HYPERRIDE
THE FUTURE OF POWER DISTRIBUTION

Hybrid Provision of Energy based on Reliability and Resiliency by Integration of DC Equipment

Work Package WP2

Definition of Requirements, Use cases and Specification

Deliverable D2.3

Enabling Technologies Requirements and Specification Report

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List of Abbreviations

AC	Alternating Current
ACDC	Alternating Current and Direct Current
ACR	Automatic Circuit Reclosers
AFE	Active Front-End
AMS	Arc Mitigation System
API	Application Programming Interface
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CFD	Continuous Fluid Dynamics
CHIL	Controller Hardware in the Loop
CI	Critical Infrastructure
CI-SAN	Critical Infrastructure Security Analtyics Network
CI-SOC	Critical Infrastructure Security Operations Centre
CPU	Central Processing Unit
CSV	Comma Separated Values
DAB	Dual Active Bridge
DC	Direct Current
DER	Decentralized Energy Resources
DFT	Discrete Fourier Transformation
DG	Distributed Generators
DMU	DC Measurement Unit
DoA	Description of Action
DSO	Distribution System Operator
DUT	Device Under Test
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FEA	Finite Element Analysis
FiT	Feed in Tariff
FMEA	Failure Mode and Effects Analysis
FPGA	Field Programmable Gate Array
FRT	Fault Ride Through
GE	Generical Enabler
ICT	Information and Communications Technology
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IOT	Internet of Things
JSON	JavaScript Object Notation
KPI	Key Performance Indicators
LV	Low Voltage
LVAC	Low Voltage Alternating Current
LVDC	Low Voltage Direct Current
LVRT	Low Voltage Ride Through
MCDA	Multi-Criteria Decision Analysis
MINLP	Mixed Integer Non-Linearized Programming
MMC	Modular Multilevel Converter
MOV	Metal Oxide Varistor
MQTT	Message Queuing Telemetry Transport

MTDC	Multi Terminal DC
MV	Medium Voltage
MVAC	Medium Voltage Alternating Current
MVDC	Medium Voltage Direct Current
NPC	Neutral Point Clamped
NPV	Net Present Value
OBD	On-board Diagnostic
OCPP	Open Charge Point Protocol
OPC UA	Open Platform Communications Unified Architecture
OPEX	Operational Expenditure
OPF	Optimal Power Flow
OT	Operational Technology
PCC	Point of Common Coupling
PDF	Probability Density Function
PHIL	Power Hardware in the loop
PMU	Phasor Measurement Unit
PV	Photovoltaics
PWM	Pulse Width Modulation
RA	Room Average
RES	Renewable Energy Sources
RLC	Resistance, Inductance, Capacity
SA Node	Security Analytics Node
SCADA	Supervisory Control and Data Acquisition
SDC	Security Data Concentrator
SE	State Estimation
SOC	Security Operations Centre
SRC	Silicon Controlled Rectifier
SSBTS	Solid-State Bus-Tie Switch
TCP	Transmission Control Protocol
TRL	Technology Readiness Level
TSO	Transmission System Operator
UMTS	Universal Mobile Telecommunications System
VARC	VSC Assisted Resonant Current
VSC	Voltage Source Converters
WLS	Weighted Least Square
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

Executive Summary

This report provides insight in the planned enabling solutions to be developed within HYPERRIDE project. The descriptions and general specifications outlined here have to be read in context with:

- D2.1: Requirements on grid infrastructure - describing systemic requirements for DC and hybrid Alternating Current and Direct Current (ACDC) grid installations with derived Key Performance Indicators (KPI)s to assess the grid quality;
- D2.2: Use case specification - a collection of use cases for the pilot installations in HYPERRIDE and relevant technologies such as Information and Communications Technology (ICT) solutions and components (converters, breakers, measurement units).

While some solutions for DC grid installations can be directly transferred from AC to DC, it is necessary that novel solutions are developed in many areas from the overall system to individual components. The areas where HYPERRIDE will provide and showcase them at the demonstration sites are:

- Grid planning and simulation;
- Grid automation methods;
- Protection methodologies;
- Safety and security;
- Meteorology;
- Converter technologies;
- Test and validation methods.

For each individual development a start and end Technology Readiness Level (TRL) description is indicated including the development path in subsequent work packages and a general specification based on the current state of knowledge.

1 Introduction

1.1 Purpose and Scope of the Document

According to the Description of Action (DoA) (*HYPERRIDE Description of Action*, 2020), this report will focus on the enabling technologies for DC and hybrid ACDC grid planning, installation and operation. Due to the wide focus of the project HYPERRIDE ranging from solutions for Distribution System Operator (DSO) to component providers, which is also reflected in the consortium structure the main emphasis lies on those technologies which are actually developed within the project.

This deliverable leverages on two other deliverables which provide the broader context of the described technologies (see Figure 1):

- D2.1: Requirements on grid infrastructure - describing systemic requirements for DC and hybrid ACDC grid installations with derived KPIs to assess the grid quality (*HYPERRIDE Deliverable D2.1 Infrastructure Requirements and DC Grid KPI Definition*, 2021);
- D2.2: Use case specification - a system architecture description followed by a collection of use cases for the pilot installations in HYPERRIDE and relevant technologies such as ICT solutions and components (converters, breakers, measurement units; (*HYPERRIDE Deliverable D2.2 Use Case Description, Specification and Implementation Roadmap report*, 2021).

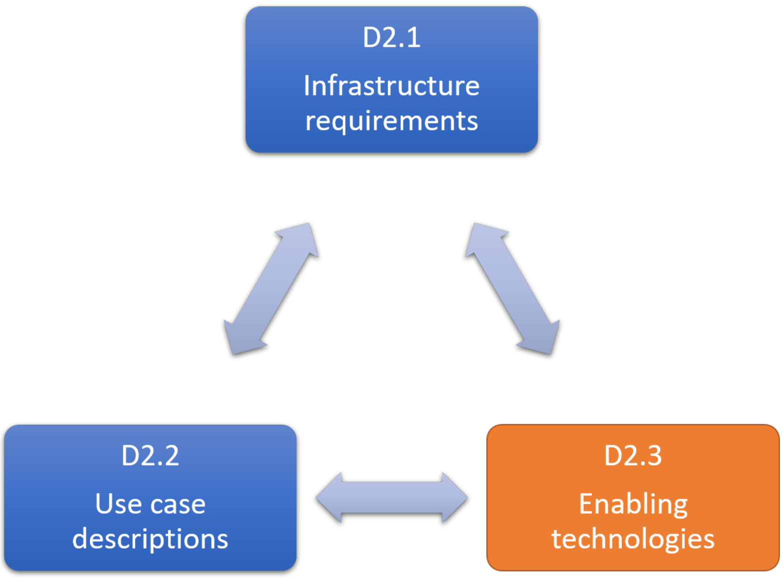

Figure 1: D2.3 in the context of other deliverables in HYPERRIDE WP2.

1.2 Structure of the Document

This document is organised as follows: Section 1 provides information about the report content. Next, Section 2 introduces general aspects of needed technologies which have been clustered to provide a better overview on the topic. The developed solutions have been clustered, starting with necessary technologies and methods needed to perform grid planning and simulation are described in Section 3. Section 4 provides information on grid automation methods and software requirements to achieve optimal power flow in DC grids. The following Section 5 deals with needed protection devices, while safety and security related topics are discussed in Section 6 including threat detection, fault mitigation and cascading prevention. Meteorology technologies for voltage and currents as well as measurement units are described in Section 7 and Section 8 provides insight in needed converter technologies for MVDC/Low Voltage Direct Current (LVDC) as well as ACDC active front ends. Finally, needed test and validation facility specifications and procedures are described in Section 9 - ACDC product testing and validation.

The topic of open issues and research/specification needs is addressed in Section 10.

The deliverable is concluded in Section 11.

2 DC Distribution Grids

With the increasing share of Renewable Energy Sources (RES) and the shift from fossil energy towards electricity, the operation of AC distribution grids becomes more sophisticated; one reason is that the increase of production and loads leads to a smaller safety margin with respect to grid congestions, which can also occur in local areas, unnoticed by the DSO. Further, the grid frequency is one main parameter to maintain grid stability. With traditional centralised energy production based on synchronous generators, a direct feedback was possible to balance supply and demand. As renewable generations (and storage) are mainly based on power electronics converters as interfacing technology, the frequency is not directly affected by imbalances. With an increasing share of converters connected to the grid, the feedback loop for generation is disturbed. During recent years intensive efforts have been made to develop methods and technologies in the area of smart grid operation, automation and component controls in order to enhance the stability of AC distribution grids even with up to 100% renewable energy share.

However, the fact that power electronics converters are almost always providing a DC bus (DC-link) in their inner topology and some renewable sources are DC based per se (e.g. Photovoltaics (PV) modules, battery cells) an additional path for future grids was established. The reasoning behind is that conversion can be reduced to DC-DC components which are often easier to control and have less devices to use. This generally leads to lower losses, lower costs etc. Even in three phase systems the fluctuations of power flow due to the base frequency of the grid, larger DC-link capacitors need to be used. This shows that from base component point of view fostering DC grids might suggest itself.

From system point of view, the local DC grid can be either fed by AC or DC lines as depicted in Figure 2. Both options are possible for medium voltage and low voltage installations.

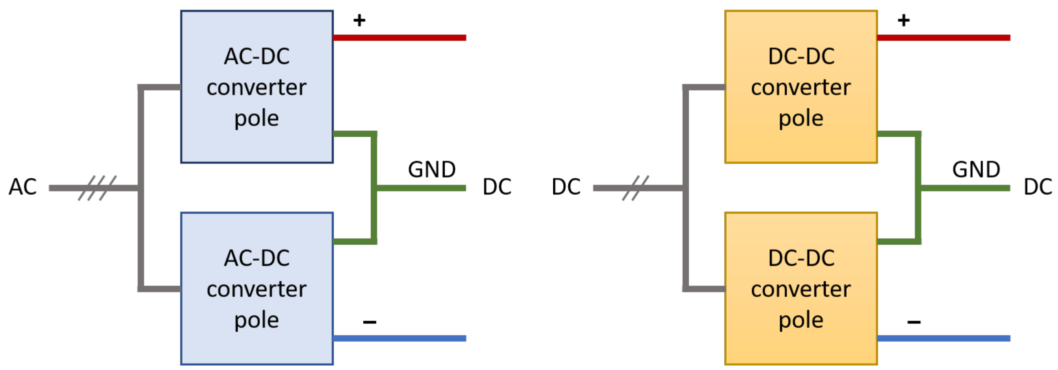

Figure 2: Schematic of bipolar systems: left - AC-DC hybrid interface (active front end); right - DC-DC interface; after (TC 8 - System aspects of electrical energy supply, 2020).

2.1 Medium Voltage Level

The voltage levels which are recommended or used for MVDC installations have been listed by e.g. Giannakis et al. (Giannakis & Peftitsis, 2018):

- Institute of Electrical and Electronics Engineers (IEEE) Standard 1709-2010 (“IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships”, 2010) provides recommended voltage levels of $1.5kV$, $3kV$, $6kV$, $12kV$, $18kV$, $24kV$, or $30kV$.

