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SHIFT to Direct Current

Deliverable D1.4
Definition and specification of tools, devices, and evaluation KPIs

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Disclaimer

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Executive Summary

This deliverable (D1.4) is part of the Shift2DC project and results from Task 1.4, "Definition and specification of tools, devices, and evaluation KPIs," in Work Package 1 (WP1).

The purpose of this document is to provide detailed specifications for the tools and devices needed to support the development and implementation of direct current (DC) systems. These specifications will serve as a guide for the activities in WP2 and WP3, focusing on feasibility, replicability, and the exploitation potential of the proposed DC solutions.

The deliverable outlines the key objectives, requirements, and features of each DC tool and solution, with "tools" referring to software solutions and "devices" to hardware components used in the project.

Chapter 2 presents the specifications for six core tools, each addressing the following critical functions for DC infrastructure design and operation:

- a DC solution design and sizing tool quantifying DC benefits and costs at a preliminary phase (SOL23) (Section 2.1),
- a protection plan methodology (SOL25) (Section 2.2),
- a simulation and control tool for system integration and validation (SOL 24) (Section 2.3),
- a control and protection integration tool dedicated to Medium Voltage DC (MVDC) infrastructure (SOL26) (Section 2.4),
- an energy management system tool (SOL21) (Section 2.5),
- a conditioning monitoring tool (SOL26) (Section 2.6).

In Chapter 3, specifications for the following eighteen DC hardware and software solutions are detailed, focusing on their benefits and applications for DC infrastructures. These solutions address existing problems or needs and will apply to the project demonstrators:

- DC cables: a smart and sustainable Low Voltage DC (LVDC) cable for DC applications (SOL4) (Section 3.1).
- Micro solar DC system: a micro-DC/DC converter (SOL5) (Section 3.2).
- V2X stations: a bidirectional DC/DC converter for EV charging (SOL6) (Section 3.3).
- LVAC-LVDC Interlink converter: an AC/DC interlink converter with droop capabilities (SOL7) (Section 3.4).
- Static protection: a protection system dedicated to DC grids specificities (SOL8) (Section 3.5).
- Vertical power delivery: for an optimized electrical distribution in Data centers (SOL9) (Section 3.6).
- Semiconductor protection: a protection system dedicated to DC grids specificities (SOL10) (Section 3.7).
- Pre-charging units for DC installations (SOL11) (Section 3.8).
- DC measurement device (SOL12) (Section 3.9).
- Fast response control algorithms to enhance and tailor DC/DC converters' support to the infrastructure (SOL13) (Section 3.10).
- DC/DC converter as a smart distribution power unit (SOL14) (Section 3.10.4).
- Multi-socket socket smart power distribution unit (SOL15) (Section 3.12).
- Plug & play infrastructure for DC-based offices (SOL16) (Section 3.13).
- Sharing voltage control to enhance DC infrastructure stability and resilience (SOL17) (Section 3.14).
- Passive thermosyphon cooling system for Data centers (SOL18) (Section 3.15).
- A scalable and rack-mounted battery energy storage system (SOL19) (Section 3.16).
- DC connectors (SOL20) (Section 3.17).

- Data center interfaces based on series stacking of servers for better efficiency (SOL22) (Section 3.18).

The document also establishes Key Performance Indicators (KPIs) to measure the performance of these tools and solutions. These KPIs will be used during the demonstration phase in WP4.

The deliverable forms the foundation for the following stages of the Shift2DC project, with its specifications guiding the development of the tools and solutions in WP2 and WP3. It marks a significant milestone in the project’s progress and sets the stage for future evaluations and implementations of DC systems.

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Keywords, Acronym

AC	Alternating Current
AI	Artificial Intelligence
Al	Aluminum
BCMs	Bus converter modules
BDs	Bypass Diodes
BESS	Battery Energy Storage System
BIPV	Building-integrated photovoltaics
CAPEX	Capital Expenditure
CCS	Combined Charging System
CM	Condition Monitoring
COC	Connector without breaking capacity
Cu	Copper
C&I	Commercial and Industrial
DC	Direct Current
DCX	DC Transformer
DPCs	Differential Power Converters
DER	Distributed Energy Resources
EMDCs	Edge Micro Data Centers
EMS	Energy Management System
EMT	Electro-Magnetic Transient
ELM CB	Electromechanical Circuit Breaker
EU	European Union
EV	Electric Vehicle
FPA	Factorized Power Architecture
GMPPT	Global Maximum Power Point Tracking
HCB	Hybrid Circuit Breaker
HPC	High Power Charger
HVDCD	High Voltage DC Distribution
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
ILC	Interlink Converter
IT	Information Technology
KPI	Key Performance Indicator
LFH	Low Fire Hazardous
LFP	Lithium Iron Phosphate
LV	Low Voltage
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
MCS	Megawatt charging systems
ML	Machine Learning
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MSE	Mean Square Error
MTDC	Multi-terminal direct current
MV	Medium Voltage

MVDC	Medium Voltage Direct Current
NaN	Not a Number
ODCA	Open DC Alliance
OPEX	Operational Expenditure
PCB	Printed Circuit Board
PDN	Power Delivery Network
PDU	Power Distribution Units
PLC	Programmable Logic Controller
PP	Polypropylene
PUE	Power Usage Effectiveness
PV	PhotoVoltaic
PVC	PolyVinyl Chloride
RE	Renewable energy
RMSPE	Root Mean Squared Percent Error
SELV	Safety extra low voltage
SLD	Single-line diagram
SPDU	Smart Power Distribution Unit
SSCB	Solid-State Circuit Breaker
STC	Standard Test Conditions
TDP	Thermal design power
TRL	Technology Readiness Level
UC	Use Case
USB	Universal Serial Bus
V2X	Vehicle-to-Everything
VPD	Vertical Power Delivery
WP	Work Package
XLPE	Cross-linked polyethylene

1 Introduction

1.1 Scope and Objectives

This deliverable (D1.4) results from the fourth task (T1.4 - Definition and specification of tools, devices, and evaluation KPIs) in the first Work Package (WP1) of the Shift2DC project.

This document is intended to provide a comprehensive **specification of the tools and devices** considered in the Shift2DC project. These specifications aim to guide the implementation and development of these tools and devices in WP2 and WP3, considering the principles of feasibility, replicability, and exploitation of the proposed DC solutions.
For each DC solution, relevant **Key Performance Indicators** (KPIs) will be defined, covering technical, social, and environmental aspects. These KPIs will allow the assessment of the solutions during the demonstrations developed in WP4.

Therefore, this deliverable addresses the following aspects for each solution, with “tools” referring to software solutions and “devices” to hardware components used in the project:

- The specific problem addressed, and the needs fulfilled,
- The advantages and characteristics/features/requirements,
- The end-users and the related applications involved within the project (use cases and demonstrators),
- The architecture and operational workflow, including execution steps, required inputs, expected outputs, and relevant existing solutions,
- The scope, current and target Technology Readiness Levels (TRLs), and defined KPIs.

The general structure of this deliverable is provided in Figure 1.1.

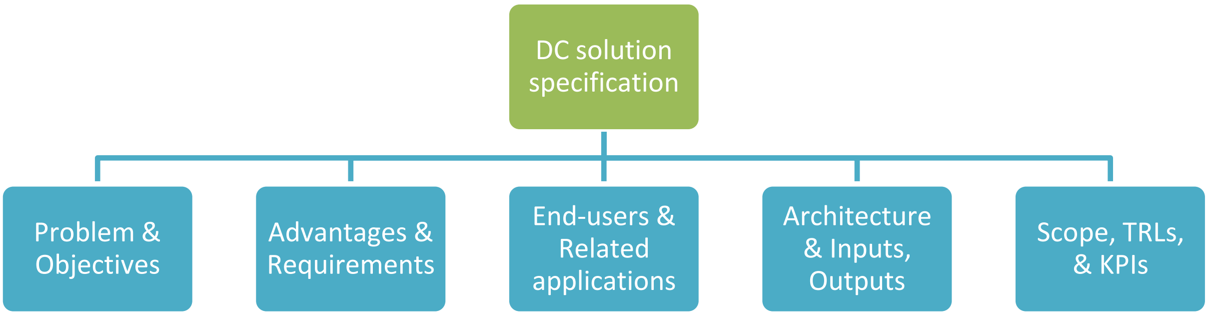

Figure 1.1 Key aspects of DC solution specification.

1.2 Structure

This deliverable is structured around four chapters, as depicted in Figure 1.2.

Chapter 1: Introduction & presentation of the deliverable objectives.

Chapter 2: Specification of the tools that will be developed in WP2.

Chapter 3: Specification of the solutions and devices that will be considered in WP3.

Chapter 4: Summary of the main findings and conclusions.

Figure 1.2 Structure of the deliverable D1.4 document.

1.3 Relationship with Other Deliverables

This deliverable (D1.4) of task T1.4 of WP1 is closely linked to the outcomes of task T1.3 of WP1 and is essential for WP2, WP3, and WP4 (Figure 1.3):

- On the one hand, task T1.4 bases its specifications on the use cases (UCs) defined in task T1.3.
- On the other hand, task T1.4 describes the requirements and main functions of the tools and devices that will guide the development activities in WP2 and WP3. In addition, task T1.4 specifies the KPIs that will be essential for assessing the technical, social, and environmental impacts of the proposed DC solutions during the demonstrations conducted in WP4.

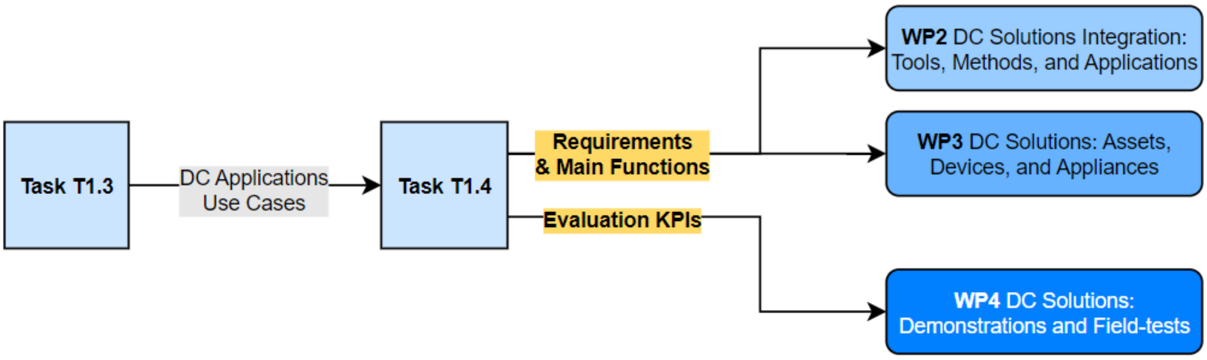

Figure 1.3 Interdependencies of task T1.4 with other project deliverables.

2 Specification of the DC Tools

This chapter provides the specification of the DC tools (software solutions) to be developed in the Shift2DC project. It is organized around three key questions to clarify the project's approach: *(1)* Why do we need these tools? *(2)* How do we meet the need for such tools? and *(3)* How do we prepare for the development of these tools?

Why do we need tools for DC systems?

- Various tools (e.g., electro-technical) are currently used by designers, utilities, regulators, developers, and academics. Traditionally, most of these tools have been designed for alternating current (AC) networks and, therefore, mainly address the specific needs and challenges of AC systems.
- Today, the potential benefits and uses of DC systems are becoming more widely recognized and promising. However, there is a lack of specialized tools quantifying these benefits. Additionally, there is a lack of standards specifying exhaustively how such systems should be implemented (mainly for commercial tools).
- For this reason, specialized DC tools are needed to support the adoption, development, and implementation of DC systems.

How do we meet the need for DC tools?

In the Shift2DC project, WP2 aims to meet this need by creating new tools for designing, protecting, simulating, evaluating, and monitoring DC infrastructures.

- These tools will offer accurate analysis, improve design processes, and provide comprehensive assessments while adhering to the principles of feasibility, reproducibility, and practical application.
- In addition, the tools are designed to address a wide range of applications and stakeholders.

How do we prepare for the development of DC tools?

To prepare for the tool development phase in WP2, this chapter focuses on specifying the requirements and main functions of six essential WP2 tools also identified by a solution number:

- SOL23: a DC solution design tool (Section 2.1),
- SOL25: a protection system tool (Section 2.2),
- SOL24: a simulation and control tool (Section 2.3),
- SOL26: a control and protection integration tool (Section 2.4),
- SOL21: an energy management system tool (Section 2.5),
- SOL27 and a condition monitoring tool (Section 2.6).

2.1 SOL23: Network Design Tool for DC Solutions

Associated task: T2.1
Leader: EDF[1]

Participants: INESC[2], NEW[3], SCHND[4], RWTH[5], EATDE[6], EATCZ[7], HITCH[8], NEXNS[9]

2.1.1 Tool ID, Quick Overview

Problem addressed:

- Existing network design tools mainly address AC systems and, therefore, are not optimized to handle DC systems.
- Lack of open-source design tools for DC systems evaluating DC implementation benefits at an early stage.

Main objective:

- Development of a design tool for DC networks, enabling evaluation and comparison of their benefits and challenges.

Needs fulfilled by the tool:

- Design of DC solutions.
- Feasibility and sizing analysis of DC solutions.
- Economic viability evaluation of DC solutions.
- Environmental and reliability impact assessment of DC solutions.

Expected advantages:

- Offering a robust framework for the efficient and reliable design and analysis of DC architectures compared to conventional AC radial networks.
- Assisting stakeholders in making informed decisions regarding the transition to and implementation of DC solutions.

Applications:

- Data centers, buildings, industrial applications, and ports, where DC technology can offer significant advantages in terms of energy efficiency, operational costs, and sustainability.

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[1] Électricité de France
[2] Instituto de Engenharia de Sistemas e Computadores: Investigação e Desenvolvimento em Lisboa
[3] EDP CNET - EDP Centre for New Energy Technologies
[4] Schneider Electric
[5] RWTH Aachen University
[6] EATON Industries GMBH
[7] EATON Elektrotechnika SRO
[8] Hitachi Energy
[9] NEXANS France

2.1.2 Requirements

Several important characteristics and requirements must be considered during the development of the DC network design tool.

- **Req1:** The tool must integrate **static models** of some specific devices, such as converters and DC cables, which are vital elements of DC grids. This is necessary for conducting feasibility studies and assessments. Voltage control strategies should be implemented in the models of all converters as an option to ensure accurate voltage level and power loss calculations.

- **Req2:** The tool must be able to implement various DC **ecosystem rules** (Current/OS[10] and ODCA[11]).

- **Req3:** The tool must cover a **wide range of applications,** including data centers, buildings, industrial applications, and ports.

- **Req4:** The tool should not require **specific in-depth knowledge** about DC technologies (end-users will be researchers, developers, or engineers).

- **Req5:** The tool is preferable to be **open source**.

- **Req6:** The tool should **output:**
  - **Electrical sizing and power losses** of the DC solution under examination, performing power flow calculations.
  - **Economic viability analysis** of the DC solution, including investment, replacement, and operating and maintenance costs.
  - **Environmental and reliability impact evaluation** of the DC solution.

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[10] Current/OS

[11] Open Direct Current Alliance

2.1.3 Architecture

2.1.3.1 Operational Workflow

The operational workflow of the DC solution design tool is illustrated in Figure 2.1.

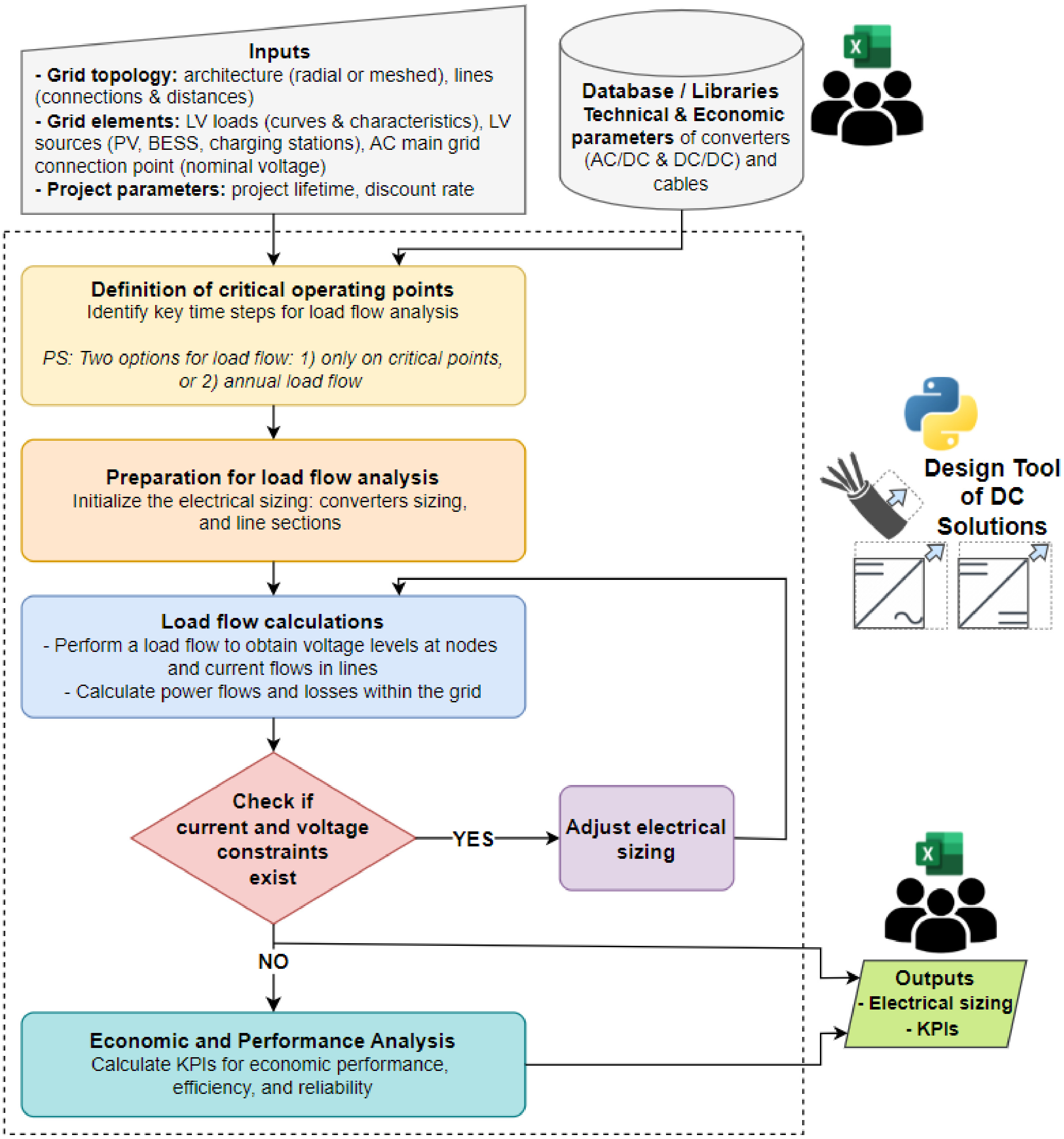

Figure 2.1 Diagram describing the operational flow of the design tool.

2.1.3.2 Inputs and Outputs

Inputs:

- **Grid topology:**
    - **Architecture**: nodes.
    - **Voltage levels**
    - **Line Connections:** connections between the grid's nodes, including distances.
- **Grid elements:**
    - **Low voltage (LV) Loads:** DC/DC converter, load curves and characteristics.
    - **LV sources:**
        - **Photovoltaic (PV) systems**: DC/DC converter, PV generation curves.
        - **Battery Energy Storage System (BESS)**: converter, BESS curves.
        - **EV charging stations**: converter, charging profiles.
    - **AC main grid connection point:** AC/DC Interlink Converter (ILC), nominal voltage.
- **Voltage control mode:** Master/slave control or droop control.
- **Project parameters:**
    - Project lifetime, discount rate.
- **Database / Libraries:**
    - **Models and technical parameters of converters and cables** (power rate, efficiency function of power, maintenance data[12]).
    - **Economic parameters of converters and cables** (CAPEX).

Outputs:

- **Electrical sizing:**
    - Sections of lines/cables[13].
    - Sizing of converters.
- **KPIs:** see §2.1.4.4

2.1.3.3 Available Tools and Options

The network design tool will be developed from scratch in Python or another general-purpose programming language.

- **Load flow:** Python or similar.
- **Libraries:** Python or similar.
- **User-Interface Database:** Excel (CSV format) or OpenDocument Spreadsheet.

Existing Python libraries for power systems modeling will be used to accelerate the development process. For example:

- Panda power (https://pandas.pydata.org/pandas-docs/stable/index.html)

However, we need to build models of cables, sources, AC/DC converters, and DC/DC converters from elementary blocks with the adequate level of detail.

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[12] This can be MTBF and/or annual downtime for maintenance.

[13] This sizing should consider the real installation conditions either with a derating factor or depreciated impedance data.

2.1.4 Expected Performance

2.1.4.1 Scope and Limitations

Scope: C&I applications.

Limitations:

- **Parameters not included in the tool:**
    - Earthing system.
    - Short circuit contributions.
- **Capacity limits of the tool:**
    - Architecture selection.
    - Limited by database.
    - Protection scheme and short circuit current calculation.

