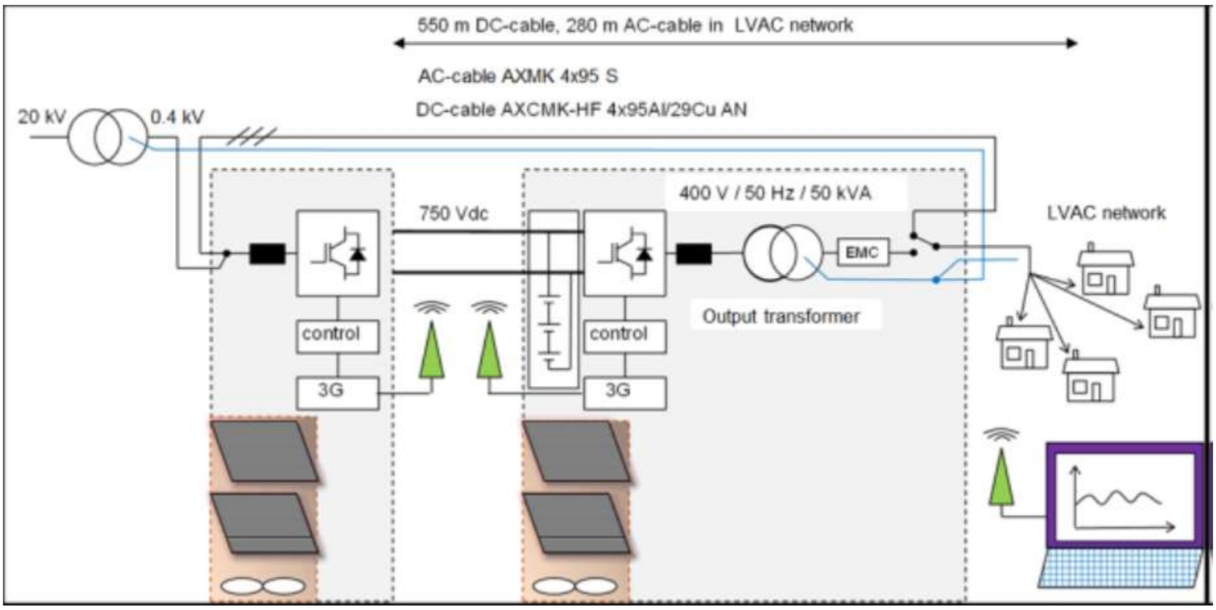


Figure 3.3-19: Schematics of the pilot setup.

Both cabinets are equipped with Phoenix 3G modem, which sends data in one-minute intervals in ABB service portal. For example, energy, current, voltage, power, reactive power and converter temperature can be monitored and plotted in a graph. Faults and alarms can also be monitored. Furthermore, the modem sends notice to the email in case of converter fault/alarm. The fault incident triggers converter data logger and signal data can be sent through the web service for analysis.

The software has specific features for power quality correction. It is possible to filter characteristic voltage harmonics and asymmetry generated by single-/two-phase loads and none-linear load. LCL-filter and DTC-modulation together with the output transformer and the EMC-filter in the secondary side guarantee low level of high frequency conductive emission.

According to measurements with 8 kVA load, the harmonic distortion THD was 3% and individual voltage harmonics are within the limits of European standard EN50160. The losses and efficiency were not primary issue when developing this research platform.

During operating time, the LVDC system has experienced high-speed autoreclosings, time-delayed autoreclosings and a few longer interruptions of the supplying MV network. In all cases, the system has worked as planned and LVAC network has been supplied from the energy storage as long as the load situation of the time has allowed it. Customers have experienced not a single high-speed autoreclosing.

LVDC-Pilot6: DC-Industry, Germany [23], [24]

"DC-Industrie" is a German initiative of 21 companies in industry sector, 4 research institutes and ZVEI (Zentralverband Elektrotechnik- und Elektronikindustrie e.V.), mainly based on two projects funded by Energy Research Programme of German Federal Government with a focus on energy efficiency and energy flexibility in industrial production, thus a kind of DC-based smart grid for industry.

It is foreseen as a setup of a manufacturer-independent LVDC system concept. Modules of in-feeds via AC-DC rectifiers for connection to the LVAC main grid, variable speed motor drives, DC-supplied machines & robots and passive DC-loads are summarized in (independent) load zones. These modules are connected by "connection-boxes" - including equipment for load zone and cable protection using fast hybrid- and solid-state LVDC circuit breakers, pre-charging and disconnection - together with photovoltaic plants and storage applications on a DC-bus (DC-backbone). The DC-network is buffered by enough intermediate-circuit capacity to keep away switching frequency-based clearing procedures from the devices in a semi-industrial environment. The industrial DC power supply includes an energy management to balance the DC-voltage - nominal 540 Vdc for uncontrolled supply on 400 V_{AC}-grid and 650 V_{DC} for controlled supply and uncontrolled on 480 V grid - within pre-defined bands like nominal, steady-state over-/under voltage, transient over-/under voltage and switch-off limits 400 / 800 V [23], [25].

Advantages of this concept are increased energy-, resources- & cost efficiency and reduced space by elimination of the rectifier converter stage (applications) and grid-filter coils of variable speed drives with direct energy recovery in the DC-bus (no bidirectional rectifiers necessary), better utilization of cable cross-sections, fault-ride through capabilities and grid support functionalities. Extension up to production halls, e.g. 400 m length, are considered. A summary of potentials of ultra-efficient power distribution in industrial DC grids is shown in Figure 3.3-20, [26].

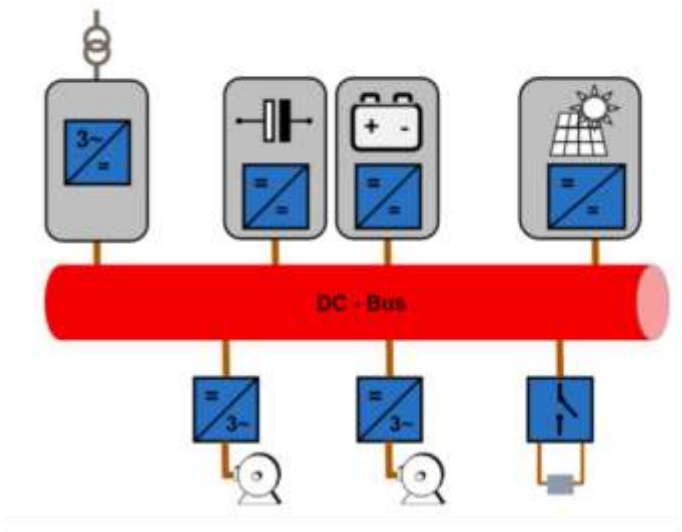


Figure 3.3-20: LVDC-based Smart grid for industry – basic concept including generation of renewables (PV) and energy storages (battery, capacitors) [23].

In 1st project phase DC-INDUSTRIE (2016-2019) the demonstration, evaluation and operational experience of the basic configuration (Figure 3.3-20 and Figure 3.3-22) for several production cells like robot cells for automotive industry" (handling, spot welding, gluing, setting of self-pierce rivets), "pneumatic drives" and a "conveying system", including photovoltaic and storages (battery, fly-wheel, and capacitors) were in focus.

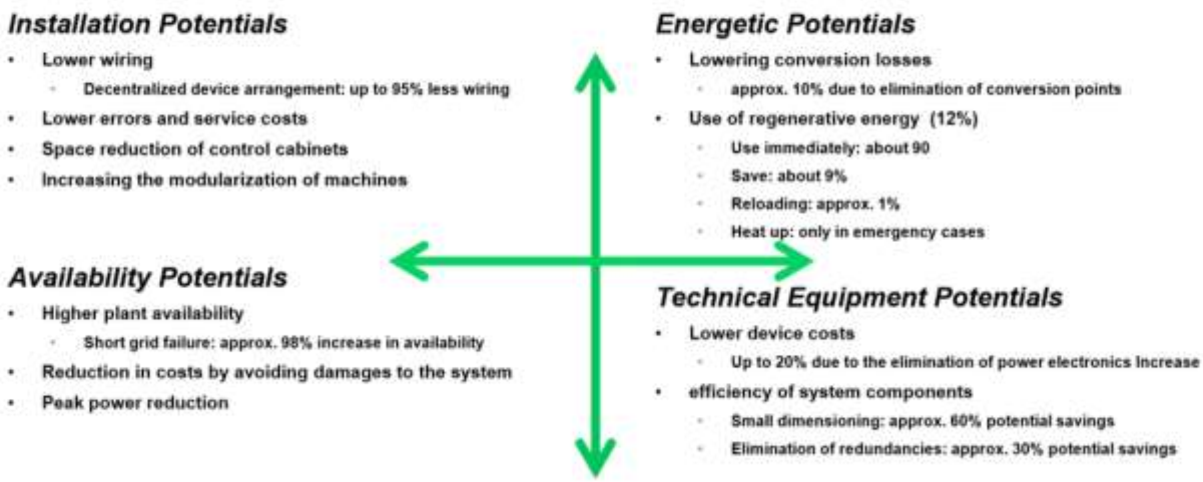


Figure 3.3-21: Potentials of ultra-efficient power distribution in industrial DC grids [27].

The objects of ongoing 2nd project phase DC-INDUSTRIE2 (2019-2022) are safe and robust energy supply of production plants (extension to whole production halls), mains-supporting connection to the supply mains, simple project planning and maximum use of decentralized, regenerative energy generation. Prove of evidence will be done in 6 model plants and transfer centres, [23].

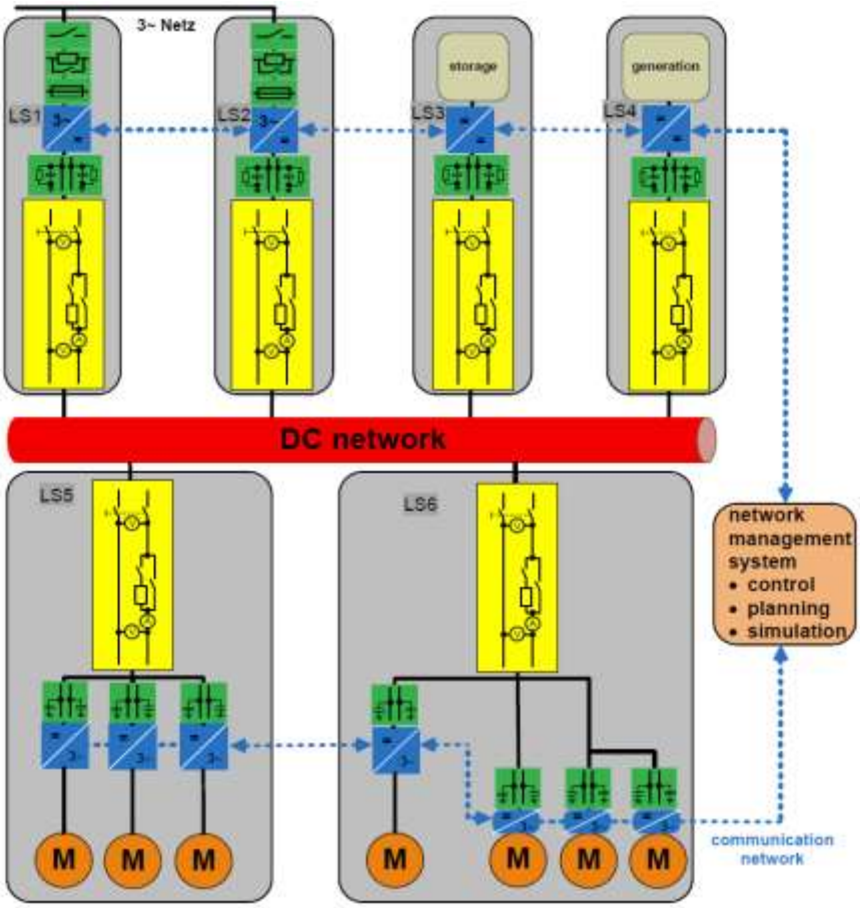


Figure 3.3-22: LVDC-based Smart grid for industry – modular, load zones based concept with grid management [23].

LVDC-Pilot7: N470 Project Netherlands [28]

Figure 3.3-23: N470 Project Netherlands.

The provincial road N470 was a one-of-a-kind project for the region, involving multiple partners. South Holland aspires to manage and maintain its roads, waterways, bridges, and locks in a carbon-neutral manner. These spectacular goals have been realised in the N470 project by creating the most sustainable road in the Netherlands, and by demonstrating to the market that this is a normal tender, not a demonstration project within the existing ecosystem.

It is the first road in the region to have been renovated entirely in a CO_2-negative manner and to generate its own energy for lighting and traffic signals. Additionally, traffic can continue to flow more freely, and the road has been made safer through the use of new DC technologies. The distances are short, which prevents electricity from being lost during transmission via high-voltage cables and conversion to AC. This minimises energy consumption and CO_2 emissions. The green battery stores the energy generated during the day so that it can be used later in the evening when the sun is not shining.

The N470 is the first to be equipped with a self-sufficient energy system. The Energy Wall is a noise barrier that also produces energy via solar panels embedded in the screen's glass plates. The generated energy can be used directly to power 332 lights and 225 traffic lights further down the road. The noise barrier is made up of 100 kW solar and generates 75 megawatt hours of electricity per year. This is approximately the same as providing green electricity to approximately 26 households for one year.

The following are some of the potential benefits of this project:

- The system is powered by a single cable that runs for 4.7 kilometres;
- The cable is powered by DC to avoid the difficulties associated with passing AC power through a water channel;
- The system is capable of operating in islanded mode if the main grid is lost;
- The system is an autonomous microgrid with distributed sources with managed power flow without digital communication. (Current/OS system);
- The system includes energy management features but does not require data or an internet connection for security reasons;
- The system is integrated with renewable energy sources such as photovoltaic (PV) and energy storage;
- It is a commercial project, not a demonstration project within the established ecosystem; and
- The first DC project was developed in accordance with the Dutch technical guide for DC installations (NPR9090).

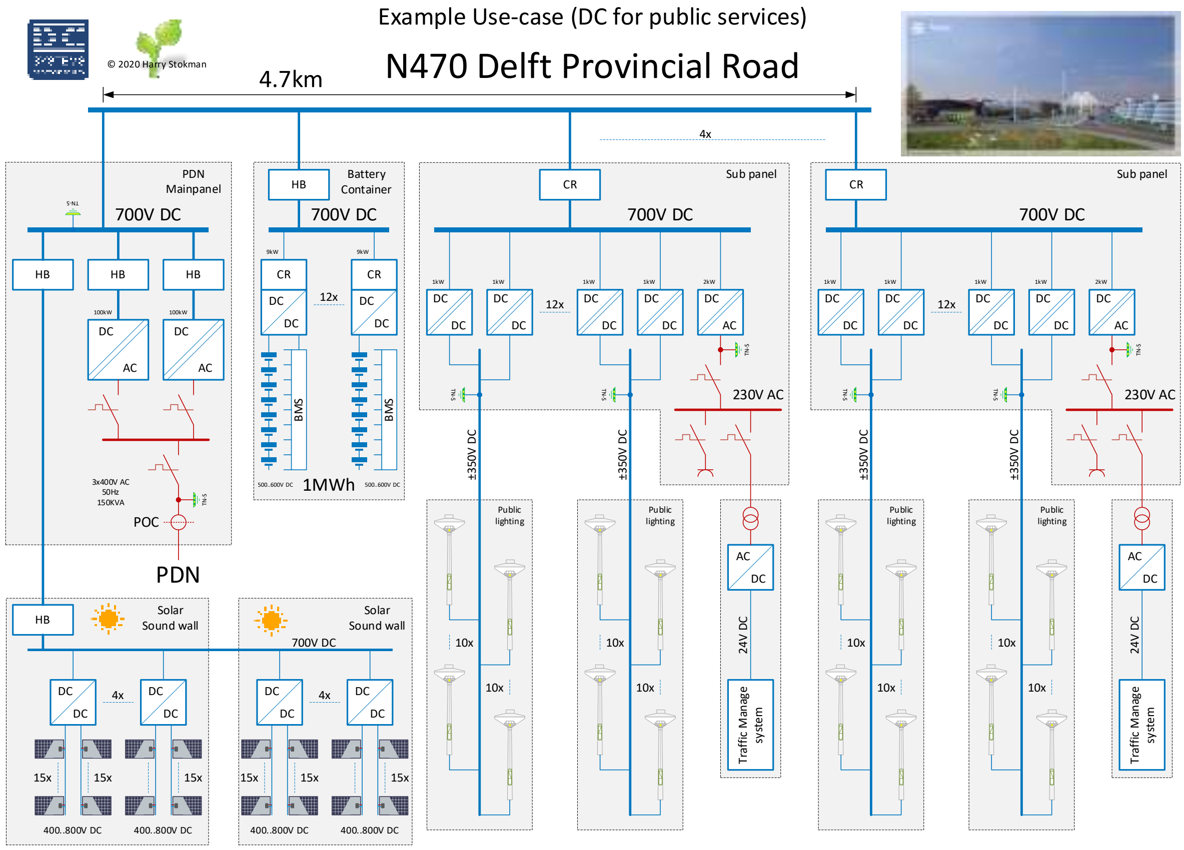


Figure 3.3-24: Single-line diagram of N470 site system.

The project's technical specification includes the following components:

- The power distribution cable is 4.7 kilometres long contains a four-core cable of +\-700 V_{DC} with a +/-60V_{DC} droop control, and a TN-S earthing arrangement;
- The network is earthed using a TN-S with multiple earthing arrangement with additional stray-current protection provided by the use of diodes to separate the metallic and electric earthing;
- The solar panels are connected to the main power distribution system via DC/DC converters;
- Two active front ends of 100kW each interface with the AC grid (it is worth noting that AC grid support is disabled in this project) and operate on 50kW with limited line currents;
- Ambient requirements include a temperature range of -20 to 50 degrees Fahrenheit and a relative humidity of 95% at sea level;
- The AC station is rated at 150kVA;
- The DC system is electrically isolated from the AC system;
- 1MWh LiFePo4 battery system based on 12 strings connected via DC/DC converters and protected by solid state circuit breakers;
- Distributed batteries equipped with autonomous system capable of communicating with the BMS and reacting to the state of the grid (SOG) in conjunction with the state of health (SOH) and state of charge (SOC);
- Streetlights connected to a network of 23 strings x ±350 V with a +/-30 V_{DC} droop control equipped with DC/DC led drivers and power line control;
- The streetlights are equipped with RCDs to protect the public against direct contact;
- The network incorporates hybrid circuit breakers and solid-state protection;

- Overvoltage protection is incorporated into the network, as well as Arc fault detection; and
- Power flow and protection, for example, are determined by the Current/OS protocol and requirements.

Figure 3.3-25: N470 Distributed batteries system.

Figure 3.3-26: N470 Outdoor substation.

Figure 3.3-27: N470 - An illustration of why RCDs and protection are necessary. A minor accident occurred during testing when one of the cars collided with the project's light pole. (safety comes first).

Figure 3.3-28: N470 Outdoor substation for public lighting.

Figure 3.3-29: The layout of the N470 project.

3.4 Medium Voltage Use Cases and Applications

This section shows DC applied in practice at medium voltage level. The first part (3.4.1) summarizes the general use cases, a second part (3.4.2) has a look at installations world-wide, covering pilot installations, technical prototypes and commercial installations. The order of use cases and pilot installations does not indicate a specific priority or relevance. Use cases and applications are still emerging. The best industrial practice will establish in the coming years together with matching industrial standards.

3.4.1 Use Cases of DC used for MV Systems

Figure 3.4-1 summarizes the application of MVDC converters in a CIGRE benchmark grid [29]. The numbers indicate the application type (connectivity, controlled load flow, transport capacity). The benchmark grid allows to locate and to simulate the impact of the application.

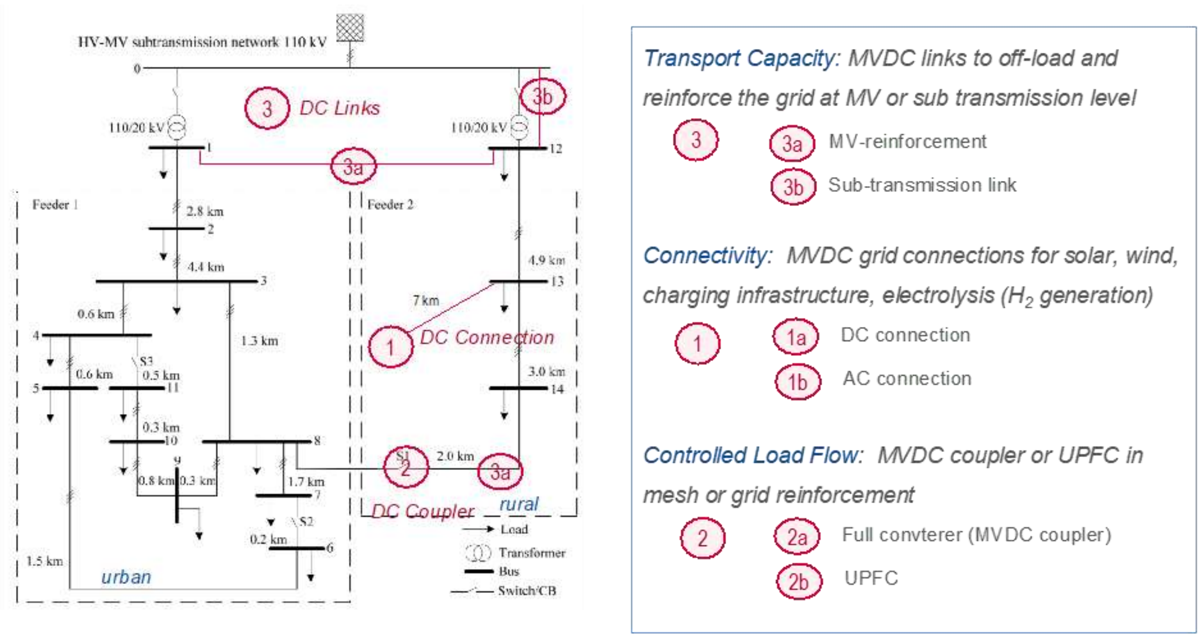


Figure 3.4-1: MV DC systems in the grid.