- Available railway DC equipment is designed for typical voltage levels of $1.5kV$ and $3kV$.
- A majority of installed DC grids and especially with integration of renewable energy sources use $5kV$ and $10kV$ (see Figure 3).

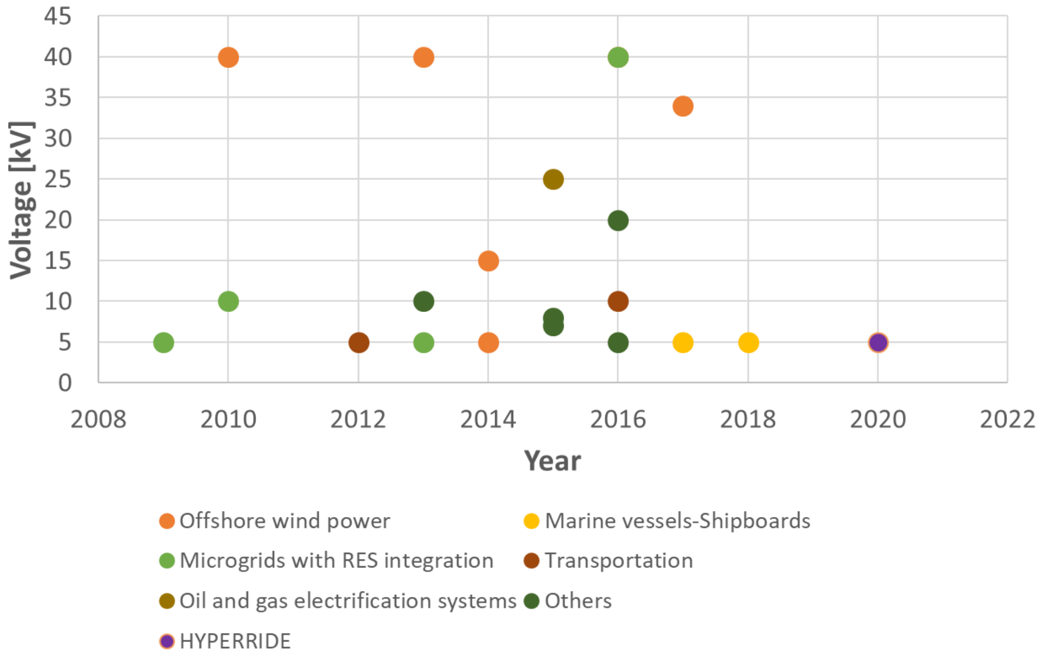

Figure 3: MVDC demonstration voltages (after (Giannakis & Peftitsis, 2018)) incl. HYPERRIDE demonstrators.

With respect to the power rating of existing MVDC installations again (Giannakis & Peftitsis, 2018) showed that, with few exceptions, the majority is found in the range from 1MW to 30MW.

According to CIGRE WG C6.31 "Medium Voltage Direct Current (MVDC) Grid Feasibility Study" (CIGRE, 2020), considering the global overview of AC voltage levels, DC and AC connection, insulation constraints, matching the voltage levels of DC loads, and safety requirements, the recommended voltage levels of MVDC networks are shown in Table 1.

Table 1: Recommended MVDC voltage levels (CIGRE, 2020).

AC voltage levels [kV]	Recommended MVDC distribution voltage levels [kV]
0.4	$\pm$1.5
3	$\pm$3
6	$\pm$6
10	$\pm$10
20	$\pm$20
35	$\pm$35
66	
110	$\pm$100

2.2 Low Voltage Level

Due to voltage limits in existing standards (e.g. IEC 60900), the majority of installations are built below and close to $1500V$ in bipolar configuration, e.g. $\pm 700V$ or $\pm 750V$. (Willems et al., 2017) propose $350V$ as a base voltage with the possibility to stack up to $1400V$ with $\pm 350V = 700V$ as a first step. This approach provides a safety margin towards the regulation limits as well as enough space to implement control algorithms based on droop control. Other installations, such as Suzhou Tongli hybrid ACDC Project in Jiangsu, China, explore $375V, 750V, 1500V$. Nevertheless, the rationale based on multiples of a base voltage remains the same.

Considering different factors such as topology, load distance, insulation, cable economy, control strategies, protection requirements, equipment characteristic, etc., the IEC technical report (*IEC TR 63282:2020 - LVDC systems - Assessment of standard voltages and power quality requirements*, 2020) recommends LVDC voltage levels listed in Table 2.

*Table 2: Recommended LVDC voltage levels (*IEC TR 63282:2020 - LVDC systems - Assessment of standard voltages and power quality requirements*, 2020).*

Recommended nominal LVDC distribution voltage levels [V]
350 V_{DC}
700 V_{DC}
$\pm$350/700 V_{DC}
$\pm$700/1400 V_{DC}

Lower LVDC voltages, such as $12V$, $24V$, $48V$, etc. have not been listed as an example of recommended voltages, but they could be included as LVDC voltages for some distribution purposes. IEC TC 8 is in charge of specifying the recommended voltages for LVDC distribution as one of the system aspects. These recommendations are expected to be the result of a factual state of the art. They are being proposed for implementation in IEC 60038.

2.3 Overview Enabling Technologies

The change from AC to DC infrastructure is considered a paradigm shift with quite substantial obstacles to overcome in order to achieve wide acceptance across all stakeholder groups. Starting from the preparation and planning phase it became clear that even planning tools are optimised for AC systems with DC as a pure offset parameter. This means, that dynamic processes are not easily simulated in the respective tools. The lack if zero current crossings, a standard process with sinusoidal voltage and current waves, triggers the need for new solutions for safety and grounding concepts as well as automation of the grid. With respect to components it is evident, that the lack of zero current crossings will also provide the challenge of arc quenching in switches and breakers. Constant voltages and currents further impose the need for new measurement sensors, which don't rely on induction as a measurement principle. Magnetic induction is also the basis of the AC transformer, which is commonly used to provide galvanic isolation and the tool for change of voltage levels, using AC transformers. Figure 4 shows schematically a hybrid ACDC grid with Medium Voltage (MV) and Low Voltage (LV) sections, where some important enabling solutions are indicated. The discussed solutions in the subsequent sections are clustered in a logic of system to component. This means that system related solutions, such as grid planning, grid simulation and grid sizing tools are presented before solutions of automation and ICT. This part also includes topics of grid reliability and threat detection. Relevant components for measurement of power, voltage and currents are followed by a section on power converters. The finalising section on test and validation methods for products and automation solution is not directly coupled to grid installation or operation but merely an important prerequisite for the proper roll-out of public infrastructure as this addresses questions of product standardisation and safety which addresses indirectly the important topics of interoperability and liability.

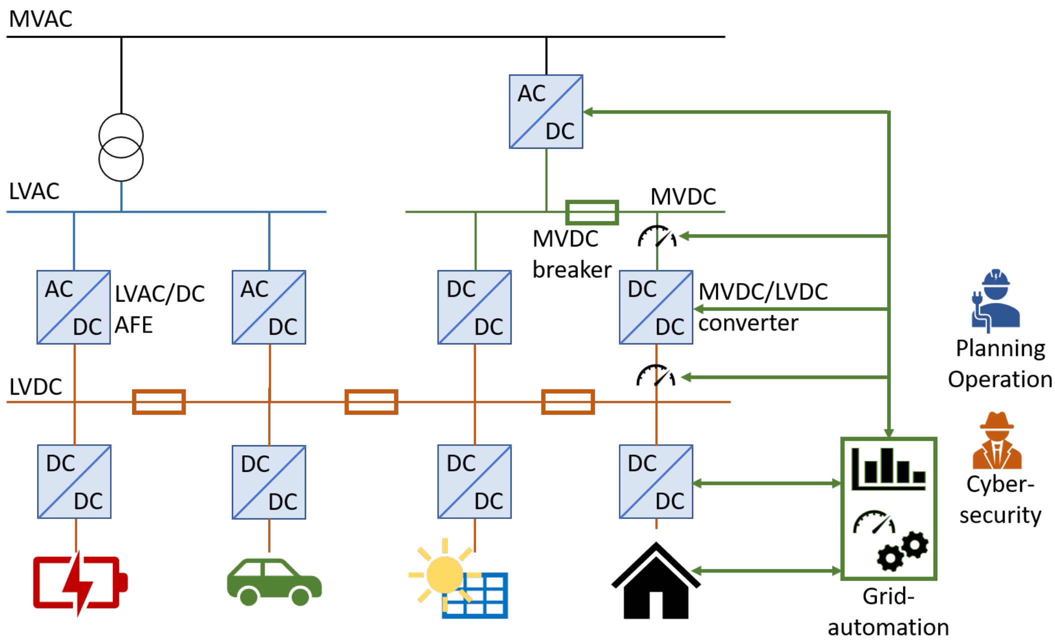

Figure 4: Overview of a hybrid ACDC grid with MV and LV sections with selected required solution indicated.

3 Grid Planning and Simulation

Grid planning and simulations represent a starting point for all grid installations. Necessary insight has to be provided in order to assess benefits such as e.g. advantages of DC with respect to AC. Depending on the system use case this involves Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) analysis and proper sizing of components (e.g. converters and storage). Following initial sizing discussions, aspects of operation are to be defined. A prerequisite is a library of functional blocks, tools for grid simulation and the respective workflow attached to it.

3.1 Grid Planning Tool for the Development of Hybrid ACDC Microgrids in Parallel with Existing MV/LV AC-Grids

The ability to evaluate the integration of DC into already existing AC grids through simulations is crucial for the implementation of DC systems. The tool enables the simulation of hybrid ACDC grids (hybridization on LV level) and economic analysis based on the simulation results. The tool supports the evaluation of the integration of DC in the LV grid from a grid planning perspective.

By applying the simulation tool on simple line and synthetic test grid models, it has been shown that the conversion of AC low-voltage grid feeders to DC is a suitable solution to mitigate overloading and decrease voltage fluctuations caused by, inter alia, the integration of Electric Vehicle (EV), PV or by an increased energy demand. Cost models were applied to the simulation results. The economical findings indicate that the implementation of DC in low-voltage grids can be financially beneficial, especially if future developments and learning curves of DC technologies are considered. Further tools will be included such as the AIT storage scaling tool or Matlab SIMULINK to adopt the tools for the needs within the HYPERRIDE project.

Hybrid ACDC simulations are performed in Power Factory, controlled via the integrated Python API. In a web user-interface, the simulation parameters can be controlled, and live simulations can be performed. Figure 5 depicts the input interface.