2.1.4.2 Advantages

- **Comprehensive Evaluation:** For a given use case, the tool combines electrical and economic evaluations by comparing DC and AC architectures.
    - Evidence: The tool performs power flow and preliminary sizing of cables and converters, ensuring optimized design.
- **Versatility and Scalability:** Agnostic design (regarding Current/OS and ODCA philosophies) allows application across multiple sectors, such as data centers, buildings, industry, and ports.
    - Evidence: Specific libraries tailored for different applications enhance usability.
- **Cost Calculation:** The tool allows the calculation of both initial capital expenditure and long-term operational costs.
    - Evidence: Incorporates detailed cost analysis, including maintenance and replacement costs.

2.1.4.3 TRL

- **Current TRL:** 3
- **Target TRL:** 6

2.1.4.4 KPIs

- **KPI1:** Ability of the tool to execute an **electrical sizing** of a defined use case.
- **KPI2:** Ability of the tool to perform **economic** calculations in comparison to conventional AC architecture. Further analysis will be performed to determine the best suitable financial indicator as extra costs compared to AC equivalent system, investment return duration, or break-even costs.
- **KPI3:** Ability of the tool to perform **efficiency** calculations in comparison to conventional AC architecture by performing power savings calculations.
- **KPI4:** Ability of the tool to perform **reliability** calculation in comparison to conventional AC architecture.
- **KPI5:** Ability of the tool to analyze the **environmental impact** of DC systems compared to AC traditional systems.

2.1.5 Partner-Provided Inputs

- **Detailed Libraries:** Develop detailed libraries for each application (data centers, buildings, industrial environments, and ports), incorporating components and configurations specific to these environments.
    - **AC/DC and DC/DC converters (EATON, HITACHI, SCHNEIDER):**
        - Efficiency rate curve
        - Power nominal rate
        - Nominal Current
        - Voltage input range
        - Voltage output range
        - Droop curves
        - Economic inputs [for every power rate, €]

    - **DC cables (NEXANS):**
        - Cross section [mm²]
        - Conductor material: Aluminum (Al) / Copper (Cu)
        - Maximum current capacity Imax [A]
        - Resistance R for various operating T°C (If necessary, including winter/summer conditions) [ohms]
        - Conditions of use: internal or outside use, or both,
        - Installation type: for in-ground or out-of-ground installation
        - Optional: Capital Expenditure (CAPEX) cost per type (approximate cost per meter) [€/meter]

2.2 SOL25: Protection Plan, Grounding & Selectivity Tool

Associated task: T2.2
Leader: SCHND[14]

Participants: INESC[15], EDF[16], FRAUN[17], EATDE[18], EATCZ[19], EATAT[20], RWTH[21], NEXNS[22], TALT[23], FCSI[24]

2.2.1 Objective

Today, there are very few LVDC-MVDC networks in existence. Demonstrations have been conducted on a case-by-case basis, and specific studies have been instrumental in this. However, there is currently no general design rule available, and no standard comprehensively specifies how the protection of such a system should be carried out. Some standards are being updated (e.g., IEC 60947-10 for semiconductor circuit breakers or IEC 60364-7-712 for PV Power Supplies), but no one specifically addresses short circuit current calculation rules for a complete system.

Moreover, the specific constraints of DC are often not well known. This includes the continuous electric field, which can lead to corrosion issues if appropriate measures are not taken in the earthing system.

The objective of Task 2.2 is to establish a methodology for:

- Identifying earthing systems that can be utilized without risking potential corrosion issues.
- Determining the necessary protection equipment in a multi-source environment and assessing the impact of isolated or non-isolated converters.
- Developing a protection plan, which involves identifying potential faults within an electrical network and defining methods for detecting and eliminating these faults.
- Performing short circuit currents calculation study, selecting appropriate protective equipment, and defining settings to ensure:
    - The installation remains undamaged in the event of an electrical fault.
    - The protection of individuals is maintained.
- Providing selectivity while considering various breaking technologies.

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[14] Schneider Electric
[15] Instituto de Engenharia de Sistemas e Computadores: Investigação e Desenvolvimento em Lisboa
[16] Électricité de France
[17] Fraunhofer Institute for Integrated Systems and Device Technology IISB
[18] EATON Industries GMBH
[19] EATON Elektrotechnika SRO
[20] EATON Industries (Austria) GMBH
[21] RWTH Aachen University
[22] NEXANS France
[23] Tallinn University of Technology
[24] Fincantieri SI

2.2.2 Requirements

The methodologies proposed in Task 2.2 are intended to facilitate the preliminary studies required for the development of the planned demonstrators in WP4 of Shift2DC. Also, these methodologies should form a foundation for the design of any other low-voltage direct current (LVDC) distribution system.

End users:

- Shift2DC use cases: Electrical architects and designers.
- Electrical design and protection engineers.

The methodologies proposed in Task 2.2 shall be **independent** of DC ecosystems.

The methodologies proposed in Task 2.2 shall address **all DC overcurrent protection technologies:** Electromechanical Circuit Breaker (ELM CB), Solid-State Circuit Breaker (SCCB), Hybrid Circuit Breaker (HCB), and fuse.

2.2.3 Architecture

2.2.3.1 Operational Workflow

The appropriate methodology will be detailed in a comprehensive document. The electrical studies workflow will cover the following objectives:

- Selecting the earthing system and its impact on electrical equipment sizing.
- Choosing and sizing electrical equipment such as over-current protection, additional protection (residual current devices), and insulation monitoring devices to protect people, cables, and converters.
- Performing a short-circuit currents calculation.
- Providing protection against overcurrent.
- Protection against electric shocks.
- Ensuring selectivity.

2.2.3.2 Inputs and Outputs

The earthing system document will delve into the electrochemical perspective of corrosion phenomena, followed by recommended practices for earthing systems. It will also explore how the earthing system influences the selection of protection devices against overcurrent and electric shocks.

For formulating a protection plan and performing a **short-circuit current calculation study**, a comprehensive description of the network and the characteristics of all potential fault contributors is vital. This includes:

- ○ Complete electrical single line diagram (SLD) of the installation, including cable lengths, characteristics, and especially impedances.
- ○ Description of all sources in short-circuit condition, encompassing internal capacitances of converters and loads exposed to the DC bus.

The proposed tool will offer a clear methodology outlining the process for performing short-circuit currents calculation and selecting appropriate protection equipment, by using existing commercial software packages (ETAP, EMTP[25], Power Factory[26], MATLAB[27], etc.).

Furthermore**, selectivity studies** will require the characteristic data of all protection devices in the system, including tripping thresholds and time-current curves. The methodology will consider various breaking technologies, using either time-graded selectivity, current-graded selectivity, logic selectivity (non-directional or directional), or differential (Zone selectivity).

2.2.3.3 Available Tools and Options

Today, comprehensive documentation for designing AC networks is readily available, but the resources required to design LVDC networks are currently inadequate.

In the realm of **short-circuit current calculations**, commercial tools, like ETAP and PowerFactory, are beginning to incorporate certain features. However, these tools are still incomplete due to the unavailability of corresponding standards. Alternatively, time-domain simulation tools like MATLAB/Simulink, Portunus, Saber, Simplorer, and EMTP-ATP can be utilized to simulate electrical networks. Nonetheless, a drawback of this approach is the need to build models of cables, sources, converters, and loads from elementary blocks with the appropriate level of detail.

Moreover, due to DC grids being dominated by power electronics, short circuits are supplied not just by sources but also by the grid side capacitances of loads. As such, current flow during faults is no longer hierarchical. This can result in the tripping of fuses of non-faulty lines. Also, depending on the overall system design, steady-state fault currents, and maximum nominal currents can be similar, so the standard approach of AC systems with a fuse tripping current of multiple times the nominal current is not applicable.

When it comes to **selectivity**, existing commercial AC software is available, but it relies on time-current curve analysis, which is insufficient for LV studies. Moreover, they do not encompass DC applications.

2.2.4 Expected Performance

2.2.4.1 Scope and Limitations

Scope:

The objective is to guide DC electrical network designers in conducting essential studies to protect the installation using suitable methodologies. The methodology will not offer new simulation software to calculate the short circuit current. Instead, it will explain how to calculate it and, as such, allow implementation and integration into the tools as needed. This includes identifying the parameters to consider and the type of simulation needed to assess the magnitude of the short circuit current. This reduces the overhead efforts since the grid does not need to be modeled using yet another tool; instead, architects and designers can use the system they are already skilled with.

Limitation:

The development of calculation/simulation software is beyond the scope of this task.

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[25] Electromagnetic transients program

[26] PowerFactory - DIgSILENT

[27] MathWorks – Editeur de MATLAB et Simulink - MATLAB & Simulink

2.2.4.2 Advantages

Presently, the existing DC literature and DC standards are inadequate. The proposed methodology aims to clarify expectations and provide a common framework that can be shared.

2.2.4.3 TRL

- **Current TRL:** 4
- **Target TRL:** 6

2.2.4.4 KPIs

The deliverables will cover the following topics:

- LVDC breaking technologies and associated protection functions.
- Earthing systems and the potential risk of corrosion in DC systems.
- Protection equipment concerning earthing systems (overcurrent and electric shock protection).
- Rules for performing a short circuit current calculation study in a DC multisource system.
- Selectivity rules concerning different breaking technologies.
- Protection plan for demo use cases.

2.2.5 Partner-Provided Inputs

Schneider Electric will lead cooperation work to build the first version of the documents and methodology (including the Current/OS solution) and consider the partners' review.

Partner contribution will be needed:

- To describe ODCA solution.
- To provide cable inputs (impedances, ampacity, and thermal withstand).
- To review draft proposals.
- To provide demo inputs for use cases protection plan studies.

2.3 SOL24: DC Microgrids Simulation Tool

Associated task: T2.3a
Leader: EDF[28], SCHND[29]

Participants: TECN[30], NEXNS[31], W&W[32]

2.3.1 Objective

Problem addressed:

- Existing Electro-Magnetic Transient (EMT) design tools and simulation environments mainly address AC systems and, therefore, not optimized to handle the DC domain.

Main objective:

- Development of a dedicated EMT simulation environment for DC microgrids enables the creation of a DC environment (grid, loads, converters, sources, etc.) in which transient and steady-state analysis can be executed to validate solutions such as the voltage droop control.
- For this solution, the term "simulation environment" refers to a set of libraries, components, and individual systems that will be implemented in already existing EMT simulation tools (MATLAB/Simulink, EMTP, PowerFactory, etc.), either as white- or black-boxes[33].

Needs fulfilled by the tool:

- Transient and steady-state analysis
- Stability analysis
- Performance of voltage droop control evaluation
- Study of the interaction between different converter-controlled grid assets/equipment
- Short-circuit simulation and protection scheme analysis

Expected advantages:

- Offering a robust library of components, sources, loads, converters, and control blocks for the reliable design of DC microgrids, analysis of transient and steady-state phenomena, and stability assessment.
- Assisting stakeholders in making informed decisions regarding the choice of different DC solutions, as well as power conversion systems, control systems, and protection systems.

Applications:

- Data centers, buildings, industrial environments, and ports, where DC technology can offer significant advantages in terms of energy efficiency, operational costs, and resiliency.

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[28] Électricité de France
[29] Schneider Electric
[30] TECNALIA
[31] NEXANS France
[32] Watt & Well
[33] White box model is an open model to which we can fully access (source code, unit models, configuration and parameters) while Black box model is not internally accessible and provides the model functionality with external interfaces and outputs only.

2.3.2 Requirements

- **Req1:** Users can do EMT studies to evaluate transient phenomena in DC microgrids and perform the following analysis:
    - Shared voltage control techniques and stability.
    - Short-circuit simulation scenarios and protection schemes.
    - Grid operation in different scenarios of local energy production and different load configurations.
    - Dynamic model implementation for each one of the demonstrators.

- **Req2:** The simulation environment must be independent of DC **ecosystems**.

- **Req3:** The simulation environment is focused in the LVDC domain; however, it can include a medium voltage direct current (MVDC) hybrid AC/DC library.

- **Req4:** The timescale used for calculations must be small enough to allow the evaluation of the transient phenomena.

- **Req5:** Asset generic models should include at least filters, regulation control loops, current limitation capabilities, and other features ensuring the accuracy of the results.

- **Req6:** The environment should be able to integrate black-box models.

2.3.3 Architecture

The **main architecture** of this tool will depend on two main aspects: (1) the base simulation environment and (2) the EMT models of different DC equipment.

The **main objective** of the tool is to create an integrated environment for users to be able to model a dynamic model of a DC microgrid. To accomplish this objective, different libraries must be available, and the multiple equipment models must be interoperable with each other.

Figure 2.2 shows the main tool components allowing transient simulations.

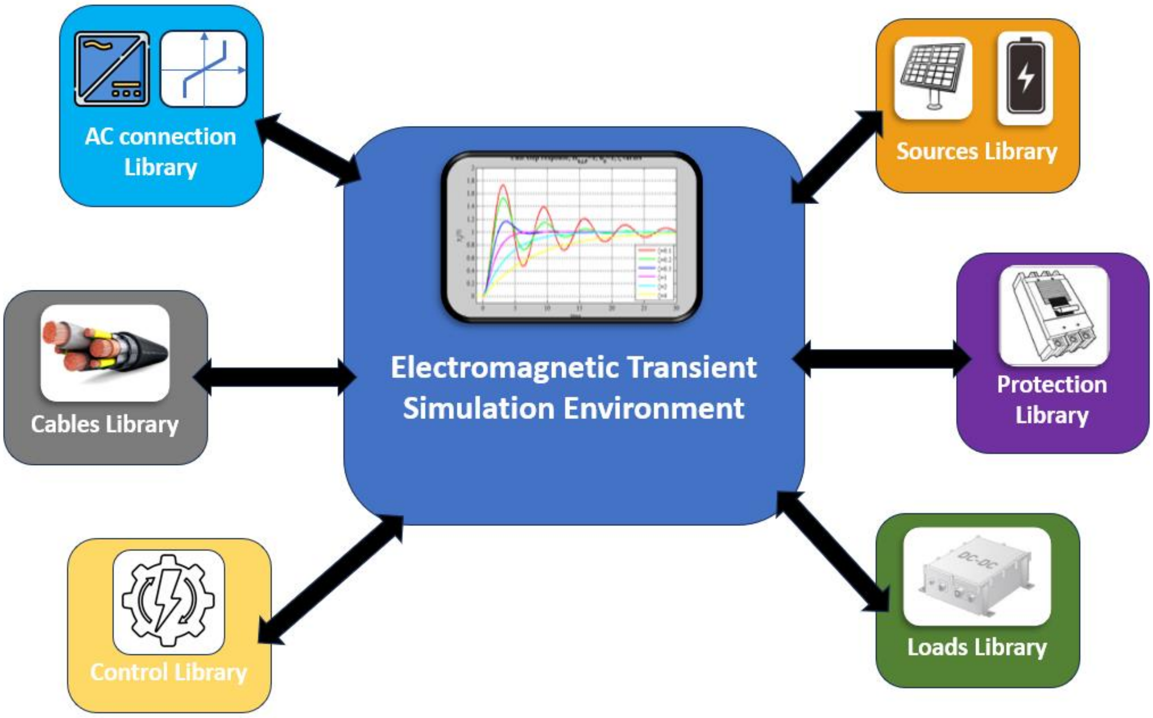

Figure 2.2 DC microgrid simulation tool main components overview.

2.3.3.1 Operational Workflow

The use of this tool will be done according to the following steps:

- **Step 1 – inputs:** a set of inputs will be needed regarding the general parameters of the DC microgrid and different grid-connected assets, such as power and voltage levels.
- **Step 2 – equipment choice:** the user will then be able to choose a set of equipment from different libraries according to the actual DC microgrid.
- **Step 3 – equipment configuration:** afterward, different parameters will be configured for each piece of equipment, regarding sizing and more advanced control features.
- **Step 4 – simulation parameters:** the simulation environment must allow proper configuration of solvers, step size, and total duration of the simulation.
- **Step 5 – unit tests:** each equipment operation may be evaluated separately from the DC grid and other equipment.
- **Step 6 – integration tests:** the user must proceed to the proper interconnection of the different equipment used in the simulation, as well as the measurement devices, to execute different EMT simulations.

2.3.3.2 Inputs and Outputs

Inputs:

In terms of grid modeling, the user must provide the architecture of the grid (radial, meshed, ring, etc.), as well as the physical installation structure with different branch lengths, buses, and connection points.

Regarding the grid elements, different models will be available in specific libraries. Users will then have to specify the set of configurations of each grid asset (loads, PV, BESS, EV charger, cables, DC/DC converters, AC/DC converters, and protections), such as power, control, operation, filter size, load/generation profiles and others.

Outputs:

The main output expected from the simulation environment proposed here is the EMT behavior of the DC microgrid. More specifically, it should allow users to verify grid stability, energy resources, load consumption management, and protection scheme performance. From this perspective, it should allow users to verify important KPIs defined for each demonstrator, such as grid resiliency.

2.3.3.3 Available Tools and Options

- **EMTP:**
    - **Advantages:**
        - Relevant for transient calculations
        - Most of the existing models have already been validated in real experimental scenarios.
- **MATLAB/Simulink:**
    - **Advantages:**
        - Well-adapted for power electronics modeling with dedicated libraries.
        - Generic models of different converters already exist.

Note: An important aspect that should guide the choice of the base tool used here is the capacity of partners to export black-box models to a specific simulation environment.

2.3.4 Expected Performance

Dynamic modeling

This specific simulation environment must allow users to reproduce the transient and steady-state behavior of a DC microgrid. Using specific libraries and their components, users will be able to create a dynamic model of different DC microgrids (be it port, industry, data centers, or buildings).

Black-box integration and compliance

Some specific grid assets and solutions developed in this project will be modeled as black-box components to be integrated into a larger simulation scheme. From this perspective, models of DC microgrids could be a more reliable representation of real equipment and their respective behaviors.

Accuracy according to real behavior

The tool must also allow the design of protection schemes through the detailed analysis of short-circuit scenarios and protection devices' behavior. White-box and Black-box models of AC/DC converters, DC/DC converters, and protection devices must operate according to their real behavior. In this stage, it is important to accurately represent input and output filters, as well as the different control algorithms that are executed when a short-circuit or a ground fault occurs. EMT behavior during cut-off phenomenon, and secondary voltage control are some of the features that must be accurately represented.

2.3.4.1 Scope and Limitations

Scope:

- **Stability**: The main scope of this tool is to guarantee the stability of the DC microgrid in different grid operation scenarios and for different equipment configurations and controls. The shared voltage droop control must be evaluated, and its behavior must be validated in this task.
- **Protection**: the transient evaluation of short-circuits and faults is also in the scope of this tool. It should be capable of calculating short-circuit currents to allow the grid designer to size the protection scheme and the protection devices properly.

Limitations:

- **Modeling**: low-level power electronics modeling (switching) is not mandatory, and some blocks may operate using an average representation.
- **Power quality**: since switching-associated phenomena are not the scope of this tool, power quality evaluation of steady-state phenomena (ripple) and spectral disturbances analysis may not be accurately performed with this tool.
- **Source/load operation**: The evaluation of different scenarios is highly dependent on the internal configuration of the components (black-box) available in the tool library.

2.3.4.2 Advantages

- **Comprehensive and detailed evaluation:** this tool uses transient simulation associated with a robust library of components, sources, loads, and converters to guarantee system stability and protection.
    - Evidence: modeling of converters, protection devices, and control systems ensures optimized design to guarantee the correct operation of the DC microgrid.

- **Versatility and Scalability:** Agnostic design allows application across multiple sectors, such as data centers, buildings, industry, and ports.
    - Evidence: specific libraries tailored for different applications enhance usability.

- **System approach:** Different equipment and sub-systems in a DC microgrid can be evaluated together in a simulation environment to facilitate integration in real demonstrators.
    - Evidence: A dynamic model will be constructed using this library.

2.3.4.3 TRL

- **Current TRL:** NAN
- **Target TRL:** 6

2.3.4.4 KPIs

- **KPI1:** Ability of the tool to perform convergent **EMT calculations** for a defined use case.
- **KPI2:** Ability of the tool to allow a **stability** evaluation for a specific DC microgrid in different source/load equipment scenarios.
- **KPI3:** Ability of the tool to perform **short-circuit and fault** calculations to allow the evaluation of the protection scheme.

- **KPI4:** Ability of the tool to ensure **a prior system integration and validation** of the LVDC demonstrators.

2.3.5 Partner-Provided Inputs

Detailed Libraries: Partners will be asked to provide white-box models if possible or to develop open-access simplified versions of components and systems. In addition, if white-box models are not available due to confidentiality, individual black-box models of different components will then be integrated into the libraries.

- **PV system (TALTECH)**
    - DC/DC converter (power electronics and filters)
    - Maximum Power Point Tracking (MPPT) + Shared voltage droop control
    - Generation profile
- **ESS**
    - DC/DC converter (power electronics and filters)
    - Shared voltage droop control
- **EV system and PDU (W&W)**
    - DC/DC converter (power electronics and filters)
    - Shared voltage droop control
    - Charging profile
- **Cables (NEXANS)**
    - R, L, C parameters and cable model.
- **ILC (SCHNEIDER)**
    - AC/DC converter (power electronics and filters)
    - Shared voltage droop control
- **Protection (SCHNEIDER, EATON)**
    - Circuit breakers (power electronics and filters)
    - Grounding systems
- **EMS (EATON)**
    - Control logic and assets management
- **MVDC library (TECNALIA)**

In general, all solution developers can provide a dynamic model for their own solution for the demonstrator's system integration and validation.