According to the target applications, the numbers indicate

1. MVDC Connection to the grid to provide **DC connectivity** for systems over (1a) DC interfaces or (2) AC interfaces (not necessarily at MV level);
2. MVDC systems providing **control of power flow** (2a) MVDC couplers or (3a) MVDC links over some distance. Instead of a MV DC coupler (2b) a UPFC could be used; and
3. MVDC Links either (3a) to reinforce the grid of (3b) to perform as a sub transmission link with high **transport capacity** (respectively low loss).

The benchmark grid allows simulating load flow and dynamic grid operation in a reference environment, with a growing amount of emission free power sources and sinks. Such systems comprise wind parks, solar power, charging stations for electric vehicles and electrolysis of water to generate hydrogen and gas. In order to incorporate a significant number of carbon free systems, the benchmark grid needs to be extended.

MVDC-UC1: Connection of Emission Free Power Sources and Loads

As of today, most DERs and emission free loads such as charging infrastructure, electrolysis for H_2 generation as well as battery storage represent DC sources or sinks. Still they connect via DC/AC converters to the AC grid. With power beyond 1 MVA, AC transformers are used to connect to the MVAC-grid.

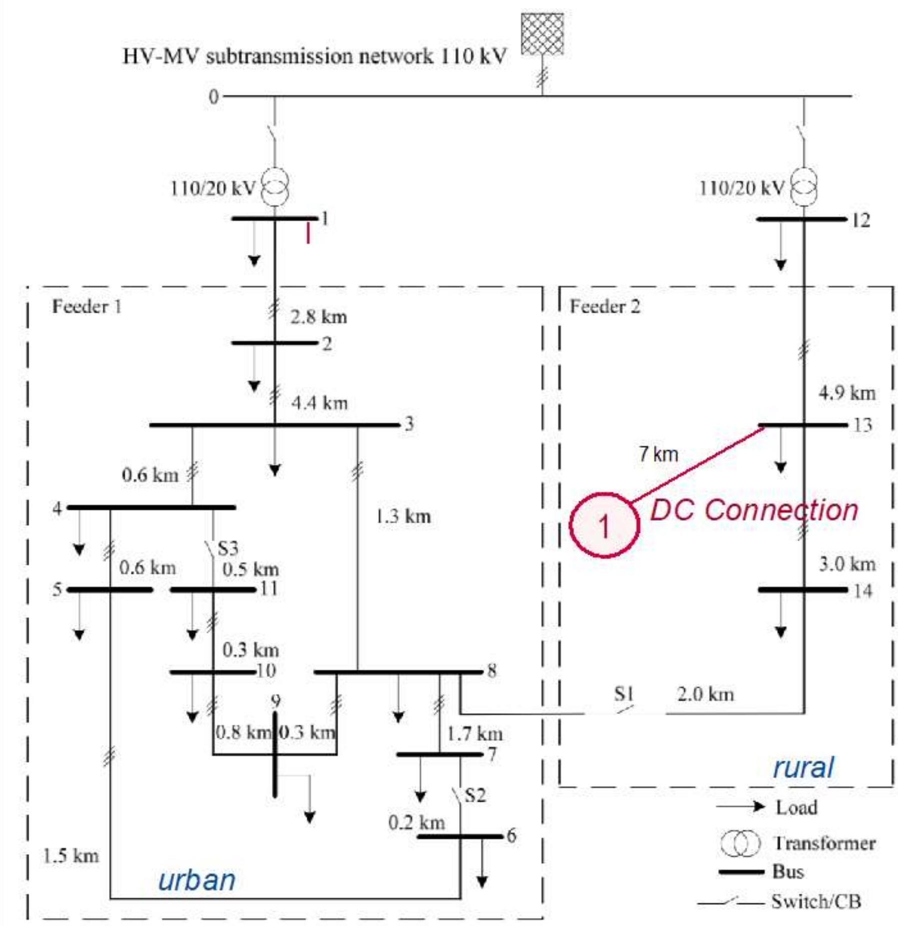


Figure 3.4-2: DC grid connection for DERs and loads.

As shown in Figure 3.4-2, an MVDC-link is introduced to connect DERs and loads, consisting of a grid-side converter (on the left), and a system-side converter (on the right). The system-side converter connects DERs and loads collected over AC transformers. The grid-side converts to the grid according to an AC grid code. It is not part of the grid, but a system on the grid.

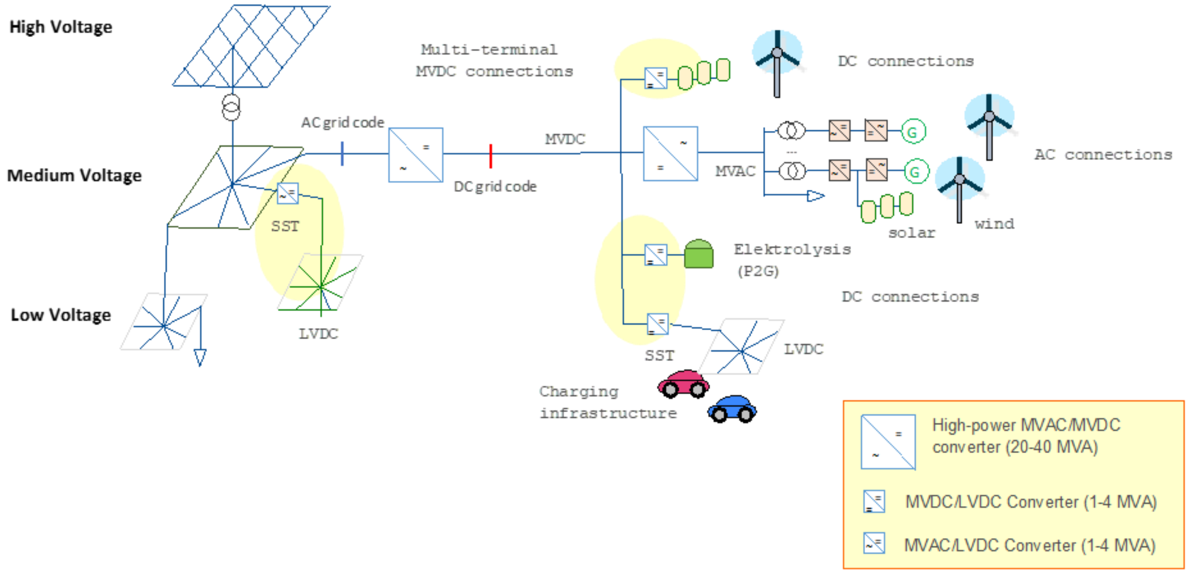


Figure 3.4-3: Options to connect DERs and loads.

The growing number of DERs and emission free loads may lead to the following developments:

1. The **grid-side converter** becoming part of the grid and closely involved in grid operation. It will need to perform more than the current supporting functions demanded by AC grid codes, such as Q(U), Q(P), fault ride through u(t), harmonic distortion and P(f). Being a grid component, it will need to support power and voltage management in a dynamic way. Most likely, grid operation will follow curative measures to achieve higher grid utilization;
2. The **system-side converter** for traditional **AC** connections. The combination of both converters follows the current practice in HVDC links, with the system-side converter being a grid forming type. The systems-side converter collects AC sources and AC loads over an MVAC grid;
3. **System-side converters** for **DC** sources and sinks. The system side converters represent SSTs by implementing the combination of {MVDC/MVAC-converter + transformer + LVAC/LVDC-converter} into one system acting as transforming converter for MVDC/LVDC, respectively MVAC/LVDC. DERs and loads are collected over an MVDC distribution grid in much the same way as current over MVAC grids, but with different protection mechanisms; and
4. The grid-side converter becoming part of the grid, the grid interface is becoming **the DC grid connection**. Among the implications are the need of a (1) DC grid code for systems connecting at MVDC, including (2) ways to handle multi-terminal connections including protection. Another impact of the DC grid connection is the clearing the way for more efficient and innovative implementations of system side converters in a competitive environment. The current AC grid codes block such options.

MVDC-UC2: Meshed Operation of MV grids by DC-Couplers

Reinforcing and extending the grid may lead to meshes with unwanted power flows. The introduction of MVDC Couplers or MVDC Links will allow handling congestions and controlling power flow. Such measures will need to be compared with other ways of handling load flows, such as UPFCs. Representing full power converters, MVDC Couplers and MVDC Links provide full control of active power between the grid sections and reactive power on both ends.

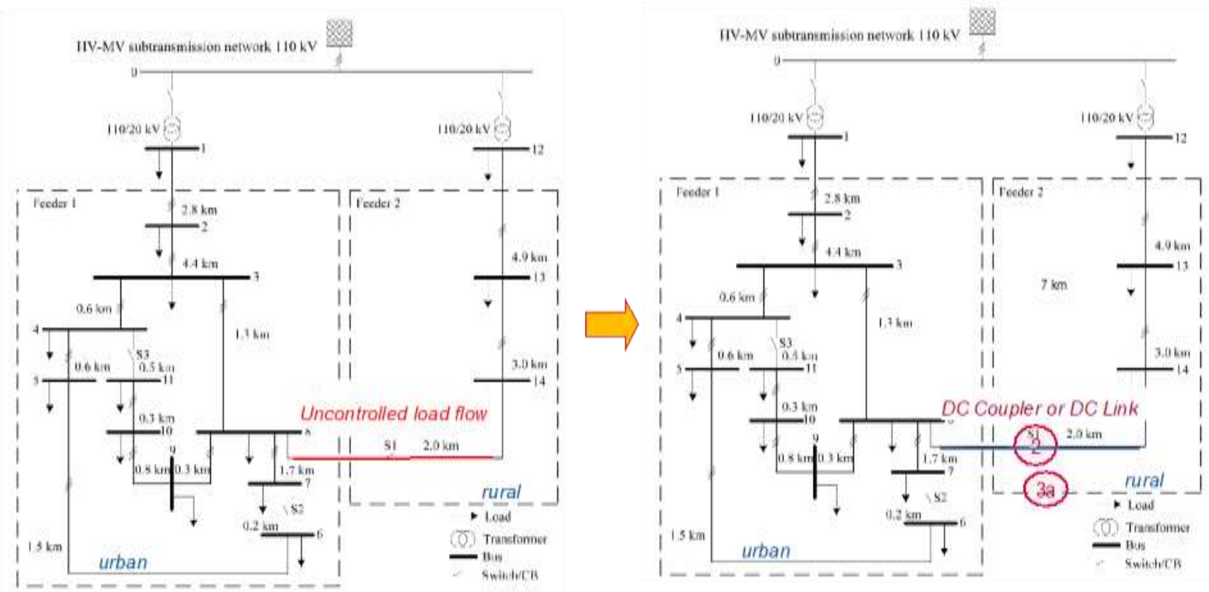


Figure 3.4-4: Operation of meshed configurations.

First Investigations on the benchmark grid show that renewable energy sources will soon outgrow the benchmark and will need additional subtransmission links and stations. So, while there is a potential for MVDC links to implement the extensions, it limits the case for congestion.

MVDC-UC3: Deployment of DC Subtransmission links

A reinforced and extended MV grid (distribution grid) may also off-load the transmission grids by

- Using high capacity MVDC links over larger distances; and
- Using high capacity MVDC links instead of 110 kV_{AC} sub-transmission links.

The possible feasibility of 50 kV_{DC} transmission over AC underground cable may allow MVDC connections over longer distances. Given the better acceptance of underground cables in comparison to overhead wire, this may facilitate grid reinforcements.

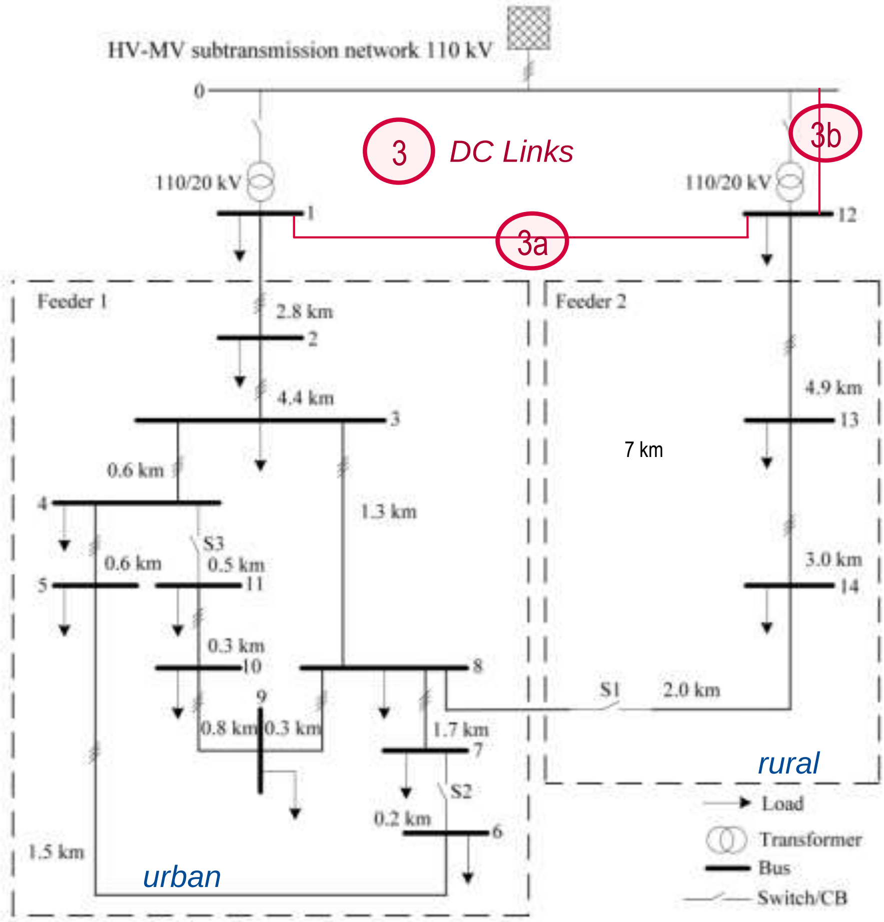


Figure 3.4-5: MV DC links to off-load the transmission grid.

On the CIGRE benchmark grid, such links would be located at the transmission layer or sub-transmission layer. The benchmark grid needs to be extended for a representative scenario.

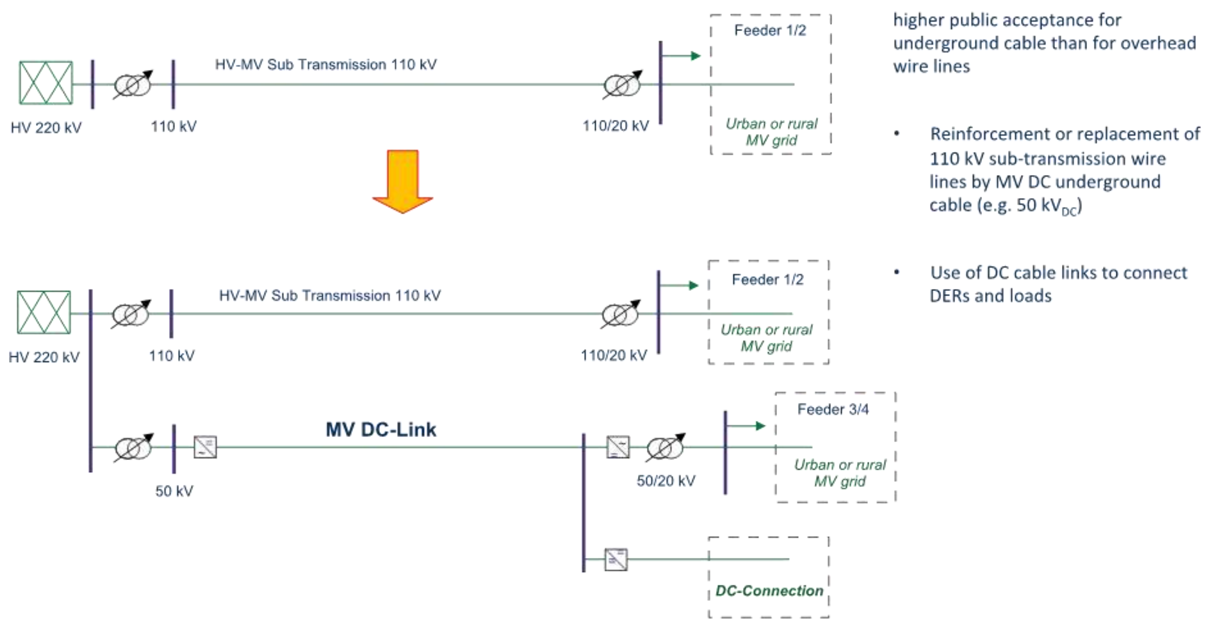


Figure 3.4-6: MV DC links at sub-transmission layer.

MVDC-UC4: Multi-terminal MVDC grid operation and control

A multi-terminal MVDC grid connects distributed systems in the same way as a MVAC grid.

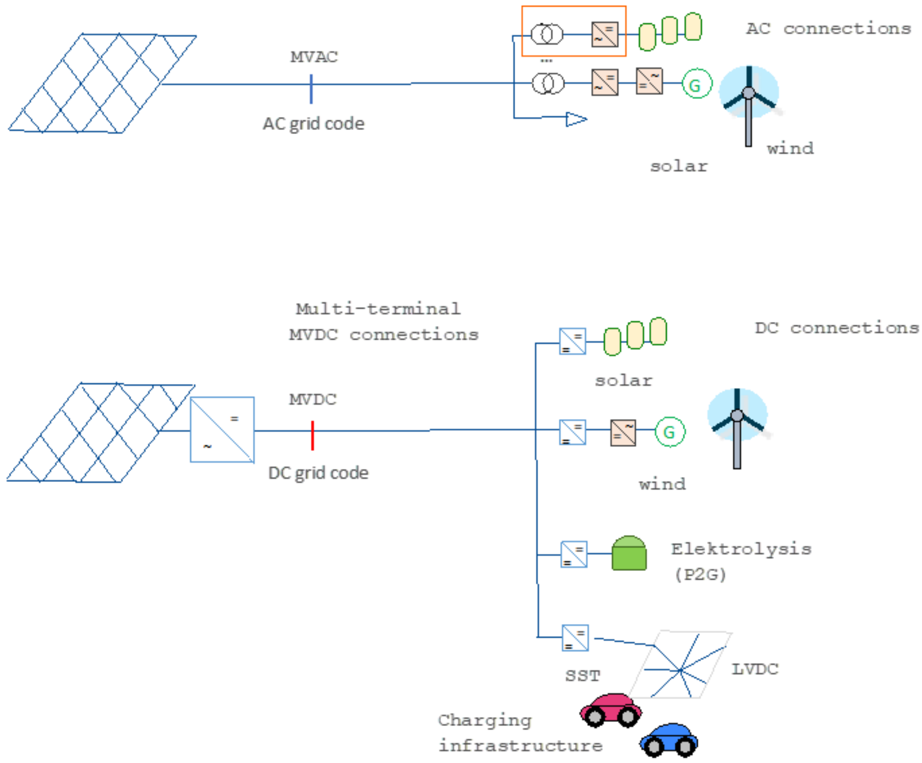


Figure 3.4-7: Multi-terminal MV DC and MV AC grids.

For the configurations indicated in the figure, the efficiencies are:

- Cable or wire:
  - The losses of an MVDC link is 2/3 of the losses of an MVAC link operated at the same RMS-currents and same power (using 2 instead of 3 wires); and
  - Total losses depend on the distance and type of cable or wire (about 2/3 for DC in comparison to AC).
- Chain of converters:
  - AC: transformer + LVAC/LVDC converter; and
  - DC: MVAC/MVDC converter + MVDC/LVAC converter

In summary, a multi-terminal MVDC grid provides lower losses than conventional MVAC grids, if the distances between systems and the grid are significant and if operated at the same power and RMS-currents. In terms of capacity, the MVDC systems provides more power and better utilization of cables or wires.

3.4.2 Solutions and Pilot Projects MVDC

While part 3.4.1 summarizes DC applications in terms of general use cases, the purpose of part 3.4.2 is to show DC applications in practice. This part presents a collection of pilot installations, technical solutions and commercial installations world-wide. The pilot projects are listed in no specific order.

MVDC-Pilot1: Network Equilibrium [30], [31]

Project Summary

Network Equilibrium is a Low Carbon Networks (LCN) Fund Tier 2 project. The LCN Fund was a funding mechanism introduced by Ofgem as part of the Distribution Price Control Review (DPCR) 5 price control period.

Network Equilibrium was successfully awarded £13m of funding in November 2014. The project started in March 2015 and was completed in June 2019. The main aim of the project was to improve the balance of voltages and power flows across the distribution network using three Methods. The development of the Methods allowed new ways of configuring and managing the network to be trialled thus releasing capacity for the more efficient connection of DG. The three Methods are as follows:

- Enhanced Voltage Assessment (EVA);
- System Voltage Optimisation (SVO); and
- Flexible Power Link (FPL)

The FPL consists of two 33 kV back-to-back AC-DC voltage source converters connected via a DC busbar link that allows two 33 kV distribution networks to be connected in parallel through the device. At both 33 kV interface points of the FPL there is a step-down transformer that transforms the network voltage down to a voltage suitable for the converters. The technology used for the FPL comprised of ABB's PCS6000 frequency converter and a schematic of the system is shown in Figure 3.4-8.

The FPL as part of Network Equilibrium was connected across two previously unconnected electricity distribution networks to enable active power (P) transfer between them and provide independent reactive power (Q) on both sides. The active power flow operation of the FPL is shown in Figure 3.4-9, where active power is transferred from a generation dominated network in Grid Group A1 to a demand dominated network in Grid Group A2. This enables a greater utilisation of the complete system, whereby previously the Grid Group A1 would have reached its capacity of generation acceptance (due to reverse power flow constraints) and significant network reinforcement would be required. Similarly, this would be the case for an increase in load on the Grid Group A2 (causing firm capacity limits to be exceeded) that could be transferred to Grid Group A1 to mitigate reinforcement requirements.