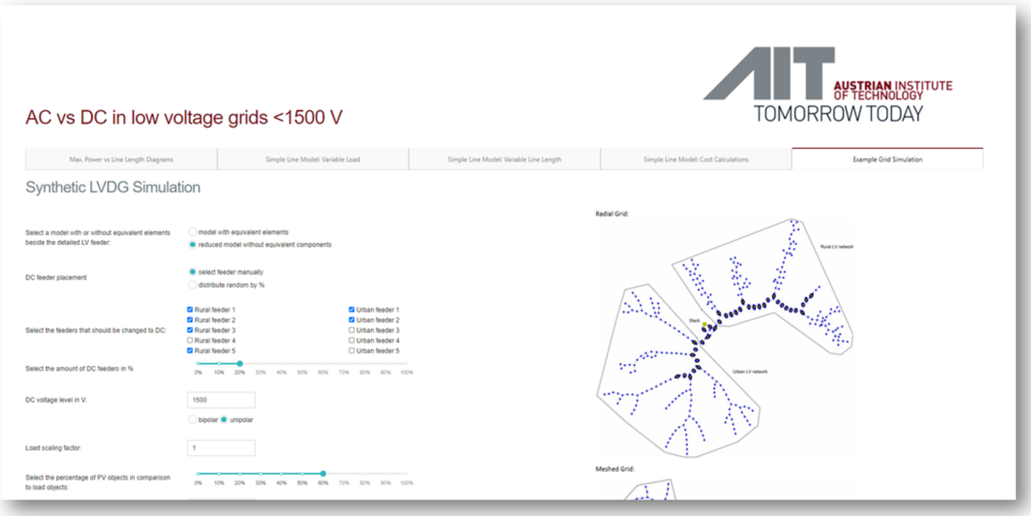

Figure 5: User-interface for hybrid ACDC grid planning simulation tool.

Different simulations can be selected and fully parameterized, as well as an economic analysis can be performed on the most recent simulation results. All input parameters are customizable, such as EV and PV penetration, hybrid scenarios, LVDC voltage level and configuration (unipolar/bipolar) etc. Furthermore, a simulation date can be selected, feeding the model with 15 min resolution load, PV and EV profiles.

For the hybridization of the LV grid, a method was developed to convert existing Low Voltage Alternating Current (LVAC) lines to LVDC lines in Power Factory, using equivalent line types and variable line configurations for DC. Using defined scenarios for future usage of DC in the LV grid, the LV feeder within a test grid can be converted to DC according to the scenarios shown in Figure 6.

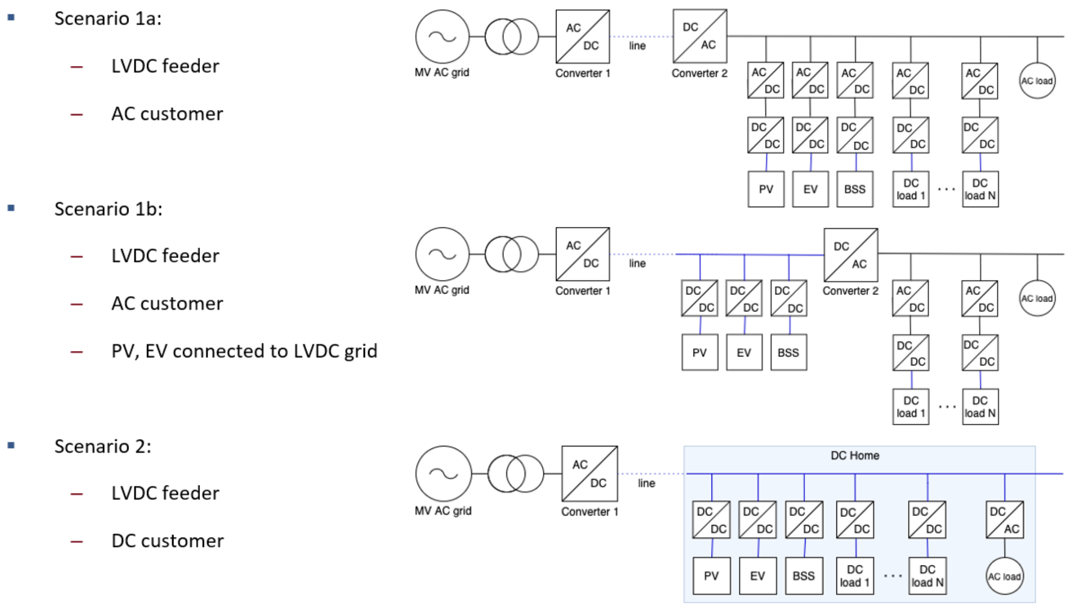

Figure 6: LV hybrid AC/DC grid scenarios.

The user-selected conversion is simulated and compared to the pure AC simulation of the model. For the economic analysis, the following parameters can be defined: Voltage Source Converters (VSC) CAPEX [€/kW], line CAPEX [€/m], VSC life cycle [a], system life cycle [a], VSC OPEX [$\%VSC_{CAPEX}$/a], line OPEX [$\%LINE_{CAPEX}$/a], energy price (losses) [ct/kWh] and equivalent yearly operation hours at max load $[h/a]$ (if necessary).

The goal is to include a model of the Italian pilot (WP8) in the simulation and link the tool with the component sizing tool (T3.2) and potentially Matlab SIMULINK for optimal storage sizing and the implementation of hybrid AC/DC control strategies. This allows a simulation-based analysis of the pilot installation for HYPERRIDE. Further possible applications within HYPERRIDE are the techno-economic evaluation of the use cases for LVDC defined in WP2 and thus the creation of a basis for the business model development in WP9.

Target TRLs and responsibility for the solution can be seen in Table 3.

Table 3: Responsibility and TRL target for grid planning tool.

Lead partner	AIT
Start TRL	5
End TRL	8

Main roles for tool development and demonstration are as follows:

- AIT: development of tool; link to component sizing tool (T3.2); lead of further collaborations and integration of other tools;
- ASM: Italian pilot technical information and data for simulation model; simulation data from other simulation tools for compariso;
- EATON: Matlab SIMULINK models for hybrid AC/DC control strategies.

A general specification of the solution can be seen in Table 4 and Table 5.

Table 4: Functional specification for grid planning tool.

Function	Description
Line type max P vs. line length	Analyse given line types in terms of their transmission capacity in chosen DC configurations and compare to AC operation
Line model variable load simulation	Select line type, maximum load and line length and simulate a linear load profile in AC and DC to compare behaviour at different load situations
Line model variable line length simulation	Select line type, maximum line length and load and simulate a linear line length profile in AC and DC to compare behaviour at different line lengths
Line model cost analysis	Apply cost model (flexible input parameter) on line model variable load or variable line length simulations for economic analysis of different scenarios
Daily synthetic grid simulations	Customizable hybridisation of synthetig grid models in the LV feeder level, daily simulations using 15-minutes profiles, additional PV and EV loads can be added to the system
Yearly synthetic grid simulations	Customizable hybridisation of synthetig grid models in the LV feeder level, yearly simulations using 15-minutes profiles, additional PV and EV loads can be added to the system
Economic analysis using yearly simulation data	Apply cost model (flexible input parameter) on synthetic grid yearly simulation results for economic analysis of conversion to DC instead of reinforcement of AC feeder

Table 5: Value based specification for grid planning tool.

Parameter	Values	Unit
GRID simulation		
Synthetic grid model w/ or w/o equiv. Loads	w/ or w/o	
LV feeder selection (rural and urban) for conversion to DC	1-5 rur. / 1-5 urb.	
LVDC voltage level	100-1500	V
DC system configuration	unipolar / bipolar	
Model heat pumps or additional customers	0.1-5	
Household load efficiency gain if connected to LVDC	0-30	%
PV penetration (Function of nr. of loads)	0-100	%
PV efficiency gain if connected to LVDC	0-30	%
EV penetration (Function of nr. of households)	0-100	%
EV efficiency gain if connected to LVDC	0-30	%
Topology for AC LV grid	radial / meshed	
AC/DC hybrid scenario	1a / 1b / 2	
VSC 1 efficiency	0.6-1	
VSC 2 efficiency (only applies to scenario 1)	0.6-1	
VSC rated power ratio (ratio of max. feeder Sin_max / max. household load Sload_max for VSC2)	0.5-1.2	
Cost model		
CAPEX VSC	100-500	EUR/kW
CAPEX rural line reinforcement	30-120	EUR/m
CAPEX urban line reinforcement	30-120	EUR/m
VSC life cycle	10-50	a
System life cycle	10-100	a
OPEX VSC	0-5	$\%VSC_{CAPEX}$/a
OPEX line reinforcement	0-5	$\%LINE_{CAPEX}$/a
Energy price (energy losses price)	0-10	ct/kWh

3.2 DC Grid Simulation Workflow

Different from the conventional AC grids which are dominated by synchronous machines with high mechanic inertia and slow dynamic transient, the DC grids are dominated by power electronics converters which are operating at high frequencies over 1 kHz. Hence, the DC grids present faster dynamic transients compared to the conventional AC grids, and an investigation of the DC grids in different time scales is mandatory. Offline computer simulation is widely used for the analysis of modern power systems. The DC grids in general include three electric components, namely power cables, DC circuit breakers and power electronics converters. At the Institute for Power Generation and Storage Systems, simulation models of different electric components used in DC grids have been developed in past research activities based on the PLECS simulation platform (see Figure 7. These components include:

- Power cables: Multi-section Resistance, Inductance, Capacity (RLC) cable model and transmission line model which can emulate travelling wave effect and skin effect of DC power cables;
- DC circuit breakers: Hybrid DC circuit breakers with Metal Oxide Varistor (MOV);
- Power electronics converters: Two-level dual-active bridge, three-level neutral-point-clamped dual-active bridge, series resonant converter three-level neutral-point-clamped active front end, modular multilevel converter.

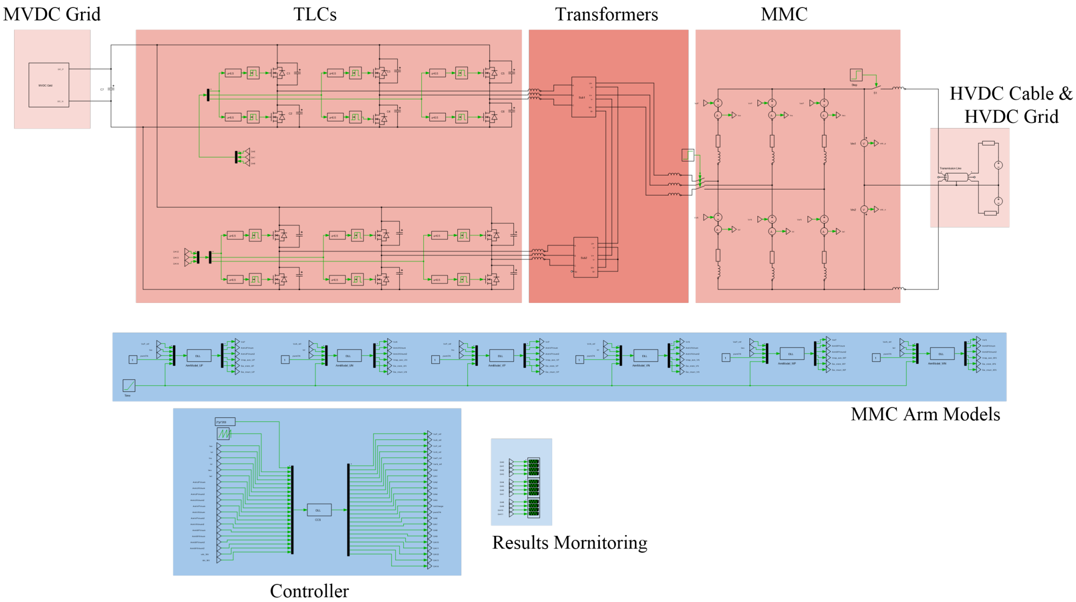

Figure 7: Simulation model of the DC-DC converter interconnected to HVDC grid via HVDC cables using PLECS simulation platform.