2.4 SOL26: Multiterminal-MVDC-grid Control and Protection Integration Tool

Associated task: T2.3b
Leader: RWTH[34]

Participants: TECN[35], NEXNS[36]

2.4.1 Objective

Problem:
Today, complete and detailed information about converter control parameters and protection settings is required to be able to:

- Maintain stable and safe MVDC system operation with diverse control and protection methods for power-electronic converters.
- Identify and solve interoperability issues that result from the interactions of core control functions in multi-terminal direct current (MTDC) networks.
- Achieve reliable protection settings and properly tune control functions in different scenarios.

Besides providing complete and detailed information, the assessments require the simulation of a great number of different operating scenarios, which cost time. Further, the information about converter and protection settings required today for the analysis is often confidential and highly sensitive to the business models of the manufacturers, thus prohibiting the assessment and implementation of multivendor systems.

Solution:

- Develop a stability analysis tool using state-space and impedance-based modeling, enhanced by artificial intelligence (AI).
- Create methodologies for assessing MVDC system stability and develop necessary protection verification.
- Provide control design specs and real-time testing for integration and ensure multi-vendor interoperability.

Objectives:

- Assure interoperability of equipment from different vendors within multiterminal MVDC grids.
- Facilitate converter integration into multivendor DC systems using easily obtained impedance profiles (Z-profiles).
- Assist in the integration of control and protection parameters in MTDC systems.
- Facilitate the integration of control and protection systems.
- Ensure interoperability in the MVDC system.

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[34] RWTH Aachen University
[35] TECNALIA
[36] NEXANS France

2.4.2 Requirements

Related use cases and demos for impedance-based stability assessment and control parameter derivation:

- Industry demo site @RWTH
- UC7 – MVDC-LVDC Interface Converter

Requirements:

- **Req1:** Z-profiles of the MVDC grid system and converter must be added to the system.
- **Req2:** Control parameters of the converter must be added and/or the converters in the grid system need to be adjustable.
- **Req3:** Control and protection parameters range of the converter must be added.
- **Req4:** A minimum of 1000 data points (voltage, current, trip signals) generated for each defined operation point of the system must be available.

2.4.3 Architecture

SOL 26 consists of two parts: (1) the impedance-based stability assessment tool (Figure 2.3) enables safe and stable operation under normal operating conditions, and (2) the control-and-protection-verification tool (Figure 2.4) ensures safe operation under fault conditions.

Structure of the impedance-based stability assessment tool:

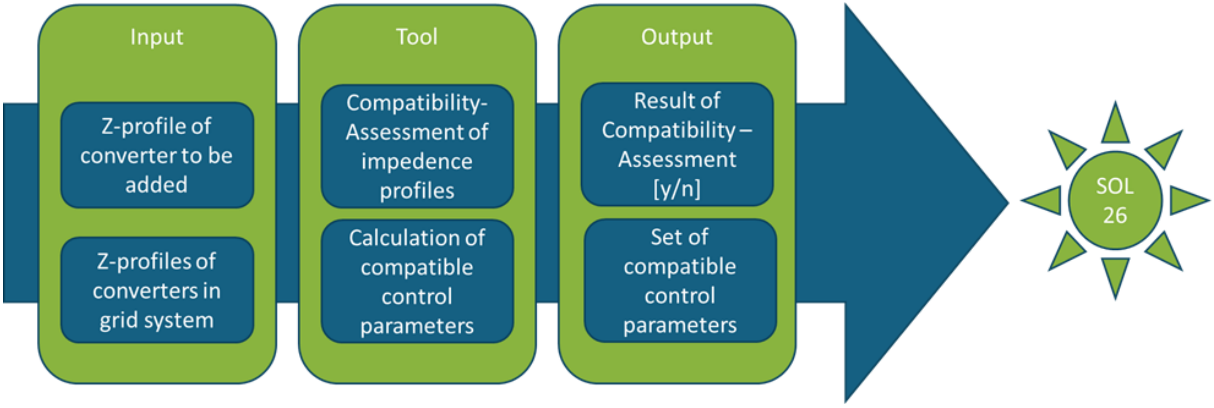

Figure 2.3 Structure of the impedance-based stability assessment tool.

Structure of the Control and Protection Verification tool:

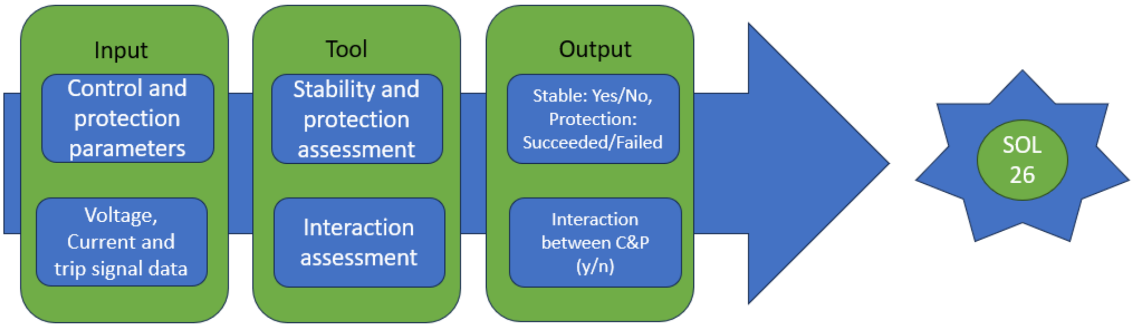

Figure 2.4 Structure of the Control and Protection verification tool.

2.4.3.1 Operational Workflow

Impedance-based stability assessment tool:

- **Step 1:** Input considered converters' Z-profiles and system topology.
- **Step 2:** Calculate total system impedance per considered operating point.
- **Step 3:** Assess the compatibility of impedance profiles – whether the system is stable or unstable.
- **Step 4:** Calculate stable control parameters and potential required action.

Control and Protection verification tool:

- **Step 1:** Gather control and protection parameters of all the converters of the system.
- **Step 2:** Generate and collect data (voltage, current, and trip signals) for each scenario.
- **Step 3:** Train AI to assess stability and protection actuation.
- **Step 4:** Verify the interaction between control and protection parameters.
- **Step 5:** Provide adequate control and protection parameters and stability margins.

2.4.3.2 Inputs and Outputs

Impedance-based stability assessment tool:

Inputs:

- Impedance profile of the converter to be added to the DC grid.
- Impedance profiles of the converters that are already operated in the grid system.
- System topology.

Outputs:

- Result of the stability assessment [yes/no].
- Set of stable control parameters.

Control and Protection verification tool:

Inputs:

- Control and protection parameters of the converter + line.
- Generated data (1000 samples): Voltage, current, and trip signal per scenario.

Outputs:

- Result of the stability and protection evaluation- Stable: Yes/No, Protection: Succeeded/Failed.
- Result on the interaction indices between Control and Protection.

2.4.3.3 Available Tools and Options

Existing tools that will be considered for adoption in task T2.3b:

- MATLAB/Simulink
- Keras[37] Library in Python
- PLECS[38], existing PLECS models
- SALib[39]

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[37] https://keras.io/

[38] https://www.plexim.com/products/plecs

[39] https://salib.readthedocs.io/en/latest/

2.4.4 Expected Performance

2.4.4.1 Scope and Limitations

Scope of Impedance-based stability assessment tool:

- Assess the stability of an MTDC system using impedance profiles.
- Provide insight into necessary action on impedance level to stabilize the system.
- Generalization of the defined operating scenarios to universal MTDC bus system.

Boundaries of Impedance-based stability assessment tool:

- The analysis is small-signal based, i.e., it must be performed per operating point.
- The outcome depends on the quality of profiles.
- Stability is a sufficient but not a necessary condition.
- The frequency range that is covered is limited by input profiles.
- Model predictive control is not to be covered.

Control and Protection verification tool covers:

- Narrow down the control and protection parameters for the design process.
- Provide a stability and protection margin.
- Analyze the interaction between Control and Protection.

Boundaries of Control and Protection verification tool:

- Binary outputs.
- Results based on the scenarios tested.
- Results need to be verified with conventional EMT tools.
- The tool results depend on the quality of the input data.

2.4.4.2 Advantages

The amount of time and information needed to assess grid stability and derive control and protection parameters is significantly reduced [1], [2] . Additionally, the implementation of vendor agnostic MTDC systems is facilitated, as the different manufacturers no longer must provide detailed/classified information [3].

2.4.4.3 TRL

- **Start TRL:** 4
- **Target TRL:** 6

2.4.4.4 KPIs

- **KPI1:** Reduction of the time needed to assess the stability of DC grids and to assess the compatibility of converters to be added to the system with existing DC grid systems (compared to the detailed simulation for various operating points that are currently necessary).
- **KPI2:** Reduction of the time needed to assess and adapt protection concepts for multiterminal MVDC systems (compared to the detailed simulation for various operating points that are currently necessary).
- **KPI3:** Reduction of the amount of information (list of inputs) necessary to derive control and protection parameters for stable and secure operation of multiterminal MVDC grids.
- **KPI4:** Reduction of multi-vendor integration effort.

2.4.5 Partner-Provided Inputs

- **RWTH-PGS (Institute for Power Generation and Storage Systems at RWTH)**: Method for impedance-based stability assessment and control parameter configuration
- **RWTH-ACS (Institute for Automation of Complex Power Systems at RWTH)**: Method for AI-enhanced protection configuration
- **TECNALIA:** Support the development of the impedance-based stability assessment method.

2.5 SOL21: “White” EMS tool for AC/DC Hybrid Systems

Associated task: T2.3c
Leader: EATDE[40]

2.5.1 Objective

This tool addresses several critical challenges in modern power systems, including optimizing power flow, maximizing the use of available power sources, ensuring efficiency and reliability of a microgrid, and adapting to changes in the grid. The solution involves developing a “white-box”[41] energy management system (EMS) designed specifically for hybrid AC and DC grids. This advanced EMS will incorporate new control functions developed in the Shift2DC project and sophisticated algorithms that enable DC devices to participate in grid system services.

The tool will be capable of connecting, controlling, and coordinating various distributed energy sources, loads, battery energy storage systems, and AC interconnections. It will manage adaptive voltage sharing, power, and energy flow control and ensure the proper operation of a DC microgrid. By integrating these features, the EMS will enhance the overall performance, flexibility, and resilience of the power grid, meeting the evolving needs of modern energy systems.

2.5.2 Requirements

The EMS tool is defined to be used in the four demonstrators, allowing several use cases:

- DC grid resilience in case of AC Grid outage or faulty asset
- Maximization of local energy consumption
- Grid services provision

The tool will provide adaptive droop control reconfiguration to address the goals of each operation mode. It will also provide a user interface to monitor system operation and control the full system or individual components.

It will be tailored to serve demo users. For example, in the building demo, the building manager or technician responsible for the building power system operation will be served.

2.5.3 Architecture

The architecture of the EMS tool is under development. It will be defined in Task T2.3.

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[40] EATON Industries GMBH

[41] Open access to source code

2.5.3.1 Operational Workflow

Figure 2.5 shows the operation of one cycle of the workflow of the tool. Such cycles are repeatedly executed with regular periods. Typically, between 5 and 30 minutes.

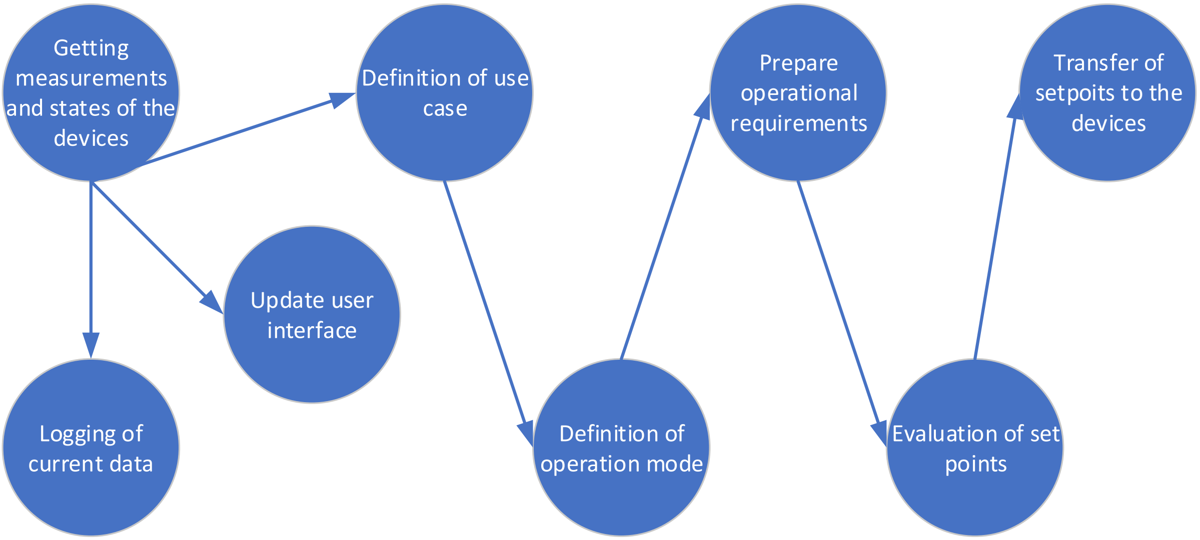

Figure 2.5 Diagram of the operation of one cycle of the EMS workflow.

2.5.3.2 Inputs and Outputs

The EMS tool will require certain information about the system, parameters of devices, and operation conditions. Based on these, the EMS will identify the operation mode, goals, and restrictions and will evaluate the new system configuration. In addition, reconfiguration setpoints will be issued to devices under control or to the communication interface, which will enable their transmission. The following data can be expected:

- **Inputs**
    - Devices parameters: limits, boundaries, capacities.
    - Device state parameters: state of switch, state of charge, warning/faults/flags, etc.
    - Voltage, current, and power measurements.
    - User inputs.
- **Outputs**
    - Setpoints for devices (reference voltage and droop coefficients or curve shapes), state of switches – on/off or threshold voltage level.

The list will be populated with more details of all parameters and data types during the development iterations.

2.5.3.3 Available Tools and Options

Edge Devices Potential Platforms

- SMP Platform: This platform is part of the substation automation gateway family and is designed for efficient and reliable operation in substation environments.
- XC300 Modular PLC: A modular Programmable Logic Controller (PLC) used in various storage solutions, offering flexibility and scalability.

Software Environments

- Codesys: An IEC 61131-3 compliant development environment for programming controller applications. It supports various programming languages and is widely used in industrial automation.
- MATLAB: A high-level language and interactive environment for numerical computation, visualization, and programming. It is extensively used in engineering, scientific research, and data analysis.
- Python: A versatile, high-level programming language known for its readability and broad applicability in web development, data analysis, artificial intelligence, and more.
- Brightlayer: Eaton’s digital platform for power management, connectivity, design, and data science. It integrates various tools and services to enhance power system performance and efficiency.

2.5.4 Expected Performance

The EMS tool will realize adaptive reconfiguration of the system based on droop control from the secondary level. In the following subsections, we will explain in more detail the benefits, boundaries, and level of demonstration to be reached.

2.5.4.1 Scope and Limitations

The EMS for hybrid AC and DC grids covers several key areas:

Connection and Coordination: It connects, controls, and coordinates distributed energy sources, loads, battery energy storage systems, and AC interconnections at the secondary level.
The EMS does not ensure direct communication to the device, which is often specific to the manufacturer and goes through a communication and control system. Thus, it might require additional software or hardware modules to realize data transfer.

Adaptive Control and Flexibility: It manages adaptive voltage sharing, power, and energy flow control and participates in the proper operation of a DC microgrid.
Limitation in ensuring the proper operation of a DC system comes from the fact that correct power sharing depends on devices’ sizing. The EMS tool also ensures system optimization with a longer time horizon, while the short time reaction and stability are covered by embedded control algorithms, including droop control on the primary level.

Integration of new functions: It includes new control functions developed in the Shift2DC project and algorithms that enable DC devices to participate in grid system services.

Code Structure and Access: “white-box” means open principle in code organization, parametrization, and testing. However, we leave space for protecting “core” safety critical features as well as IP-protected algorithms in analytics or advanced features, which can be seamlessly integrated or interfaced within the EMS tool.

2.5.4.2 Advantages

Current state-of-the-art EMS primarily consider the AC grid and typically exclude droop control mechanisms. These systems are designed to forecast power balance in the system and optimize the temporal evolution of power flow, often with the primary objective of minimizing electricity costs. However, they frequently overlook the stability and reliability of the system's power delivery.

This project aims to demonstrate an EMS that integrates droop control operations, thereby ensuring robustness, flexibility, and reliability in powering installations. Consequently, the focus of energy management will shift, with the EMS leveraging the flexibility of distributed control of a DC power system based on droop control principles.

2.5.4.3 TRL

- **Current TRL:** The EMS of the AC/DC system was validated at the lab level, but the feature set will be significantly increased. Therefore, we consider **TRL 3** to be relevant in describing the status of the development.
- **Target TRL:** Until the project ends, we will achieve testing and validation of the technology in the under-study commercial building environment, but the EMS system might have a different platform than the final product. Therefore, we consider reaching **TRL 6** to be the target for EMS development.

2.5.4.4 KPIs

The final system will control at least four flexible devices or groups of devices. It will enable online monitoring of the system operation and smooth reconfiguration after a transition between the operation modes. If devices' power capacities are well designed, the EMS system will keep voltage levels and power setpoints in safe operation boundaries, enabling continuous operation on a time scale longer than hours or days. In more detail, the expected system parameters are:

- Update of monitoring – every 2 seconds.
- Smooth reconfiguration during the transition between operation modes of Resilience, Self-Consumption, Flexibility services, and Self-healing.
- Control of more than four controllable components of the distribution grid. For instance, breakers, contactors, converters, loads.

2.5.5 Partner-Provided Inputs

Information about the power system, control system, individual devices datasheets, and operation rules will be needed for the EMS design. System modeling will help to configure, test, and troubleshoot the design before real installation. In addition, it will facilitate the streamlined commissioning of the Demo sites. However, the development of the model and system will run in parallel and will require an iterative and flexible approach. The following inputs are expected to help with the design and testing of the EMS tool:

Demo leader:

- Demo Architecture.
- External inputs if needed.
- Use case target parameters and goals.
- System model.
- Connectivity architecture, communication interfaces for each device, data models for reading parameters of devices, and controlling operation.

Components providers (Schneider, Watt and Well, TalTech):

- Specification of controlled devices, such as converters, EV chargers, breakers, contactors, and loads. This includes monitoring, diagnostic, state, and control parameters.

2.6 SOL27: Condition Monitoring and Maintenance Planning Tool

Associated task: T2.4
Leader: INESC[42]
Participants: NEXNS[43], TALT[44]

2.6.1 Objective

The main aim of the proposed tool is to integrate algorithms based on machine learning (ML), allowing for the anticipation of faults (mechanical or electric) that can occur in different assets and devices. This process is normally called condition monitoring (CM) [4], [5]. CM is an important aspect of predictive maintenance that improves the normal operation of global systems. To achieve a CM model, several three main steps should be considered, namely:

- **Install measurement and monitoring systems:** A crucial component of the system is the data related to its operation. This data can be collected using meters and weather stations, particularly for renewable generators. However, many devices used in DC grids have built-in monitoring capabilities. For instance, a BESS power converter can provide information about grid voltage and current, individual cell data, and overall system health. Yet, in many cases, this information is underutilized.
- **Establish an operational baseline:** By analyzing the collected data, combined with theoretical operating characteristics and expert knowledge, we can define a baseline for device performance. This baseline is essential for identifying abnormal device behavior. This task is complex as it is specific to each type of asset and device.
- **Performance evaluation and diagnostics:** The CM aims to assess system performance and provide diagnostics by utilizing data from monitoring systems and established baselines. The quality and depth of these diagnostics will significantly depend on the number of sensors and the historical incident data. If an operational abnormality is detected, the system will send an alert and analyze the data to determine whether immediate action is required or if the machine can continue operating until scheduled maintenance.

Based on the presented concepts, the main objective of this tool is to include CM algorithms for different assets and devices. The type of assets and devices will depend on the available data. The proposed methodology will be tested, at least, for wind generators using the data available in [6].

2.6.2 Requirements

As mentioned in the previous section, the requirements will depend on the type of asset to be analyzed. As much data is available, more detailed diagnostics can be obtained. In the case of wind generators, it is possible to have data/measurements of the Hydraulic system, Generator, Generator Bearing, Gearbox, Transformer, and Power Converters. Afterward, measurements of the weather conditions per turbine are also available. Beyond the measurements, a Logbook of the failures per turbine is also available. This detailed information allows for the identification of several fault types and the probable cause of the fault.

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[42] Instituto de Engenharia de Sistemas e Computadores: Investigação e Desenvolvimento em Lisboa
[43] NEXANS France
[44] Tallinn University of Technology

Considering the development that will be performed in the Shift2DC project, it is expected that measurements of photovoltaic (PV) systems and BESS will be available, allowing the application of the proposed methodology to this kind of asset. Other specific devices, such as converters, power routers, and cables, which are key in DC grids, can be "theoretically" integrated into the tool, but real measurements will be challenging to obtain.

2.6.3 Architecture

2.6.3.1 Operational Workflow

The tool will include a set of ML algorithms with the goal of establishing a baseline for the operation of the asset/devices and, subsequently, identifying deviations from this baseline. The ML used to define the baseline fitting models will be based on techniques such as clustering, regression, and neural networks. Therefore, the logical extension is to detect deviations from this expected normal behavior that are indicative of a future fault. An ML algorithm typically comprises four stages:

- **Step 1:** data description and fault analysis,
- **Step 2:** data acquisition and preprocessing,
- **Step 3:** feature selection,
- **Step 4:** model selection, and validation using various evaluation metrics.