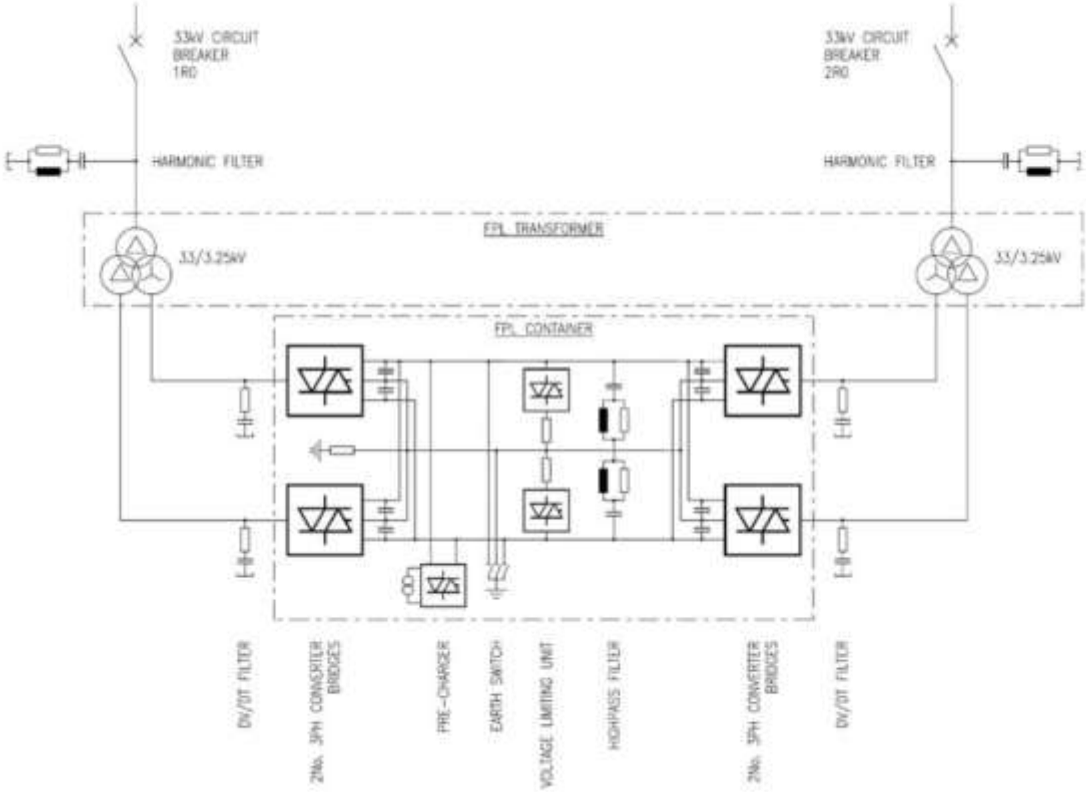


Figure 3.4-8: Schematic of FPL system.

This parallel configuration would not have been able to be safely achieved without the FPL due to circulating currents, protection grading and fault level issues. The FPL can actively manage the real and reactive power flow at its terminals to release network capacity and provide voltage support in both normal and abnormal network running conditions.

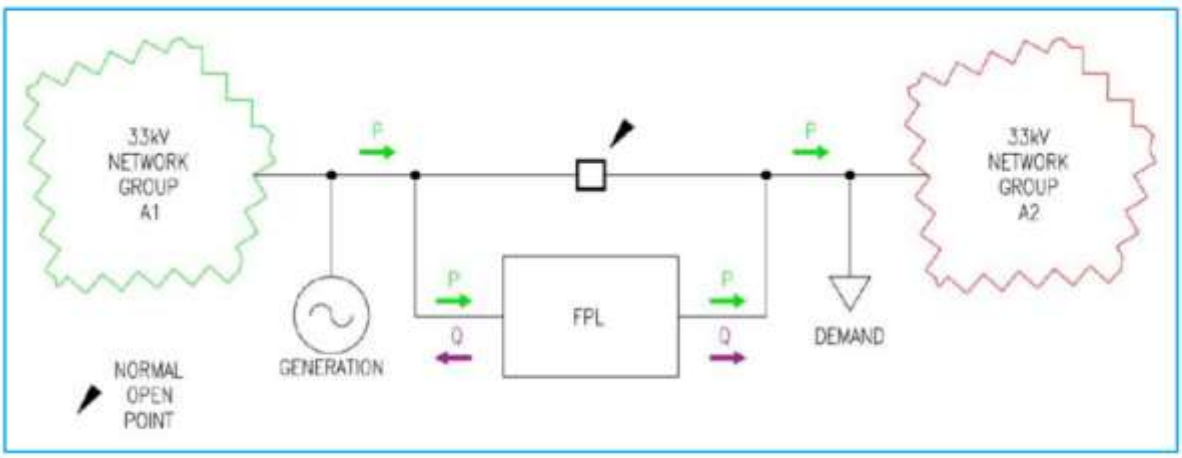


Figure 3.4-9: Overview of FPL operation.

<u>Feedback on the Project:</u>

The outcomes of the FPL have shown that it is possible to develop a fully operational back-to-back power electronic converter on the British 33 kV distribution network and successfully use it to manage power flows between two distribution systems that could not otherwise be permanently connected in parallel. The work carried out for Network Equilibrium has shown that the FPL can release significant capacity on the 33 kV network by enabling active power transfer between distribution systems. In addition, the ability of the FPL to independently control reactive power on both sides enables the device to provide voltage support on both networks.

The architecture and full operational system required for implementing an FPL control system has also been developed and implemented along with the associated power system network models that are used to calculate the FPL set-points.

MVDC-Pilot2: Angle DC [32]

Angle DC is a Network Innovation Competition Project developed by Scottish Power Energy Networks. It was awarded funding from the UK energy regulator, Ofgem, in 2015 and is due to be completed in April 2020. The aim of the project is to convert an existing AC double circuit 33 kV line into a symmetrical monopole MVDC link i.e. each circuit carries one of the poles +/- 27 kV_{DC} in this case. The double circuit connects Lanfair PG substation on Anglesey Island with Bangor substation on the North Wales mainland. A high level schematic showing the location of the link and the components of the system in Figure 3.4-10 and Figure 3.4-11 respectively.

The island of Anglesey is experiencing both load and distributed generation growth in the form of renewable generation such as wind, solar and tidal. The 33 kV circuit in question is forecast to experience thermal limitations and voltage will be increasingly difficult to manage. It is anticipated that changing the existing AC circuits to DC operation will increase the cable nominal rating by 23% allowing for increased power flows. The MVDC link will allow greater control of the power flow through the circuit and also improve voltage management at either end of the link.

The MVDC technology is being supplied by GE and for this application they are utilising 12 units of their MV7000 converters at each converter station. This product is normally used as a Variable Frequency Drive (VFD) system for MV motors and it is unknown at this stage how they will be adapted for the MVDC link application. This information will likely become known when SDRC-4 and SDRC-5 project reports are published by SPEN.

The Technical Specification for MVDC Converter Stations (SDRC-2) has been published and a summary of the requirements are as follows:

- Fully rated power is required in both directions through the MVDC link;
- The nominal DC voltage is ±27 kV;
- Real power control implemented either by set power levels (i.e. 90%, 80% etc.) or through Vernier control; and
- Independent reactive power control at each MVDC terminal.

Figure 3.4-10: Location of Angle DC MVDC link (GE, 2017).

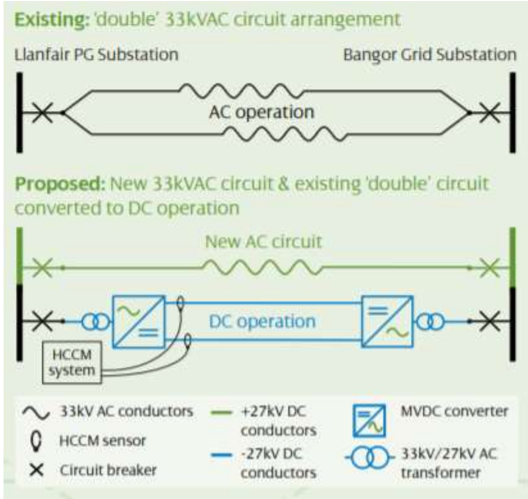


Figure 3.4-11: Angle DC high level system diagram.

MVDC-Pilot3: ABB HVDC Light [33]

HVDC Light is a VSC converter technology developed by ABB. It is particularly suitable for small to medium scale applications and has been implemented in over 20 international projects. The majority of these projects utilise transmission level voltages, however, there are a limited number of applications that are approaching distribution level voltages and these are described below:

<u>Eagle Pass</u>

This was a 36 MVA back-to-back VSC installation at Eagle Pass Substation in the State of Texas, US, which is a part of American Electric Power (AEP) electricity network. The location of the installation is provided in Figure 3.4-12. The converter was designed to interconnect the transmission grid of Texas with the Mexican power system. The Eagle Pass Substation is supplied by two 138 kV transmission circuits but is situated a large distance from the nearest generation, which gives weak voltage support to the area; this is especially the case for a loss of one of the transmission circuits. The Piedras Negras substation is located just across the border in Mexico and is connected to Eagle Pass via a single circuit 138 kV transmission line. This circuit is normally open and utilised only for emergency conditions to support the load at Eagle Pass.

The back-to-back VSC was installed across the NOP at the Eagle Pass site. Refer Figure 3.4-13 for the simplified single line diagram of the installation. The device provides the required voltage support at Eagle Pass by being able to inject or absorb reactive power (+/- 36 MVar). In addition, the device allows uninterrupted bidirectional active power transfer between the USA and Mexican grids, enhancing the reliability of the power supply. The VSC utilises IGBT power electronics controlled by Pulse Width Modulation (PWM). The DC link voltage is +/- 15.9 kV and the AC output voltage from the VSCs has a nominal value of 17.9 kV, which is stepped up to 138 kV to interface with grid.

Figure 3.4-12: Eagle Pass VSC location.

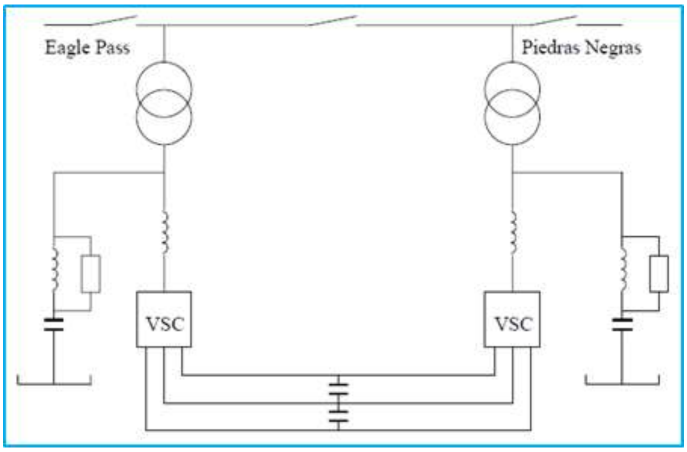


Figure 3.4-13: Eagle Pass VSC simplified single line diagram.

Mackinac

This project involved the installation of a 200 MW back-to-back VSC installation at Mackinac Substation near St. Ignace, Michigan (US). It has been operational since 2014.

The American Transmission Company (ATC) identified a need for a new solution to introduce power flow control between Michigan's Upper Peninsula and Lower Peninsula. This was in response to increasing levels of hydro and wind generation to the West of Lake Michigan pushing power across the Upper Peninsula and causing voltage and thermal constraints on this network. The traditional approach was to split the network in the Upper Peninsula to force the generation to the load centre in the South. This is shown in Figure 3.4-14. Splitting the network in this manner reduces network security and the reconfiguration can cause network transients. It was found to be prohibitively expensive to build new high voltage lines to resolve this issue and therefore a HVDC VSC solution was adopted.

The Mackinac HVDC converter station was connected to the 138kV AC network between the Upper and Lower Peninula as shown in Figure 3-25. The converter was designed for 200 MW bi-directional power transfer and to provide reactive power (+/- 100 MVAr) for local voltage support during steady state and dynamic conditions.

A symmetrical monopole topology was chosen. The converter is a Cascaded Two-Level (CTL) converter with reduced losses and reduced harmonic generation compared to older generations of VSC converters. The simplified single line diagram is shown in Figure 3.4-15. A DC voltage of ±71kV was selected to achieve the 200MW bi-directional power transfer.

There are additional benefits of the VSC technology such as the ability of the converter to automatically enter a Power Transfer Mode that can temporarily serve an island created on the North side of the device under certain contingencies. In this mode the converter designed to operate at fixed frequency / voltage mode with droop settings. The converter is also able to provide black start capability.

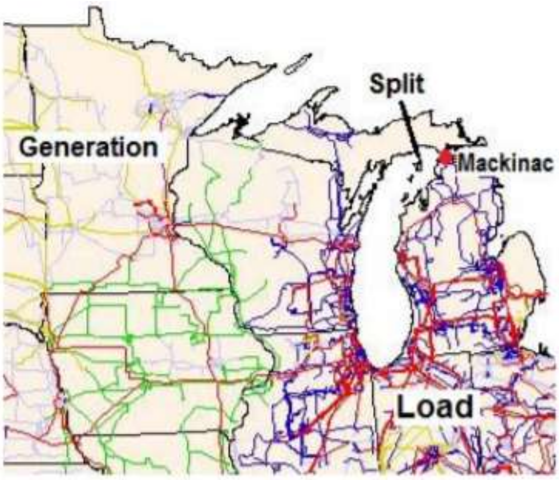


Figure 3.4-14: Mackinac VSC location.

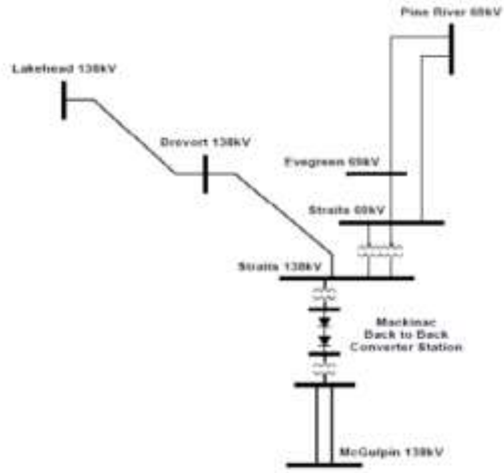


Figure 3.4-15: Mackinac VSC proposed scheme.

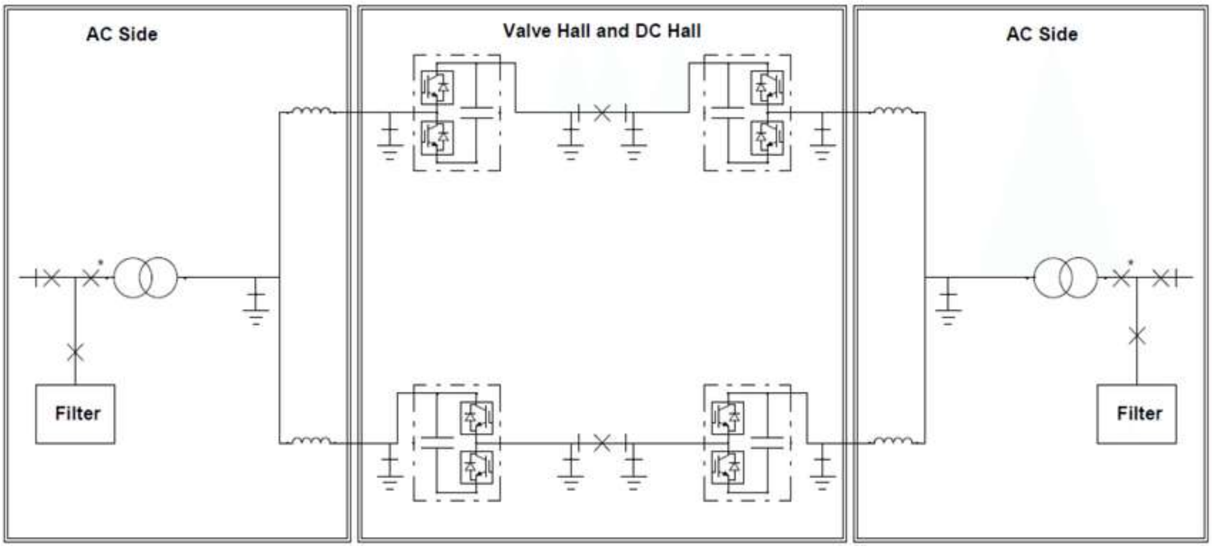


Figure 3.4-16: Mackinac VSC simplified single line diagram.

Åland Islands

Åland is an archipelago of 6500 islands in the Baltic Sea. It is a self-governing region of Finland but is geo-graphically closer to Sweden. Kraftnät Åland owns, operates and maintains the electrical infrastructure that supplies power to the region. Åland has relied on its main power supply coming through a submarine 110kV AC power connection to the Swedish grid rated at 80-100MW. There is also a 45kV connection to mainland Finland, however, this is only rated at 10MW and cannot be synchronised to the Swedish system.

The utility commissioned a 100MW +/- 80kV HVDC transmission link between the main island of Åland and mainland Finland that is shown in Figure 3.4-17 and Figure 3.4-18. The two converter stations are connected by two 80kV submarine cables 158km long. The link will provide security of supply to the island, allow existing fossil fuel back-up generation on the island to be closed and allow a much faster black start capability. The black-start system can restore power in under five minutes.

The HVDC link was designed with a multi-terminal configuration, which allows for additional in-feed from stations, such as future wind power plants.

Figure 3.4-17: Aland HVDC link location.

Figure 3.4-18: Aland converter station.

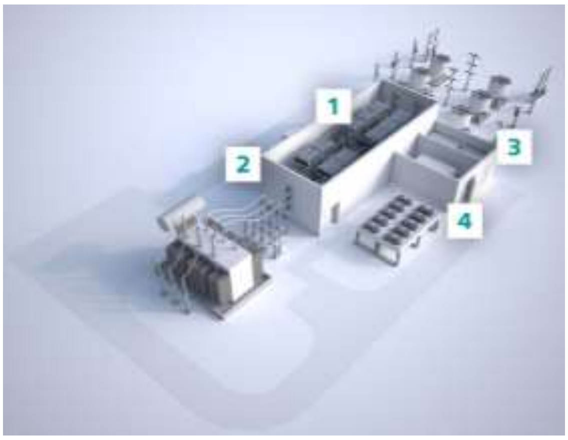
MVDC-Pilot4: Siemens MVDC PLUS [34]

Medium Voltage Direct Current Power Link Universal System (MVDC PLUS) is a new DC transmission system developed by Siemens launched in 2017. Figure 3.4-19 shows a layout of the MVDC technology. It is designed to serve medium voltage AC grids between 30-150kV. The MVDC PLUS technology can transfer DC power over a maximum distance of 200km and is offered in three ratings (50, 100 and 150MW) at DC transmission voltages of 20kV and 50kV.

The Siemens MVDC PLUS technology is a reduced version of their HVDC PLUS technology that is used on Siemens' HVDC transmission system projects. The MVDC PLUS system uses VSC technology utilising a Modular Multi-Level (MMC) architecture. The number of sub-modules and DC voltages are selected based on the application. Siemens has improved cost efficiency by using AC components where possible in the design to comply with standardisation. The system utilises a symmetric monopole design as shown in Figure 3.4-20. The sub-modules used are the same as those used in the HVDC systems ensuring nominal current ratings are comparable. Since fewer sub-modules are required relative to HVDC applications the size of the converter housing can be reduced.

At the time of writing there does not appear to be any MVDC PLUS devices that have been commissioned on the distribution system. Siemens lists the following benefits that the MVDC PLUS solution could bring to customers:

- Connect island, platforms and remote areas;
- Integrate and stabilise weak grids;
- Enhance existing infrastructure;
- Fulfil new tasks as a DSO; and
- Minimise the visual impact.



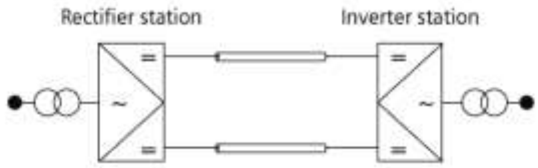


Figure 3.4-19: Siemens MVDC PLUS technology.

Figure 3.4-20: MVDC PLUS symmetrical monopole configuration.

MVDC-Pilot5: RXPE Wenchang Project [35]

Rongxin Power Engineering (RXPE) is an international developer based in China and provider of high voltage power electronic solutions that include STATCOM and HVDC systems. RXPE are also able to offer MVDC solutions as part of their offering. They are able to provide 5kV-50kV VSC MVDC systems able to transmit power over up to 100km.

RXPE have installed a number of MVDC systems to facilitate power supplies for offshore oil platforms. An example of one of these projects is given below.

A main oil platform in the Western South China Sea was supplying a remote platform via three single phase AC subsea cables. One of the cables suffered an insulation failure and meant that the remote platform had to run on back-up diesel generation. An 8MVA +/-15kV MVDC system was installed to restore the electricity supply. A block diagram showing the MVDC system layout is shown in Figure 3.4-21. The system was a symmetrical bipolar arrangement that utilised the healthy AC phases as the positive and negative DC cables and the faulted phase as the neutral. The MVDC solution has been operating successfully since 2013.