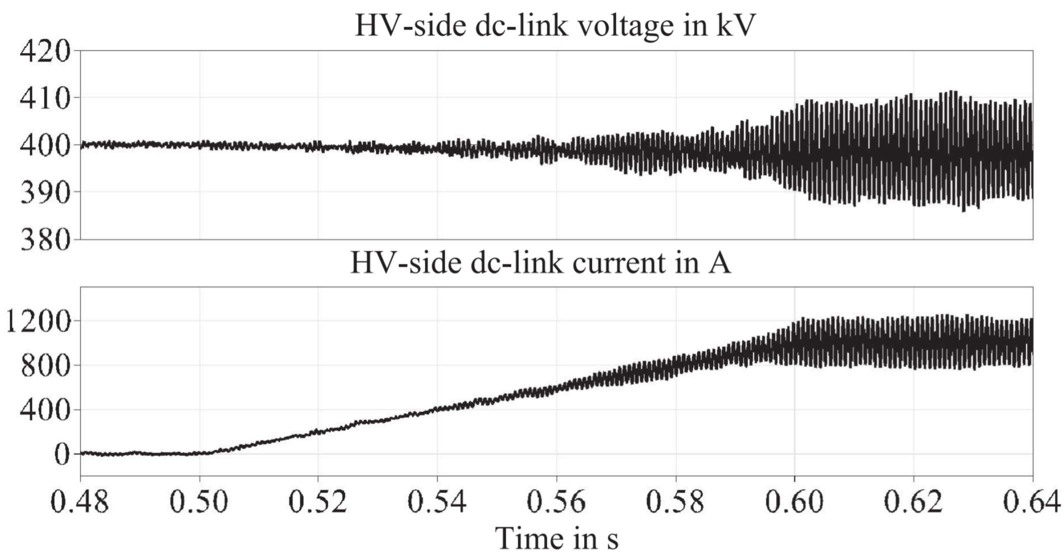

Figure 8: Simulation results of the case study where interaction of the DC-DC converter and the HVDC cable results in harmonic instability (Cui et al., 2020).

With the available complete category of electric components in DC grids (supported by other enabling technologies), the investigation of the DC grids can be easily performed in a modular approach. A typical simulation result can be seen in Figure 8. Besides the offline simulation models, real-time simulation models and hardware as well as down-scale converter prototypes have been developed and commissioned. Hence, the current tools/infrastructure/know-how enables a multi-stage commissioning, investigation, and validation of DC grids related study, e.g., optimal power flow control and harmonics propagation as depicted in Figure 9 Workflow of DC grids investigation.

Figure 9: Workflow of DC grids investigation.

Target TRLs and responsibility for the solution can be seen in Table 6.

Table 6: Responsibility and TRL target for DC grid simulation workflow.

Lead partner	RWTH
Start TRL	5
End TRL	8

Main roles for tool development and demonstration are as follows:

- RWTH: development of tool based on the workflow depicted in Figure 9, link to hybrid converter control (T3.11) and field test activities at German pilot site;

A general specification of the solution can be seen in Table 7 and Table 8.

Table 7: Functional specification for DC grid simulation workflow.

Elements	Description
Offline simulation	Dynamic simulation of DC grids based on power electronics converters.
Software	PLECS
Cable model	Transmission line mode, multi-section RLC model.
DC circuit breaker model	Hybrid DC circuit breaker.
Converter models	2L-Dual Active Bridge (DAB), 3L-DAB, 3L-Neutral Point Clamped (NPC), Modular Multilevel Converter (MMC), Silicon Controlled Rectifier (SRC).

Table 8: Value based specification for DC grid simulation workflow.

Parameter	Values	Unit
DC-link voltage of downscale converter prototypes	120	V
Switching frequency of downscale converter prototypes	20	kHz
DC-link current of downscale converter prototypes	10	A

3.3 Microgrid Model

The energy transition towards high integration of Decentralized Energy Resources (DER) and EV charging can be enabled by the development of DC and hybrid ACDC power systems, at the low and medium voltage levels. The design of such solutions needs to consider the grid stability, as well as better power flow control and optimization algorithms. For a faster and cost-effective development process, modelling and simulation at component (energy assets) and system level is of great help.

For certain use cases, a virtual microgrid model can be used to validate the control strategy, test grid stability when large (load jump, in-rush currents, short-circuits) and small (converter instabilities) disturbances are applied. In this task, the team will build the simulation model in Simulink (see Figure 10, Figure 11 and Figure 12) or PSCAD for the charging infrastructure system (or the proposed demonstrator). The control algorithm, based on a decentralised control strategy (such as virtual impedance method), will be implemented in the system model. The virtual microgrid model will be linked with the higher level hybrid ACDC grid model and the interaction and the macro-stability will be verified and optimised.

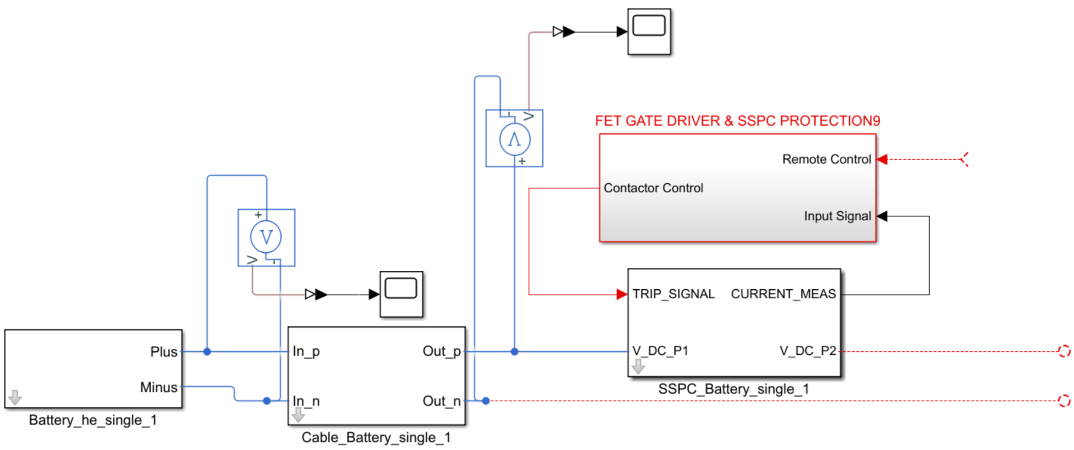

Figure 10: Battery bay model in Simulink (example).

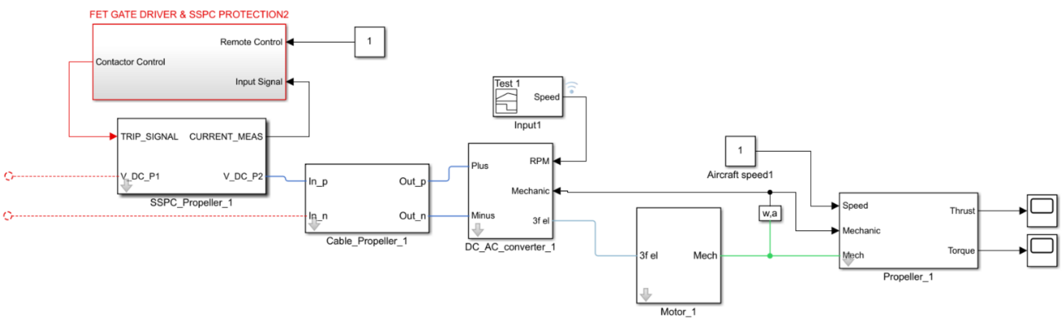

Figure 11: Propeller bay model in Simulink (example).

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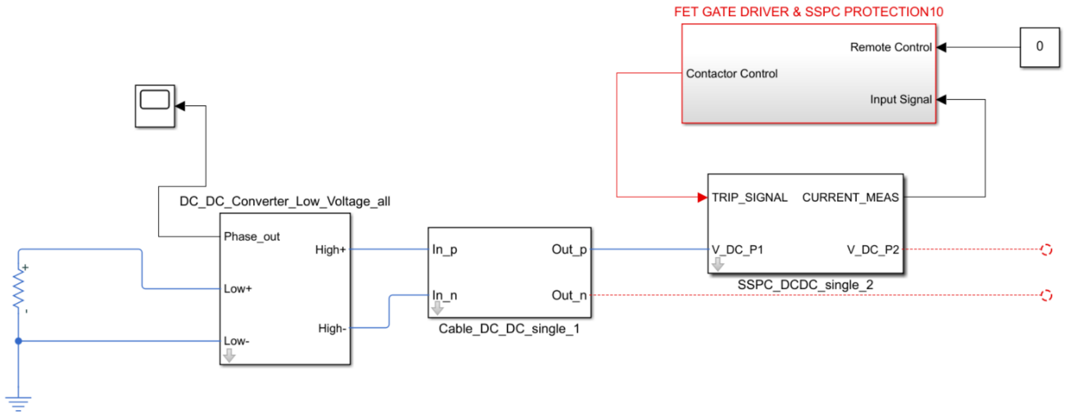

Figure 12: Load bay model in Simulink (example).

For each considered use case, a virtual microgrid will be designed to include the models of the energy assets integrated in the system (see Figure 13). A list of relevant scenarios will be defined, and the system performance will be verified by Simulink or PSCAD simulations. The system model will include the Active Front-End (AFE) component and the effect of AC grid activity on the DC grid behavior. Also, the virtual impedance control strategy will allow the simulation of functional choices for the user, such as maximum self-consumption, EV charging using mainly green-energy, peak shaving, etc.

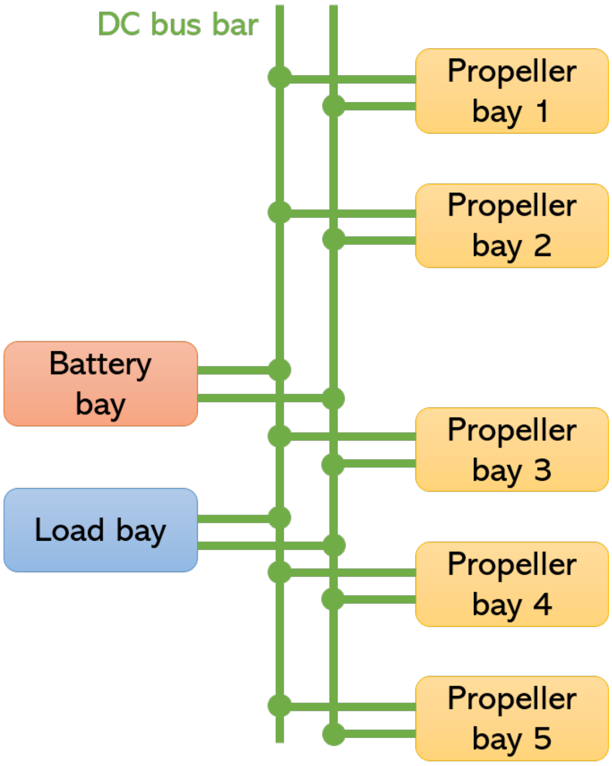

Figure 13: Aircraft power system diagram example, implemented in Matlab Simulink.