The early prediction of faults will result in higher availability and, consequently, in increased consumption and production, depending on the type of device. A generic architecture is presented in Figure 2.6.

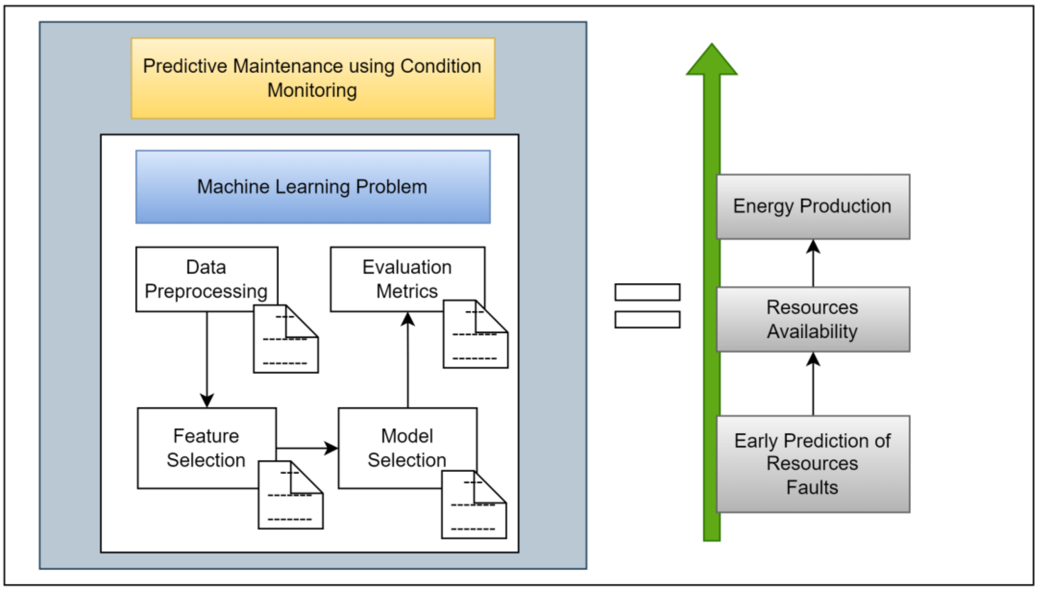

Figure 2.6 Condition Monitoring Tool Implementation Concept.

It is important to mention that several algorithms will be developed to perform fault detection. However, it is expected that algorithms with better performance can differ based on the types of faults. This is why model selection is important and integrated into the development methodology.

Concerning the architecture of the tool, the first step consists of training the models. For this purpose, the historical data and faults logbook available on the SCADA/EMS will be used. This data will be divided into periods of Normal Operation and Faults. The normal operation periods will be used to create the baseline, and the fault periods will be used to train the model. After this baseline, Prediction models will be used to estimate the normal behavior of the asset/device according to the features selected previously. The deviation between the model and the real values will be analyzed to predict faults. This architecture is presented in the figure below.

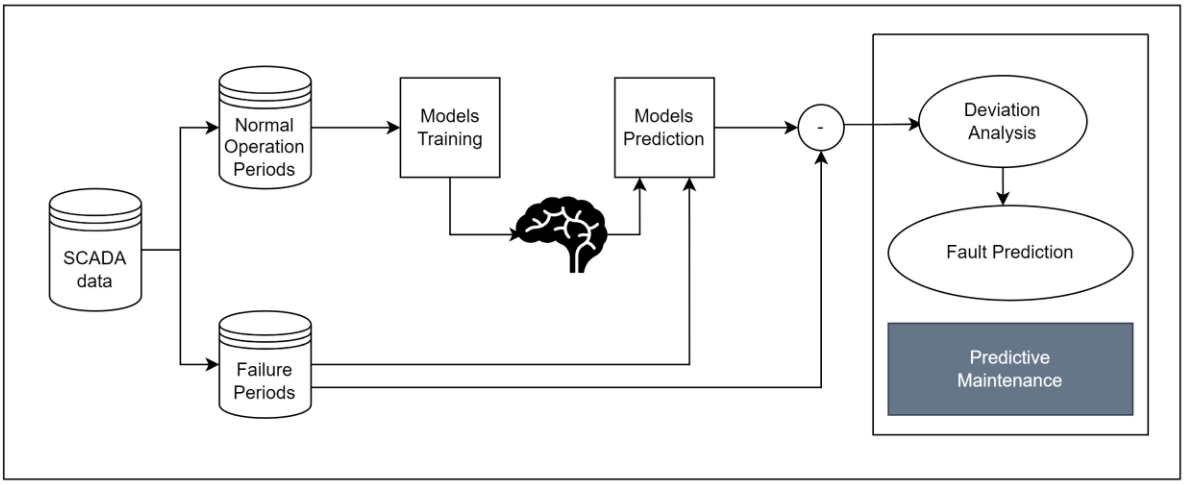

Figure 2.7 Condition Monitoring Tool Architecture.

2.6.3.2 Inputs and Outputs

In general, the tool will require **two main inputs**: the measurements available in the SCADA/EMS or obtained directly from assets/devices and the logbook of the faults. As presented in Figure 2.7, the SCADA/EMS data will be used to design the baseline. The information needed depends on the type of asset/device. Some examples of input data are the following:

- **Wind turbines:**
  - Active Power production [W]
  - Wind speed [m/s]
  - Wind direction [º]
  - Pitch of the blades [º]
- **PV systems:**
  - Active Power production [W]
  - Radiation [W/m2]
  - Temperature [ºC]
  - Latitude [º]
  - Tilt Angle [º]
- **BESS systems:**
  - Active Power production [W]
  - SoC [%]
  - Temperature [ºC]
  - DC Voltage [V]
  - DC Current [A]

The mentioned information can be used to define the baseline and to identify deviations from the baseline. However, the fault logbook will be used to detail the type of fault that can occur. This will significantly improve the results of the tool.

2.6.3.3 Available Tools and Options

The condition monitoring tool will be developed from scratch in Python. Nevertheless, several existing libraries will be used to accelerate the development process. Some of the libraries that will be used are:

- Pandas (https://pandas.pydata.org/pandas-docs/stable/index.html)
- Pickle (https://docs.python.org/3/library/pickle.html)
- Keras (https://keras.io/)
- Scikit-learn (https://scikit-learn.org/stable/)
- TensorFlow (https://www.tensorflow.org/)
- PyTorch (https://pytorch.org/)

2.6.4 Expected Performance

As mentioned, the performance will be directly related to the available data and the complexity of the technologies. As an example, PV technology has many fewer than wind turbines. However, fault detection accuracy is expected to be higher than 90%.

2.6.4.1 Scope and Limitations

The primary limitation of the models is related to the available data. However, other significant factors can be mentioned. First, characterizing faults and their potential causes can significantly aid in feature selection for the models. The inability to identify causes can be considered a limitation of the tool. Second, data quality is a concern. Some datasets exhibit issues such as missing data and recording errors, which can hinder the definition of the baseline. Third, model selection is crucial for the tool's accuracy. As mentioned, model selection will be conducted for different types of faults. However, model accuracy also depends on defining their hyperparameters, which is a time-consuming and complex process.

2.6.4.2 Advantages

The tool will support maintenance teams in scheduling maintenance actions. A better maintenance scheduling will increase the availability of the system and improve the production (in the case of generators) and consumption by increasing the quality of service.

Another interesting advantage of the tool is that defining the baseline allows a better comparison of the real performance of the devices when compared with the ones announced by the manufacturers and allows clear identification of the aging effects in the performance of the systems. This can be particularly interesting in the case of PVs and BESS.

2.6.4.3 TRL

- **Current TRL:** 3
- **Target TRL:** The CM tool should have the final TRL of 6 (Prototype demonstration).

2.6.4.4 KPIs

- The **main KPI** will be the accuracy of the model in predicting faults.
- Depending on the data that will be available, **other KPIs**, such as the identification of the type of fault and the time of anticipation of the fault, can be calculated.

To quantify the KPI, several metrics can be computed, such as mean square error (MSE), mean absolute error (MAE), mean absolute percentage error (MAPE), or root mean squared percent error (RMSPE).

2.6.5 Partner-Provided Inputs

The first version of the model will be developed using an open dataset. Afterward, data obtained during the demonstrators can be used to improve the developed method and, mainly, to define the baselines for different assets.

Some meetings will be held with the partners to identify available data that can be used in the development of the CM tool.

3 Specification of DC solutions: Assets, Devices, and Appliances

This chapter provides the specification of the DC solutions (hardware components) to be developed in the Shift2DC project. It is organized around three key questions to clarify the project's approach: *(1)* Why do we need these devices? *(2)* How do we meet the need for such devices? and *(3)* How do we prepare for the development of these devices?

Why do we need DC devices?

- Various devices (e.g., cables, protection) are currently used by designers, utilities, regulators, developers, and academics. Traditionally, most of these solutions have been designed for AC networks and, therefore, mainly address the specific needs and challenges of AC systems.
- Today, the potential benefits and uses of DC systems are becoming more widely recognized and promising. However, there is a lack of standard regulations specifying exhaustively how such systems should be implemented (mainly for commercial tools).
- For this reason, specialized DC solutions are needed to support the adoption, development, and implementation of DC systems.

How do we meet the need for DC devices?

In the Shift2DC project, WP3 aims to meet this need by developing new solutions specifically adapted for DC infrastructures and applications.

How do we prepare for the development of DC devices?

To prepare for the solutions' development phase in WP3, this chapter specifies the requirements and main functions of eighteen solutions (sections 3.1 to 3.18).

3.1 SOL4: Smart and Sustainable DC Cables

Associated task: T3.1
Leader: NEXNS[45]
Participants: RWTH[46], NEXSE[47]

3.1.1 Solution ID: A quick overview

In a DC microgrid, cables are essential to the installation, providing the interface between energy sources and loads. The design of specific cables for DC applications is mandatory to meet the requirements of DC microgrids in terms of efficiency, reliability, safety, and durability. The new LVDC cable is focused on the building application (commercial, offices, data centers, public and private buildings). There is currently no standard for designing cables for building microgrid applications. LVDC cables will conform to the Current/OS specifications and rules.

3.1.2 Solution Description: requirements and characteristics.

- The solution will select the most appropriate formulation: **"Electrothermal aging"** of insulation materials under DC electrical stress will be investigated. A test protocol will be implemented, and various types of insulation will be studied (Cross-linked Polyethylene (XLPE), Low Fire Hazardous (LFH), PolyVinyl Chloride (PVC), and Polypropylene (PP)).
- The new cable design will be **in line with the Current/OS architecture specification** and the "System Reference Document." It allows the possibility of incorporating an **intertripping wire** into the same cable as the power cable.
- A test method to validate overvoltage behaviors will be defined.
- **The product's Environmental impact** should be at least equivalent (or better) to that of the AC cable design.

3.1.2.1 Requirements

- **Req1:** Ensure high aging performances under DC constraints.
- **Req2:** Improve sustainable solutions by optimizing the design and seeking sustainable formulation (e.g.: removal of different plasticizers or peroxides that should become banned soon, fully separable layers to prevent recyclability).
- **Req3:** At least the same durability as under AC conditions for equivalent application.

3.1.2.2 Main characteristics

Visually, DC cables will be comparable to traditional cables. In addition, color coding and marking will be different to avoid confusion with AC solutions. Their ability to be handled and installed will also be comparable. The new cable design is under study.

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[45] NEXANS France
[46] RWTH Aachen University
[47] NEXANS Sweden

3.1.3 Expected Performance

3.1.3.1 Advantages

- **Specific Design:** the new design will be adapted to the constraints of DC architecture. A specific design will be developed for the application with a particular reliance DC bus cable design.
- **Aging performance:** a cable system optimized for DC applications using an insulating material with long-term aging properties.
- **Efficiency:** more power transmitted than in AC cables with the same cross-section (need to be quantified).
- **Safety:** the cable includes inter-tripping wire features (optionally) that enable safely de-energizing the microgrid section for maintenance purposes, according to the Current/OS technical specifications (zone 3).
- **Sustainability:** The new cable design will use materials with lower environmental impact and will be more easily recyclable.
- **Ergonomics:** the cable design will be easy to install.

3.1.3.2 TRL

- **Current TRL:** 4
- **Target TRL:** 7

3.1.3.3 KPIs

- **KPI1:** Number of prototypes to be validated according to architecture and demonstrator specifications (protection zones, inter-tripping wire, CPR “Construct Products Regulation,” etc.).
- **KPI2:** Quantity of raw materials saved (Cu/Al, plastics, etc.)
- **KPI3:** Better recyclability than standard LVAC cables (%) – based on the quantity of recycled content.
- **KPI4:** Rate of transmitted power compared to LVAC cable.

3.1.3.4 Application within the project

The solution will be used in the DC building Demonstrator. The possibility of implementing the cable solution in another demonstrator (RWTH University live demonstrator, the Data Center, and the Port demonstrator) needs to be verified.

3.2 SOL5: Micro Solar DC Systems

Associated task: T3.2a
Leader: TALT[48]

3.2.1 Problem

Solar PV technology offers a highly effective solution for on-site energy generation within buildings. Building-integrated photovoltaics (BIPV)— encompassing solar roofs, solar façades, and solar windows—emerges as a promising innovation in this domain. The increasing electrification of buildings necessitates novel approaches to energy distribution. DC distribution is advantageous for enhancing energy efficiency, as it is more compatible with the DC output of PV modules and BESS.

The reference [7] provides a comprehensive overview of commercial PV and BIPV modules. Figure 3.1 illustrates the current-voltage (I-V) curves under standard test conditions (STC), which typically involve a cell temperature of 25 °C and solar irradiation of 1000 W/m². In practical applications, both the open-circuit voltage and the voltage at the maximum power point (MPP) tend to be lower than those indicated under STC due to elevated operating temperatures of the PV cells. Notably, most PV modules are equipped with bypass diodes (BDs) designed to operate in parallel with the internal substrings of PV cells. These diodes can facilitate current flow when one or more cells within a substring are subjected to shading, leading to a global MPP that manifests at a diminished voltage. The quantity of BDs can vary among manufacturers. Predominantly used silicon-based PV modules typically incorporate three or four BDs, resulting in either three or four potential regions where the global MPP may occur. The approximate locations of these MPP regions are indicated by dashed lines in Figure 3.1.

The operating voltage for the most commonly used Si-based PV modules (60- or 72-cell) is generally below 50 V, which results in MPP currents exceeding 10 A. ***Partial shading can result in several MPPs featured by a PV module.*** For example, Figure 3.2 shows a typical 60-cell Si-based PV module with three BDs. This example includes slight shading of the cell no. 50, considerable shade on the cell no. 51, and opaque shading of the cell no. 30 by a fallen leaf. As a result, ***I-V characteristics feature three distinct MPPs***. Depending on the shading conditions, one of the peaks will be higher than the others. ***If a converter implements global maximum power point tracking (GMPPT), it can find this maximum and harvest the maximum possible energy from a shaded PV module*** [8]. Recent PV-related standards show that electric and MPPT efficiency are essential, and their product defines the overall efficiency of a PV system [9], [10]. Hence, ***GMPPT is essential to provide high overall PV energy conversion efficiency***.

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[48] Tallinn University of Technology

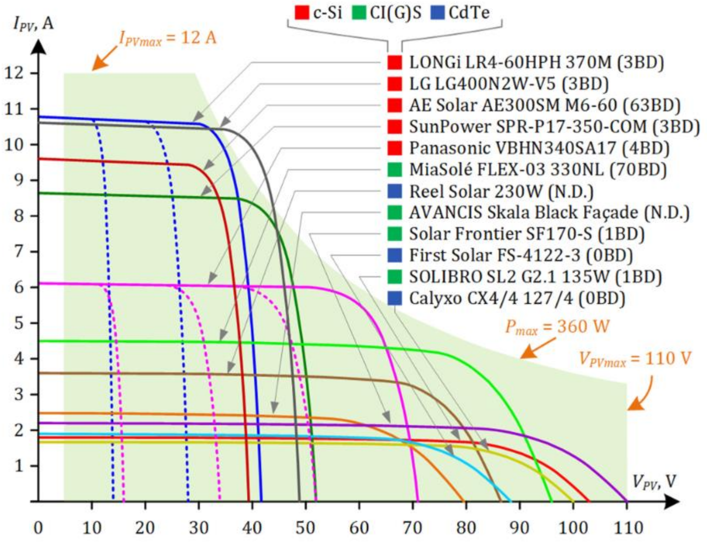

Figure 3.1 I-V characteristics of selected residential PV and BIPV modules under standard test conditions [7]

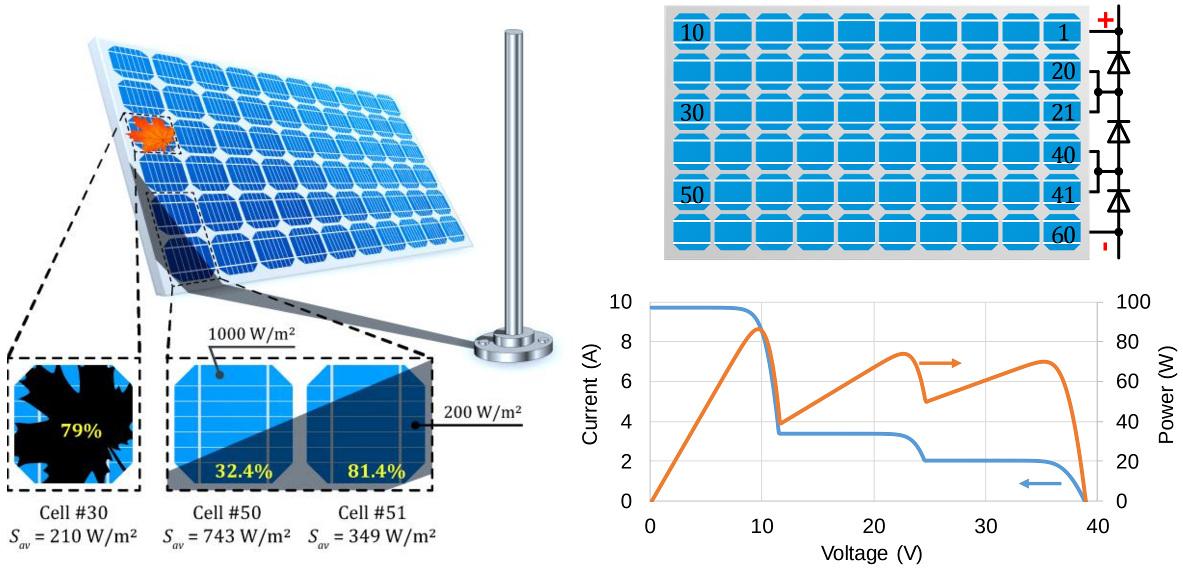

Figure 3.2 Partial shading conditions and resulting I-V characteristic of a 60-cell Si PV module [8]

3.2.2 Solution Description

This section describes FlexiVerter technology, the backbone solution proposed for implementing micro solar DC systems.

Considering all the information about typical Si-based PV modules (60- and 72-cell) and low-voltage Lithium Iron Phosphate (LFP) batteries, the input voltage range of 8 V to 60 V could be justified using Figure 3.3. Under opaque or partial shading, the global MPP could appear at lower voltages due to the utilization of three bypass diodes in the junction box. Therefore, each type of PV module features three possible operating input voltage ranges. Inside each range, a box filled with color shows the most probable operating range within the possible operating range. Similarly, the LFP batteries can feature charging and discharging voltage ranges due to the presence of the equivalent series resistance. This results in relatively wide boxes for each battery to account for the most probably charging and discharging voltages. The charging and discharging voltage ranges are adjacent and, thus, are shown as a single box in each case.

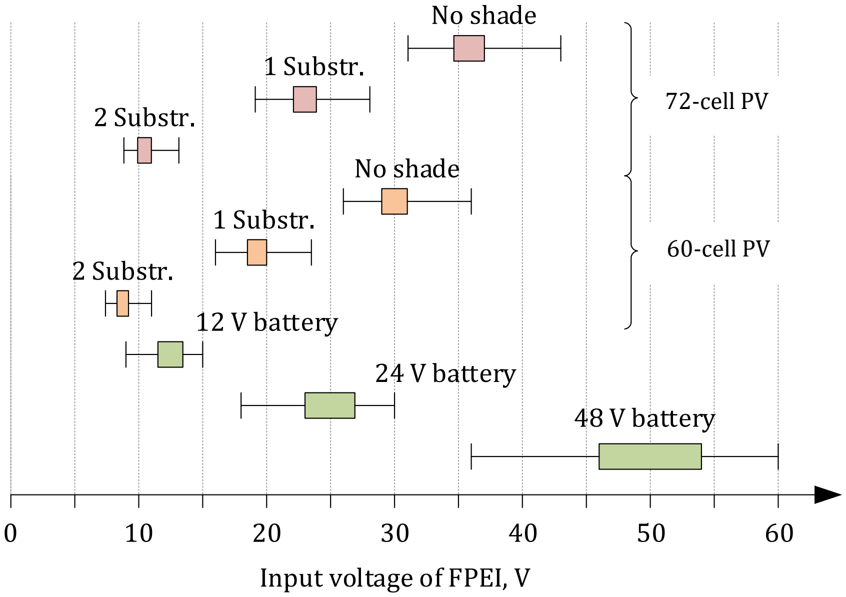

Figure 3.3 Input voltage range of FlexiVerter and operating ranges of target applications [11]

Apart from the input voltage ranges, the FlexiVerter must be capable of handling the DC microgrid voltage from the two bands defined by Current/OS: 350 V ± 30 V and 700 V ± 60 V, which include droop control implementation. Since the DC microgrid voltages are variable, the FPEI must handle a very wide range of the DC voltage gain values to satisfy optimal performance in the target operating ranges depicted in Figure 3.3. Basically, it means that FlexiVerter must handle DC voltage gain values between 320 / 60 = 5.3 and 760 / 8 = 95. This means that the DC voltage gain range is roughly 1:18, which is an unseen requirement for the galvanically isolated DC-DC converter. This solution aims to break through these requirements through intelligent design and control.