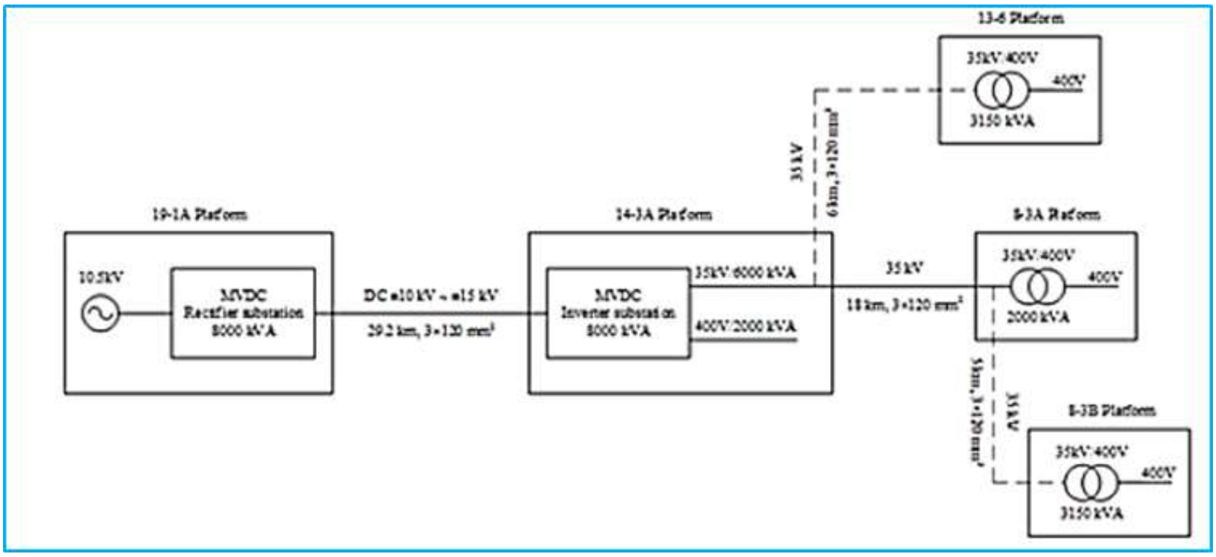


Figure 3.4-21: Wenchang MVDC system layout.

MVDC-Pilot6: Flexible Electrical Networks (FEN) Research Campus, RWTH Aachen University [36]

The FEN Research Campus at RWTH Aachen University concentrates on DC technologies for the distribution of electrical energy. The FEN Research Campus is a public-private partnership of science and industry and consortium of science and consists of (currently) 17 companies and 16 university chairs. Its landmark project is a private multi-terminal medium-voltage DC grid for research purpose, connecting three large research centres (Center for Wind Power Drives, CWD, E.ON Energy Research Center, E.ON ERC, and Center for Aging, Reliability and Lifecycle Assessment, CARL, currently under construction) on the University campus Melaten. The project started by the end of 2014 with investigation into regulations, safety requirements, required permits and identification of available components. Practical construction started during spring 2018 and concluded in summer 2019. Regular operation commenced in fall 2019 after a period final testing. Figure 3.4-22 shows the outline of the research grid on the RWTH Aachen University Campus Melaten. The track is partially placed beneath the public foot-walk along the street, partially running through a supply tunnel next to other infrastructure (public ac grid, heat, gas, data). The target application is testing of MVDC grid equipment, operational behaviour and as productive function, power flow sharing between the connected research centres during high performance testing.

Figure 3.4-22: Outline of MVDC Research Grid at FEN Research Campus [36].

The line configuration of a line segment is a double symmetric monopole line. An additional neutral conductor is provided, but normally not used for power transmission. The line is built from conventional single-core shielded aluminium cables, rated for a maximum voltage of 18kV (RMS) vs. shield, with water tightness in axial and radial direction. The insulation capacity could allow operation up to 50kV line-to-line voltage. Figure 3.4-23 shows the cross section of the underground line installation.

Figure 3.4-23: Cross-sectional model of the underground line, two power strings (left upper and lower pair), neutral and data cables (right).

The current operating parameters of the MVDC research grid are +/-2.5kV line-to-line voltage and 680A (RMS) rated current per cable. The substations are designed for a rated power of 5MW and connect between the DC bus installation of the connected research centres and the switchgear. The internal DC installation the two existing centres operate at +/-2.5kV as well, the third one shall operate at 1kV after completion of the centre.

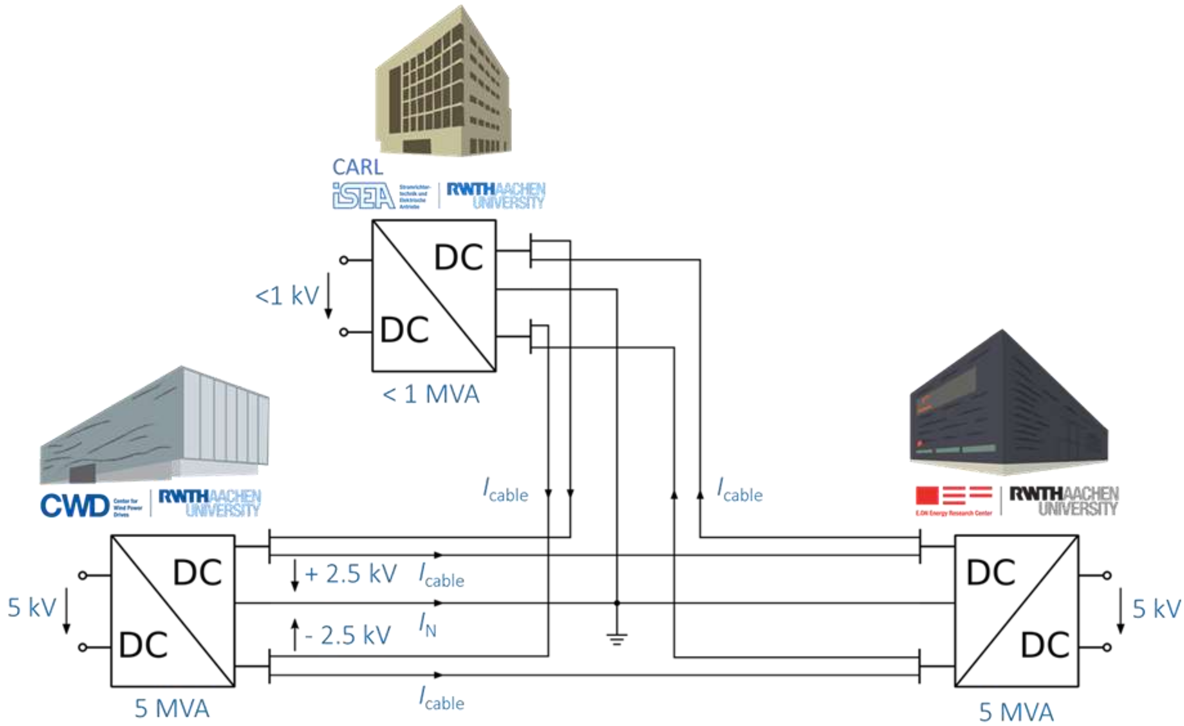


Figure 3.4-24: Grid topology in ring configuration [36].

The converters in the substations are implemented as 3-Phase-Dual-Active-Bridge (3~-DAB) DC-DC converters. Internally they use medium frequency three phase transformers for galvanic isolation, produced by high-grade magnet steel, allowing the fundamental frequency of 1kHz at 1T flux density, resulting to a at least 10 times smaller transformer volume. As the external and internal DC voltages are equal, the transformers have a 1:1 turn ration.

The smart switchgear flexibly allows change between parallel, ring, and star configuration. It allows also configuration for testing of line dynamics, power electronic components and other grid assets, independent from the connected centres. Figure 3.4-25 shows the configuration of the switchgear at E.ON ERC, connecting to the MVDC grid at the top and to the converters in the substation at the bottom. It consists of three cabinets of equal design (Figure 3.4-25, small photo right) which contain the contactors, designed for switching the maximum operation current, the sensing equipment, and the interface to the control system. As the short-circuit current is limited by the converter design, large short-circuit capacity has not to be provided by the contactors.

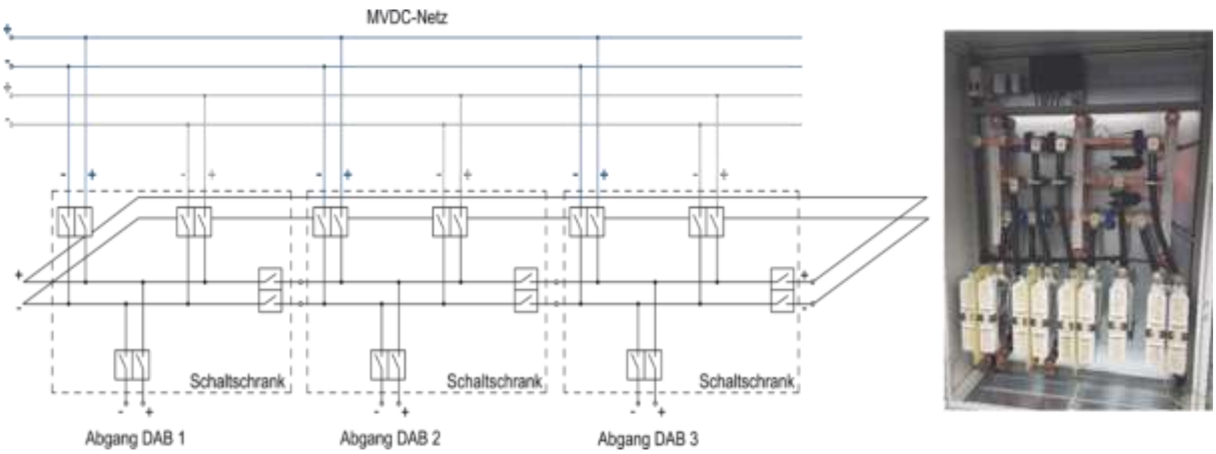


Figure 3.4-25: Switchgear configuration at E.ON ERC (left), picture of one cabinet (right) [36].

The MVDC Research Grid is controlled by central control station (Figure 3.4-26), visualizing the main grid conditions in overview and the detailed operating parameters of the substations. It allows also changing the grid configuration remotely over the control network.

Figure 3.4-26: Control station at FEN Research Campus.

MVDC-Pilot7: Suzhou MVDC system [13]

The Suzhou DC distribution network is a typical MVDC project with multiple voltage levels and multiple application scenarios as shown in Figure 3.4-27, sponsored by 2018 National key research and development projects of China. This project is aimed to explore the power supply mode, grid structure of MVDC system, realize the DC power transmission in long distance and improve the reliability of power supply and energy utilization.

A variety of key equipment of MVDC system, such as DC transformer, medium voltage DC circuit breaker and DC adapter, have been developed. Concretely, Suzhou MVDC system contains two 10MW AC/DC converters, 4 DC circuit breakers, 82 DC load-break switches and 19 DC transformers with the capacity of 1MW or 2MW, which has three stage of voltage levels as ± 10kV$_{DC}$, ± 375V$_{DC}$ and ±48V$_{DC}$. Besides, there is a 6.4MW PV generator integrated, and it will supply power to various kinds of loads with the capacity up to 10.7MW, including resident load/data centre/commercial load/industry load and charging pile.

It's a big challenge to make this complex system safe, stable and economical. To consider above objectives, different strategies and topologies are applied in consideration of different scene characteristics to make the system operate with high efficiency, high power density, high reliability and economic separately. Furthermore, in order to realize the DC adaptation of the end users, 10 kinds of household appliances such as refrigerators, washing machines, etc. are remaking, which is expected to improve the comprehensive energy efficiency of electricity consumption by 2%.

The project is to be completed and put into operation by the end of 2020.

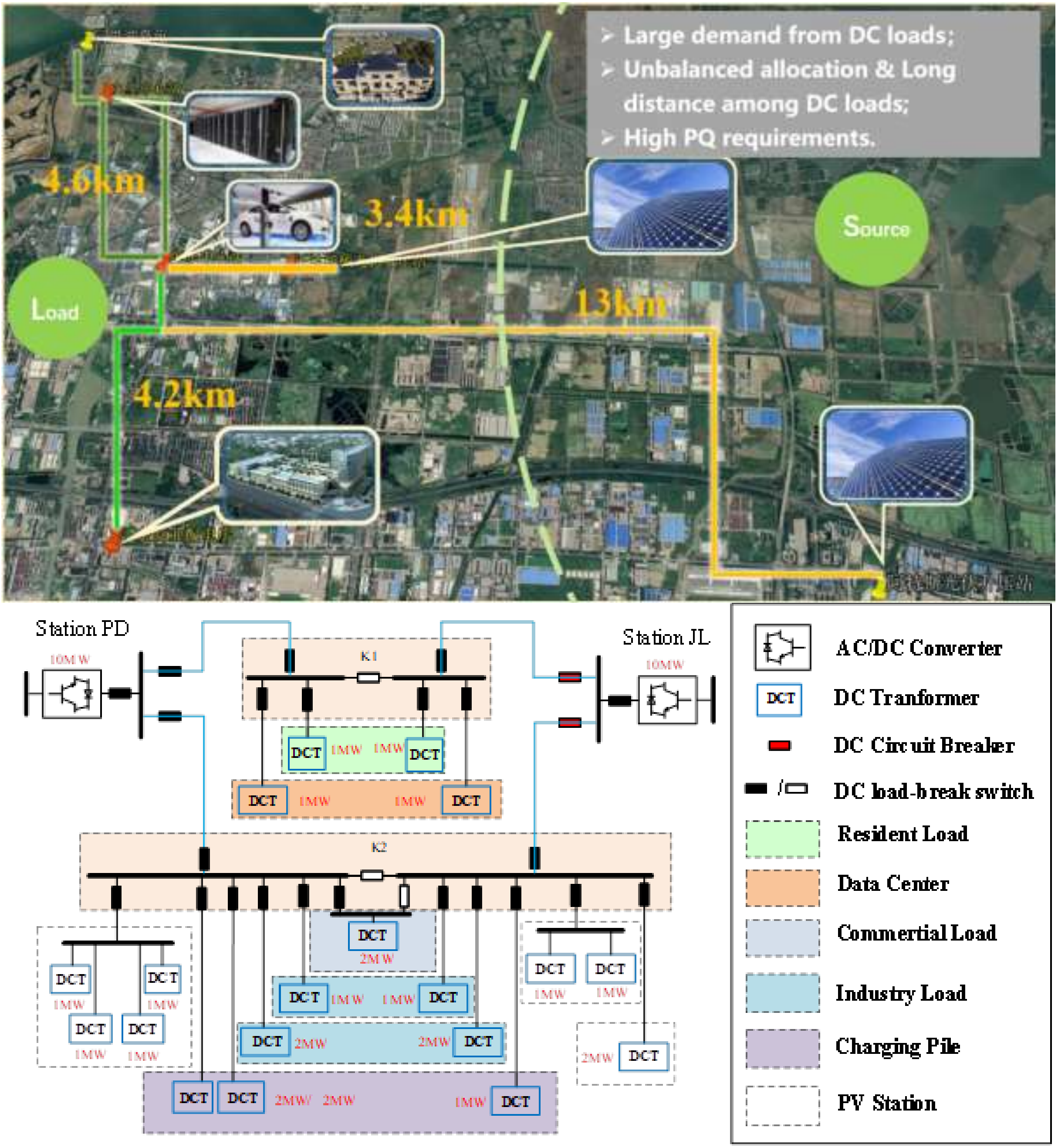


Figure 3.4-27: The Suzhou MVDC system in China.

4 STATE OF THE ART OF COMPONENTS & TECHNOLOGIES

Chapter 4 summarizes the state-of-the-art of components and technologies to set up DC distribution networks. It starts with the findings of Academic/RTOs (Section 4.1) and Manufacturers (Section 4.2) positioning surveys. These surveys were carried out by the Working Group collecting data within the WG-members and interested worldwide companies and members of European organizations and research networks. Section 4.3 gives a short overview about key components and technologies given high-priority to set up DC distribution networks based on a literature survey and with a focus on MVDC. Concerning the Circuit Breakers also LVDC developments are discussed.

4.1 Academic/RTOs Survey

4.1.1 Survey Objectives and Methods

This survey was sent to academic/research institutes active in LVDC and MVDC systems. It asks about existing systems that have been created and installed, laboratory capabilities and past experiences. The questions included refer to a variety of aspects including size of teams, laboratory features, target applications, technologies and relevant standards.

The Working Group (WG) was formed in 2019 with the aim of highlighting the status of existing knowledges, applications and laboratory capabilities of building LVDC and MVDC systems in different countries and regions. To accomplish this, the WG carried out a public survey from August 2020 till October 2020. The survey was realised in the form of a web-based questionnaire and structured into three main parts which aimed to obtain information on three main aspects of LVDC and MVDC distribution networks:

- Part 1: Respondent general background information;
- Part 2: Technical information and business potential; and
- Part 3: Validations and verifications associated with DC systems

4.1.2 Respondent General Background Information

Part 1 of the questionnaire was aimed at producing information about the respondents. Analysis of the responses reveals the types of organizations and nationalities of these respondents, the fields of industry involved, and the number of people working on topics related to LVDC and/or MVDC systems. Figure 4.1-1 presents the nature of respondent organisations. The participants belong to Universities, industry and research organisations. The majority of participants works in the University setting. The industry participation makes up for a quarter of all participants and lastly, only 9% of participants work in Research and Technology Organisation (RTO).

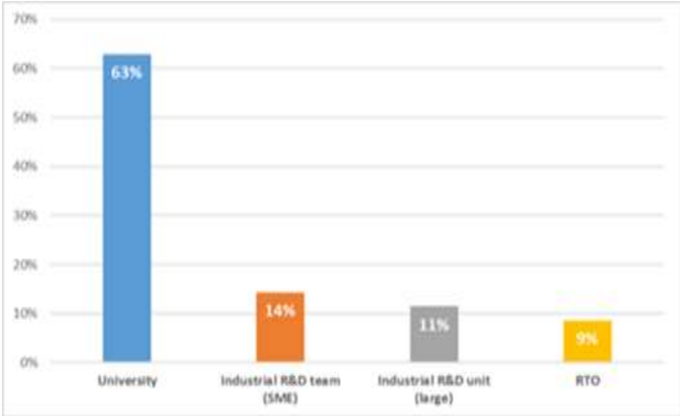


Figure 4.1-1: The nature of the respondent organisations.

From the previous analysis, it is not surprising that more than half of all participants have academic research roles: Senior Researchers or Senior Academic staff. Figure 4.1-2 presents the distribution of the respondents' nationalities. Germany, UK, and Netherlands were the most represented countries in this survey, followed closely by Spain and China. Central Europe was only mildly represented with only 1 to 2 responses per country. We only had 2 responses USA. The African continent was represented by Kenya with only 1 response.

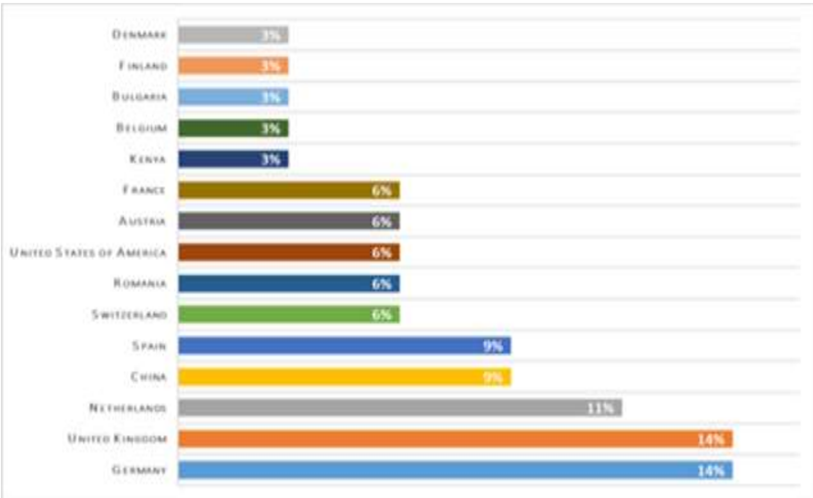


Figure 4.1-2: Nationalities represented by the respondents.

The number of people working in LV/MV DC systems varies between different settings. Figure 4.1-3 presents the average of people working in the areas of DC distribution amongst University, industry (Small and Medium-Sized Enterprises (SME)), industry (Large) and RTO. It is not startling that the distribution of the number of the undergraduate/master and PhD students working in DC topic is higher in University than the other settings. While the number of the technician working in the industry (SME) has higher distribution compared to other settings.

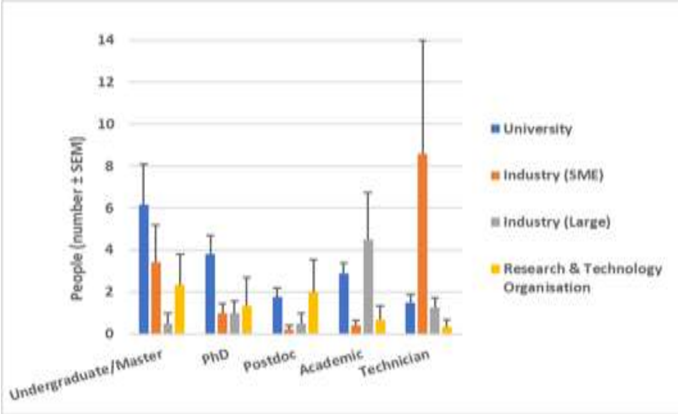


Figure 4.1-3: Work categories of people working in DC distribution in each setting.

4.1.3 Technical Information and Business Potential

There are several questions being asked regarding the technical properties of DC systems and their business potential. These technical properties were addressed in Part 2 of this questionnaire. In this section, the participants were asked to describe the main research areas, the natural and approximate level of the power involved, the target voltage levels, and nature of funding for the DC systems considered in the DC laboratories.

DC distribution has a vast array of applications and this is clearly depicted on Figure 4.1-4. Looking at the results, we can see that the main topics covered are DC microgrid and Hybrid AC/DC systems. Emerging areas are Microgrid with solar systems (9%), control and stability of microgrids (9%), LVDC systems (6%) and Protection schemes (6%). Curiously, areas like Net zero building, Telecom systems, Marine systems, and Aircraft systems, that were previously hot topics are now at the bottom of the picking list.