Any company or customer that designs and exploits a DC and hybrid ACDC power distribution system can verify the performance and analyse the advantages and the challenges, without the need of building a prototype. In this way, better solutions can be built in shorter time and with less cost.

Target TRLs and responsibility for the solution can be seen in Table 9.

Table 9: Responsibility and TRL target for microgrid model solution.

Lead partner	Eaton
Start TRL	5
End TRL	8

Partner roles:

- Eaton: build the virtual microgrid model, using the component model library and the use case description;
- ASM: provide the parameters for the hybrid AC/DC grid where the microgrid will be integrated;
- All partners: provide relevant use case descriptions and measurement results that will allow model validation, both at component and microgrid levels.

The input parameters and functional specifications of the solution can be found in Table 10 and Table 11.

Table 10: Parameter specification for microgrid model.

Input Parameters	Description
Component parameters	Each asset will have a default value (storage: [kWh] and [kW], PV: [kWp], AFE: [kW]), which can be changed for the defined use case.
PV production profile	PV production over the simulation time, with a resolution of 15 min. Can be from a predefined group of profiles, or can be provided by the user as .csv file.
Load profile	Load consumption over the simulation time, with a resolution of 15 min. Can be from a predefined group of profiles, or can be provided by the user as .csv file.
Simulation time	Time duration of the simulation, in which the PV and load consumption are following the selected profiles. The bus voltage and the current at each asset is calculated for each simulation step.
Droop curve parameters	Each asset is connected to a local controller, which will run a droop curve algorithm, in which a direct dependence between the bus voltage and the current is set. The parameters of the droop curve can be defined manually at the beginning of simulation, or can be calculated by the optimization algorithm.
Optimization scenario	The decision algorithm used to operate the microgrid towards an optimization criterium: maximize self-consumption, minimize cost, minimize public grid impact. Based on this algorithm, the central controller will change the parameters of the local droop curves for microgrid operation.

Table 11: Functional specification for microgrid model.

Functions	Description
Component models	MATLAB/Simulink models of the assets to be included in the grid model.
Microgrid architecture	The list of assets and the power connection diagram between assets.
Control algorithm	The algorithm used to take decisions for grid stabilization and power flow distribution between the DER and loads.
Virtual microgrid	System level model that can simulate the functional microgrid, including the component models and the control algorithm.

3.4 Component Sizing Tool

The Component Sizing Tool is an online tool, which can be used for sizing system components of ACDC and DC grids.

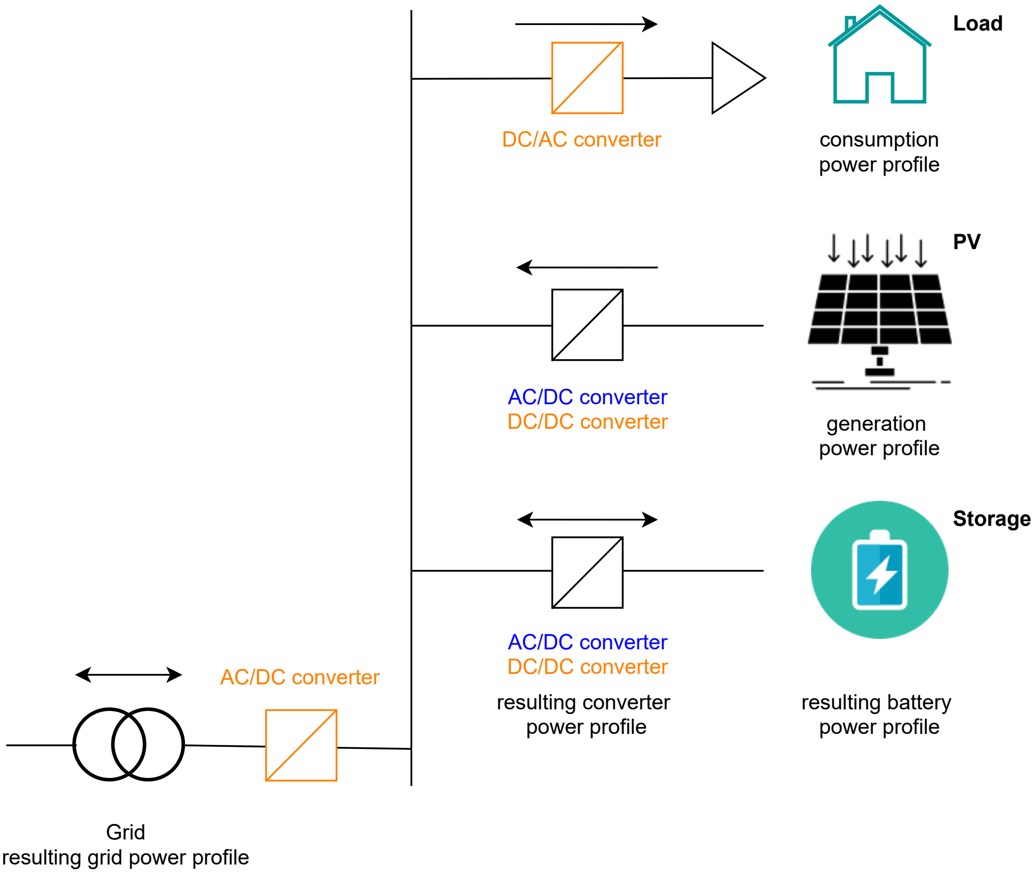

Figure 14: Component sizing tool.

The Deliverable of T3.2 is a demo version of the online Component Sizing Tool, with an additional report explaining the calculations and simulations in the background. The simulation model and the online tool, however, will remain the intellectual property of AIT, the code itself will not be made public. The Component Sizing Tool for technical and economic optimisation is under the lead of AIT. The main partners are EMOTION and ASM, anyhow, other partners also expressed interest in the tool. The main partner participation will be providing profile data for the simulations. The simulation model and evaluations used for the tool was developed beforehand by AIT and was further improved during the HYPERRIDE project.

The Component Sizing Tool for economic optimisation will provide a technical and economic base for finding the optimal component size solution for different use cases. There are three specific use cases where the Component Sizing Tool will be used within the HYPERRIDE project. The first use case is as an addition to the Grid Planning Tool for the development of Hybrid ACDC microgrids, for the simplified simulation of battery storage within Hybrid ACDC microgrids. Secondly, the tool will be used for simulations in the Italian pilot as EMOTION and ASM are the main contributors. Therefore, input data from the partners will be pre-implemented into the online tool to simplify the tool usage. As a third use case, the tool will be used to generate input parameters for creating business models, regulatory and identify consumers. The user therefore has the opportunity to download HTML reports as well as simulation value details of the whole simulation time frame as Comma Separated Values (CSV) file.

The simulation code behind the Component Sizing Tool is a steady state simulation based on a consumption and a generation profile, a Battery Energy Storage System (BESS) and a Point of Common Coupling (PCC) to the main MV grid. Further included are different converters which can be defined by the user in order to differentiate between AC grids and hybrid ACDC grids. The system components can be seen in Figure 14. The core functionalities of the Component Sizing Tool were developed within AIT over the last years. Further existing was a similar online tool to the Component Sizing Tool. The core focus however was not component sizing but mainly battery sizing and evaluating different behind the meter battery use cases in solely AC grids. During the HYPERRIDE project, the already developed code was restructured and partly re-written, such that the results were independent code components that can be linked to any specific use case as well in AC grids as in ACDC hybrid grids. Further, the online tool was completely re-written based on the new system components and adding the possibility to simulate ACDC grids as well as DC grids and ACDC hybrid grids.

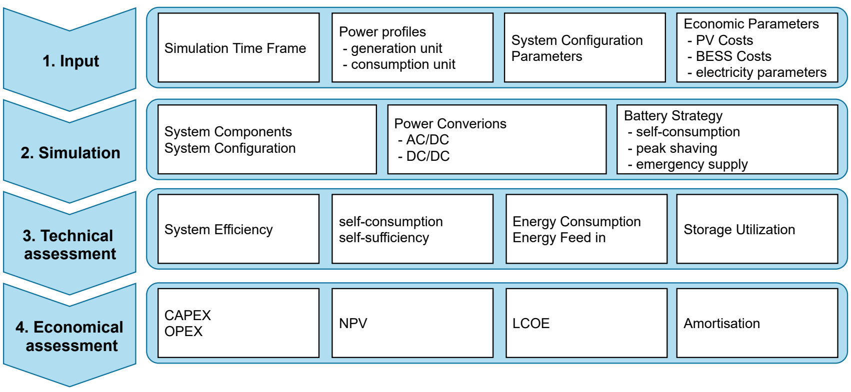

Figure 15: Workflow of the component sizing tool.

The Workflow of the component sizing tool can be seen in Figure 15. Figure 14 shows the Component Sizing Tool components as they were implemented in the end. The orange converters were added specifically for the HYPERRIDE usage. Anyhow, the load profile is expected to already include any conversion losses. The resulting power profile at the Medium Voltage Alternating Current (MVAC)/LVAC transformer also does not include any converter nor transformer losses. These would have to be accounted for independently. The now available Component Sizing Tool can simulate up to five system configurations at once. While the load profile remains constant, the PV power plant, the BESS and the converters can be configured independently for each system configuration. This enables the user to evaluate and compare system configurations with different generation power plants and/or equal system configurations in AC grids with AC/DC hybrid grids.

Main roles for tool development and demonstration are as follows:

- AIT: development of tool; link to grid planning tool for the development of Hybrid AC/DC micro-grids in parallel with existing MV/LV AC-grids (T4.8); further tool developments as required within HYPERRIDE; techno-economical input data for the evaluation and comparison of HYPERRIDE business models
- ASM: Italian pilot technical information and profile data for system configuration
- EATON: Italian pilot EV charging profile data for system configuration

Target TRLs and responsibility for the solution can be seen in Table 12

Table 12: Responsibility and TRL target for component sizing tool:

Lead partner	AIT
Start TRL	5
End TRL	8

A general specification of the solution can be seen in Table 13 and Table 14.

Table 13: Functional specification for component sizing tool.

Simulation Functions	Description
set point power definition	The set point power is the output of the operation strategy (self consumption optimisation)
storage simulation	The set point power is forwarded to the main simulation, the set point power is converted and the storage charged or discharged with the fitting available storage power
grid connection	The grid connection is calculated by the difference between load, generation and storage charging/ discharging power per time step
Technical evaluations	evaluating self-consumption, self-sufficiency, battery usage, grid connection power etc.
economic evaluation	Calculating revenues, costs, Net Present Value (NPV), amortisation time
Tool Output	HTML reports for profile analyses,battery usage analyses, application analysis and the technical results as CSV file.

Table 14: Parameter specification for component sizing tool.