The topology utilized within the FlexiVerter technology is shown in Figure 3.4. Its operating principle is based on the use of hybrid full-bridge switching cells that can be reconfigured into equivalent half-bridge cells [12]. Topology morphing control is used to adjust converter operation by switching between topology configurations, such as full-bridge/full-bridge and full-bridge/half-bridge. As a result, each topology configuration is used to step up or down the voltage not more than two times relative to the normalized voltage gain for this configuration. Preliminary tests of this technology given in [11] have proven the effectiveness of the FlexiVerter technology for individual integration of low-voltage PV modules and LFP batteries in residential and small commercial DC microgrids. It requires further development to resolve practical issues related to its use in different environments. The general specifications of the design are as follows:

- Input voltage range: 10…60 V
- Input current range: ±12 A
- Output voltage ranges: 320…380 V and 640…760 V
- Switching frequency: 100 kHz
- Rated power: 350 W

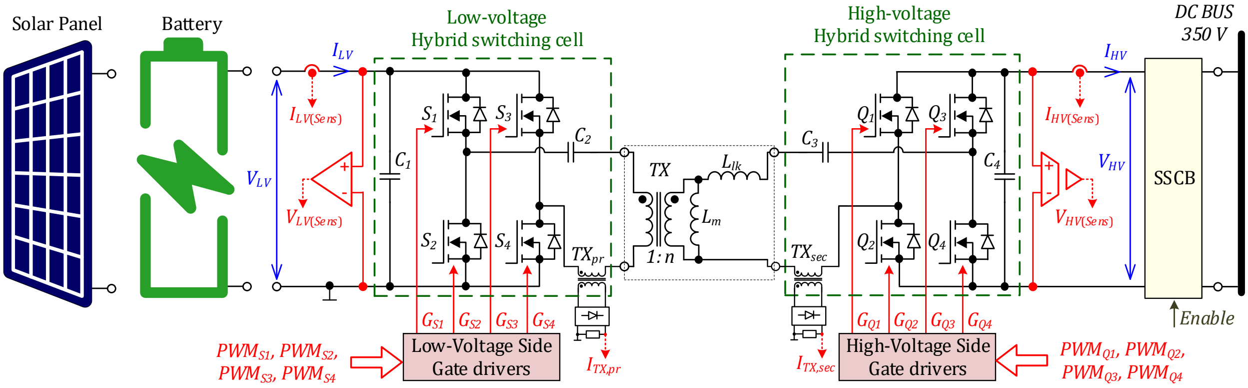

Figure 3.4 Topology of the FlexiVerter [11].

3.2.3 Expected Performance

This solution demonstrates the universal integration of low-voltage energy sources in DC microgrids of different standardized operating voltages.

3.2.3.1 Advantages

- FlexiVerter features input source type identification and can adapt its control algorithms to the type of the input power source, i.e., maximum power point for PV and droop control for a battery.
- FlexiVerter employs topology morphing control, making it compatible with 350V and 700V DC grids (following the set of rules developed by the Current/OS Foundation).
- It can implement global maximum power point tracking to efficiently harvest energy under partial shading, which is a typical issue in residential and small commercial PV installations, especially those integrated or attached to a building.
- Using the same stock-keeping unit enables simpler supply chain management and fast design and deployment of residential DC grids, reducing the soft costs of such a system design.

3.2.3.2 TRL

In this project, we plan to increase TRL from 5 to 7 by making the given solution applicable in real outdoor environments. Therefore:

- **Current TRL:** 5
- **Target TRL**: 7

3.2.3.3 KPIs

- Peak efficiency of over 98%, including on-board auxiliary power consumption to minimize cooling requirements.
- Smooth start and stop operation with a PV module in the morning and evening, respectively, when available PV power is very low and can cause unstable system operation.
- IP67 ingress protection rating or better, making it feasible for any environment.

3.2.3.4 Application within the project

Micro solar DC system will be deployed in the DC Building Demo in France to demonstrate the unification and smooth integration of low-voltage energy sources in residential DC microgrids.

3.3 SOL6: High Density Bidirectional V2X DC Stations

Associated task: T3.2e
Leader: W&W[49]

3.3.1 Problem

Despite the huge potential of smart grid technologies that can transform the electricity supply chain, they still face some major challenges. One major issue is the limited ability to monitor the grid in real time, which can lead to difficulties in quickly detecting and responding to inefficiencies. Additionally, the supply chain must be controlled to ensure the balance between the electricity supply and demand to respond to fluctuating consumption patterns. The optimization of energy distribution remains a crucial task, and EV batteries can play an important role in solving these problems by acting as energy storage units that can help balance supply and demand. For that, the used EV chargers must be bidirectional and controllable.

3.3.2 Solution Description

To solve the abovementioned problems, W&W proposes a DC V2X charger described in the figure below (Figure 3.5) that includes bidirectional DC/DC converters. The output power of each converter is rated up to 11 kW with a peak efficiency that reaches 97%. Communication with the charger is based on CAN communication following the CAN open protocol. This charger has a high level of controllability that can help in energy management. In fact, the proposed charger allows configuring the electrical characteristics parameters and controlling the V2X output current and voltage. It also allows Serial and Parallel operations of the power units. This solution can significantly increase the efficiency of the supply chain and the power density by using cutting-edge technologies.

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[49] Watt & Well

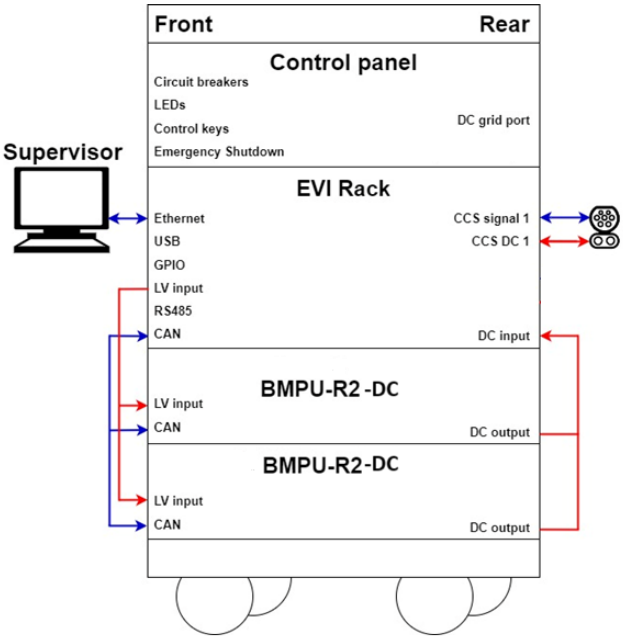

Figure 3.5 Description of the proposed solution.

3.3.3 Expected Performance

3.3.3.1 Advantages

The proposed bidirectional DC station has many advantages:

- It enables the bidirectional energy exchange between the DC grid and the EV batteries, which allows for the control of the flow of energy.
- The EV batteries can store the excess energy generated during low-demand periods. The stored energy can be injected back into the grid during demand peak times, which enhances the grid stability and reduces the need for additional power generation.
- It ensures a high level of monitoring and controllability, making the DC smart grid more reliable, efficient, and sustainable.

3.3.3.2 TRL

- **Current TRL:** TRL5.
- **Target TRL:** TRL7.

3.3.3.3 KPIs

The SOL6 KPIs are as follows:

- **KPI1:** Charge and discharge 400V and 800V CCS EV models.
- **KPI2:** Control the energy flow between the DC grid and the EV batteries.
- **KPI3:** Contribute to the resilience of the DC grid thanks to its high efficiency. The peak efficiency reaches 97%, and efficiency is consistently above 94% for a wide range of voltage and current.

3.3.3.4 Application within the project

The proposed charging station can be used in the building demonstration. It can manage the power flow between power sources and loads even at different voltage levels.

3.4 SOL7: LVAC-LVDC Interlink Converter

Associated task: T3.3a
Leader: SCHND[50], DCS[51]

3.4.1 Problem

The absence of an Interlink AC-DC Converter in a DC microgrid poses a significant challenge to the stable operation and effective power allocation of the power system. Without this vital device, the seamless integration of renewable energy sources, energy storage systems, and other distributed energy resources becomes difficult, potentially leading to inefficiencies and instability within the DC microgrid. Additionally, the absence of droop control functionalities limits the DC microgrid's ability to respond to dynamic changes in power demand and generation, potentially compromising its resilience and overall performance. Therefore, the presence of an Interlink AC-DC Converter is crucial to address these challenges and ensure the efficient and reliable operation of the DC microgrid.

3.4.2 Solution Description

The solution involves the development of a bidirectional Interlink AC-DC Converters. Both of these solutions are depicted in Figure 3.6 (refer to the green box). This solution aims to address operational challenges and enhance system performance. This proposed converter ensures bidirectionality and safety through isolation. Moreover, it will incorporate droop control to simplify system regulation. By integrating the Interlink AC-DC converter, the DC microgrid gains the ability to efficiently manage the integration of diverse energy resources, including renewables and energy storage systems. This facilitates smoother power flow and effective utilization of available energy inputs within the DC microgrid.

In summary, the integration of the Interlink AC-DC Converter in the DC microgrid provides a comprehensive solution to the challenges associated with power integration, stability, and operational flexibility, ultimately leading to improved system performance and reliability.

As part of this task, two different solutions will be developed, referred to as SOL7.1.A and SOL7.1.B.

- **SOL 7.1.A** entails a single ready-to-use device with an expected power capacity of 100 kW and a nominal voltage level of 700 VDC. Galvanic isolation will be achieved using a low-frequency AC transformer.
- **SOL 7.1.B** involves a modular device with an expected power capacity of 20-30 kW and a nominal voltage level of 700 VDC. Galvanic isolation will be achieved using a high-frequency DC/DC converter.

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[50] Schneider Electric
[51] DC Systems

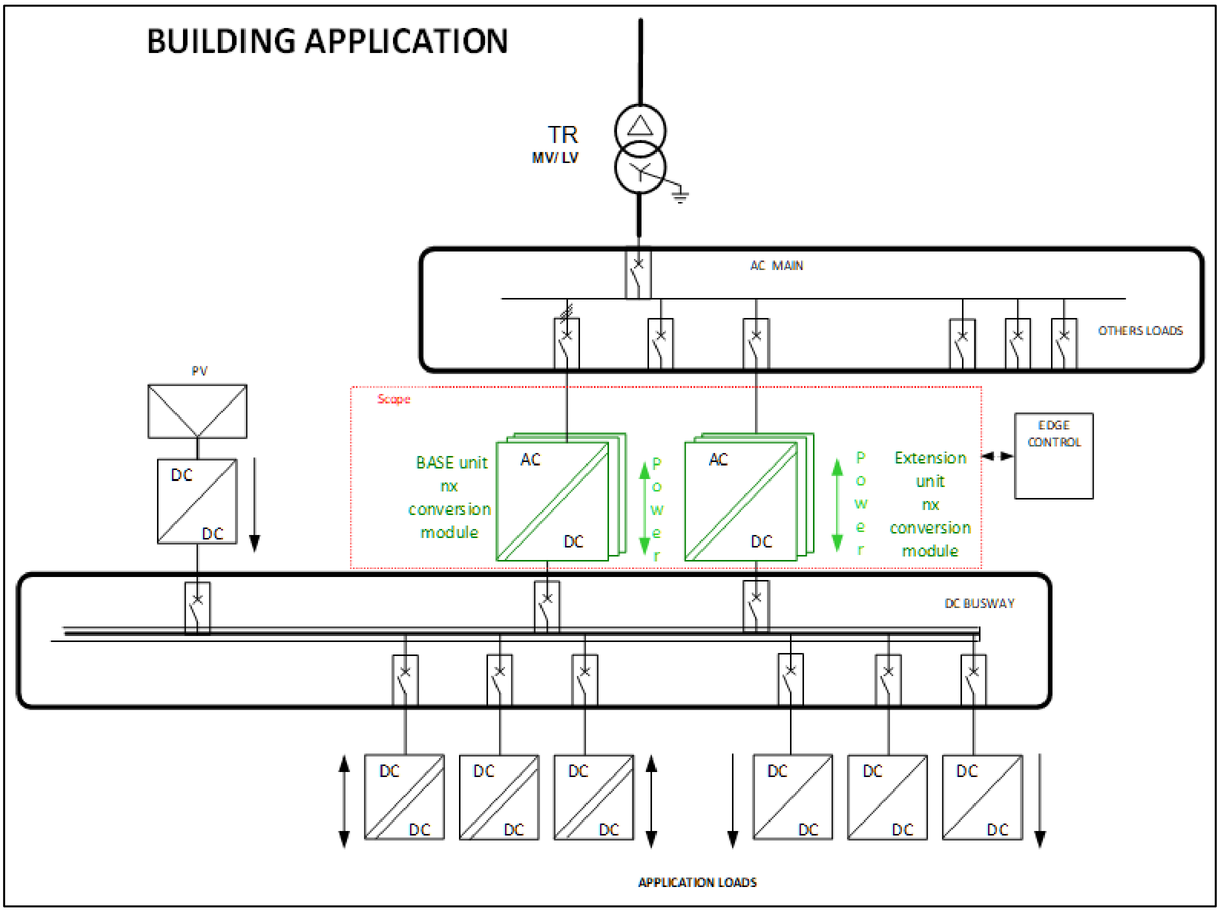

Figure 3.6 High-level architecture depicting the integration of AC-DC converter inside the building.

3.4.3 Expected Performance

3.4.3.1 Advantages

The proposed interlink AC-DC converter for DC microgrids has many advantages:

- **Resilience:** Interlink Converter (ILC) is a firewall that avoids propagation of AC grid faults to the final customer
- **Grid support:** reduce the infrastructure sizing for peak demand thanks to bidirectional energy transfer capability.
- **Droop control** built into**:** build-in interlink converter allows the system self-stability to avoid complex real-time system regulation.

3.4.3.2 TRL

SOL7.1. A:

- **Current TRL:** 7,
- **Target TRL:** 8.

SOL7.1. B:

- **Current TRL:** 2,
- **Target TRL:** 5.

3.4.3.3 KPIs

The SOL7 KPIs are as follows:

- **KP1**: Easy to use (installation, operating, and maintenance).
- **KP2**: Seamless transition of power flow between AC and DC connection.
- **KP3**: DC bus voltage stability. DC bus voltage stays within the voltage range defined by Current/OS (640-760V nominal, 500-640V emergency, 760-800V overshoot).
- **KP4**: DC voltage droop control capabilities.

3.4.3.4 Application within the project

SOL7 will be implemented and prequalified in the DC building demonstration.

3.5 SOL8: Static Protection System

Associated task: T3.4a
Leader: SCHND[52]

3.5.1 Problem

In DC Microgrids, which are primarily capacitive in nature, fault currents escalate exponentially. This exponential rise in DC fault current emphasizes the critical need for ultra-fast protection mechanisms to swiftly detect and mitigate faults within the microgrid. Additionally, with the presence of numerous sources and loads interconnected within the microgrid, ensuring the resilience of the system is critical. Hence, the implementation of protection schemes that offer selectivity is required. Still, the requirement for **ultra-fast protection** and **selectivity** in the face of escalating fault currents and sources and load diversity poses a notable obstacle to the effective use of electromechanical DC breakers within DC microgrids. This is the reason why we propose the use of ultrafast and naturally selective DC static breakers.

3.5.2 Solution Description

The challenge of DC fault currents escalating exponentially in primarily capacitive DC microgrids necessitates a solution focused on ultra-fast protection mechanisms and enhanced selectivity to ensure the resilience of the system.

To address this challenge, a potential solution could involve the development and integration of an advanced fault detection method and ultra-fast protection device that can rapidly identify and isolate DC faults within the microgrid. The proposed solutions of solid-state circuit breakers could be either 16 A, with a voltage range of 640-760 VDC unidirectional and compatibility with Current/OS zone 3 to zone 4, or 32 A, with a voltage range of 640-760 VDC unidirectional and compatibility with Current/OS zone 3 to zone 4.

Additionally, implementing intelligent protection schemes that offer selectivity (either natural or thanks to a specific algorithm depending on fault type) enhances the overall reliability of the microgrid.

3.5.3 Expected Performance

3.5.3.1 Advantages

The proposed solid-state circuit breaker for DC microgrids offers numerous advantages that align with its specifications:

Key advantage	Mean	Validation criteria
Ultrafast	Use of SiC semiconductor	1 to 100 microseconds
Smooth	Use of an inductor as a time buyer	Switching overvoltage < 100 V
Naturally selective	Use of a high-frequency filter	Does not require particular settings
Efficiency	By design	> 99.4 %

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[52] Schneider Electric

3.5.3.2 TRL

- **Current TRL:** 5,
- **Target TRL:** 6-7.

3.5.3.3 KPIs

The SOL8 KPIs are as follows:
- **KP1:** Breaking time for a short circuit at the output poles of the breaker.
- **KP2:** Selectivity in a DC microgrid with prosumers.

3.5.3.4 Application within the project

SOL8 will be implemented and prequalified in the DC building demonstration.

3.6 SOL9: Vertical Power Delivery (VPD) solution

Associated task: T3.2b
Leader: HIRO[53]

3.6.1 Problem

The primary problem with traditional AC power delivery in data centers lies in their inefficiency, primarily due to multiple energy conversions between AC and DC. Most IT equipment, including servers, operates on DC power, but power from the grid is delivered in AC (see Figure 3.7). This requires several conversion stages: AC from the grid is converted to DC to charge batteries in uninterruptible power supplies (UPS), then converted back to AC for distribution, and finally converted once more to DC within servers. Each of these conversions introduces energy losses, typically 5-10% per step, compounding inefficiencies throughout the system. Additionally, the cooling infrastructure needed to support AC systems, along with harmonics caused by AC power, increases energy consumption and operational complexity. This results in higher energy costs, increased maintenance, and challenges in integrating renewable energy sources, which naturally generate DC power, adding to the overall inefficiency.

Problems Related to AC Power Delivery in Data Centers:

1. **Conversion Losses:**
    - In a traditional data center, AC is delivered from the grid, which must then be converted multiple times before reaching the servers and IT equipment. AC to DC conversions occur at several stages:
        - First, AC from the grid is converted to DC to charge uninterruptible power supplies (UPS).
        - Then, it is converted back to AC for distribution within the data center.
        - Finally, it is converted back to DC at the server level, as most IT equipment operates on DC.
    - These repeated conversions incur significant energy losses (5-10% or more at each step), decreasing overall efficiency and increasing operational costs.
2. **Inefficiency in Cooling and Power Equipment:**
    - Traditional AC-based data centers require extensive cooling and power infrastructure, including transformers, cooling fans, and additional wiring, which increase both energy consumption and complexity in managing the systems.
    - AC systems also generate harmonics, which cause inefficiencies, requiring filters to minimize the effects.
3. **Complex Infrastructure and Maintenance Costs:**
    - Due to the repeated AC/DC conversions, power distribution and backup systems are more complex and costly to maintain.
    - Cooling systems for transformers and conversion equipment also increase the data center’s energy footprint, reducing efficiency and increasing maintenance needs.
4. **Integration Challenges with Renewable Energy and Battery Backup:**
    - Most renewable energy sources (like solar panels) and battery storage systems generate DC power. When integrated into an AC system, DC must be converted to AC for use within the data center, which adds another layer of energy loss.

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[53] HIRO-MicroDataCenters

- Managing the interplay between AC-based infrastructure and renewable energy systems requires more sophisticated equipment and software to handle these conversions and optimize energy use.

3.6.2 Solution Description

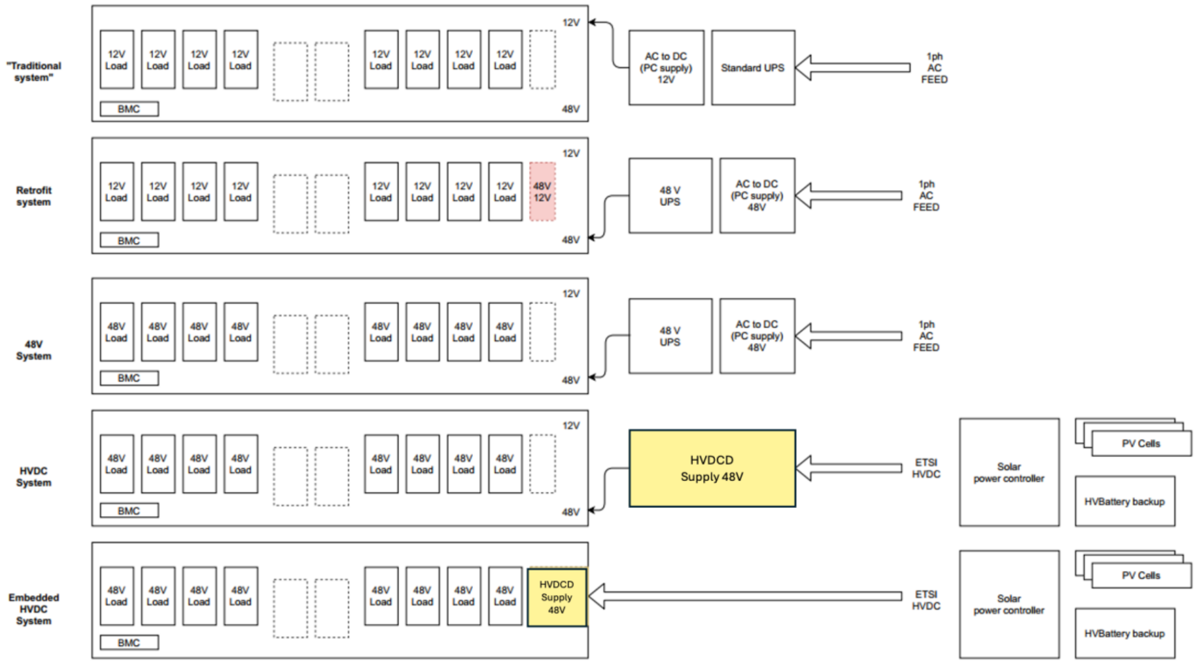

Figure 3.7 From conventional horizontal power delivery to vertical power delivery.