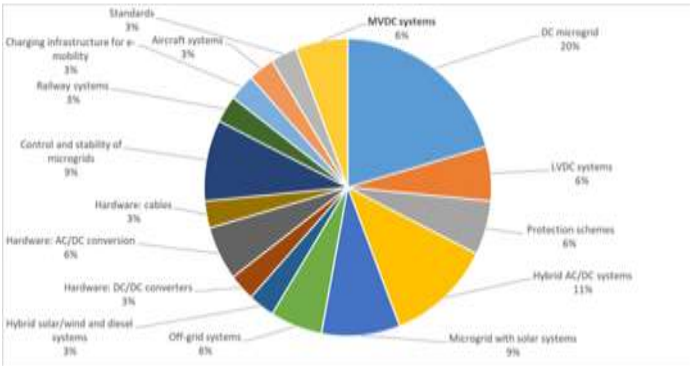


Figure 4.1-4: Main research areas of academic/ industry team associated with DC distribution laboratories.

The participants were then asked to identify the voltage level that used in their DC laboratories. The preferred voltage identified were low voltage (120-1500V) with 83%. This is the main voltage for installations in residential and commercial buildings, industry, and transportation and, thus the most ubiquitous. This was followed by extra low voltage (up to 120V) with one fifth of participants working with this level, and lastly, medium voltage (1.5kV-100kV) as the third preferred voltage. Results are shown in Figure 4.1-5.

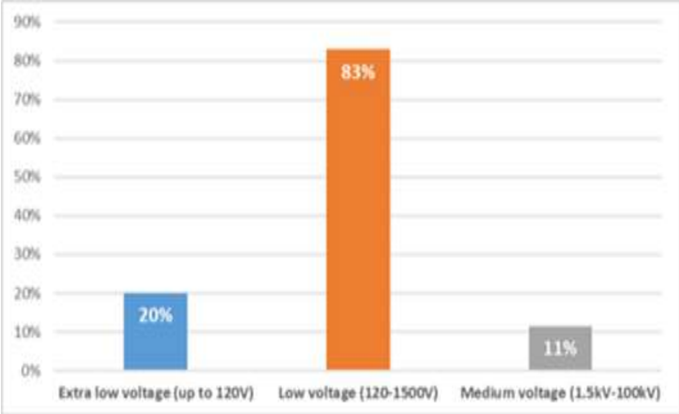


Figure 4.1-5: 6 Voltage levels dominating in DC laboratories.

The participants were asked to identify the main power level in their DC laboratories. The main power level identified were in the University from <1kW to >100kW. While in industry (SME) the main power level available in DC laboratories is only in the range of <1kW and above >100kW, in the industry (large) the power level available in the DC laboratories is 5-10kW as shown in Figure 4.1-6.

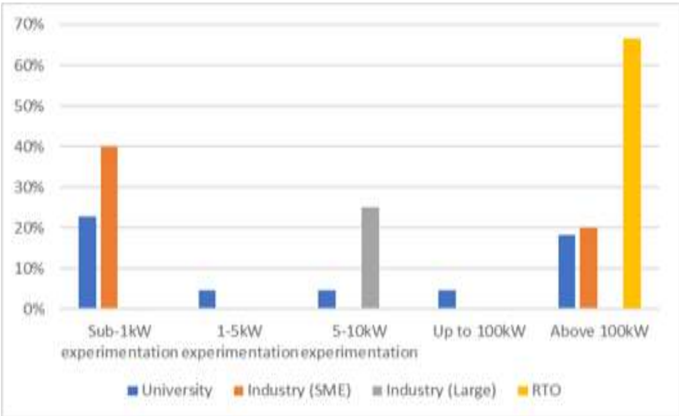


Figure 4.1-6: The approximate value of power levels available in DC laboratories.

The main funding body is National Grant as depicted in Figure 4.1-7. This is however not surprising given that the majority of participants belong to the University setting. With the increase of interest from industry in this area, it is observed that a bold presence of industry participation with 30% of funding coming in from this funding body. The results show that there is interest in industry and government to develop more innovation solutions and commercial products related to LV/MV DC.

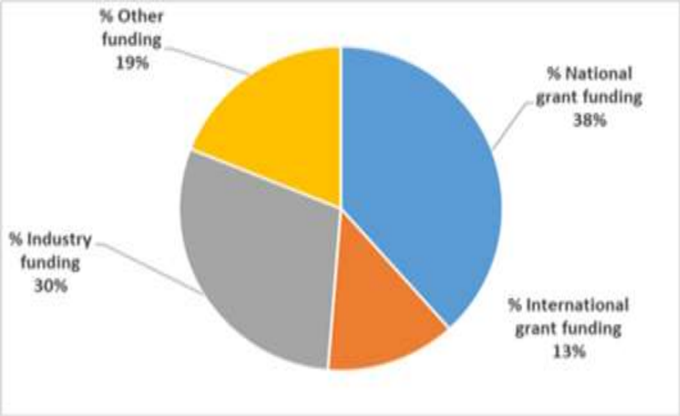


Figure 4.1-7: Nature and approximate balance of funding sources.

The technology readiness level (TRL) is usually recognized as an indicator of the maturity of technology. According to the responses, the LV/MV DC technology and markets have reached Mid TRL (4-6) with 44%, which denotes validation in industrially relevant environments. The participants have also reported Low TRL (1-3) with 36% as the majority of participants belong to the university settings, where the main focus is on the R&D and experimental proof of concept. It is worth noting that 20% of participants have reported High TRL (7-9) such as developing solid state DC breaker and new grounding topologies, and the use of $48V_{DC}$ systems (USB type-C) for tertiary building for IT equipment.

Figure 4.1-8 presents the overall TRL in the current research.

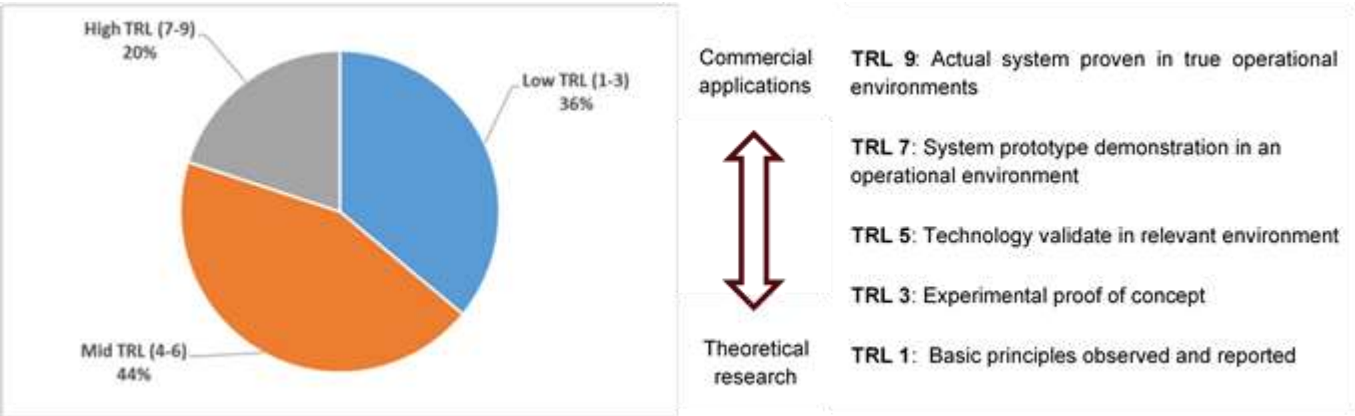


Figure 4.1-8: The maturity levels in the current research.

The participants were asked to indicate the future research and development associated with DC applications. The participants believe that DC for building, DC for EV charging and DC for medium voltage distribution will continue to grow at least over the next decade. This is followed by DC for last mile distribution, DC for industrial application and DC for wind and solar power collection. It worth noting that electrified railway, DC for marine, and DC for aircraft had lower importance than expected, probably because the current performance of existing technologies fulfils the expectations. Results are presented Figure 4.1-9.

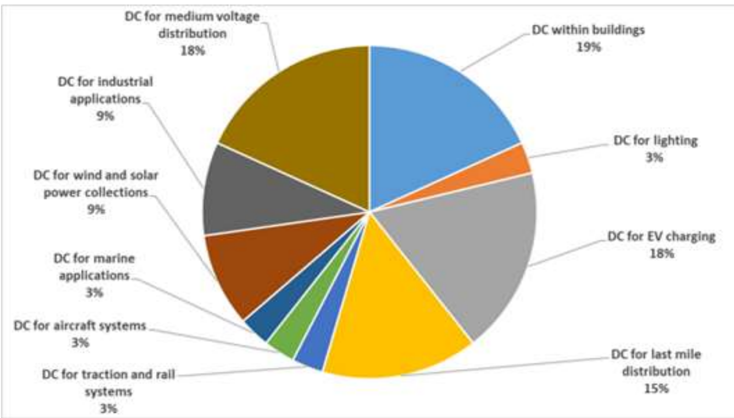


Figure 4.1-9: The target DC applications.

The participants were requested to indicate which energy storage technologies are involved in the DC R&D. The most common energy storage used in DC R&D is Li-Ion batteries (89%) followed by super capacitor (43%) and flywheels (20%). This is because the energy density of the flywheel energy storage is not high as well the self-discharge rate is high, this means the energy will be exhausted in a few to several tens of hours, whereas the efficiency of Li-ion batteries is high, and it is more cost-effective.

The participants were also asked to indicate which communication technologies are employed in the management of the DC systems. The main communication technology used in DC laboratories is Wi-Fi (37%). This is because Wi-Fi communication technology has several advantages such as easy to set up in the lab, low installation and maintenance cost and the flexibility to add on new devices when required. This is followed by optical fibre (29%) and fieldbus (23%).

4.1.4 Validations and Verifications Associated with DC Systems

There are several questions being asked regarding the validation and verifications associated with DC systems. These questions were addressed in part 3 of the questionnaire. In this section the participants were inquired to reveal the main standard that actively impact in DC R&D, the main tools for validation, and the target journal and conferences for publications.

Standardisation will help facilitate application of LV/MV DC technologies, accelerate their commercialisation by offering a platform to manufactures, to ensure that the most productive sequences and work practices were being documented. The participants have reported that the standard that currently have most widespread impact on the DC distribution R&D are from IEC and IEEE as depicted in Figure 4.1-10. This is mainly, IEC has published many standards for DC systems for existing DC applications and has a number of ongoing activities on the utilisation of DC power distribution in several applications.

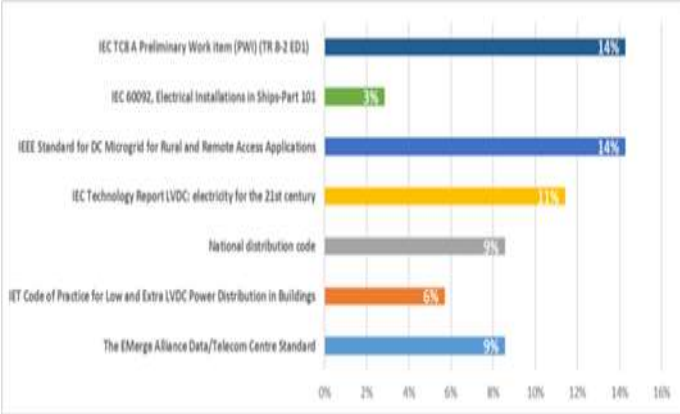


Figure 4.1-10: The standards material that actively impact in DC R&D.

The journal’s publication method will determine how beneficial the published work will be to researcher and to the public. The participants were asked to determine which journals and conferences they targeted when publishing about LV/MV DC systems. According to the survey, the journals targeted for DC distribution publication were dominated by IEEE transactions on power electronics (20%) and smart grid (11%). The conference papers targeted mainly by CIRED (14%) and IEEE ICDCM (11%) as depicted in Figure 4.1-11.

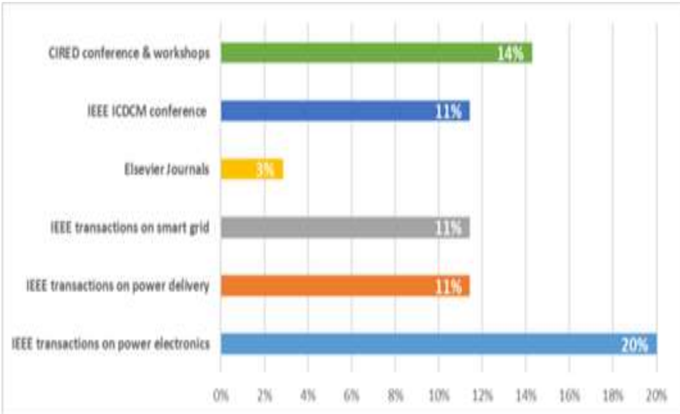


Figure 4.1-11: Target journal /Conference for publications.

Conceptual development and experimental validation of a power system with highly dynamic and transient behaviour is essential. The participants were asked to determine the main source for validation of a modelling and simulation work accompanying with DC R&D. In accordance with the survey, the main source of validation is experimentation (63%). Validation experiments are preformed to improve fundamental understanding of physical behaviour, improve mathematical models, and generate high quality data for the purpose of assessing the accuracy of a model. This is followed by peer reviewed publications (11%) and industrial partners (9%) making up the rest as depicted in Figure 4.1-12.

With regarding to the software tools that are used in modelling work associated with DC system. The participants indicated that the most used software tools are MATLAB/Simulink, PLECS and HOMER. MATLAB/Simulink is mainly used by Universities and research labs and is the most popular electrical engineering software.

In terms of hardware in the loop simulation tools, participants revealed that the most used hardware in the loop is Opel-RT (46%) followed by Typhon HIL (9%) and RTDS (9%). RT box National Instruments is used by 3% of participants along with Speedgoat. Predominantly, Opel-RT offers offline simulation, real time simulation, and real hardware test capabilities on a single test bench.

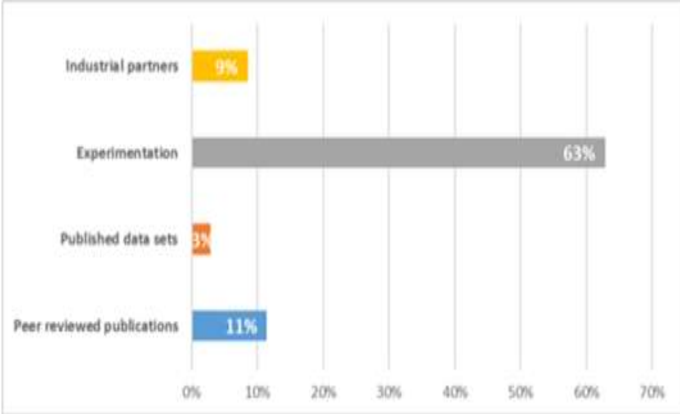


Figure 4.1-12: The main tools for validations.

4.1.5 Conclusions

Based on the survey results and analysis, discussed in this chapter, the following conclusions can be drawn:

- The main research areas of academic/industry team associated with DC distribution laboratories are DC microgrid and Hybrid AC/DC systems. Areas like Net zero building, Telecom systems, Marine systems, and Aircraft systems, that were previously hot topics are now at the bottom of the picking list;
- The preferred voltage level that dominates DC laboratories is the low voltage (120-1500V), then extra low voltage (up to 120V) and finally medium voltage (1.5kV-100kV);
- The power level available in the DC laboratories are as follows. In the University, the power level varies from sub-1 kW to above 100kW. In industry (SME) the power level is only sub-1kW and above 100kW, and in industry (large) the power level is 5-10kW;
- The main funding body is national grant (38%), followed by industry (30%);
- The most technology readiness level (TRL) of research and development of DC applications is defined as Mid TRL (4-6). This includes integration of battery energy storage systems in distribution and developed DC power protection systems for multilevel voltage networks;
- The most targeted research and development associated with DC applications is DC for building, followed by DC for EV charging, and then DC for medium voltage distribution;
- The most common energy storage used in DC R&D is Li-Ion batteries (89%) followed by super capacitor (43%), and then flywheels (20%);
- The main communication technologies used in DC laboratories is Wi-Fi of (37%) followed by optical fibre (29%) and then fieldbus (23%);
- The standards that currently have most widespread impact on the DC distribution R&D are from IEC and IEEE;
- The main target journal for DC distribution publication is dominated by IEEE transactions on power electronics (20%) followed by smart grid (11%). The conference targets are dominated by CIRED (14%) and IEEE ICDCM (11%);
- The main source for validation of a modelling and simulation work accompanying with DC R&D is experimentation (63%), followed by peer reviewed publications (11%) and then industrial partners (9%);
- The most used software tools are MATLAB/Simulink, PLECS and HOMER; and
- The most used hardware in the loop simulation tool is Opel-RT (46%), followed by Typhon HIL (9%) and then RTDS (9%);

4.2 Manufacturers survey

4.2.1 Survey Objectives and Methods

The manufacturers survey in the frame of the CIRED DC working group has been launched from August to November 2020.

The aim was to investigate the already commercialized types of DC products and solutions. The different aspects addressed in the survey are:

- Who is commercializing DC solutions?
- The markets and area of commercialization;
- The voltage levels of the DC solutions;
- Some key characteristics of the DC systems where the solutions are integrated;
- The most promising technologies and their levels of maturity; and
- Which standards are the most relevant for the DC commercialized solutions?

The anonymous survey has been published with “Forms” (office 365) and the link distributed from end of July until mid-November. The analysis of the 20 answers has allowed identifying 44 product items, 9 domains of applications and 13 products families.

4.2.2 Respondent Organizations

The respondents are mainly small and medium enterprises (13) or multinational group (4) (Figure 4.2-1) with still a dominant presence of the technical department (Figure 4.2-2) showing the needs of expert guidance to choose the product corresponding to the customer needs.

Figure 4.2-1: Organizations of the Manufacturers survey respondents.

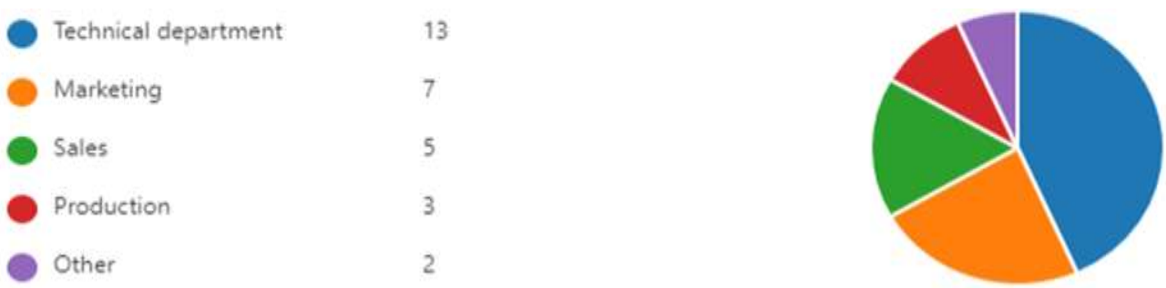


Figure 4.2-2: Department(s) of the Manufacturers survey respondents.

4.2.3 Respondents Markets

The detailed analysis of the respondent's answers gave the different application domains and markets where the products are mostly used (Figure 4.2-3).

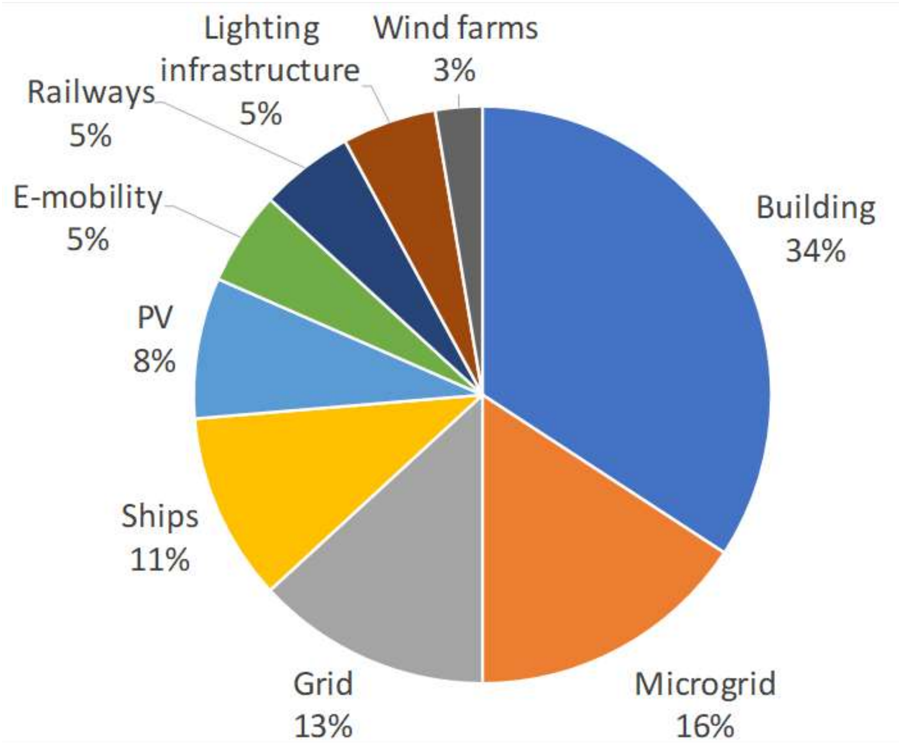


Figure 4.2-3: Distribution of the Markets addressed by the Manufacturers survey respondents.

The building and microgrids markets represent 50 % of the respondent application domains.

The stabilization of AC grid using DC components is also present (13%) followed by transport (ships (11%) and e-mobility (5%)) The renewable production represents 8% for PV and 3% for wind. DC solutions is also commonly used in infrastructures: Railways (5%) and lighting (5%).

Taking in account the voltage levels ELV (<20A), LV (between 120A and 1500A) and MV (above 1500A), we were able below (Figure 4.2-4) to give more details about the market distribution for each level.