Input Parameters	Description
Unit setting	In order to run the simulation it has to be defined whether the simulation shall be done in kW or MW, all profiles will be converted to the chosen unit
consumption profile	Consumption profiles can be chosen from a variety of predefined profiles or uploaded as a csv profile.
generation profile	Generation profiles can be chosen from a variety of predefined profiles, generated directly in the online Tool, or uploaded as csv profile .
Load Profile scaling	The load profile can be scaled by te amount of annual consumption.
simulation time horizon	The simulation can be done for any time frame within the profile. Note: The longer the time frame, the longer the simulation takes.
converter efficiency	define the overall converter efficiency, based on the necessary conversion steps, for the PV converter and the BESS converter.
PV sizing	The amount of installed PV power can be defined for each system configuration.
BESS sizing	The BESS can be defined by capacity and power for each system configuration
economic parameters	Economic input parameters such as investment and operation costs for the generation power plant and the battery as well as Feed in Tariff (FiT) if applicable

3.5 Component Model Library for LVDC

DC power systems are showing promising features for enabling the energy transition towards DER and EV charging integration. However, the benefits of DC sub-grids and hybrid ACDC grids are maximised with the proper design of the grid and sizing of the DC components, as well as the control software and hardware. A good understanding of MV and LVDC components and their interaction in systems is needed for an efficient operation in hybrid ACDC grids.

In this task, a list of components is defined, and a simulation model is developed for each component in MATLAB, including the components developed in WP3. All the developed modules will constitute a library that can be used to define system models for the LVDC grid in various use cases. Each model will be configurable using model parameters and will be verified in basic simulation configurations, including MVDC protection scenarios, in Simulink or PSCAD.

The models will be suitable for simulating various operation conditions of the components, power converters, storage, PV generation and EV or aircraft charging, controllers, as well as most relevant use cases. The model description, parameters and the detail level will be decided based on the type of simulation that is requested. The targeted model types are:

- Average model: less complexity and faster time domain simulation studies of grid connected converters, while preserving a certain level of converter dynamic accuracy (converter interaction phenomena, stability, short circuit analysis);
- Switching model: These models will be used to assess the control loop of the converters,

with more accurate time steps, although longer time for simulations. This method is suitable for transient behaviour analysis, including in-rush currents peaks and fault reaction;

- Dynamic phasor model: dynamic behaviour and stability of power systems;
- Small signal model: to analyse the effect of the converter parameter variations. These studies can be used to design robust control strategies, that will recover from instabilities triggered by converter functional disturbances;
- Large signal model: to analyse the converter and system functionality when the operating conditions of the grid are changing (load jump, in-rush currents, overvoltage, etc);
- Real-time model (OPAL-RT or similar): the grid configuration and the effects of the converter dynamic behaviour on the grid stability will be assessed using OPAL-RT real time models and hardware (Central Processing Unit (CPU) or Field Programmable Gate Array (FPGA)).

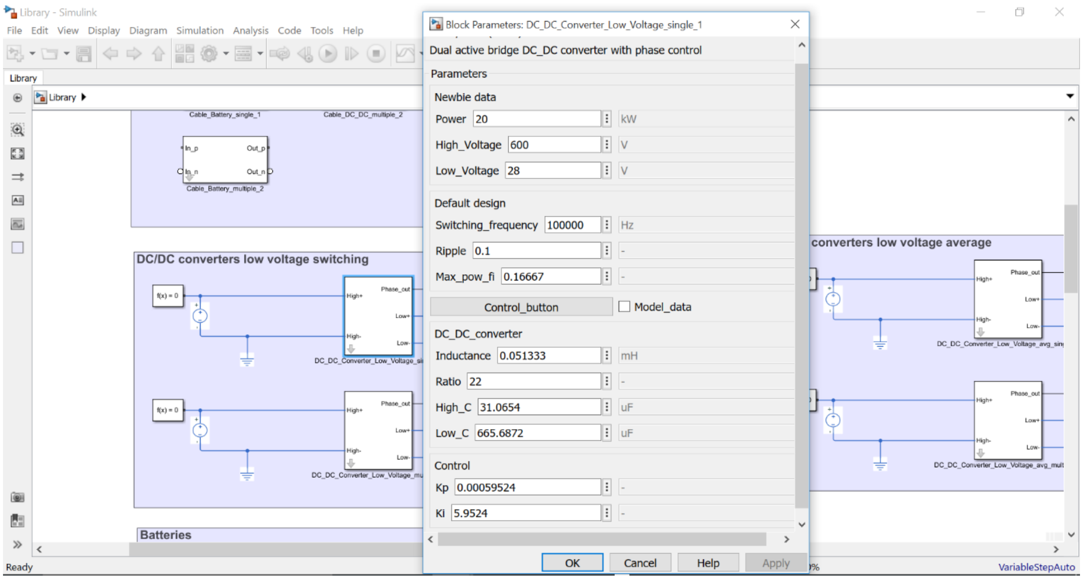

Figure 16: Screenshot of the library, with the dialog window for setting the parameters for the model. Example on DC/DC DAB converter

The component model library, allowing model-based design through the grid modelling and simulation, will facilitate the assessment of the proposed solutions for the DC and hybrid AC/DC distribution. Furthermore, the grid control and topology configurations can be optimised by using system modelling and use case simulations.

Therefore, all the component and system providers may benefit from the availability of the model library, being able to quickly integrate and adapt the models to the existing hardware parameters, so that the final system functionality and stability can be verified in a virtual testing. At the same time, the potential customers searching for energy transition solutions, to integrate DER and EV charging, can assess the benefits of adopting DC and hybrid ACDC power systems. The models can be accessed from the library, together with benchmark configurations that will allow the evaluation of model performance and model validation using experimental results.

Target TRLs and responsibility for the solution can be seen in Table 15.

Table 15: Responsibility and TRL target for component model library for LVDC.

Lead partner	Eaton
Start TRL	5
End TRL	8

Within the project, the main contributors are:

- Eaton:
  - Build models for the unitary or distributed charging units, DC protection devices and aircraft circuitry, including the battery (aircraft charging infrastructure use case).
  - Create model data base using models created by Eaton and provided by partners.
- EPFL, ASM, RWTH:
  - Provide existing models for DC power components, planned for building DC micro-grids on site.

A general specification of the solution can be seen in Table 16.

Table 16: Model specification for component model library for LVDC.

Model	Description
Switching model	Component model implementing a detailed working principle of the converter, capturing high time resolution signal changes. The simulations involving these models show fast phenomena, such as bus precharging, over-current during switching and current rise during short circuit fault, as well as parasitic effects. However, these simulations take longer, therefore are used for short time studies.
Average model	Component model implementing the general behaviour of the converter, close to ideal converter. The simulations involving these models are faster, although are not showing the short changes in signals. These models are used for validating the system functions and to estimate the effect of changes in system design.
Small signal model	Small signal model of a power converter is implementing the averaged, linearized, small signal AC behavior around a steady state operating point of the converter. It can be used to predict the system transfer functions that are useful in the design and validation of the converter control algorithm.
Dynamic phasor model	Dynamic phasor models are developed from time-domain descriptions using the generalized averaging procedure. It consists in demodulating the signal in its frequency components using a Fourier series represenatation. Dynamic phasor formulation supports fast computations for systems with large number of switched converters including a large distribution feeder. The dynamic phasor circuit models can be modeled directly into circuit simulators such as MATLAB, PSCAD, MODELICA, or any other ordinary differential equation solver.
Input: Model parameters	Each model can have a number of setting parameters which can be used to adapt the model to a certain design specifications or a concrete converter that is used in one of the demonstrators. The model parameters for a real component can be tuned by comparing a set of measured results with the results of the simulation for the same scenario.

4 Grid Automation

To realise planned DC grid installations it is necessary to provide grid control algorithms for stable operation, automation solutions which might be more time critical as AC solutions due to missing zero current (and voltage) crossings. Further, tools for power flow optimisation, state estimation for more flexible control and means of fault mitigation need to be provided. All of them differ from state-of-the-art AC solutions. Further, it is important to monitor and control grid assets and infrastructures such as EV charging posts.

4.1 Grid Control Algorithms

In order to enable the integration of a high share of RES, hybrid ACDC microgrids can be included in parallel with current (large-scale) AC distribution grids. The benefits of LVDC distribution grids and sub-grids are given by their control strategy, which allows optimised operation and flexibility. A well-defined control algorithm enables automatic response of the grid to the fluctuations in the energy supply, given by distributed, renewable sources, and in the energy demand, as given by the EV charging. Enhanced by automation features, the control strategy can provide innovative technology solutions for resilient autonomous self-healing as well as protection, while improving network observability through real-time system awareness. Therefore, modular grid planning and control can assure the transition from typical pure MVAC/LVAC grid architectures to hybrid ACDC structures that integrate microgrids topologies.

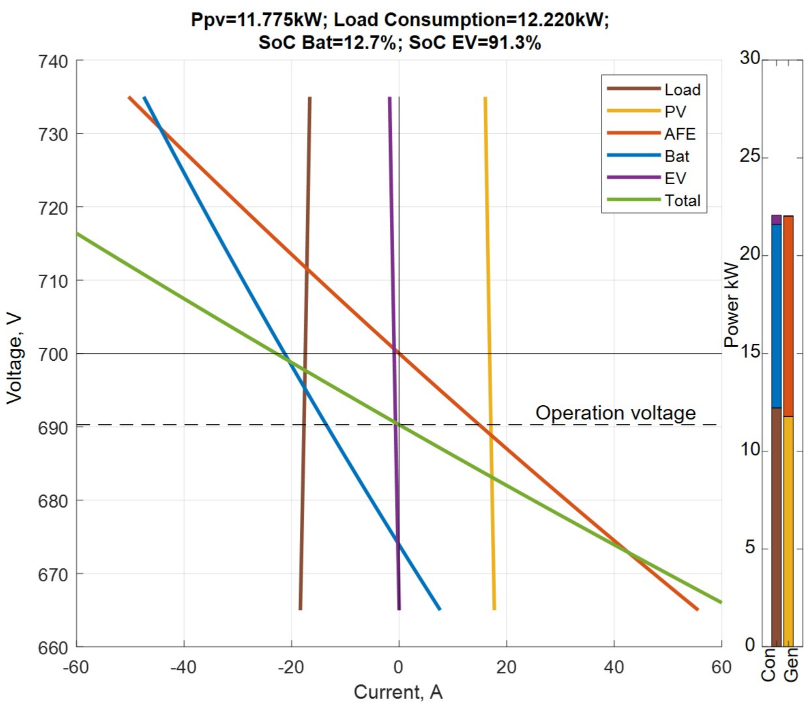

Figure 17: Example of the droop curve inter-dependencies for all the energy assets in the grid (virtual impedance control method).

The control strategy designed for LVDC microgrid configuration will assure the microgrid stability, while offering control over power flows between the distributed generation and controllable loads. The algorithm can also be used to assist the energy management system and optimisation procedures. At the same time, the control of the LVDC grid must be aligned with the overall hybrid ACDC grid control and automation requirements, for maximum benefits. Figure 17 shows an example of the inter-dependencies of droop curves for different grid participants.

The control algorithm is using the virtual impedance method, implemented through local and central controllers.