VPD allows for more efficient distribution of power to high-current loads by delivering power directly to where it's needed, avoiding bottlenecks caused by long horizontal traces or complex (Power Delivery Network) PDNs.
During this task, we will evaluate the power delivery options for various delivery scenarios.
edge micro data center (EMDC) hardware demonstrator will be used to demonstrate various use cases, starting with traditional power delivery, and continuing with High Voltage DC Distribution (HVDCD) power delivery. Particularly through bus converter modules (BCMs), operating in a voltage range of 260V to 410V DC for input, converting down to output voltages compatible with 48V distribution (safety extra low voltage (SELV)) as required in data centers.

3.6.3 Expected Performance

3.6.3.1 Advantages

VPD has the following advantages:

- **Power Delivery Network (PDN) efficiency:** By shortening the power delivery path through vertical delivery, VPD reduces resistive losses and ensures that more of the supplied power reaches the target component. This boosts overall power efficiency, especially in systems where high-current delivery is critical, such as AI workloads and high-performance computing.

- **Improved thermal performance:** VPD's shorter power paths reduce the energy lost as heat, helping to alleviate thermal challenges. In addition, the compact nature of VPD helps with better heat dissipation as it reduces hot spots caused by inefficient power delivery. Improved thermal performance helps maintain component stability and performance in high-density systems.
- **Minimization of Board Space (Footprint Constraints):** VPD frees up valuable PCB space by delivering power vertically. The power modules are located beneath the board, reducing the need for large horizontal traces and power components on the top side. This enables designers to pack more functionality into the available space without sacrificing power delivery efficiency.
- **Scalability and Future Power Requirements:** VPD is inherently scalable to meet the growing power needs of future computing systems. It supports the high currents required by modern processors and is designed to handle future increases in power demand without sacrificing efficiency. By delivering power directly from the bottom of the board to the processor, VPD can accommodate higher power densities and scale as system requirements grow.
- **Power Conversion Losses:** VPD integrates Factorized Power Architecture (FPA), which separates power regulation and transformation stages, allowing for more efficient power conversion. This reduces the number of conversion steps, minimizing energy losses and improving overall efficiency. Vicor’s power modules deliver power in a more streamlined and optimized manner.
- **High Current Load Balancing:** VPD allows for more efficient distribution of power to high-current loads by delivering power directly to where it is needed, avoiding bottlenecks caused by long horizontal traces or complex PDNs. This direct approach helps in better load balancing across multiple components.
- **Interference and Noise in Power Delivery:** VPD reduces the length of the power delivery path, which minimizes the introduction of electrical noise and interference. This leads to cleaner power delivery and improved signal integrity, especially in systems where noise-sensitive components like AI accelerators or high-performance processors are in use.

3.6.3.2 TRL

While the VPD components from suppliers are reaching TRL levels 6-7, their implementation into the PCBs and design of the cooling has just started for some high-end OEMs. Hence, it has not yet reached the maturity level. Therefore, dummy PCBs will be implemented with a transient stage of VDP implementation and the supportive cooling infrastructure to test and simulate the design and calculate gains from VDP and cooling for the EMDC.

For end-to-end power delivery, we expect a target TRL of 6.

3.6.3.3 KPIs

The SOL9 KPIs are as follows:

- **KPI1:** Energy efficiency improvement between 5-10 % compared to traditional power delivery solutions.
- **KPI2:** Solution volume, expect to decrease by a minimum of 50%.

3.6.3.4 Application within the project

The solutions will be installed in the data center demonstrator.

3.7 SOL10: Semiconductor-Based Protection

Associated task: T3.4c
Leader: EATDE[54]

3.7.1 Problem

The protection of DC grids presents a significant challenge due to the absence of natural zero-crossing in the DC systems. This characteristic complicates the interruption of fault currents, making traditional AC protection methods ineffective. In the event of a fault, it is crucial to have a quick response protection system to limit the fault-induced energy from spreading to the rest of the system. This rapid response is essential to prevent extensive damage and ensure the stability of the grid. Consequently, the performance and reliability of the protection system are of paramount importance in DC grids, as they directly impact the overall safety and efficiency of the power network. Ensuring robust and dependable protection mechanisms is vital for the successful operation and integration of DC grids into modern power systems.

3.7.2 Solution Description

To address the challenges in protecting DC grids, the development of a solid-state circuit breaker (SSCB) is proposed. This advanced circuit breaker described in the figure below (Figure 3.8) will enable rapid and reliable interruption of fault currents, overcoming the limitations posed by the absence of natural zero-crossing in DC currents. The SSCB will be capable of detecting and isolating faults within the DC grid following Current/OS and ODCA specifications, ensuring compliance with industry standards. Furthermore, it will be designed to communicate and exchange necessary information with the central controller of the DC grid, facilitating coordinated protection and control. The protection architecture will be further enhanced by incorporating an adaptive protection scheme, which dynamically adjusts to varying grid conditions to ensure optimal performance.

Additionally, developing adequate selectivity methods will be crucial in accurately identifying and isolating faulted sections of the grid, thereby minimizing the impact on the overall system. Together, these innovations will significantly improve the robustness and reliability of DC grid protection, ensuring a safer and more efficient power network. The specifications of the under-development solution are shown below:

- Voltage: 800V
- Target current rating: 100A
- Maximum Current: 105A
- Ambient temperature: max 40°C

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[54] EATON Industries GMBH

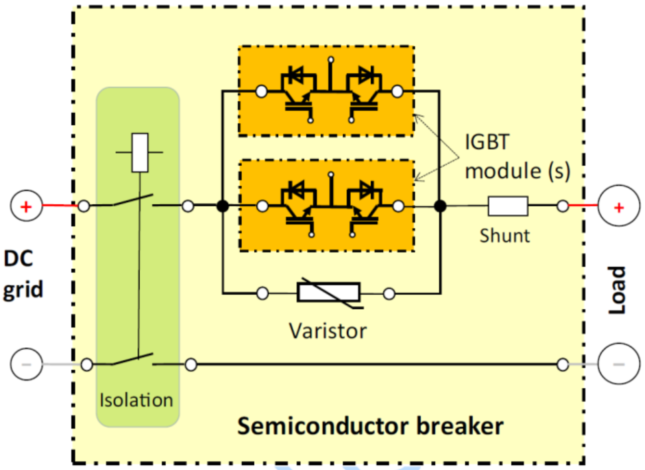

Figure 3.8 SOL10 description.

3.7.3 Expected Performance

The implementation of SSCBs in DC grids is expected to yield significant improvements in grid protection and reliability. Key advantages include fast fault interruption time, low peak fault current, and robust, resilient operation. Additionally, the integration of smart grid technologies will provide advanced monitoring and control capabilities, along with secured communication. The TRL for SSCBs is anticipated to be high, reflecting their advanced development stage. Key performance indicators will focus on fault detection and isolation speed, fault current reduction, and SSCB performance. These expected results will contribute to a safer, more efficient, and intelligent DC network.

3.7.3.1 Advantages

The proposed solution of Semiconductor-based Circuit Breaker offers numerous benefits for modern DC grids. Here are some key advantages:

- Fast fault interruption time.
- Low peak fault current.
- Robust and resilient operation.
- Integration of smart grid technologies to provide advanced monitoring and control capabilities together with secured communication.

3.7.3.2 TRL

- **Current TRL:** 6
- **Target TRL:** 7

3.7.3.3 KPIs

The KPIs of SOL10 are listed below:

- **KPI1: Fault detection time:** The time taken by SSCB to detect a fault from the moment it occurs, with a target value of less than 10 microseconds.
- **KPI2: Fault isolation time:** The time taken by the SSCBs to isolate the fault once the fault is detected, with a target value of less than 100 microseconds.
- **KPI3: Current interruption capability:** The maximum fault current that SSCBs can interrupt without failing. The instantaneous tripping current would be settable up to 500A.

- **KPI4: Thermal performance:** The ability of SSCBs to operate within safe thermal limits during normal and fault conditions. The maximum ambient temperature is 40°C.

3.7.3.4 Application within the project

SOL10 will be implemented and tested in the DC industry demonstrator.

3.8 SOL11: Pre-Charging Units for DC Circuit Breakers

Associated task: T3.4d
Leader: EATDE[55]

3.8.1 Problem

Connecting loads with input capacitors to a DC grid often produces high capacitive inrush currents. These inrush currents can be significantly higher than the normal operating currents, leading to potential issues in the electrical system. One of the primary concerns is the nuisance tripping of the upstream protection devices, such as circuit breakers or fuses. This tripping occurs because the protection devices are designed to respond to overcurrent conditions, and the sudden surge of inrush current can be misinterpreted as a fault condition. Consequently, this can cause unnecessary interruptions in the power supply, affecting the reliability and stability of the entire electrical system. Addressing this issue is crucial to ensure the proper functioning and protection of the DC grid and connected loads.

3.8.2 Solution Description

To address the issue of high capacitive inrush currents in DC grids, pre-charging units can be employed for bi-directional pre-charging of DC loads with input DC-link capacitors. The basic principle of this pre-charging technology involves an efficient method to enable the pre-charge and discharge of the DC grid capacitances, thereby mitigating the initial surge of current. By incorporating the pre-charge operation into the main Solid State Circuit Breaker (SSCB) hardware and properly controlling the SSCB main switches during ON-OFF operations, this novel and efficient concept supplements the primary function of the SSCB. This integration not only enhances the reliability and stability of the DC grid but also prevents nuisance tripping of upstream protection devices, ensuring a more robust and resilient electrical system. The nominal voltage would be 800V, in accordance with the SSCB specifications.

3.8.3 Expected Performance

The proposed pre-charging unit for modern DC grids offers key benefits such as reducing inrush currents, preventing nuisance tripping of upstream protection devices, and enabling safe bi-directional pre-charge/discharge of DC grid capacitances. It also supports the connection of various loads in dynamic industrial processes. Currently, the device has TRL 4, while the target is to reach TRL 6. Key performance indicators include Pre-Charge Time, Inrush Current Limitation, and Reliability.

3.8.3.1 Advantages

The proposed solution of a pre-charging unit offers several benefits for modern DC grids. Below are some of the key advantages:

- Reduction of inrush currents.
- Avoid nuisance tripping of the upstream protection device.
- Safe bi-directional pre-charge/discharge of DC grid capacitances.

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[55] EATON Industries GMBH

- Facilitate the connection of different types of loads and machines in dynamic industrial processes.

3.8.3.2 TRL

- **Current TRL:** 4
- **Target TRL:** 6

3.8.3.3 KPIs

The KPIs of SOL11 are listed below:

- **Pre-Charge Time:** the time it takes for the DC bus to be appropriately pre-charged before normal operation can be initiated, target value < 3s.
- **Inrush Current Limitation:** the effectiveness of the pre-charging unit in limiting inrush current is crucial.
- **Reliability:** the reliability of the pre-charging unit in consistently performing its function without causing nuisance tripping of the upstream protection device.

3.8.3.4 Application within the project

SOL11 will be implemented and tested in the DC industry demonstrator.

3.9 SOL12: DC Measurement Device

Associated task: T3.4e
Leader: PHNIX[56]

3.9.1 Problem

Measurement solutions for DC were not in focus since AC grids were and are still dominant. Therefore, the market does not provide a wide portfolio of solutions for DC grids. Often, retrofit measurement solutions need to be installed, which becomes a challenge if it comes to accurate, reliable, sustainable, and reproducible measurement quality. Since DC requires other technological solutions for measuring a current than AC grids, there's room for solutions and improvements for highly reliable products to be used in industrial DC grids.

In this development, Phoenix Contact targets a solution with the named attributes, especially easy retrofit installation, and reproducible measurements at reasonable accuracy without the need for calibration at the client site.

Furthermore, the device shall guarantee a wide range measurement of voltage and currents, typical for industrial applications connected to a DC grid of a production facility.

3.9.2 Solution Description

For easy installation of the retrofit measurement solution, the development goal is a compact device as shown in the figure below (Figure 3.9) that can be installed easily, even in challenging space-limited conditions. Furthermore, the device shall offer a high flexibility of mounting on either the DIN rail bus bar or mounting it in different settings using screws. To achieve the best possible accuracy without client site calibration needs, a combination of several Hall sensors is likely to be used.

The compact measuring device will be powered by a 24 V DC supply, typical for automation equipment in industrial sites. While the current measuring is integrated into the housing, the voltage will be provided by a voltage sensor cable to ensure a safe and enduring proper voltage probe fixing. The measurement data and calculated values will be provided via a Modbus RTU/TCP interface, which is commonly used in industrial automation. The developments of the measurement device comply with IEC IEC 60688:2012.

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[56] Phoenix Contact

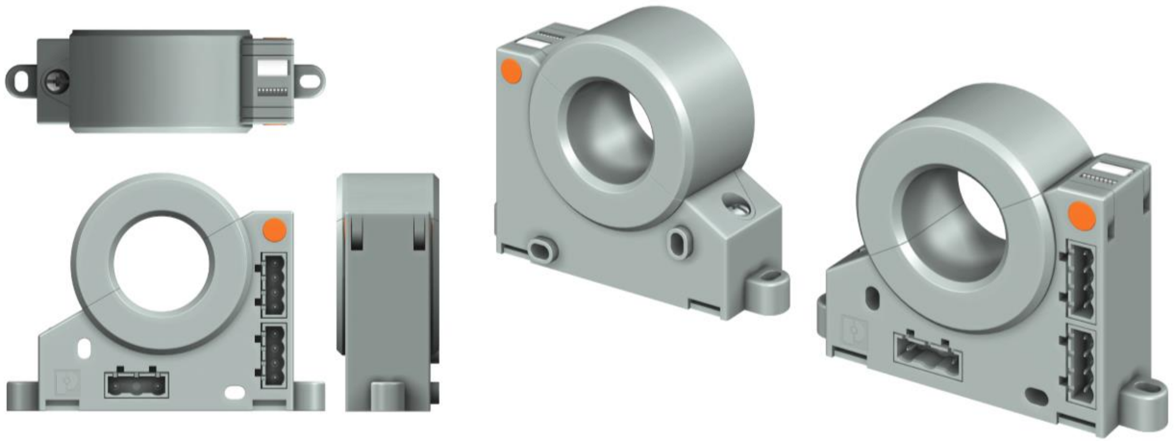

Figure 3.9 Compact DC Measurement Solution - Initial Draft.

3.9.3 Expected Performance

- Easy retrofit installation without the need for client site calibration.
- High installing flexibility due to compact design and multiple mounting opportunities.
- Targeted current limit at 1000 A DC.
- Targeted voltage limit at 1500 V DC.
- Calculated power values of up to 1.5 MW.

3.9.3.1 Advantages

- Compact design and easy retrofit installation without the need for client site calibration
- High installation flexibility due to compact design and multiple mounting opportunities
- Retrofit solution for existing DC distributions without the need to switch off the supply.
- Bidirectional current measurement
- Digital interface

3.9.3.2 TRL

- **Current TRL:** 4
- **Target TRL:** 6

3.9.3.3 KPIs

- **KPI1:** Easy, failure-safe retrofit installation with highly flexible, multiple mounting opportunities.
- **KPI2:** Targeted current limit 1000 A DC
- **KPI3:** Targeted voltage limit 1500 V DC
- **KPI4:** Targeted accuracy level is defined to reach 1% of the measuring range end value

3.9.3.4 Application within the project

The DC measurement solution is foreseen to be installed and used within the Industrial DC grid demonstrator site at Phoenix Contact in Blomberg, Germany.

3.10 SOL13: Fast-response Control Technologies for the Power Electronics

Associated task: T3.2d
Leader: TECN[57]

3.10.1 Problem

DC grids of significant size will incorporate numerous distributed energy resources. Some of these DERs will be dispatchable and will contribute to the primary regulation of the DC grid voltage. The most extended method for primary DC voltage regulation relies on the use of droop controllers. These controllers distribute the DC voltage regulation tasks among a predefined set of DERs, eliminating the need for fast communications and master-slave approaches.

However, while effective in many scenarios, droop controllers lack an inherent mechanism to provide configurable dispatchability among DERs during both steady-state and transient conditions. Therefore, it is not possible to adjust separately the steady-state and transient responses of a given DER after a load change. This feature is necessary to effectively operate DERs with different dynamic responses, energy, and power densities. For instance, different types of energy storage devices, such as batteries or supercapacitors, or batteries with different chemistries, each have unique operational characteristics that necessitates the use of a control mechanism that can adapt to their specific needs while contributing to the global regulation of the DC voltage.

SOL13 will consist of fast-response device-level control strategies for DERs in DC grids. Using droop controllers, these strategies will offer a seamless and unambiguous method to provide configurable static and dynamic dispatchability between DERs, including dispatchable loads. This will permit them to adjust separately their steady-state and transient responses, thus facilitating an optimal operation of DERs with different speeds, power, and energy densities in the DC grid.

3.10.2 Solution Description

The proposed algorithm is based on the droop controller and incorporates a mechanism to emulate configurable virtual capacitance and damping gain. This is like how grid-forming algorithms provide virtual inertia and damping in AC systems. In this way, the DC/DC converters of a given DER will behave at the point of common coupling akin to a configurable capacitor with its DC voltage regulated by the droop controller. Figure 3.10 shows the equivalent electrical model seen from the point of common coupling of a DC/DC converter when a possible implementation of the proposed algorithm is used. The converter behaves as an equivalent virtual capacitor (C_v) connected in parallel to a current source (i_i) that provides the droop response. A virtual resistor (R_v) connected in series to the positive pole of the DC bus is used to emulate/provide the desired damping level.

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[57] TECNALIA

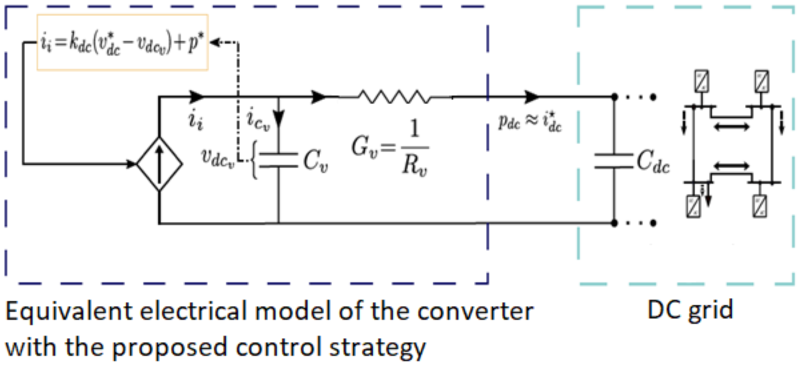

Figure 3.10 Behavioural equivalent electrical model of the proposed control strategy.

By adjusting the virtual capacitance (C_v) and the droop gains (K_{dc}), the dynamic response of the DC/DC converter can be tailored during changes in the load, achieving uncoupled steady-state and transient behaviors. If the virtual capacitor is set high and the droop gain is low, the DER related to this DC/DC converter will provide most of the transient power during load variations while providing minimal or even zero power once the steady state is reached. This configuration is ideal for DERs like supercapacitors. Alternatively, if the virtual capacitance is small and the droop gain is high, the DER will provide little power during the immediate transient following a load change but will meet the steady-state power requirements. This setup is suitable, for instance, for battery chemistries with low power and high energy densities.

3.10.3 Expected Performance

3.10.3.1 Advantages

- Allows for a simple and unambiguous way to provide configurable dispatch ability between DERs with different power and energy densities, thus facilitating the achievement of uncoupled transient and steady-state behaviors.
- Allows for the dynamic adjustment of the system's response to changes in load.
- Provides a stiffer DC grid voltage regulation with reduced *dv/dt* against load changes than droop controllers.

3.10.3.2 TRL

- **Current TRL:** 3
- **Target TRL:** 5-6

3.10.3.3 KPIs

KPIs to quantify the steady-state and dynamic performance of the proposed algorithm:

- **KPI1**: Time required to release/absorb the required power in response to load variations (unit ms).
- **KPI2**: Under and overshoot of the DC voltage after load variations (% with respect to the steady-state value).
- **KPI3**: Ability to provide configurable steady-state and dynamic dispatchability between DERs (0= it fails to provide desired dispatchability between DERs; 1= provides required dispatchability).

- **KPI4**: Ability to implement active damping as an inherent capacity to attenuate oscillatory modes of the DC-voltage and interactions between electrically adjacent DERs.

<u>KPIs to quantify the implementation ability of the proposed algorithm:</u>

- **KPI5**: Increased hardware requirements. This KPI will measure the constraints and additional requirements for hardware components (if any) necessary to implement the control strategy.

3.10.3.4 Application within the project

SOL13 will be implemented and prequalified in the LVDC laboratory.