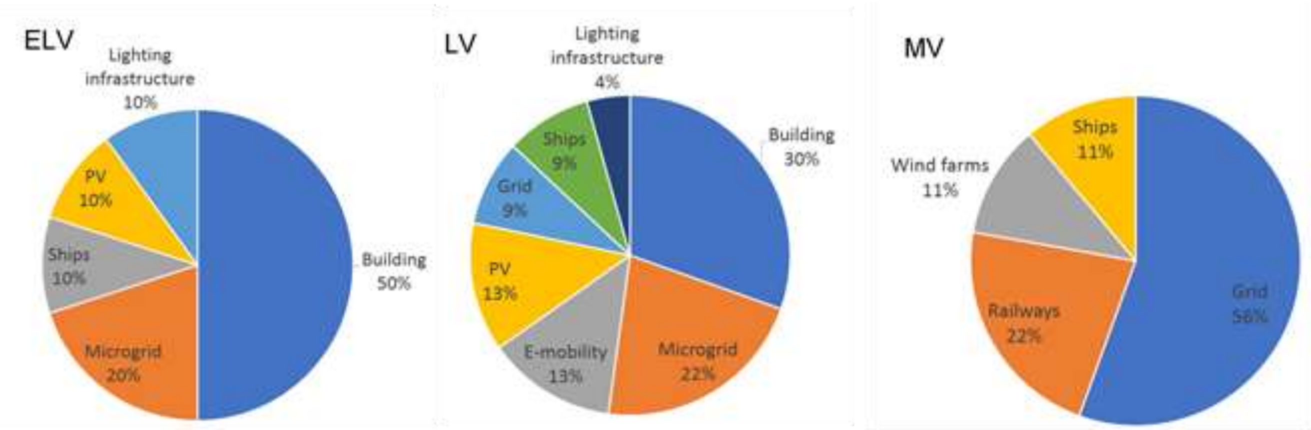


Figure 4.2-4: Distribution for each voltage level (ELV, LV and MV) of the Markets distribution addressed by the Manufacturers survey respondents for each.

As shown in the Figure 4.2-4, for ELV and LV the predominant markets stay building and microgrid. Ships and renewable are present on the 3 levels of voltages.

The geographical areas of activities of the respondents show a global commercialization of DC products (Figure 4.2-5).

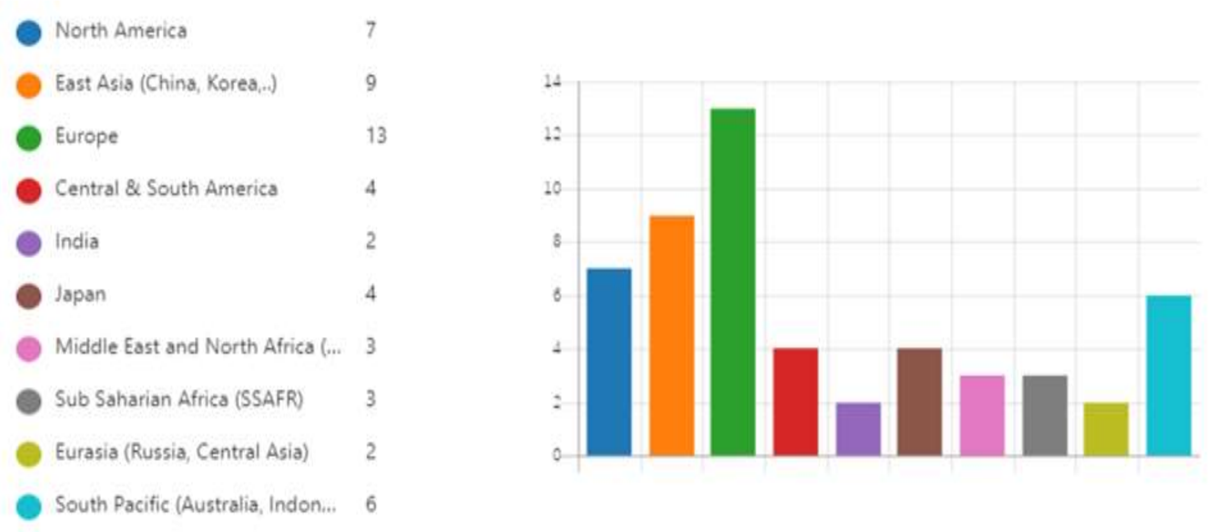


Figure 4.2-5: Geographical area of commercialization for DC solutions of the respondents.

From the answers it is difficult to draw a predominance of certain markets in different countries.

The distribution of the answers is consistent with distribution of pilots with major players in Europe, East Asia and North America.

It seems that even small enterprises have access to a worldwide area of distribution of their products.

4.2.4 Respondent Products Categories

The products are categorized by voltage levels:

- ELV = Extra Low Voltage (<120V);

- LV = Low Voltage (from 120V to 1500V); and
- MV = Medium Voltage (>1500V).

The Figure 4.2-6 shows the distribution of voltage level among the respondents' solutions.

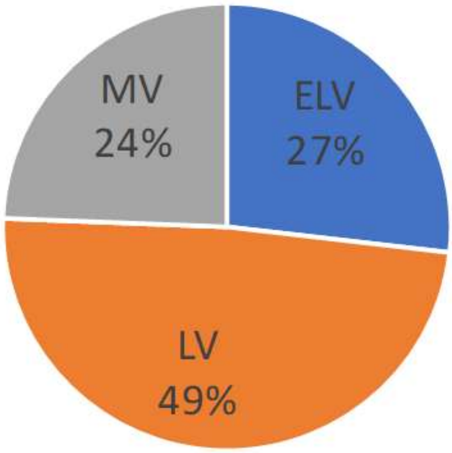


Figure 4.2-6: Voltage level distribution among the DC solutions of the respondents.

Clearly the extra low and low voltage solutions are most of the products commercialized for energy networks.

The average TRL for each voltage level (Figure 4.2-7) is showing a well-established product portfolio for ELV and ELV whereas MVDC is progressing from first industrial pilots to series productions.

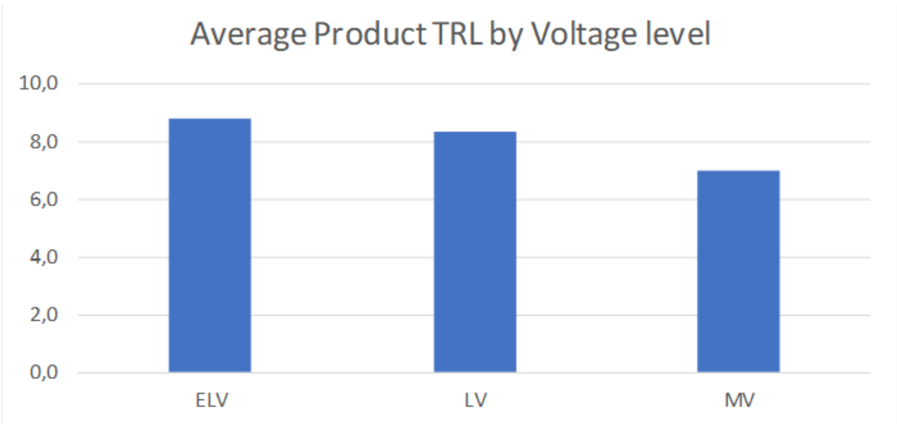


Figure 4.2-7: Technology readiness Level as a function of Voltage level for DC solutions of the respondents.

The lack of standards at MV level is limiting the deployment to pilot projects (TRL7) and can represent are real lock for the acceptation by customers for further investment and testing to reach higher TRLs.

Note that the other markets using massively ELV and LV components, like electronic equipment's (multimedia, PC, mobile…) are not covered by the survey but it is likely that the maturity level of such neighbouring markets is actively participating to the maturity of similar components used in energy networks.

The categorization by family of products is presented on the Figure 4.2-8.

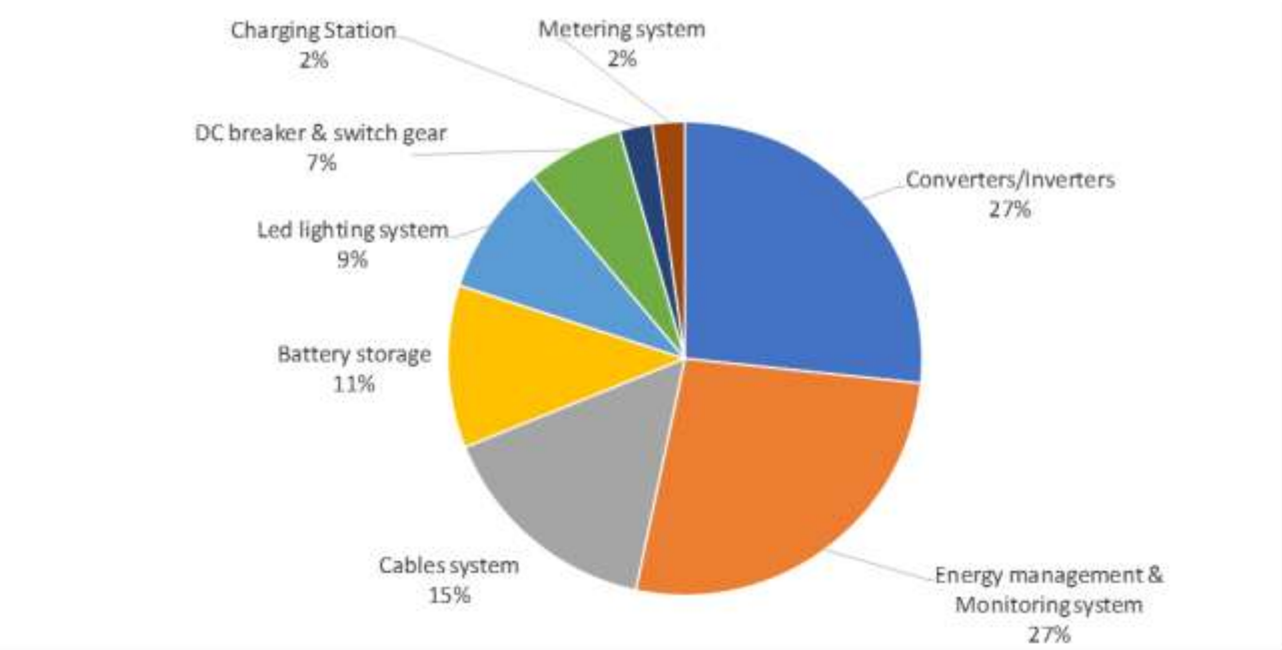


Figure 4.2-8: Types of DC products/solutions commercialized by the Manufacturers survey respondents.

The product families extracted from the respondent's answers are covering all what you need to build an energy network from conversion and cable to DC terminal appliances and protection components. The importance of energy management and monitoring is noticeable and probably more pronounced than for AC networks in relation with the possibilities offered by power electronics natively present in DC solutions.

DC solutions needs ICT and automation concept.

Charging station (EV) has a low score probably due the use of DC only for high power (above 50 kW).

4.2.5 Respondents DC Systems Characteristics

The characteristics of the DC systems are key to design and manufacture the DC products and solution. The voltage polarity is the most important (Figure 4.2-9).

Figure 4.2-9: Different type of Voltage polarity in the DC solutions of the respondents.

The general trends as soon as power is transmitted is to choose metallic return, probably for safety reasons. Certain types of products exist in both type of polarities as well as with ground or metallic return.

The tables below give the statistics of configurations for the different voltage levels. Ground return is disappearing completely for MV products.

Table 4-1: Pole(s) and return configurations statistics for ELV products.

ELV	Bipole	Both	Monopole
Both	0%	18%	0%
Ground	0%	0%	18%
Metallic	9%	55%	0%
Total	**9%**	**73%**	**18%**

Table 4-2: Pole(s) and return configurations statistics for LV products.

LV	Bipole	Both
Both	0%	38%
Ground	4%	0%
Metallic	25%	33%
Total	**29%**	**71%**

Table 4-3: Pole(s) and return configurations statistics for MV products.

MV	Bipole	Both	Monopole
Both	0%	40%	0%
Metallic	30%	0%	30%
Total	**30%**	**40%**	**30%**

To ensure safety the protection scheme of the network is the second key parameters (Figure 4.2-10).

The load break switch is only able to interrupt rated current but not fault, whereas circuit breaker is designed for fault protection.

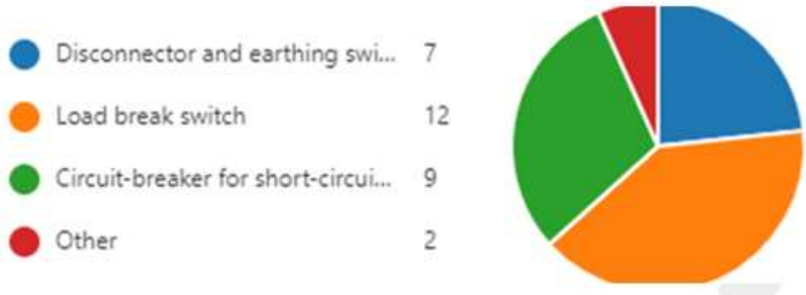


Figure 4.2-10: Different type switchgear for DC solutions of the respondents.

4.2.6 Collaborations with High Impact on DC Distribution

Several types of collaborations are existing to develop DC distribution:

<u>Bipartite:</u>

- Direct Collaborations on
  - Storage/inverter; and
  - Switching protection.
- Direct collaborations with
  - National DSOs (local projects: Smart grids;
  - Building owner or designer; and
  - OEMs (Railways industry, Wind)

<u>National or regional funded programs:</u>

- UK
  - Ofgem Electricity Network Innovation Competition project ANGLE-DC 2016-2020; and
  - FLEXIS (Flexible Integrated Energy Systems).
- US:
  - “Sustainable Building Initiative (SBI) in 2007;
  - The Future Renewable Electric Energy Delivery and Management (FREEDM) in 2011; and
  - The DOE is also active in supporting collaboration frame between labs, manufacturers and final users (EPRI, NREL, Eaton, DSOs).
- China:
  - National Key Research and Development Program of China (2018).
- Europe initiatives
  - Recent funded projects on DC interoperability and system issues (PROMOTION (HVDC - finished), HYPERRIDE (MV, LV) started, SHIFT2Rail (MVDC) started) in the frame of H2020 but for high power energy networks; and
  - The European distributed Energy resources laboratories (DERlab) is associating leading laboratories to promote smart grids and green distributed energy resources using DC networks and components.

4.2.7 Most Promising Works and TRLs

When asking respondent on what they consider to be the most promising works and how long it will take to have them commercialized, respondents' answers are summarized in Table 4-4. Typically, to progress of 1 degree of maturity on the TRL scale requires at least 1 year of work.

Table 4-4: Most promising work and related TRLs according to respondents.

TRL 1-3	TRL 4-6	TRL 7-9
Battery storage connected to grid systems	Power flow and state estimation solutions for DC railway systems	DC distribution for Automotive charging stations.
Proper DC electricity metering for billing purposes	Battery storage from solar production	Improvements in monitoring of power quality in conversion systems
The real requirement of the END device	Ultrafast DC breaker for MVDC applications	Hybrid systems for ships
	New distribution energy application	New point to point END GRID structure application

Surprisingly the lack of well-defined end device requirements is cited as one of the key subjects that will take several years to become mature.

The next results to come on the market in the coming years (TRL7-9) are linked to EVs and electrification of transport in general.

The second wave (TRL 4-6) seems to be more related to distributed renewable resources within distribution networks.

The last wave (TRL 1-3) is closer to the customers or prosumers with the monetization of energy exchanges based on DC systems.

4.2.8 Impact of Standardization

The ranking of most used standards is presented in Figure 4.2-11: Ranking of most used standards among the respondents.

1	IET Code of Practice for Low and Extra Low Voltage Direct Current Power Distribution in Buildings
2	The EMerge Alliance Data/Telecom Centre Standard
2	National Distribution Code
3	IEC Technology Report LVDC: electricity for the 21st century
4	IEC TC8 A Preliminary Work item (PWI) (TR 8-2 ED1) on "Assessment of standard voltages and Power Quality requirements for LVDC distribution",
4	IEEE Standard for DC Microgrid for Rural and Remote Access Applications
5	IEC 60092-101:2015, Electrical Installations in Ships-Part 101: Definitions and general requirements.
6	IEC 60479-1 Effects of current on human beings and livestock - Part 1: General aspects

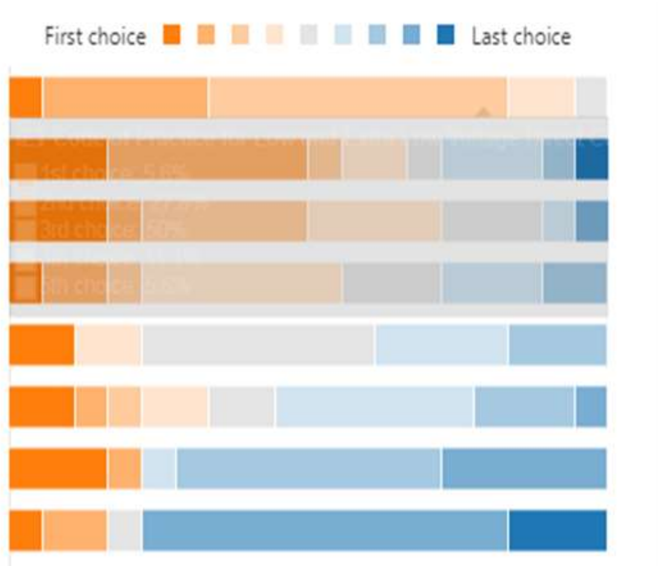


Figure 4.2-11: Ranking of most used standards among the respondents.

The ships and building related standards are the most advanced and used by manufacturers even for other applicative domains.

The high ranking of Emerge Alliance Data/Telecom shows that DC networks are by essence connected.

As soon as protection is at stake, systematic reference to IEC 60479-1 (Effects of current on human beings and livestock), especially for Railways, micrograms and grids applications.

National distribution codes used for grid applications and systems having a connection to grid (microgrids in cities, e-mobility).

The power quality standards are keys drivers/guides for solutions specification & development.

4.2.9 Manufacturers Survey Conclusion

Despite a low number of respondents to this survey, each manufacturer gave details that allow us to sort out the diversity of products offered for a wide range of markets.

The level of maturity of DC products for energy grid is directly linked to the level of voltage.

For extra low voltage and low voltage level the TRL are high thanks to standardization and neighbouring markets which give a high level of confidence to the end users.

For medium voltage, missing standards (voltage levels, safe operation, power quality, EMC, etc.), grid codes & test methods/infrastructure and regulations especially for MVDC hamper the development of commercial products/systems. This is mostly addressed to standardization bodies and regulators. Indeed, the manufacturers realize that end users have some difficulties to specify the products.

From the survey, we see that for ELV and LV products the main DC applications are in the building and microgrid with sill some challenges for power qualities and metering. Dealing with Low-inertia configurations (e.g. AC, DC, hybrid AC/DC nano & microgrids) there is a need for an energy & grid management for energy balancing/congestion management (grid automation) in comparison with state of the art high-inertia AC-grids.

The renewable generation uses the full scope of voltage with PV at ELV and LV and Wind at MV.

MVDC networks products are present for Railways infrastructure and are developing in Grids and e-mobility system with the increase power demand for transport, renewable production and storage.

TRLs for key technologies for components and systems must be raised to higher levels to allow field trials and a bigger role-out. Clear use-cases and business-models must be developed. Get more experience in planning and operation of this rather new technology. Therefore, more R&D and pilot projects are needed (funding, direct contracts).

Except for already settled niches no/less commercial DC-supplied applications are on the market (standard is AC/DC grid connection of mass products). This makes the setup of new DC grid configurations and also the refurbishment of existing AC grids a challenging task when almost all existing (end) applications are actually AC-supplied and non-cost & energy efficient DC to AC back-conversion is needed for DC-grid connection (as use-case then less attractive). Somehow a chicken-egg problem.

4.3 Overview of Components and Technologies

In this section available key components and technologies given high priority to set up DC distribution networks as well as their market readiness with a focus on MVDC and based on a literature survey are analysed. Concerning the Circuit Breakers also LVDC developments are included. In 4.3.1, converter technologies are presented, 4.3.2 analyses DC circuit breakers, 4.3.3 cable and overhead lines and in 4.3.4 protection is discussed.

4.3.1 Converter

The inclusion of medium voltage direct current (MVDC) grids into the AC grids requires converters and inverters. The main purpose of converters is the conversion of AC to DC, DC to AC or DC to DC. For this task, semiconductor elements such as diodes, thyristors and transistors are installed. Currently two different converter-technologies are commonly used, which are the voltage source converter (VSC) and the line-commutated converter (LCC). The LCC-technology works with thyristors and changes the power flow direction via a polarity reversal of the voltage. This is necessary because the current flow cannot be changed in the thyristors. The VSC works with IGBTs (Insulated Gate Bipolar Transistors) and changes the power flow over the direction of the current flow. The polarity of the voltage remains the same during the process. Figure 4.3-1 shows the principle of these two common technologies.

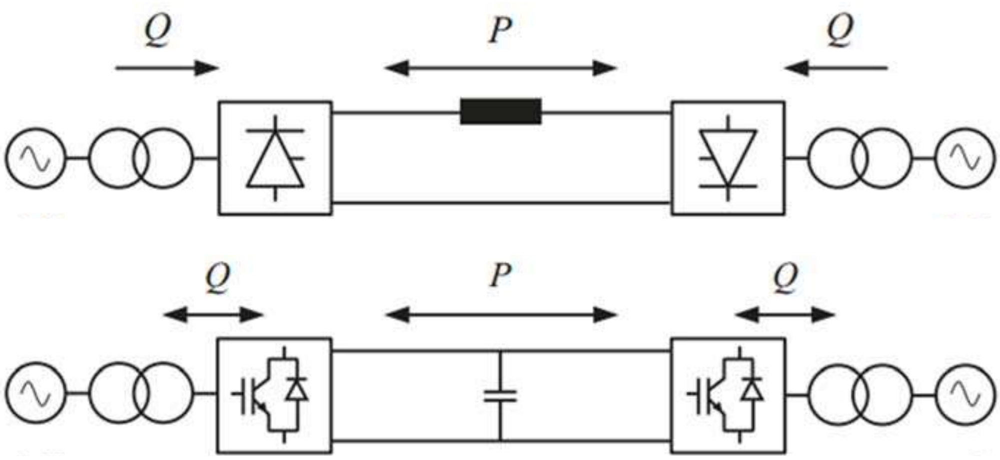


Figure 4.3-1: Different converter technologies of DC transmission.