The main features of the solutions are:

- Seamless integration of DER (PV and other), energy storage and EV charging;
- Control of the power flow distribution between the distributed generation and controllable loads;
- Automatic adjustment of the bus voltage and current levels, based on droop curve settings stored in the local controllers;
- Optimization algorithms can be implemented using a central controller, for different scenarios: maximize auto-consumption, minimize energy price, smart charging, etc.;
- Use renewable energy generation and energy storage for reducing the impact of EV charging on the distribution grid.

The solution is aimed to be used by the providers of power distribution components and systems, public administrations who want to implement green energy solutions, as well as potential customers (collective housing, light commercial buildings, EV charging for public transport, including aircrafts);

Target TRLs and responsibility for the solution can be seen in Table 17.

Table 17: Responsibility and TRL target for grid control algorithms.

Lead partner	Eaton
Start TRL	5
End TRL	8

Within HYPERRIDE the following partners are main contributors:

- Eaton's tasks are to:
  - develop the DC microgrid control algorithm;
  - validate control strategy in the virtual microgrid model, using the component model library;
  - implement the algorithm in Eaton's controllers and verify in a Controller-in-the-Loop configuration;
  - Build the microgrid in Terni and demonstrate the control algorithm.
- ASM:
  - integrates the LVDC demonstrator within the Terni demonstrator site.

A general specification of the solution can be seen in Table 18.

Table 18: Functional specification for grid control algorithms.

Function	Description
Droop curve	In the Virtual Impedance Droop Curve (VMDC) microgrid control strategy, represents the current-voltage diagram that each asset is following during automatic functioning of the microgrid. For a certain voltage of the DC bus, each asset will draw or provide a current according to the droop curve.
Local control	The control algorithm implemented locally for each asset. For the VMDC control, it takes the bus voltage as input and calculates the corresponding current. It can be implemented as a formula or as a look-up table.
Central control	The control algorithm implemented at the system level, which determines the local control parameters. For the VMDC control, it calculates the droop curve parameters (the virtual impedances and the operation limits) for each asset.
Virtual impedance	It implements a controlled reduction of the current drawn or provided by an asset, such that it complies with a power flow distribution decided by the user. A droop curve controlled grid uses a set of virtual impedances for each optimized regime.
Control algorithm	The algorithm used to take decisions for grid stabilization and power flow distribution between the DER and loads.
Virtual microgrid	System level model that implements the control algorithm to simulate the functional microgrid.
Input: Optimization regime	Input value or set of input values for the central control. Possible options are maximum self consumption, peak shaving, minimum price, minimum impact to the public grid. For each option, the central control will send the set of droop curve parameters for each local control loop.
Input: Local droop curve parameters	The virtual impedance and the limits of the droop curve for each asset. If the local control implements a look-up table, the central control will send the entire table to the local control.

4.2 State Estimation Energy Service for Hybrid ACDC Distribution Grids

To manage the correct operation of power systems, various application functions such as contingency analysis, corrective real and reactive power dispatch could not be executed without knowing the real-time operating conditions of the system. However, the information provided by the Supervisory Control and Data Acquisition (SCADA) system may not always be reliable due to the errors in the measurements, telemetry failures, communication noise, etc. Furthermore, the collected set of measurements may not allow direct extraction of the corresponding AC operating state of the system. For instance, bus voltage phase angles are not typically measured, and not all the transmission line flows are available. Besides, it may not be economically feasible to telemeter all possible measurements even if they are available from the transducers at the substations. Moreover, state estimators also function as filters against incorrect measurements, data and other information received through the SCADA system.

The State Estimation (SE) is a mathematical approach applied to power systems and consists of processing redundant measurements in order to provide an optimal estimate of the current operating state. Usually, the states are constituted by voltage phasors at all of the system buses at a given point in time. Consequently, all the other electrical quantities of the network are computed via the fundamental electrical functions. The mathematical technique called Weighted Least Square (WLS) is frequently implemented in the state estimation, by integrating the accuracy of measurements and aiming at iteratively minimising the error of estimated states. State estimation has traditionally been applied for the monitoring of transmission systems, gaining more and more attention from the scientific community and grid operators. In the recent years, its use has been extended also to distribution grids, considering the necessary adaptations in the algorithms due to, for example, the different size of network nodes, the possible phases unbalances, the reduced availability of measuring devices. However, the expansion to the hybrid ACDC grids has not reached a maturity level yet: in the dedicated current literature, in fact, only a few research works addressed this specific grid configuration.

The critical point is represented by the buses that interface AC and DC systems: the modelling of the power flow values through the ACDC converter constitute the difference among the existing methods, in particular with respect to the converter losses. Several approaches rely on successive iterations of a sequential SE algorithm, without considering the converter power losses. On the contrary, the state estimation approach considered in the HYPERRIDE implementation is a two-step technique, developed at the Flexible Electrical Network (FEN) research campus. It guarantees fewer iterations and computation times than the iterative methods: in the first step two separated state estimators, for the AC and DC sub-systems respectively, are carried out; successively, the estimates are merged together, accounting for the converter losses (Pau et al., 2016).

The AC/DC converter considered in the approach is a VSC type, represented in Figure 18; the power exchange among AC and DC side is:

$$P_c^{DC} = P_c^{AC} - P_c^{loss} \tag{1}$$

In which the power loss P_c^{loss} is modelled as:

$$P_c^{loss} = a + b \cdot I_c^{AC} + c \cdot (I_c^{AC})^2 \tag{2}$$

Where a, b and c are loss coefficients characterizing the switching and conduction losses of the converter.

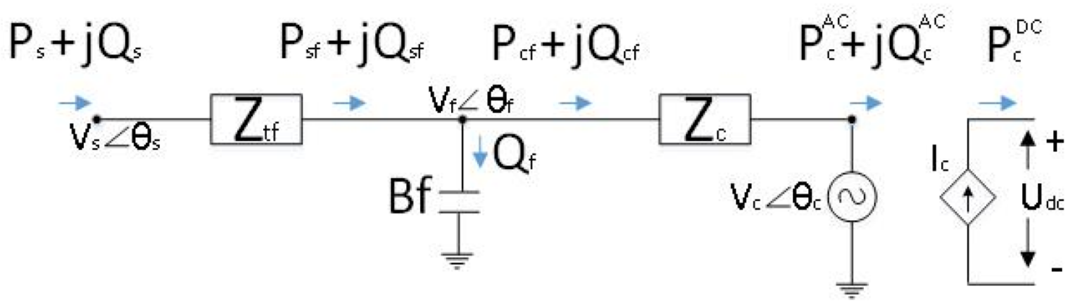

Figure 18: Single-phase model of AC/DC converter (Pau et al., 2016).

The flowchart of the technique that is being used is shown in Figure 19. SE is crucial for the development of other HYPERRIDE activities; in particular SE is leveraged by energy services (e.g., service restoration and optimal power flow) that are developed in Task 4.5, integrated in the HYPERRIDE ICT platform and tested in the pilot sites. In fact, the accurate and reliable depiction of the electrical grid behaviour is strictly necessary for the correct operation of the energy management, particularly in emergency conditions (as in fault situations).

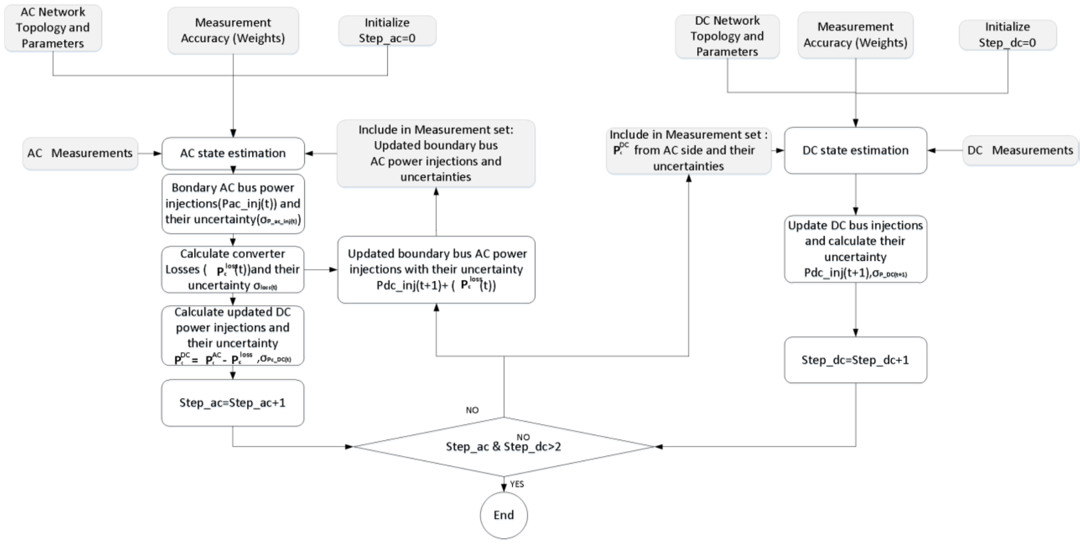

Figure 19: Flow chart of the AC/DC state estimator (Pau et al., 2016).

Target TRLs and responsibility for the solution can be seen in Table 19.

Table 19: Responsibility and TRL target for state estimation energy service for hybrid AC/DC distribution grids.

Lead partner	RWTH
Start TRL	5
End TRL	8

Main roles for tool development and demonstration are as follows:

- RWTH: responsible for the development of the referred state estimation method as a middleware software component; it will deploy, among the main features, scalability, open access and reusability.

A general specification of the solution can be seen in Table 20 and Table 21.

Table 20: Functional specification for state estimation energy service.

Function	Description
WLS for AC	Weighted Least Square (WLS) method for AC portion of the grid
WLS for DC	Weighted Least Square (WLS) method for DC portion of the grid
Integration for AC/DC	two-steps AC-DC exchange to determine AC/DC estimation

Table 21: Value based specification for state estimation energy service.

Parameters	Values	Unit
Grid measurements	Node voltage (waveform)	kV
	Branch current	A
	Switch status	on/off
	Branch power flow	kW; kVar
	Node power injection	kW; kVar
Forecasts	Load consumption	kW; kVar
	RES power generation	kW; kVar

4.3 Optimal Power Flow Energy Service for Hybrid ACDC Grids

Optimal Power Flow (OPF) is a grid management technique that consists of determining the most optimal set of variables in an electrical network, in order that the related power flow results fulfil pre-determined criteria. The variables considered in the adjustment can be, for example, the power set points of Distributed Generators (DG) or power converters, the position of transformers tap-changers or the position (open - close) of tie-switches. Among the objective criteria, the minimization of power losses, together with the exploitation of renewable energy sources, can be considered. The topic which has been well addressed for several years for traditional AC networks, gained additional interest in the scientific community since its application to the hybrid ACDC grids. This grid configuration introduces additional control variables and constraints (related to AC/DC power converters). Due to the binary behaviour of the switches (open - close) and the non-linear functions that relate electrical quantities, some activities concentrated on the analysis and resolution of Mixed Integer Non-Linearized Programming (MINLP). Moreover, several approaches make use of additional mathematical techniques for the determination of candidate solutions, as genetic algorithms, neural networks or heuristic methods.