3.10.4 Problem

A direct connection is not feasible when two DC grids operate at different voltage levels. Such a connection can lead to voltage mismatches, and it can cause equipment damage and safety hazards. It can also create instability within the grids. In fact, to address the technical challenge of interconnecting two DC grids with different voltages, specialized power electronics such as DC-DC converters are required to bridge the gap between the two voltage levels. These converters should be robust enough to handle fluctuating loads and varying grid conditions. They must also be highly efficient to minimize energy losses.

3.11 SOL14: DC/DC Converter - Smart Power Distribution Unit

Associated task: T3.3b
Leader: W&W[58]

3.11.1 Solution Description

To ensure a robust and efficient connection between the 700V DC grid and the 350V DC grid, W&W proposes a bidirectional DC/DC converter described in the figure below (Figure 3.11) used as a smart power distribution unit (SPDU). The output power of the converter is rated at 11 kW with an efficiency that is consistently above 94% for a wide range of the operating area and reaches 97% at its peak. Communication with the device is based on CAN communication following the CAN open protocol.
The proposed DC/DC converter has a high level of monitoring and controllability. Due to its monitoring capability, the proposed solution enhances the performance and reliability of DC grids by allowing the real-time tracking of key parameters such as voltage, current, and temperature. Thanks to its high controllability, the SPDU can also contribute to load balancing and peak shaving, improving overall grid stability and ensuring a more resilient and sustainable energy infrastructure.

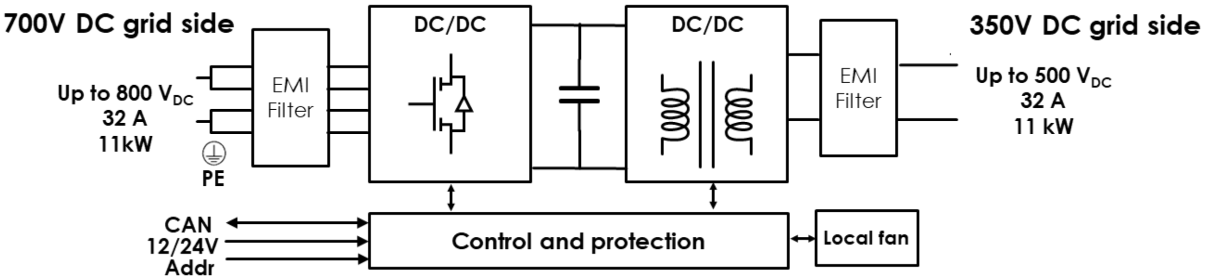

Figure 3.11 Solution description.

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[58] Watt & Well

3.11.2 Expected Performance

3.11.2.1 Advantages

The proposed DC/DC converter has many advantages:

- Allows the interconnection between 700V DC grid and 350V DC grid.
- Reinforced galvanic isolation between input and output.
- Advanced control and monitoring capabilities.

3.11.2.2 TRL

- **Current TRL:** TRL5.
- **Target TRL:** TRL8.

3.11.2.3 KPIs

The SOL14 KPIs are as follows:

- **KPI1:** Manage the energy flow between two battery sets using different technology or state-of-charge.
- **KPI2:** Energy flow controllability between 700V DC grid and 350V DC grid.
- **KPI3:** Efficiency of over 94% and contribution to DC grid resilience.

3.11.2.4 Application within the project

The proposed solution will be used in the building demo as a power distribution unit.
It can be also used to manage the energy flow between two battery sets using different technology or state-of-charge.

3.12 SOL15: Multisocket-Smart Power Distribution Unit

Associated task: T3.3d
Leader: BACH[59]

3.12.1 Problem

Power distribution units (PDU) are crucial for a reliable power supply of information technology (IT) equipment in server racks of traditional AC-powered data centers.

- Granular measurement on the rack level, including network communication, is a state-of-the-art and important source of relevant data.
- Direct current in data centers offers significant advantages in terms of energy efficiency and integration of renewable energies.

However, no such smart DC-based PDU is available yet.

3.12.2 Solution Description

The smart DC-based rack solution described in the figure below (Figure 3.12) is equivalent to existing AC solutions. For this, DC-capable components are needed. For example, wiring, sockets, power supply of the controller unit, measurement unit, and further electronics.

Figure 3.12 Solution description.

3.12.3 Expected Performance

The Smart DC PDU will distribute reliant power to connected devices, enable measurement of relevant parameters (like load, voltage, power, energy), and provide remote communication to read the measurements via Web GUI or to deploy data to higher-level systems.

3.12.3.1 Advantages

- Secure and reliable power distribution of DC-based IT equipment.
- Measurement of important parameters and centralized data aggregation.
- Enabling efficiency comparison between new DC and traditional AC data center infrastructure.

3.12.3.2 TRL

- **Current TRL:** 5
- **Target TRL:** 8

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[59] BACHMANN

3.12.3.3 KPIs

- **KPI1: Input Measurement Accuracy:**
  - Definition: Ensure the accuracy of voltage and current measurements at the input.
  - Target: Achieve a measurement tolerance within 5%.
- **KPI2: Load Distribution Uniformity:**
  - Definition: Ensure even distribution of voltage and current across multiple sockets.
  - Target: Maintain uniform voltage and current distribution across the socket outputs, each supporting up to 1.5 kW (+190V, -190V, up to 8A).
- **KPI3: Measurement and Monitoring Accuracy:**
  - Definition: Continuous monitoring and measurement of voltage and current across the system.
  - Target: Achieve a measurement accuracy of 1% across three measurement channels.

3.12.3.4 Application within the project

The Smart DC PDU will be piloted in the DC Data Center Demonstrator.

3.13 SOL16: Plug & Play Infrastructure for DC-based Office.

Associated task: T3.3e
Leader: BACH[60]

3.13.1 Problem

During and after the pandemic, there was a radical change in office work. Working from home and remote working increased rapidly. At the same time, the needs of users in office buildings changed. The impact on the office environment is very noticeable. Movable furniture, digital whiteboards, and conference displays are on the rise. Fixed sockets can no longer fulfill all the requirements of the modern electrical infrastructure. In addition, devices are becoming increasingly mobile and intelligent. With USB-C, a new power supply standard has been established. The switch from alternating current to direct current has begun. High-performance USB-C sockets will be the new standard in desktop electrification. To achieve the best performance when powering such new devices, switching to direct current is crucial. In the best case, we have the same input voltage as the server racks with 380 VDC.

3.13.2 Solution Description

A battery-operated system supplies power for all electrical devices at the desk. Safety and availability requirements are met. There are high requirements for the flexible use of alternating and direct current. Non-professionals can connect all devices via plug-and-play.

In particular, devices such as lamps, notebooks, monitors, height-adjustable drives, smartphones, etc., can be operated. The system can be controlled remotely by connecting it to a cloud service platform. An inverter supplies alternating current for non-USB-C-based products. The input voltage of 380 VDC is converted to 48 VDC. The efficiency target for the converter 380 VDC/48 VDC is > 90%. 48 VDC is the main voltage of the system. Each of the three USB-C ports can supply 100 W. An additional adjustable DC output can supply 24 to 36 VDC.

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[60] BACHMANN

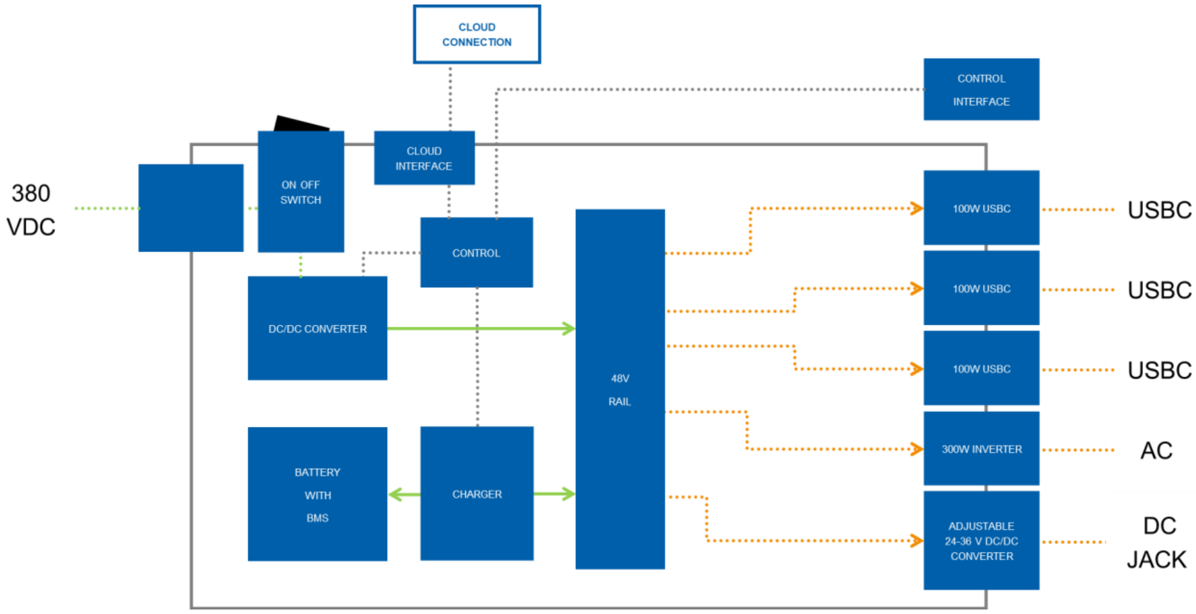

Figure 3.13 Solution description.

3.13.3 Expected Performance

3.13.3.1 Advantages

Safe and efficient independent power supply for professional use in office environments based on DC technology. The output power of 400 W enables the user to supply all the devices on the desk with power. The current power requirement in such environments is approx. 120 W.
The main advantages of SOL16 are as follows:

1. Mobile power supply without cables to a power outlet.
2. Compact all-in-one device for the special requirements of a modern office workplace.
3. LVDC system (48VDC) with reduced safety requirements.

3.13.3.2 TRL

- 1st step TRL: TRL 4
- Target TRL: TRL 5

3.13.3.3 KPIs

1. **KPI1:** Independent operation for at least 4 hours.
2. **KPI2:** Power output 400W.
3. **KPI3:** Operation by laymen.

3.13.3.4 Application within the project

The solution is used in the DC data center demonstrator. There is a need for a mobile and flexible office workstation for tests, analysis reports, and video calls, as well as the participants' demo equipment.

3.14 SOL17: Sharing Voltage Control Approach

Associated task: 2.3a
Leader: EDF[61]/EATON[62]

3.14.1 Problem

In an LVDC microgrid, power may flow in different directions simultaneously since multiple energy generation sources are often present. From this perspective, an energy management system is needed to allow proper coordination of grid assets and to guarantee grid stability and energy efficiency.

However, most of the already known systems to manage energy around the grid are complicated to execute and often need communication between assets. To avoid unnecessary complexity, the solution proposed here is to ensure grid stability through a shared voltage control using a decentralized droop approach.

3.14.2 Solution Description

As already stated, this approach makes it possible to execute a primary control of the energy generation/consumption of different sources/loads in a decentralized way. In practice, it can be done using a droop-based control system. In a DC microgrid, the DC bus voltage mirrors the balance between energy generation and consumption. From this perspective, the main idea is to adapt the different contributions of energy sources to the locally measured DC voltage.

More specifically, different I(V) or P(V) curves (droop curves as shown in Figure 3.15) will be implemented in each DC/DC and AC/DC converter to execute the droop control. Each droop curve is designed based on the characteristics of specific equipment (power, operation, limits, etc.). The general structure of the control loops will be composed of an internal and faster current loop and an external and slower droop control loop as shown in Figure 3.14.

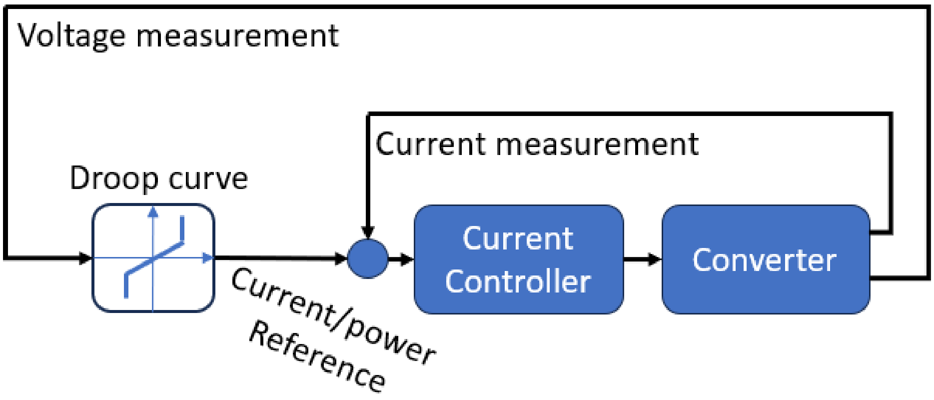

Figure 3.14 Simplified local droop control structure.

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[61] Électricité de France
[62] EATON Industries GMBH

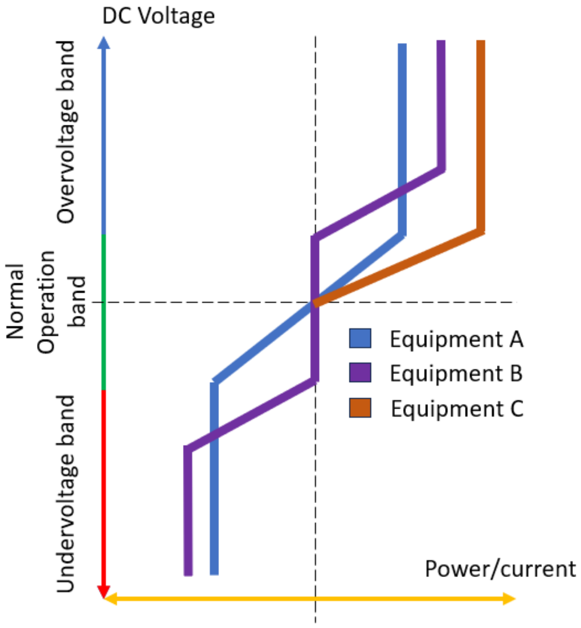

Figure 3.15 Generic example of different equipment droop curves.

3.14.3 Expected Performance

To guarantee system stability, one must consider how the performance of the controller is influenced by multiple factors, such as cable length, since voltage drop results in different voltage level measurements in equipment level, and time response coordination between assets to avoid escalatory phenomena. From this perspective, global energy management electrical installations and different equipment are needed.

3.14.3.1 Advantages

When compared to other energy management system techniques proposed in the literature, the shared voltage control has a set of advantages. Among them, it is possible to highlight the following:

1. This approach proposes a decentralized approach that can be executed within the local DC/DC and AC/DC converters associated with DC loads and DC sources.
2. It represents a relatively simple, resilient method that is not expensive to execute since the primary control can be integrated into local converters.
3. Regarding the primary control, it does not require the implementation of a communication system, either between assets or between assets and a central controller.
4. The theory behind this control approach has already been explored in the literature with promising results [13], [14].
5. The DC microgrid stability does not rely on only one specific piece of equipment, which may increase the grid's resiliency indices.

3.14.3.2 TRL

- **Current TRL:** 4, which corresponds to a small-scale prototype.
- **Target TRL:** 6, which corresponds to a real-scale prototype.

3.14.3.3 KPIs

Three different KPIs can be highlighted for this solution:

- **KPI1 – Grid stability**: it can be evaluated through the monitoring of the grid during specific events, such as source-type asset failure during the test phase in demonstrators.
- **KPI2 – Simplicity of implementation**: it can be evaluated during software implementation and real operation during the test phase in demonstrators.
- **KPI3 – Resiliency index**: it can be evaluated through the period of continuous operation of the grid in degraded mode (main source disconnection).

3.14.3.4 Application within the project

This solution will be used in all the demonstrators of this project since the four DC pilots that will be implemented will need a control system capable of ensuring grid stability and optimized use of energy sources at the same time to maximize energy efficiency.

3.15 SOL18: Passive Thermosyphon Cooling System for High-density Data Centers

Associated task: T3.2c
Leader: JJC[63]

3.15.1 Problem

Due to the continuous increase in microprocessor performance and miniaturization, conventional cooling approaches are reaching their limit to cool down, increasing power dissipation and on-chip power density in data centers. In addition to this technological limitation, reducing the energy consumption of cooling systems has become a major concern. Finally, in data centers, the excess is often dissipated in the environment.

3.15.2 Solution Description

To address the problem described in the previous section, our solution is to update the design of a two-phase closed loop thermosyphon connected to all the computing nodes of an edge data center architecture to cool them down by converting from present air-cooled condenser to a water-cooled condenser. A schematic representation of a two-phase closed-loop thermosyphon is presented in Figure 3.16.

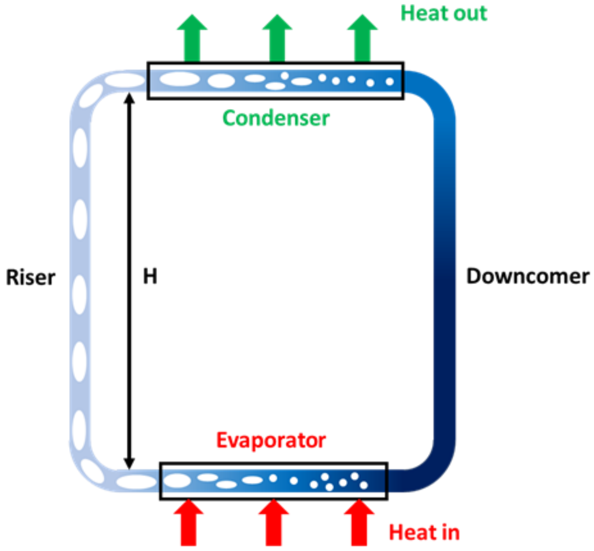

Figure 3.16 Schematic representation of a two-phase closed loop thermosyphon.

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[63] JJ Cooling Innovation

In the evaporator, the partial evaporation of the working fluid ensures the cooling of the heat source, which can be, for example, a CPU. Then, due to buoyancy, the two-phase working fluid flows upward in the riser to reach the condenser, where it condenses by exchanging heat with a secondary coolant (air, water, or sometimes another fluid). To close the loop, the downcomer brings the fluid back to the evaporator. As the flow inside the thermosyphon is gravity-driven, there is no need for a pump to circulate the working fluid.

The newly designed water-cooled condenser will transfer the heat to a water loop to reuse the waste heat or disperse it to the environment when no heating services are needed.

3.15.3 Expected Performance

3.15.3.1 Advantages

The main advantage of the thermosyphon cooling system is that flow boiling in the evaporator enables it to reach higher thermal performance. Indeed, as presented in Figure 3.17, with an air-cooled two-phase closed loop thermosyphon developed for the European project BRAINE with an edge data center architecture composed of 10 computing nodes in 3U, power dissipation up to 160 W per node was reached without exceeding 80°C case temperature.

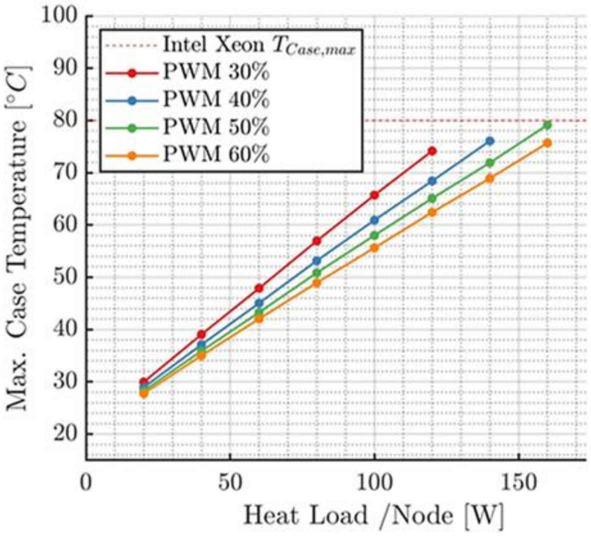

Figure 3.17 Maximum case temperature for the BRAINE air-cooled two-phase closed loop thermosyphon.

Moreover, since there is no need for a pump to circulate the working fluid inside the loop thermosyphon, the energy efficiency of the system is high. Figure 3.18 shows the Power Usage Effectiveness (PUE) (defined as the total system power consumption, nodes, and fans, divided by the fans' power consumption) of the BRAINE air-cooled two-phase closed loop thermosyphon for which values as low as 1.02 were measured.

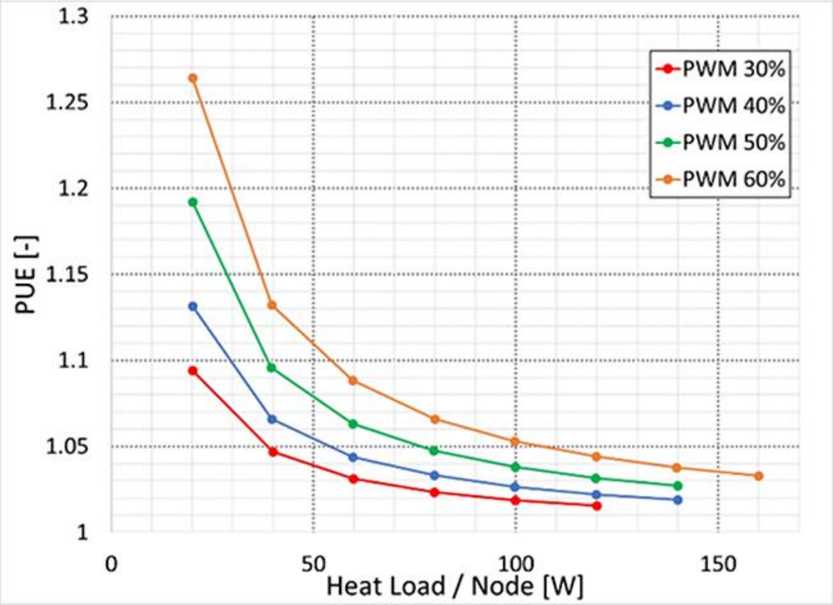

Figure 3.18 Power Usage Effectiveness (PUE) for the BRAINE air-cooled two-phase closed loop thermosyphon.