During the last years, the modular multi-level converter (MMC) technology comes more in the focus of the DC conversion. The big advantages of the MMC technology are the modularity, the scalability for voltage and power, the short circuit tolerance, the possibility of a connection without a transformer and the high quality of the output voltage. Figure 4.3-2 shows the principle of the MMC. The MMC is connected to all three phases of the AC system over the positive and the negative side of the DC system. Every connection has a group of IGBTs and an inductance to limit the current.

The number of IGBT-modules depends on the aim of the task. The modules are realizable as half-bridge, full-bridge or more complex circuit variations, which have the required properties depending on the application. The VSC-technology needs a pulse-with-modulation to produce a sinusoidal output voltage with a frequent switching. On the other side, the MMC technology works with selective switching originating in the modules and therefore reduces the switching pulses.

As mentioned in chapter 3.4.2 the project “MVDC-plus” works with the MMC technology. The products have a fixed expansion level to reduce the costs of the displayed product.

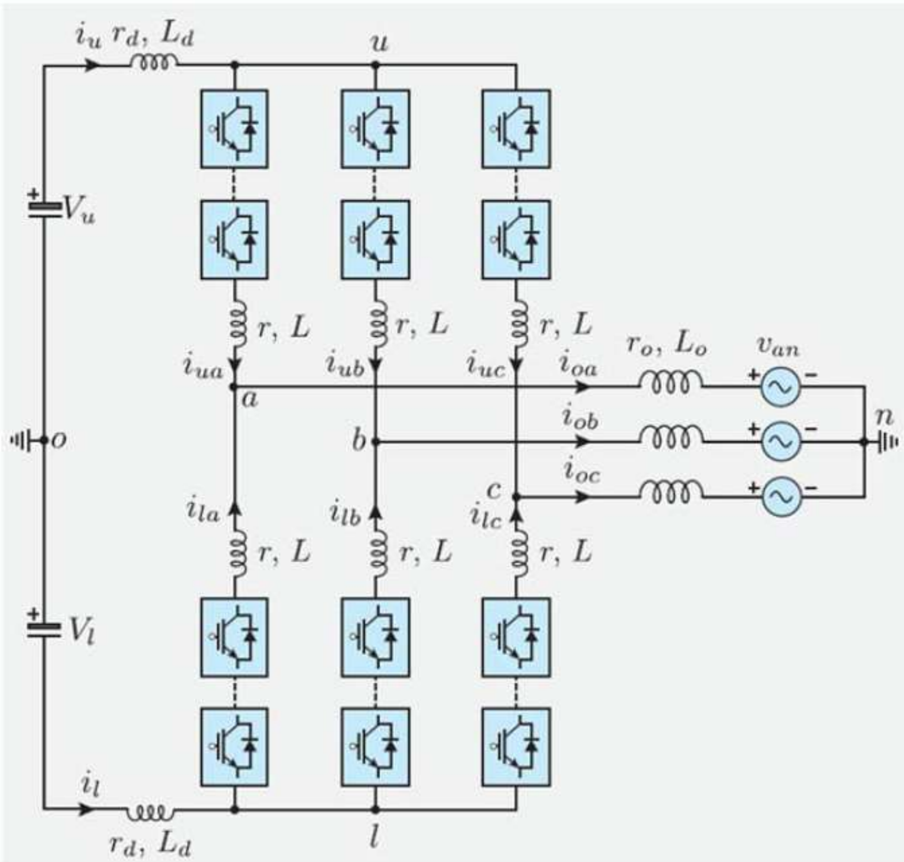


Figure 4.3-2: Principle of the modular multi-level converter.

4.3.2 Circuit Breaker

The interruption of DC current is more challenging than the interruption of AC currents. In the case of AC, the current has a sinusoidal waveform. The sinusoidal waveform has the advantage that the current crosses the zero point. Most of the common use circuit breakers use this advantage to interrupt the AC current. The AC current breakers usually require 20-60ms (50 Hz) for the interruption. In case of an error in a DC system, the currents never pass the zero line. The fault current increases to a certain level without any zero points. Therefore, it is necessary to create zero points in the direct currents by force.

DC circuit breakers are classified as MCBs (operated by traditional mechanical switches), SSCBs (which include power electronic solid-state switches), and HBCBs (combined MCB and SSCB) and Z-Source CBs for more complex DC applications. The circuit breakers' main function is to provide the force necessary to bring a current to zero, to dissipate the energy saved in the system, to withstand switching overvoltage, and to ensure a rapid interruption.

Mechanical DC circuit breakers such as Moulded Case Circuit Breakers (MCCB) or air circuit breakers are able to interrupt small currents. The design of the mechanical circuit breaker is almost the same as the design of the AC circuit breakers. Therefore, they can also be used for DC applications without any additional components. However, when the system voltage reaches higher values, it is very challenging to interrupt the DC currents with mechanical circuit breakers without additional components, such as electric circuits or power semiconductors. The switching of semiconductor circuit breakers happens normally a lot faster than the switching of mechanical circuit breakers. Interrupting DC currents can be achieved very quickly using power semiconductors or electrical circuits. Another advantage of including power semiconductors is, that there is no arcing of moving mechanical parts (which limits the lifetime) because the DC current switching is transferred into the semiconductors area. In DC systems, the fault current increases with time. As a result, it is a significant advantage to use a large number of semiconductors to interrupt the fault current in a very short period of time. The fault current will be interrupted at a lower value in this case. However, increasing the number of power semiconductors results in increased power losses, allowing for the use of a large cooling system.

LVDC circuit breaker Technologies:

The majority of safety regulations mandate the deployment of sufficient protection devices to isolate a DC fault. The absence of natural zero crossing and the high current changing rate (di/dt) present a significant challenge to interrupting a fault in an LVDC network. This increases the difficulty of interrupting DC current, posing additional design challenges for DC circuit breakers (DCCB). Circuit breakers must be designed and implemented properly in order to develop a protection scheme for a DC power system.

Numerous DC circuit breaker technologies have been developed, implemented, and analysed in a variety of DC applications. This section assesses these DC current breaking technologies in terms of their design, operating time, and power loss.

- *Moulded case circuit breaker (MCCB)*

Mechanical circuit breakers are a common type of protective device found in the majority of LVAC and LVDC systems. To facilitate the opening of a DC circuit, it has been proposed that the tripping device in conventional MCCBs operate via resonance circuitry to generate zero crossing [37]. This circuit breaker operates on the principle that when a fault current is detected, the MCCB switch opens, and the resonance circuit generates a negative transient current to counteract the fault current flow in the main circuit. The negative current grows to a point where it may eventually exceed the fault current when a zero-crossing is created [38]. These MCCBs are referred to as passive resonance DCCBs as illustrated in Figure 4.3-3 (a). The active MCCB configurations employ similar principles to achieve zero-crossing but add an additional switch and pre-charge the capacitor to excite the resonant circuit as illustrated in Figure 4.3-3 (b) [39]. The distinction between passive and active resonance DCCBs is that the latter can accelerate the rise of the resonance current, resulting in a faster rate of operation for the MCCB.

Mechanical circuit breakers are well-developed and mature technologies, with an average fault interruption time of 30–100 milliseconds [40]. Due to the fact that a DC transient current can reach tens of the nominal value in a few milliseconds, the application of mechanical circuit breakers requires a higher level of system tolerance to withstand a let-through energy (i2t) for a longer period of time than those DCCBs that can operate faster.

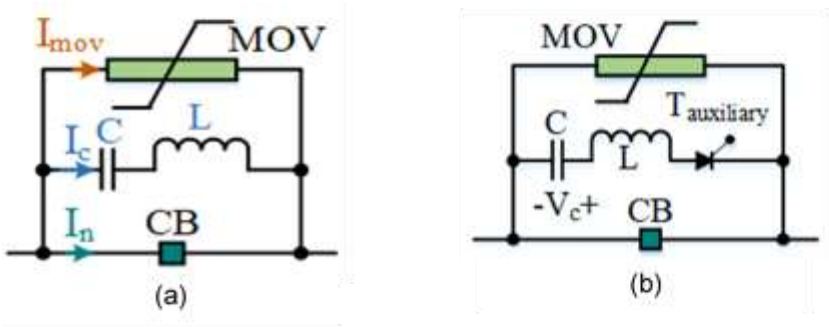


Figure 4.3-3: Moulded case circuit breakers (a) with passive commutation, (b) with active commutation [41].

- *Solid-state circuit breaker (SSCB)*

The main drive of SSCB development is to overcome the slow response time associated with fuses and MCCB. To increase the current handling/limiting capability of SSCBs, they are integrated with fast switching and high current rating semiconductor devices such as IGBT, GTO, and IGCT [42], [43]. These types of CBs require an energy dissipation element to protect switching devices from being damaged by the pulsing energy. Normally, these energy dissipation elements include Metal-Oxide Varistors (MOV), capacitors, switched resistors, and their combinations [44], [45]. For DC applications, a variety of SSCB configurations have been proposed. The Figure 4.3-4 (a) illustrated one of the simplest architectures for unidirectional power flow. It is made up of a surge arrester branch (i.e. MOV) connected in series with a free-wheeling diode connected in parallel with the DC bus. Under normal conditions, the semiconductor device remains turned on and load current flows through it. When a fault is initiated, the semiconductor is turned off, forcing the fault current to commutate through the free-wheeling diodes using the surged energy fully utilized by the MOV [46]. Due to the fact that such a CB structure contains only one fully controllable semiconductor device, it is only suitable for unidirectional operation. Bi-directional SSCB is then proposed as an improved version, as illustrated in Figure 4.3-4 (b) [47]. Two unidirectional SSCBs are connected in anti-series directions. This arrangement makes it possible that the current flowing in both ways can be switched off. In addition to enabling bidirectional operation, such a structure introduces twice as much as the conduction losses during-steady state operation for unidirectional SSCB. Solid-State circuit breakers have a very fast operating time of less than 100 microseconds, which enables the system to have rapid fault isolation capabilities. However, significant conduction losses in SSCBs in steady state are the primary disadvantage [48].

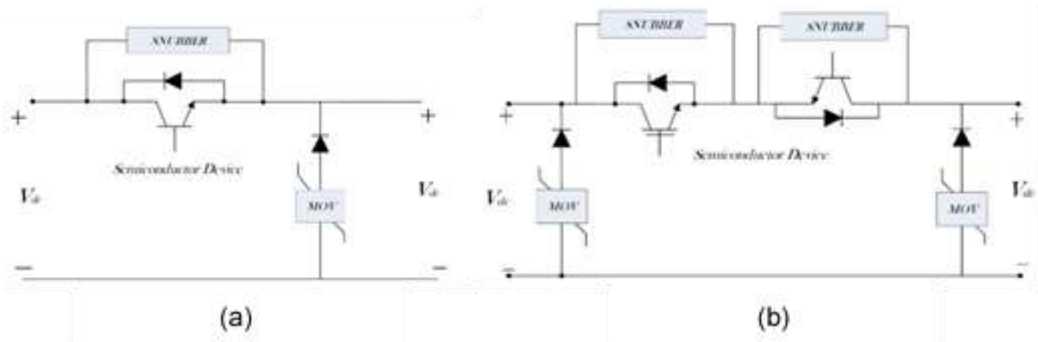


Figure 4.3-4: : Solid-state circuit breakers: (a) General configuration of SSCB, (b) Bi-directional SSCB configuration [49].

- *Hybrid circuit breaker (HCB)*

To meet the requirements of high current handling in the on state with nominal conduction loss and rapid transition from operating to blocking mode during a fault, the Hybrid Circuit Breaker (HCB) structure was invented [50], [51]. By incorporating multiple switching devices into the main CB structure, arcing during current interruption is reduced [52]. As illustrated in Figure 4.3-5, all current flows through the bypass branch under normal conditions, whereas current remains zero in the main branch. When a fault occurs, the fast mechanical switch opens and the fault currents are immediately commutated to the primary SSCB via load commutation switches. Although HBCB allows for significantly faster operation with low conduction losses, the complexity of the operation has increased concurrently. It is worth noting that while Hybrid SSCBs have been modelled for 320kV HVDC systems operating in less than 5ms [53], the HBCB concept is not widely used or developed for LVDC applications due to its inherent complexity and costs.

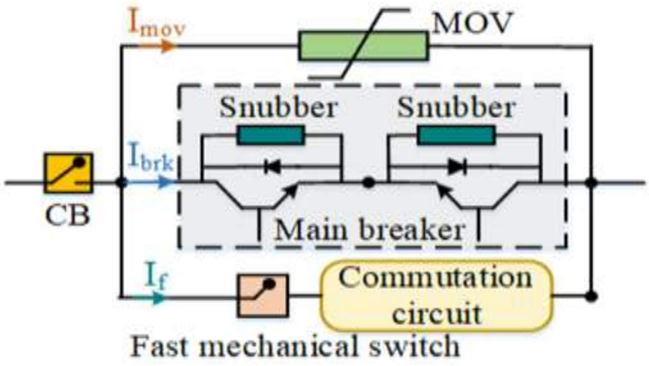


Figure 4.3-5: Hybrid Circuit Breaker [41].

Market availability for LVDC Circuit Breakers

The rapid expansion of Photovoltaic (PV) generation, along with the availability of a variety of mechanical CBs between 500 V_{DC} and 1000 V_{DC}, has resulted in a spectrum of mechanical CBs suited for LVDC networks [54]–[56]. PVGard circuit breakers are used to protect the wire connecting the modules to the combiner box or inverter from excessive current and to act as an isolation device. PVGard DC circuit breakers are available in lineups of 500 V_{DC} and 1000 V_{DC} with interrupting capacities ranging from 1.2 kA to 7.5 kA [55]. Both are capable of safely disconnecting in response to a signal from a DC arc or ground fault detector.

In terms of market availability for LVDC circuit breakers, companies such as ABB, Eaton, and Schneider Electric offer a diverse range of circuit breakers for DC overcurrent protection in LVDC Microgrids, including air type circuit breakers (ACBs), miniature circuit breakers (MCBs), and moulded-case circuit breakers (MCCBs).

ABB's Emax-series breakers have breaking capacities ranging from 35kA to 100kA and operate at 500, 750, and 1000 V_{DC}. The SACE Tmax,T-model case circuit breakers series are typically designed for 500, 750, and 1000 V_{DC} applications and offer break capacities of up to 150 kA. Additionally, the MCBs S200M UC, S800 UC, and S800 PV series are available with a rated operational voltage of 220 V_{DC} to 1200 V_{DC}. These breakers have a short-circuit interruption capacity of between 5 kA and 10 kA [55].

Eaton offers two distinct lineups of PVGard solar circuit breakers. The first type is a 600 V_{DC} per-pole breaker and switch. The second type is a 1000 V_{DC} poles-in-series breaker and switch. These breakers have a short-circuit interruption capacity of between 3 kA and 7.5 kA [54].

Schneider Electric offers a variety of DC circuit breakers, including the Compact NSX and Masterpact NW. These breakers are used to protect and control low-voltage distribution systems and are compatible with the majority of DC systems and applications. Compact NSX is designed for DC voltages ranging from 24 V_{DC} to 750 V_{DC} and offers a diverse range of models suitable for a variety of applications. It has a high breaking capacity, with four performance levels ranging from 36 kA to 100 kA (F, N, M, and S). The Masterpact NW series is designed for DC voltages ranging from 24 V_{DC} to 900 V_{DC} and is available in two configurations: C/D (3 poles) and E. (4 poles). They offer three current ratings: 1000, 2000, and 4000, as well as two high-break-capacity levels: N (35 kA) and H (85, 50, and 35 kA) [56].

Current OS Protocol Foundation

Current OS protocol is a non-profit, open, and self-sustaining foundation dedicated to the promotion and adoption of active DC microgrids. A protocol that enables the design of scalable DC grid architectures and specifies all system parameters for loads and sources, including voltage levels, protection, grounding, and corrosion mitigation. The foundation's goal is to establish a unified standard for grid control, it provides its partners with an open protocol and clear guidelines for manufacturing products that operate in a Current OS-based DC environment. Significant electrical corporations such as Schneider Electric and Eaton support this protocol and are working to make it a global standard for DC infrastructures. According to the current OS protocol foundation, traditional electromechanical protection devices are technically incapable of competing with solid-state protection devices when it comes to protecting DC microgrid systems. This is because solid state protection devices do not require moving parts to open or close contacts on a circuit and have the rapid fault isolation capabilities necessary to protect DC microgrids. Although solid state circuit breakers do offer significant performance improvements over standard electromechanical circuit breakers in some critical areas, there is currently no protocol or guidelines for connecting the SSCB between DC sources and DC loads. As a result, the Current OS protocol for solid state-based DC microgrids focuses mainly on congestion management, safety, resilience, cybersecurity, and makes use of distributed and resilient real-time control [57].

4.3.3 Cables and Overhead Lines

Nowadays there are no specific MVDC cables are available on the market due to different reasons and therefore MVAC cables will be used under DC voltage. Overhead lines do not have a specific structure for direct current applications. Because of that, MVAC overhead lines can also be used for MVDC applications considering the insulation coordination procedure (e.g. influence of contamination of insulators to breakdown voltage). The main technical challenges in the development of DC cables present themselves as:

- Insulation ageing aspects:
    - The lifetime law is not as clear as under AC applications.
- Electric field distribution:
    - The electric field distribution depends on the temperature and the applied voltage;
    - The electric field distribution changes by a polarity reversal; and
    - The electric field distribution changes due to the accumulation of space charges.
- Power transfer under DC voltage:
    - There are no specific AC losses as the skin and proximity effect, the dielectric losses and the capacitive current;
    - The ampacity from DC cable systems is higher than from AC cable systems;
    - The voltage drop under AC conditions is higher as under DC conditions; and
    - The transient switching under AC is much more serious than under DC.

Recent laboratory investigations show that new extruded MVAC cables can operate at DC voltages of about 4.5 times the AC voltage (±55 kV_{DC} vs. 12/20 kV_{AC}). This leads to a drastic increased of power transfer for a cable links.

4.3.4 Protection

Typically, current and voltage in DC systems are continuously monitored. If a fault is detected in a point-to-point link, the AC circuit breaker at both sides of the DC link is tripped by the protection system and the fault is cleared. The literature states that a protection group in medium voltage grids can only reach a maximum of four terminals per converter. The maximum number of converter stations in a specific multi-terminal group is also limited. Every protection group has their circuit breakers only on the ends of the system. Because of this, there are no special DC circuit breakers required for MVDC grid in the current state.

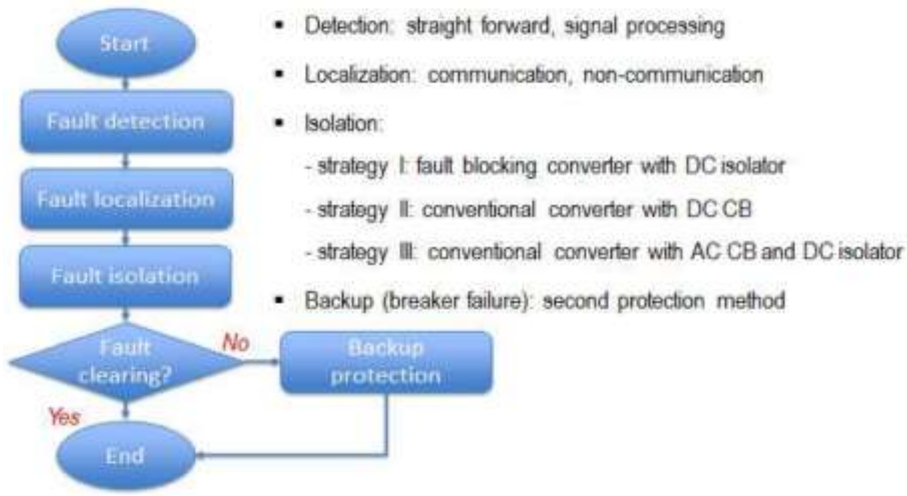


Figure 4.3-6: DC power system protection.

Figure 4.3-6 shows the protection process for DC power supply systems.

There are three different protection approaches which are used to protect VSC technology in HVDC networks and which need to be considered for MVDC grids:

- Conventional converter with AC breaker and DC isolator;
- Fault blocking converter with DC isolator; and
- Conventional converter with DC breaker.

Conventional converter with AC breaker and DC isolator: The hand-shaking method is the most well-known scheme in terms of a conventional converter with AC breaker and DC isolator. The location of the fault is determined over the current flow and the current direction. The fault currents are switched off with AC circuit breakers and after that, the DC isolators segregate the fault point selectively for the system. This method can localize and remove a fault in a DC system without any expensive circuit breakers. The big disadvantage is that the whole system is switched off with AC circuit breakers and therefore healthy parts are switched off as well as damaged parts. There is also the possibility that the freewheeling diode in the VSC may be damaged by the slow operation of the AC circuit breakers or that the antiparallel diodes may be destroyed in case of failure.

Fault blocking converter with DC isolator: A full bridge MMC can limit the failure current from the converters. The disadvantage in this case is that four semiconductor devices will be needed in a full bridge MMC. The full bridge reduces the fault current and the DC isolator isolates the fault with an effective fault location method. Under normal circumstances, a half bridge is used. The cost of full bridge MMCs is higher and twice as many semiconductors are required for the same task.

Conventional converters with DC breakers: There are no commercial DC breakers available on the market. If they are ready for application, the protection could be established easily with these circuit breakers. The challenging part of DC circuit breakers is, that the DC current never passes the zero line. As mentioned before, the DC current must pass the zero line by force. Under normal conditions, the DC current increases and the arc extinction cannot be achieved. Because of these facts, the arc extinction under DC is very hard. Another point is that the semiconductor devices from the converters have a very low thermal capacity. For this reason, DC faults must be cleared within a few milliseconds. The most promising solution are hybrid or solid-state circuit breakers.

One of the main components of the DC fault is the discharging current from the capacitors. To protect the system, it could be necessary to add active current limiters and hybrid circuit breakers. The active current limiter uses an inductance and a capacitor to reduce the current during a failure process. The main task of the inductance is to limit the rise of the current. The capacitance is used to change the sign of the applied voltage on the inductance. This is necessary to decrease the current and to get the DC current to the zero point. The hybrid circuit breakers are switching of the fault current selectively if a failure occurs. The circuit breakers can switch of regions due to the current limiters and the time delay between the different circuit breakers. If a communication failure occurs, the selectivity cannot be graduated as all hybrid circuit breakers will interrupt if they recognize the overcurrent. Limiting the fault current with current limiters could also allow mechanical circuit breakers in some applications. If it is not important to extinguish the fault current as soon as possible, the logic selectivity can be achieved, and non-electric circuit breakers could be used in this case.

5 STATE OF THE ART OF STANDARDIZATION AND REGULATORY FRAMEWORK

The distribution grid and its components are highly regulated and standardised, ensuring safe, secure and reliable operation. Before DC can make the step towards implementation in the public LVAC grid, these aspects have to be clarified. Standardisation is a crucial necessity for DC systems to be implemented in the public grid for safe and reliable operation as well as to enable further technological development of equipment.

In Table 5-1 relevant international standards and recommendations for DC systems are listed and categorised. The categorization follows the in [58] proposed structure. Standardisation is an ongoing process for various DC applications and will need continuous effort and updates.

Table 5-1: Overview of relevant standards for DC systems. More information on highlighted standards can be found in the next section.

	Application	Design	Protection criteria	Safety	Power quality	Earthing & Bonding	Switchgear & circuit breaker
LVDC ≤1500 V	General	IEEE 946-2020 IEC 60038 IEC 60364-1	BS EN 60947-2	**IEC 62477-1**	**IEC TR 63282**	IEC 50162	IEC 60947-1 **IEC 60947-2** **IEC 60947-3**
	Microgrids	IEEE P2030.10					
	Public Networks	IEEE P2030.10.1 IEEE P2030.10.2	BS EN 60947-3	IEEE P2984 **IEC 61439-2** IEC 61557	**IEC TR 63282** IEC 61000-2-2	**ESQCR**	IEC 61439-1
	Power Converter	**IEC TS 62578** **IEC 60146-1-1** **IEC 60146-2** IEC 62909-1 IEC 62909-2		**IEC 62477-1**	IEC 61204-3		
	Residential	IEEE P2030.10.2 IEEE P2847			IEC 61000-4-17 IEC 61000-4-29		IEC 61008-1
	Telecom / ICT	ITU T Rec. L.1201 ITU T Rec. L.1204			ITU T Rec. L.1200		
	Data Centre			IEC 62040-1			
	LED Lighting			IEC 60598-1 IEC 61347-1			
	Solar PV		IEC 60269-6	IEC 61643-32			
	Ship power	IEC 60092-201	IEC 60092-202 IEC 60092-507				
MVDC 1.5-ca. 100 kV	Public Networks	CIGRE WG C6.31 CIGRE WG C6/B4.37	IEEE PC37.01	**IEC 62477-2** IEC TS 61936-2	IEC 61000-4-30	IEC 50162	
	Power Converter	**IEC TS 62578** **IEC 60146-1-1** **IEC TR 60146-1-2** **IEC 60146-2**		**BS EN 50122** **IEC 62477-2**			
	Ship power	IEEE 1709-2018					
	Traction	**BS EN 50123** **BS EN 50328** IEC 62924		IEC 62128-1 IEC 62128-3	IEC 62590		IEC 61992
HVDC >ca. 100 kV	Public Networks	CIGRE WG B4.52	IEEE P2832		CIGRE WG B4.68		IEC 62271
	Power Converter		IEC 60099-9				

In Section 5.1, the most relevant standards for the presented pilot installations are discussed in more details. A list of national standards for selected countries which have already implemented some DC specific standards and recommendations can be found in Section 5.2.

Analysing the presented pilots, no references on national regulatory frameworks were found. As standardization is progressing, it is likely that further regulations will be implemented by regulatory agencies.

Beside this CIRED working group, CIGRE WG C6/B4.37 is working on recommendations for future MVDC systems with a report pending.

5.1 Relevant Standards for Pilot Installations

Some of the standards that have been most relevant in LVDC and MVDC pilot projects are described in more detail below (see highlighted standards in Table 5-1), with their relevance indicated in each case.

IEC TR 63282:2020 − LVDC systems - Assessment of standard voltages and power quality requirements

This technical report collects information and reports experience in order to make recommendations for the standardisation of voltage levels and related aspects (power quality, electromagnetic compatibility, measurement, etc.) for LVDC systems, with rated system voltages not exceeding 1500 V_{DC}.

Rationale for the proposed voltage values are given. Variation of parameters for the voltage (power quality) and recommendation 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. For example: the recommended voltage for unipolar systems: 350 V_{DC} (with nominal variation range from 320 V_{DC} to 380 V_{DC}), the recommended voltage for bipolar systems: ±350/700 V_{DC} (with nominal variation range from 640 V_{DC} to 760 V_{DC}). For both, there is a second voltage level, 2 times higher (700 V_{DC} and ±700 V_{DC}). Systems in which a unipolar voltage is interrupted periodically for certain purposes, e.g. pulse voltage, are not considered.

Traction systems are excluded from this document. It is a Technical Report at the stage (not yet a standard) and mainly escribes the assessment for voltage for LVDC systems. Future version will describe more specifically power quality requirements.

IEC TR 63282 has facilitated in the standardisation of LVDC application requirements in UK trial projects.

IEC 62477-1:2012 − Safety requirements for power electronic converter systems and equipment

This standard applies to Power Electronic Converter Systems (PECS) and equipment, their components for electronic power conversion and electronic power switching, including the means for their control, protection, monitoring and measurement, such as with the main purpose of converting electric power, with rated system voltages not exceeding 1000 V_{AC}. or 1500 V_{DC}.

IEC 62477-1 has helped to ensure standardisation of safety requirements for power electronic converters for LVDC/MVDC applications in UK trial projects. This is particularly useful in order to set minimum requirements when developing new power electronic equipment for use on the distribution network.

IEC 62477-2:2018 − Safety requirements for power electronic converter systems and equipment

This standard applies to power electronic converter systems (PECS) and equipment, their components for electronic power conversion and electronic power switching, including the means for their control, protection, monitoring and measurement, such as with the main purpose of converting electric power, with rated system voltages from 1000 V_{AC} or 1500 V_{DC} up to 36 kV_{AC} or 54 kV_{DC}.

As per IEC 62477-1, part 2 provides similar requirements but for high voltage applications up to 54 kV_{DC}

IEC TS 62578:2015 − Power electronics systems and equipment - Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz

This standard describes the operation conditions and typical characteristics of active infeed converters (AIC) of all technologies and topologies which can be connected between the electrical power supply network (lines) AC side and a constant current or voltage type DC side and which can convert electrical power (active and reactive) in both directions (generative or regenerative).

This IEC Technical Specification sets out the basic criteria to be met when designing converters that connect the AC power distribution network to DC equipment. It provides details on the control, performance and overall system of different types of converter, which helps to develop these new technologies. This standard was particularly useful for the development of both LVDC and MVDC converters as part of many different UK trial projects.

IEC 60146-1-1:2010 − Semiconductor converters - General requirements and line commutated converters. Specification of basic requirements

This standard specifies the requirements for the performance of all semiconductor power converters and semiconductor power switches using controllable and/or non-controllable electronic valve devices. It is primarily intended to specify the basic requirements for converters in general and the requirements applicable to line commutated converters for conversion of AC power to DC power or vice versa. Parts of this standard are also applicable to other types of electronic power converter provided that they do not have their own product standards.

IEC 60146-1-1 was particularly useful during the project Network Equilibrium where a back to back AC-DC converter was implemented to control voltages and power on the 33kV distribution network. The standard provided detail on the overall design aspects and the testing requirements for the converter equipment.

IEC TR 60146-1-2:2019 − Semiconductor converters. General requirements and line commutated converters. Application guide

IEC TR 60146-1-2 gives guidance on variations to the specifications given in IEC 60146-1-1 to enable the specification to be extended in a controlled form for special cases. Background information is also given on technical points, which facilitates the use of IEC 60146-1-1. This technical report primarily covers line commutated converters and is not in itself a specification, except as regards certain auxiliary components, in so far as existing standards may not provide the necessary data.

This technical report supplements IEC 60146-1-1 and provides further guidance on the specification of converters. For example, the report covers special environmental/service conditions helping ensure that converters can be designed to meet a variety of different applications.

IEC 60146-2:1999 − Semiconductor converters - Self-commutated semiconductor converters including direct d.c. converters

This standard applies to all types of semiconductor inverters of the self-commutated type and semiconductor convertors which contain at least one part of a self-commutated type, including direct AC convertors and DC convertors for all applications.

This standard is specifically for self-commutated converter technology and is particularly useful for converters being used in LVDC and MVDC applications. Similar to the other IEC 60146 standards, this provided further detail on the specific technology design and testing techniques for a number of UK based trial projects.

IEC 61439-2:2020 − Low-voltage switchgear and controlgear assemblies - Part 2: Power switchgear and controlgear assemblies

The standard IEC 61439 applies to enclosures with a rated voltage of less than $1000V_{AC}$ or $1500V_{DC}$. The purpose of the standard EN IEC 61439-2 (low-voltage switchgear and controlgear assemblies) is to harmonise all general rules and requirements applicable to low-voltage switchgear and controlgear assemblies in order to achieve uniformity in assembly requirements and verification and to avoid the need for verification to other standards.

IEC 61439-2 has helped to ensure standardisation of safety requirements for LVDC switchboard for LVDC applications in UK trial project. This is especially beneficial for minimising the risk of accidental contact with live conductors, which is a risk associated with the compact fuse-boards used in the majority of DSO substations.

BS EN 50122:2011 − Railway applications. Fixed installations. Electrical safety, earthing and the return circuit.

This suite of European Standards specifies the requirements for electrical safety in fixed installations associated with AC. and/or DC. traction systems and to any installations that can be endangered by the traction power supply system. They also apply to all aspects of fixed installations that are necessary to ensure electrical safety during maintenance work within electric traction systems.

BS EN 50122 is primarily for railway applications; however, it forms another useful reference for safety aspects of DC systems and complements the requirements detailed in the equivalent electricity standard (BS EN 50522). The standard highlights the limits and requirements for protection design and performance.

BS EN 50123:2003 − Railway applications. Fixed installations. DC switchgear

This suite of European Standards covers DC. metal-enclosed and non-metallic enclosed switchgear assemblies used in indoor stationary installations of traction systems, with nominal voltage not exceeding 3000 V.

Similar to BS EN 50122, this suite of standards provides guidance on railway applications but for DC switchgear. LVDC and MVDC trial projects in the UK rely on DC switchgear to allow users to safely operate and maintain equipment. As such, this suite of standards allows users to specify the requirements for a range of different DC switchgear applications.

BS EN 50328:2003 − Railway applications. Fixed installations. Electronic power convertors for substations

This standard specifies the requirements for the performance of all fixed installations electronic power converters, using controllable and/or non-controllable electronic valves, intended for traction power supply. The devices can be controlled by means of current, voltage or light. Non-bistable devices are assumed to be operated in the switched mode.

Although this standard focuses on converter technology for railway applications, the basic requirements detailed within are also applicable to installations on the distribution network. The standard was a useful reference when determining the converter design aspects for MVDC applications in Network Equilibrium.

BS EN 60947-2:2017 − Low-voltage switchgear and controlgear. Circuit-breakers

This BS EN 60947 series standard applies to circuit breakers with main contacts intended to be connected to circuits with a rated voltage of not more than 1000 V_{AC} or 1500 V_{DC}; it also includes additional requirements for integrally fused circuit breakers.

BS EN 60947-2 has helped to ensure standardisation of protection and safety requirements for LVDC applications in UK trial project. This is particularly beneficial when selecting appropriate protection equipment (i.e. MCCBs) for protecting LVDC feeders connecting DC customers.

BS EN 60947-3:2020 − Low-voltage switchgear and controlgear. Switches, disconnectors, switch-disconnectors and fuse-combination units

BS EN 60947-3 applies to switches, disconnectors, switch-disconnectors and fuse-combination units and their dedicated accessories to be used in distribution circuits and motor circuits of which the rated voltage does not exceed 1000 V_{AC} or 1500 V_{DC}.

BS EN 60947-3 has helped to ensure standardisation of protection and safety requirements for LVDC applications in a UK trial project. This is particularly beneficial when selecting appropriate protection equipment (i.e. switch-disconnectors) in LVDC switchboards.

ESQCR 2002 − The Electricity Safety, Quality and Continuity Regulations

The ESQCR establishes safety standards aimed at protecting the general public and consumers. Additionally, the Regulations specify requirements for power quality and supply continuity to ensure that consumers receive an efficient and cost-effective electricity supply service. The Regulations apply to public and private operators, as well as to electricity networks that supply electricity to consumers in England, Scotland, and Wales.

The ESQCR has helped to ensure standardisation of earthing and safety requirements for LV applications in a UK trial project. This is particularly beneficial when selecting an appropriate earthing scheme, in order to minimises the risk of stray DC currents reaching earth.

5.2 National DC Guidelines and Standards

Exemplary national standards for DC distribution grids are listed below. This is not a complete collection; the selection serves to highlight that standardisation is already being worked on at national level as well.

B.1 China

GB/T 35727-2017 Guideline for standard voltages of medium and low voltage DC distribution system stipulates the voltage levels and deviation range in medium and low voltage DC distribution system whose voltage is equal to or smaller than ±50 kV.

GB 10963.2-2020 Electrical accessories - Circuit-breakers for overcurrent protection for household and similar installations – Part 2: circuit-breakers for AC and DC operation deals with AC and DC circuit breakers. This document is based on another standard, *GB 10963.2-2020 Electrical accessories - Circuit-breakers for overcurrent protection for household and similar installations – Part 1: circuit-breakers for a.c. operation*. In particular, *GB 10963.2-2020* complements *GB 10963.2-2020* by adding the recommendations for DC circuit breakers. The nominal voltages for DC circuit breakers are given for different earthing schemes.

In addition to the above national standards, China Electricity Council also issued a standard in 2016, namely *T/CEC 107-2016 DC distribution voltage*. It gives recommendations for both the voltage levels and the power rating for DC distribution systems between ±100 kV and ±110 V.

B.2 Finland

Finnish national standard SFS 6000 “Low-voltage electrical installations”. Part 8-801 (2017): “Supplementary requirements. Public distribution networks.” include appendix C regarding the LVDC installations. The content comprises of recommendations for power supply system characteristics, system grounding methods, and protection in TN and IT systems. There is also recommendation for marking of conductors and commissioning inspections.

B.5 Netherlands

The presented solution “N470 Project Netherlands” in section 3.3.2 is in accordance with the Dutch standard for DC:

NPR 9090:2018 − DC installations for low voltage

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.

This standard serves as the legal foundation for installation requirements, as the law refers to the wiring standards. As a result, this was an important standard to have when constructing DC installations for N470 project.

6 CONCLUSION WITH OPEN POINTS AND CHALLENGES FOR THE FUTURE

The following conclusions can be drawn in light of the DC distribution network study presented in this report.

In comparison to state-of-the-art AC power grids, the outstanding high-level benefits of DC and hybrid AC/DC distribution grids are as follows:

- Expanding the capacity of power lines and grids to accommodate a high-share of renewable energy sources (photovoltaic, wind), e-mobility other DC-based loads (better utilization/capacity enhancement of power line conductors, power flow control via DC links and meshed structures);
- Increased power supply radius/improved power quality through the implementation of new DC grids and the restructuring of existing AC grids with DC (line inductance steady-state not active, MVAC to LVDC and HVAC to MVDC conversion);
- Improving the system energy and resources efficiency (by reducing system losses through the use of high-efficient power converters and more efficient DC/DC power conversion on application side; and by reducing the number/better utilization of power line conductors);
- Enhanced grid resiliency in case of grid faults ("decoupling" of healthy grid parts by active power converters, utilizing free conductors of existing AC power lines, soft linking of before separated operated AC grids/feeders by active power converters with short circuit limitation and power flow control capability); and
- More environment friendly and sustainable use of resources in production, installation and operation (solid-state semi-conductor materials/insulation based on silica instead of copper/aluminium, steel and insulating oils consisting AC power transformers, and improved utilization of power lines and grids, resulting in less restructuration effort and reduced CO_2 footprint), have been indicated and some early technologies for distribution grid purpose have already been proven in a raising number of current, practical pilot installations and research platforms by several countries in the last decade.

Like any smart AC grid applications (e.g. photovoltaic inverters), DC distribution grids with active front end power converters will be used to provide grid support to the coupled AC network (e.g. P(U), Q(U) control, fault ride through u(t)) thereby enabling capacity expansion. Additionally, compared to pure local AC microgrids as option for future autonomous, resilient grid parts, which are operated on and also disconnected from the AC main grid, DC microgrids can be easier implemented (only DC voltage control, no frequency/phase parameter, no reactive power flows/DC node voltages determine the active power flow in the resistive network) and there is no inherent synchronization issue. However, any type, AC and DC or hybrid AC/DC microgrids needs to be managed on system/component level to balance the generation and loads and to avoid grid congestions, especially when operated disconnected from the main (AC) grid, but also for grid optimization in case of grid-connected mode. Hence, they are following the general requirement and trend for a higher degree of grid automation in state-of-the-art LV and MV distribution grids to achieve the set decarbonization goals.

Because of its unique characteristics, operation with DC will have an influence on all components which are required to setup and operate the main power grid. As a result, there new key technologies and standardized grid codes are required for widespread use. For example, higher fault currents and dissipated fault transient energy (I^2t) values were reported in literature in case of DC compared with AC grids (discharging current from the capacitors used for stabilizing the DC grid voltage), especially close to the source/point of common coupling, depending on the active power rectifier topology and external current liming inductances (first 1-2 milliseconds and below). In this case classical electromechanical protection devices, which are based on AC dynamics, are too slow. Therefore, new faster, cost-effective protection devices (hybrid- and solid-state circuit breakers) and selective protection strategies have to be developed for the market to bring the DC-currents to zero and to avoid inefficient power converter oversizing due semiconductor device's limited thermal capacity.

According to the findings of the initial pilots are that DC distribution networks will be at least an additional instrument for grid optimization and stabilization, paving the way into a low carbon and renewable energy future. Moreover, they will help to reduce the transformation costs of the distribution grids and therefore of the whole energy supply system into the renewable future. Therefore, it is very realistic that AC and DC grids and links will coexist as hybrid AC/DC grids in future power distribution networks behind (prosumer) and in front the meters (utility, energy communities?).

The following actions and investments in this field will be required as open points to foster the commercial break-through of DC distribution networks:

- Essential research questions have to be answered and key technologies as well as techno-economic planning tools to be developed by universities/RTOs in collaboration with OEMs;
- Clear use-cases, exploitation strategies and business models for their products and services have to be formulated by RTOs, OEMs and service providers;
- International standards and regulations have to be defined by standardization bodies and regulation authorities;
- Answers to the long-term impact of DC integration into the public MV and LV networks (in terms of capacity and ease to connect future customers in the surroundings of a DC investment, or capacity to reconfigure the grids at least the same way it is done in AC);
- and last but not least, operational safety and experience have to be gained for these systems by distribution grid operators in more pilot projects on a short and mid-term perspective to keep a safe, reliable and trustful future supply system.

Therefore, standardization (particularly for LVDC and especially for MVDC) is mandatory and one main factor for success.

Although DC distribution networks have obvious advantages as outlined above, there are still some technical challenges that need to be addressed through continued research and detailed studies. In particular, further studies should include recommendations and standardization of MVDC voltages and power quality, transition strategies from AC to hybrid ACDC grids, LVDC and MVDC grid topologies for different applications, methods and tools for DC or hybrid ACDC distribution system planning, analysis as well as simulation and reliability/component aging studies, improved semiconductor materials and modules (voltage and power rating, losses, switching frequency, space), LVDC and MVDC cost-effective power conversion and protection devices, LVDC and MVDC system grounding (corrosion), hybrid ACDC coordinated control and energy management systems as well as stability assessment and design, MVDC sensors, measurement units and meters, LVDC and MVDC test and validation infrastructure/methods and interoperable hardware and ICT platforms.

Although DC distribution networks have significant advantages, as previously stated, there are some technical challenges that must be addressed through ongoing research and detailed studies. Further research should focus on the following topics in particular:

- MVDC voltage and power quality recommendations and standardization;
- Transition strategies from AC to hybrid AC-DC grids;
- LVDC and MVDC grid topologies for various applications;
- Methods and tools for DC or hybrid AC-DC distribution system planning, analysis, simulation, and reliability/component ageing studies;
- Improved semiconductor materials and modules (voltage and power rating, losses, switching frequency, space);
- LVDC and MVDC cost-effective power conversion and protection devices;
- LVDC and MVDC system grounding (corrosion);

- Hybrid AC-DC coordinated control and energy management systems;
- MVDC sensors, measurement units, and meters;
- LVDC and MVDC test and validation infrastructure/methods; as well as
- Interoperable hardware and ICT platforms.

To realise the major benefits of LVDC, MVDC, and hybrid AC/DC distribution grids, the operation and control technologies must be explored further, with particular attention paid to the following aspects:

- The practical implementation of new flexible network topologies (more pilots); and
- The practical implementation of new protection and control strategies/protocols.

The progress and learnings from DC and hybrid AC/DC distribution grid key enabling technologies, pilot projects and implementations, use-cases/functionalities, and standardization/regulation will be updated and refined in a continued second phase of the Working Group, as well as further conclusions and recommendations.

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