Finally, another advantage of the proposed solution is that the computing nodes are unaffected by vibrations because there are no components with moving parts in the thermosyphon.

3.15.3.2 TRL

- **Current TRL:** 5, meaning the system has been validated in a relevant environment.
- **Target TRL:** 8, meaning the system is proven in an operational environment.

3.15.3.3 KPIs

The KPIs for the thermosyphon cooling system are described below:

- **KPI1:** Heat dissipation per computing node: 200 W per node.
- **KPI2:** Water-cooled condenser compactness: 1/3 the volume and weight compared to state-of-the-art.
- **KPI3:** At a maximum of 2% of the total dissipated heat in the computing nodes.

3.15.3.4 Application within the project

The thermosyphon cooling system will be installed in the data center demonstrator.

3.16 SOL19: Scalable and Modular rack-mounted BESS

Associated task: T3.2g
Leader: PHNPS[64]

3.16.1 Problem

Industrial production sites are often modified due to extensions and changes in the production processes. Therefore, power demands are likely to vary over time, which is even typical for many production processes. Furthermore, industrial DC grids require high power supply reliability and face the upcoming integration of RE, such as PV systems, as well as new loads like DC charging connected to the production facility grid. Thus, it is obvious that volatile power demand and, therefore, DC voltage variations are likely, depending on the maximum peak power compared to nominal power supply limits and cable cross sections.

Another phenomenon that also appears in industrial grids is slowing down or stopping the movements of robots, machines, etc. Nowadays, companies are striving for high energy efficiency, which often results in feeding back such breaking power rather than wasting it by heating up breaking resistors.

3.16.2 Solution Description

To cope with the mentioned phenomena, a further voltage stabilization unit is requested, which can solve these challenges and support a stable and reliable power supply. A battery energy storage system is what can do this and even more. It supports a stable DC voltage by feeding additional power to the grid in case of voltage dips, e.g., in the case of AC grid failures in front of a central converter. Furthermore, it supports balancing the DC grid by feeding power to or consuming power from the DC grid to compensate for voltage fluctuations.

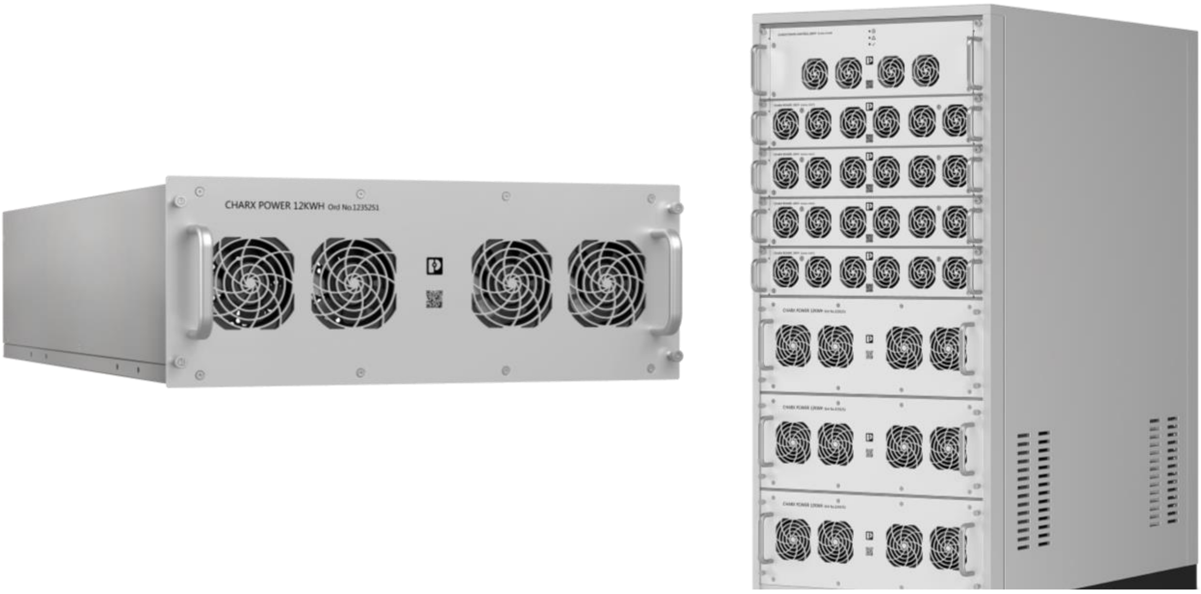

Figure 3.19 Modular and scalable DC-coupled 19-Inch BESS system.

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[64] PHOENIX CONTACT POWER SUPPLIES GMBH

It also allows the storage of excessive RES power. In the case of rare peaks that go far beyond the main power supply, e.g., DC fast charging by a High Power Charger (HPC) for EV or even Megawatt charging systems (MCS), the BESS can provide extra power for a defined time, depending on the size of the BESS.
To match the power demand, which very likely varies over time due to production changes, the BESS comprises a scalable, modular system approach for increasing power and energy to easily match the optimal level. Once the power or energy demand drops, these modules can be easily swapped and plugged into another BESS at another location. Therefore, the solution is based on industrial 19-inch racks similar to the one depicted in Figure 3.19.

To optimize the overall energy efficiency of the used DC grid, the BESS is connected by a DC/DC converter. The supporting voltage limits can be parameterized to define the supporting level and priority. It can be controlled, and its settings can be adjusted by an external EMS.

3.16.3 Expected Performance

- BESS with modular and scalable system approach, allowing the best dimensioning of power and energy:
    - Module power: 30 kW.
    - Module energy: 10 kWh.
- Power modules embed a DC/DC converter.
- Adjustable DC voltage support characteristics for an intrinsic supporting mechanism.
- Wide range of DC voltage level 150-1000 V DC.
- Communication interface for external EMS to set parameters.

3.16.3.1 Advantages

- BESS is a modular and scalable system approach that allows for the best dimensioning of power and energy due to individual power and energy modules.
- Cost-efficient solution for variations of power and energy demand over the lifetime.
- Easy swapping system approach for modules in a 19-inch industrial cabinet.
- DC-coupled BESS for increased energy efficiency and intrinsic DC voltage support.

3.16.3.2 TRL

- **Current TRL:** 4
- **Target TRL:** 6

3.16.3.3 KPIs

- **KPI1:** Efficiency of the Power Module >96% (@650V DC)
- **KPI2:** Roundtrip Efficiency Battery Module >90%

3.16.3.4 Application within the project

The battery system will support and ensure the stability of the industrial DC grid of the industrial demonstrator at the Phoenix Contact site in Blomberg. It will provide the flexibility to scale the system in terms of energy and power rating according to the individual and emerging requirements of the DC grid.

3.17 SOL20: DC-Connectors

Associated task: T3.3c
Leader: PHNKG[65]
Participants: Nexans[66]

3.17.1 Problem

DC is a challenge for connectors coupling the DC grid with field devices and applications due to missing zero current events like in AC grids. Thus, it is common for *arcs* to occur in a disconnecting event and, can destroy metal contacts and potentially harm users, depending on the interrupted current and the grid voltage. However, connecting and disconnecting field devices or applications must be possible at a live DC grid up to specified voltage and current levels.

For any use where disconnection under load is not relevant and applicable, the rated power of these DC connectors can be significantly higher. Such are out of scope since they are already available as of today.

3.17.2 Solution Description

The solution for connecting and disconnecting devices and applications under load can be split into two types of DC connectors: active and passive arc extinguishing connectors.

Active arc extinguishing DC connectors are characterized by a smart electronic device within the DC connector housing. The embedded electronics detect a disconnecting moment and actively prevent an arc at the power contacts (Figure 3.21).

Alternatively, in the case of lower currents, a robust connector with a specified withstand capability of a certain number of disconnecting events can be a solution for rare connection/disconnection events within the connector's lifetime. Such DC connectors provide a **passive** arc extinguishing method. An appropriate design and reasonable dimensioning of the power contacts and entire DC connector result in a safe solution for a connected device.

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[65] PHOENIX CONTACT GMBH & CO KG
[66] NEXANS France

Both approaches and types of DC connectors provide a safe solution and allow unskilled people to handle the connections.

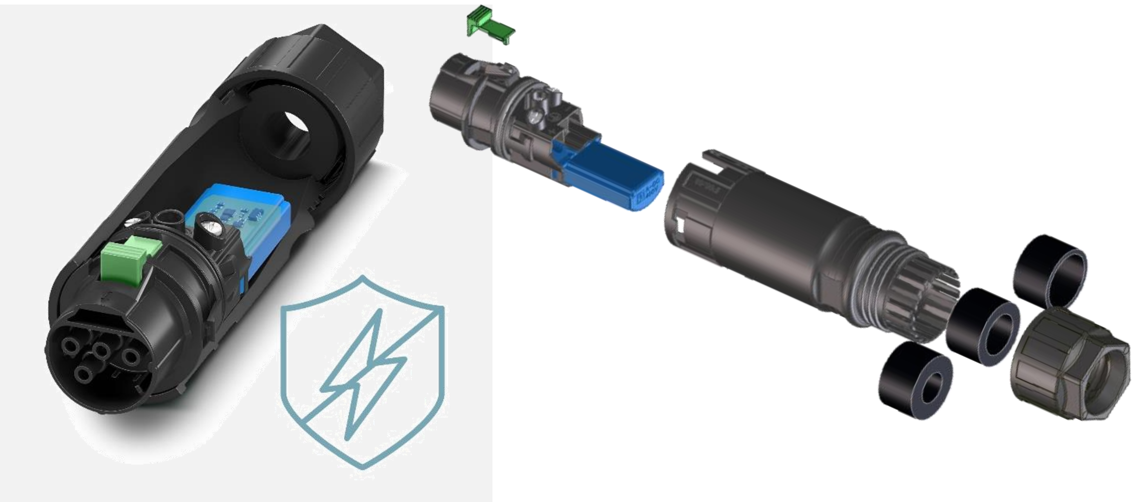

Figure 3.20 Zero Arc Technology for Active Arc Extinguishing.

3.17.3 Expected Performance

The following characteristics indicate the performance of the DC connectors:

Use by unskilled people:

- Easy and safe field device DC connector series for wide range use in DC grids for multiple purposes to connect field devices and applications.

Passive DC connector:

- At least 25, typically >50, disconnection events defined by requirements and depending on individual power at the moment of each disconnection event.
- Voltage rating of up to 400 V. Current rating of up to 5 A (max breaking current; rated current can be higher)
- Maximum power: ca. 2.5 kW

Active DC connector:

- 500 cycles (full load equivalent) of disconnection events
- Voltage rating of up to 800 V. Current rating of up to 20 A.
- Maximum power: 16 kW

Connector without breaking capacity (COC):

- If no disconnecting under load is needed, DC Connectors can handle higher voltage and current. Used for fixed installation. No operation under power, therefore, usually locked.

3.17.3.1 Advantages

- The first active arc extinguishing DC Connector is available on the market. It allows the setting and use of devices and applications in DC grids more cost efficiently.
- In most cases, this technology can avoid additional costs for connecting devices and DC applications to the DC grid without the need for further protection devices.
- Unskilled people can handle the DC connectors safely.

- Preventing arcs with a zero-arc technology using an embedded electronic circuit within the DC connector results in its long useful life.
- Easy installation by two options:
    - locking/unlocking mechanism can be exclusively operated by special tools.
    - version for manual release without tools.

3.17.3.1.1 TRL

- **Current TRL:** 4
- **Target TRL:** 6+

3.17.3.2 KPIs

KPI1: Passive DC connector:

- **KPI1.1:** At least 25 typically >50 disconnection events due to requirements and depending on individual power at the moment of each disconnection event
- **KPI1.2:** Voltage rating up to 400V
- **KPI1.3:** Current rating up to 5 A

KPI2: Active DC connector:

- **KPI2.1:** 500 cycles (full load equivalent) of disconnection events
- **KPI2.2:** Voltage rating of up to 800V
- **KPI2.3:** Current rating of up to 20 A

KPI3: COC Connector without breaking capacity:

- **KPI3.1:** No capability of current breaking under load
- **KPI3.2:** Voltage rating of 1500 V (or higher)
- **KPI3.3:** Current rating of up to 150 A

3.17.3.3 Application within the project

The DC Connectors were developed and adopted to the consortium partner requirements, and general market requirements will also be used to connect individual devices. It will be shown how those can be handled by untrained, regular people without any dangerous situation occurring by DC arcs. Both solution approaches of DC connectors, active and passive arc extinguishing technology, will be shown. The DC connectors are not assigned to a specific application but comprise a general connection solution for any kind of device within the specified power range. Thus, for the passive DC connectors, a range of up to 2 kW, and for the active DC connectors, a range of up to 16 kW is a valid power limit.

3.18 SOL22: Highly Efficient Power Electronic Interfaces for Data Centers

Associated task: T3.2f
Leader: TALT[67]

3.18.1 Problem

The primary consumers of power within data centers are servers, which perform data storage and processing functions. These servers operate as computational loads utilizing low DC voltages, typically 12 V or 48 V. Consequently, power conversion is necessary to transform the high-voltage AC utility input to the distributed low-voltage loads. Recent explorations into DC power delivery architectures for data centers suggest the potential for enhanced reliability alongside a reduction in the number of power conversion stages compared to traditional AC distribution systems. However, it is important to acknowledge that power conversion stages are subject to losses; thus, significant power conversion losses are unavoidable in both AC and DC architectures.

Given the substantial power demands of data centers, numerous solutions have been proposed in literature aimed at improving energy efficiency. Commercially available power equipment that achieves mid-90% efficiency is marketed for data center applications. Although enhancements in conversion efficiency at each power stage are achievable, these improvements often come at the expense of increased costs and/or volume of power electronics. As power electronics already occupy a significant amount of space in modern servers, there is a pressing need to investigate alternative architectures that can deliver both high efficiency and a reduced overall volume.

The proposed technology seeks to enhance the energy efficiency of data centers by proposing a novel system-level solution rather than concentrating solely on the efficiency enhancement of individual power components within the system. While the proposed architecture realizes substantial efficiency gains, there are consequential considerations regarding reliability and practical challenges, such as hot-swapping and hardware protection, which are currently under examination. Lastly, it is noteworthy that due to the relatively rapid replacement cycles of modern data centers, typically within 3 to 5 years, the architecture advanced in this study has the potential for widespread deployment in a relatively short timeframe as data centers undergo replacement.

3.18.2 Solution Description

Series stacking of servers allows for delivering low-voltage DC power to individual servers without conversion. In the ideal case, when all servers connected in series draw exactly the same power, efficiency close to 100% could be achieved [15]. In practice, it is unlikely that each server has the same load. As a result, differential power converters (DPCs) are needed to divert the current difference between two adjacent servers, as shown in Figure 3.21. Each server could have either a 12 V or 48 V power input. Moreover, this technology can support the hot-swap of a server in a rack, as demonstrated in [16]. On one side, servers connected in series can feature certain voltage potential on conductive parts of their cases, requiring galvanically isolated communication links and redesigned server enclosures. Even though a standardized rack can be built to match the distribution bus of a data center, for example, 400 V DC. There is also a demand for smaller (edge) racks to match the needs of

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[67] Tallinn University of Technology

a particular client. Therefore, a DC transformer (DCX) converter may be needed to match the DC data center bus voltage of V_{bus} (e.g., 400 V) and rack voltage V_{rack} (e.g., 48 V). This approach makes the given solutions easily scalable to different applications, as DCX can be designed for nearly any rack voltage required.

It is worth mentioning that similar power delivery approaches were also demonstrated for data storage within a server [17], proving the high flexibility and scalability of the technology under development.

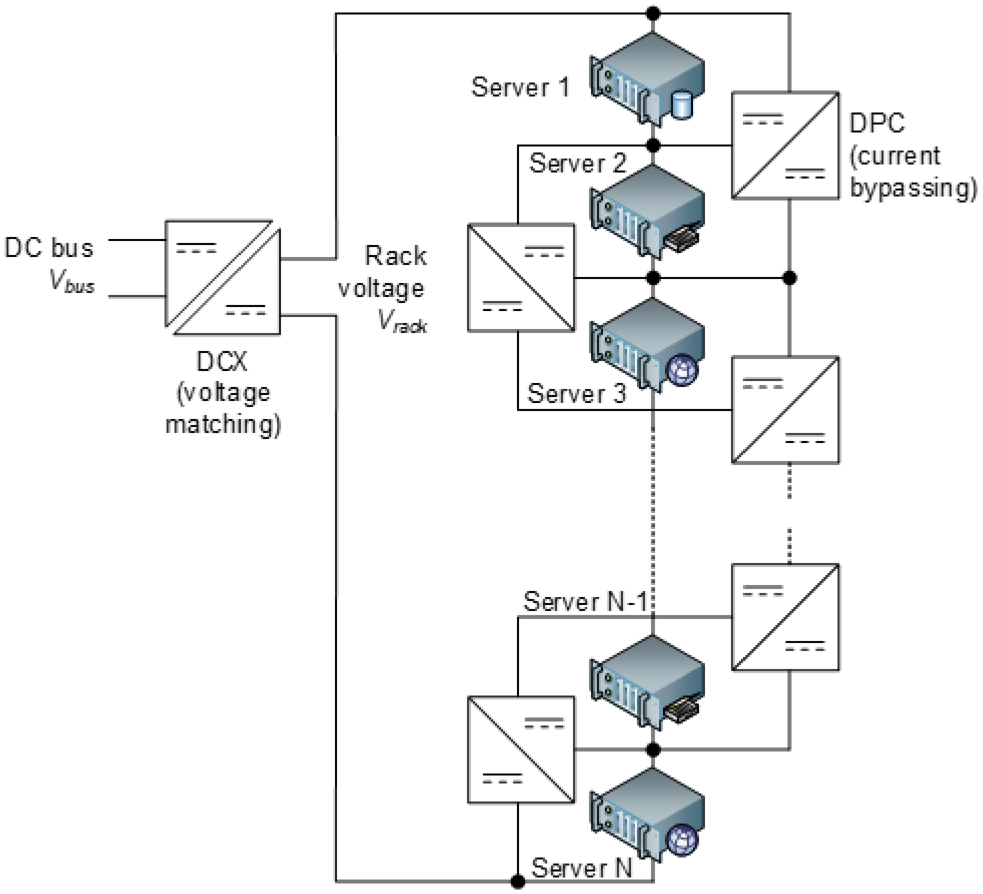

Figure 3.21 Proposed series-stacked server rack architecture.

3.18.3 Expected Performance

The proposed solution aims to demonstrate a new DC data center design approach with ultimate rack-level efficiency. It is worth mentioning that galvanic isolation and the safety of operations could be challenging to achieve.

3.18.3.1 Advantages

- Significantly reduced conduction losses at the rack level.
- Technology scalability is achieved by applying a DCX voltage-matching converter.
- Fast balancing dynamics as each bypassing converter is rated for a fraction of the rack’s total power.
- Hot swapping can be achieved.
- Standardized modules compatible with 400 V data centers could be developed for simple scalability.

3.18.3.2 TRL

The solution is planned to be elevated from TRL 4 to TRL 6 in the course of this project.

- **Current TRL:** 4
- **Target TRL:** 6

3.18.3.3 KPIs

- **KPI1:** Electric power conversion efficiency of over 99% at the rack level.
- **KPI2:** Volumetric power density of over 5kW/l to demonstrate lower use of materials.
- **KPI3:** Server-level voltage stabilization within ±5% even during dynamic transients in a series-stacked string of servers.

3.18.3.4 Application within the project

A small-scale demo rack will be deployed and tested in the demo at the DC data center in Germany.

4 Conclusion

4.1 Summary

This deliverable (D1.4) presented the results of Task 1.4, “Definition and specification of tools, devices, and key performance indicators,” as part of the Shift2DC2DC project.

Chapter 2 provided specifications for the tools to be developed in WP2. Six main tools have been identified, each with clearly defined objectives, requirements, architecture, and expected performance. These tools are intended to support the design, protection, simulation, evaluation, and monitoring of DC infrastructures.

Chapter 3 outlined the specifications of the DC solutions to be developed in WP3. Eighteen key solutions have been specified, focusing on their objectives, requirements, and expected performance, which address the technical needs and challenges of DC systems.

4.2 Progress

This document has played a key role in laying the foundations for developing the tools and solutions to be implemented in the Shift2DC project. It represents a significant step towards achieving the project's objectives, providing detailed guidance for future work in WP2 and WP3.

4.3 Main Challenges

The tools and solutions specified in this task require considerable technical expertise and the collaboration of partners with diverse backgrounds. Thus, the production of this document involved coordination between multiple partners, some of whom were not directly involved in WP1.

4.4 Next deliverables

As mentioned above, the work carried out in this task will directly feed into WP2 and WP3. More specifically, the specifications provided here will guide the development of tools and solutions in these work packages. This document forms an essential basis for future technical developments in the project, supporting the evaluation and eventual implementation of DC systems in WP4.

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