The project partner RWTH Aachen has developed an algorithm, related to the project FISMEP (FIWARE for Smart Energy Platforms), specifically tailored to the network reconfiguration of hybrid ACDC grids and based on graph theory. Network reconfiguration, in general, is defined as altering the topological structure of feeders by changing the state of switches. In other words, thanks to the switches we have the possibility of configuring the grid, depending on the number of switches in the network. Having N number of switches, there are 2^N possible combinations considering every on/off combination regarding the state of each switch, by which the network can be reconfigured. Having said that, the wide number of possible combinations leads to a difficult and time-consuming research of the optimal solution, i.e. optimal configuration.

Generally, distribution networks are operating in radial configurations to increase effectiveness and coordination among protection devices. Open tie units allow to overcome fault or overload conditions. The target of OPF could be the reduction of power losses by changing the network topology while keeping the radial configuration, and keeping every node connected. The algorithm works by analyzing all the possible combinations of open/closed switches for the network. The constraints about the radial topology and the need to feed all the load allow to determine the specific numbers of open and closed switches (depending on the amounts of primary substations and switches) and to filter the suitable combinations, which will be ordered according to the power flow results. The power flow analysis is performed thanks to “pyacdcpf”, a free Python based open source program for AC/DC power flow analysis. The program uses a sequential AC/DC power flow algorithm and allows to simulate interconnected AC systems and multi-terminal DC VSC systems. Considering the particular configuration of AC/DC grids, an important aspect is the system control, necessary to regulate the power flow among the AC/DC converters and guarantee the stability of the network. In this case, the droop control is applied. In the case of DC voltage droop control, two or more terminals participate in DC voltage control, thereby sharing the duty of instantaneous (primary) power balancing among them. Considering together the errors between the measured and the nominal values, for power and voltage level, a Proportional-Integral (PI) controller allows to obtain the current reference to be used for the energy injection (or absorption, in case of negative value) in the DC grid.

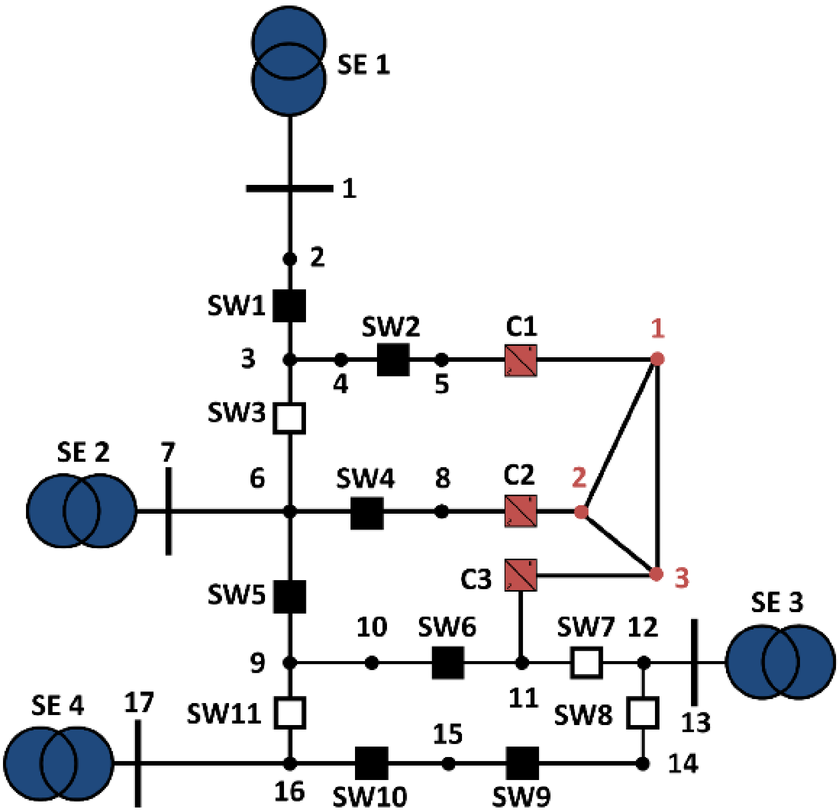

Figure 20: ACDC distribution grid model.

The algorithm has been applied for the optimal reconfiguration of a MV distribution grid modelled with the Real Time Digital Simulator (RTDS), shown in Figure 20. The Multi Terminal DC (MTDC) portion interfaces the AC sub-system via three AC/DC converters. The algorithm is performed once per hour (but differently scheduled frequencies are possible) and evaluates the variation of the load consumption to determine the best solution in that periods. Multiple analyses have been conducted, considering the repeated variability of the loads during the day (between the day and night the power flows change considerably) and in different seasons of the year, affecting the generation from DERs - see Figure 21.

Additional features are being added to the presented algorithm, in the context of HYPERRIDE activities for Task T4.5. Particularly, the integration consist of different roles for the AC/DC power converters with respect to the control variables, and the integration with the measurements accuracy by making use of the hybrid AC/DC state estimation deployed in the project. Once the basic algorithm will be upgraded, its development as a scalable and open source software component (middle-ware) will constitute its integration with the FIWARE based HYPERRIDE ICT platform. Moreover, the optimal power flow algorithm will be tested in the FEN research grid

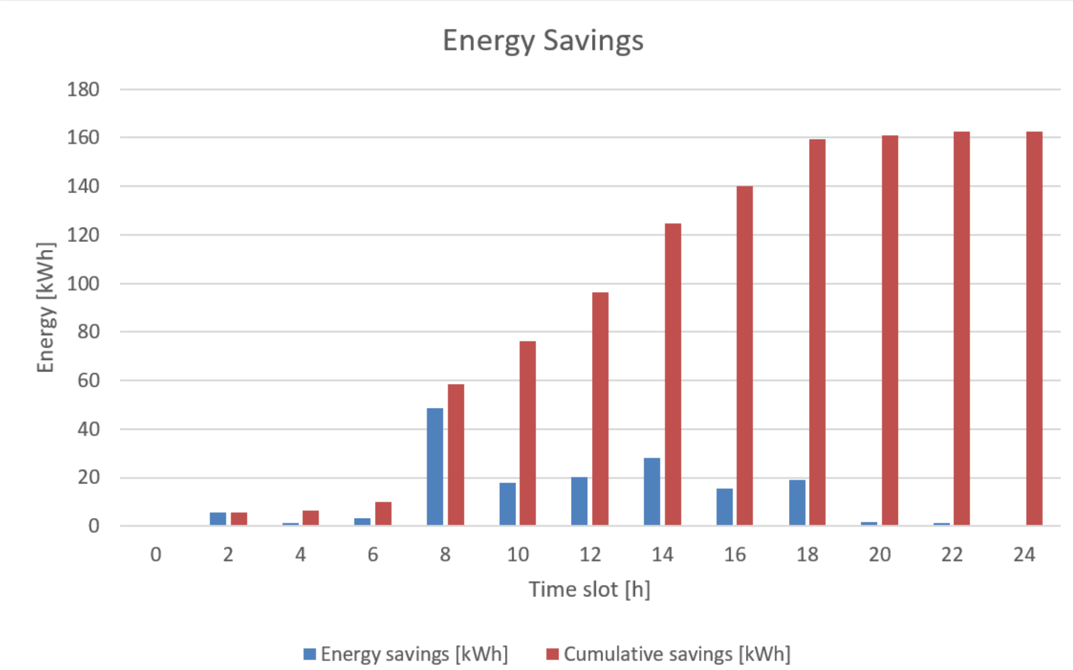

Figure 21: AC/DC distribution grid savings due to reconfiguration.

of the German field test in WP7, by integrating the real-time measurements from the existing components.

Target TRLs and responsibility for the solution can be seen in Table 22.

Table 22: Responsibility and TRL target for (OPF) energy service for hybrid AC/DC grids.

Lead partner	RWTH
Start TRL	5
End TRL	7

Main roles for tool development and demonstration are as follows:

- RWTH: definition and implementation of the algorithms, test and validation in German pilot.

A general specification of the solution can be seen in Table 23 and table 24.

Table 23: Functional specification for optimal power flow energy service.

Function	Description
Candidate solution	Determination of candidate topology (switches status) and power flow (RES and AC/DC converters setpoints)
State estimation	To check the constraints respect and quantify the criteria
Multi-Criteria Decision Analysis (MCDA)	To determine the most optimal solution

Table 24: *Value based specification for optimal power flow energy service.*

Parameters	Values	Unit
Grid measurements	Node voltage (waveform)	kV
	Branch current	A
	Switch status	on/off
	Branch power flow	kW; kVar
	Node power injection	kW; kVar
Forecasts	Load consumption	kW; kVar
	RES power generation	kW; kVar
Commands	AC/DC converters setpoints	kW; kVar; kV
	Operation of switch	on/off
OPF frequency	Time execution	min

4.4 Fault Location, Identification and Service Restoration for Hybrid ACDC Grids

When a fault occurs in an electrical distribution grid, the protection system has to act in the fastest way possible, according to the selectivity plan, in order to limit the security risks of people and the damages to the installed components. By opening the upstream and all the nearest downstream switching devices, the fault is cleared and the fault zone is isolated. If the first operation of the Automatic Circuit Reclosers (ACR) is not effective, the restoration process will take place. Distribution networks are managed with radial scheme; therefore, the nodes downstream of the faulted zone become de-energised and they have to be re-powered from an alternative source: the main goal of service restoration is to reconnect these healthy portions of the network that are electrically disconnected after the fault clearance. This is pursued by finding an alternative path, from another power source, and closing the normally open tie switches. The algorithm being used in the HYPERRIDE activities is based on the Rule-Based Optimization (RBO) developed by RWTH Aachen in the project FISMEP (FIWARE for Smart Energy Platforms) (*FISMEP – FIWARE for Smart Energy Platform*, n.d.). It considers, among the de-energised nodes, the one with highest priority as target for the restoration and identifies which is the most suitable primary substation to energise it, by closing the normally open bus-tie unit. The restoration schemes from each substation toward the target node are evaluated with a state estimation approach (which also allows checking the voltage, thermal and radiality constraints). The criteria considered by the algorithm are:

- The total power losses in the grid, P^a considering the reconfiguration from electrical substation a;
- The utilization of electrical lines, which indicates the current that can still flow in a line (among nodes x and y) related to its maximum value, as:

$$\Theta_{x,y} = \frac{I_{x,y}^{max} - |\overline{I_{x,y}}|}{I_{x,y}^{max}} \tag{3}$$

For each network topology that is analyzed, the three minimum values of $\Theta_{x,y}$ are recorded, related to the specific electrical line having the current magnitude $|\overline{I_{x,y}}|$ most close to its specific ampacity, $I_{x,y}^{max}$.

The selection of the optimal solution requires the combination of these two aspects and involves the use of MCDA techniques: initially, the user's priority criteria are hierarchically classified and, successively, among the possible reconfiguration schemes, the one having the highest closeness to the ideal solution is chosen and implemented. Once the selected tie unit successfully closes, the process repeats until all the de-energized loads are restored or the constraints are violated. The algorithm is able to manage multiple/cascade faults in active distribution grids (with Distributed Energy Resources).

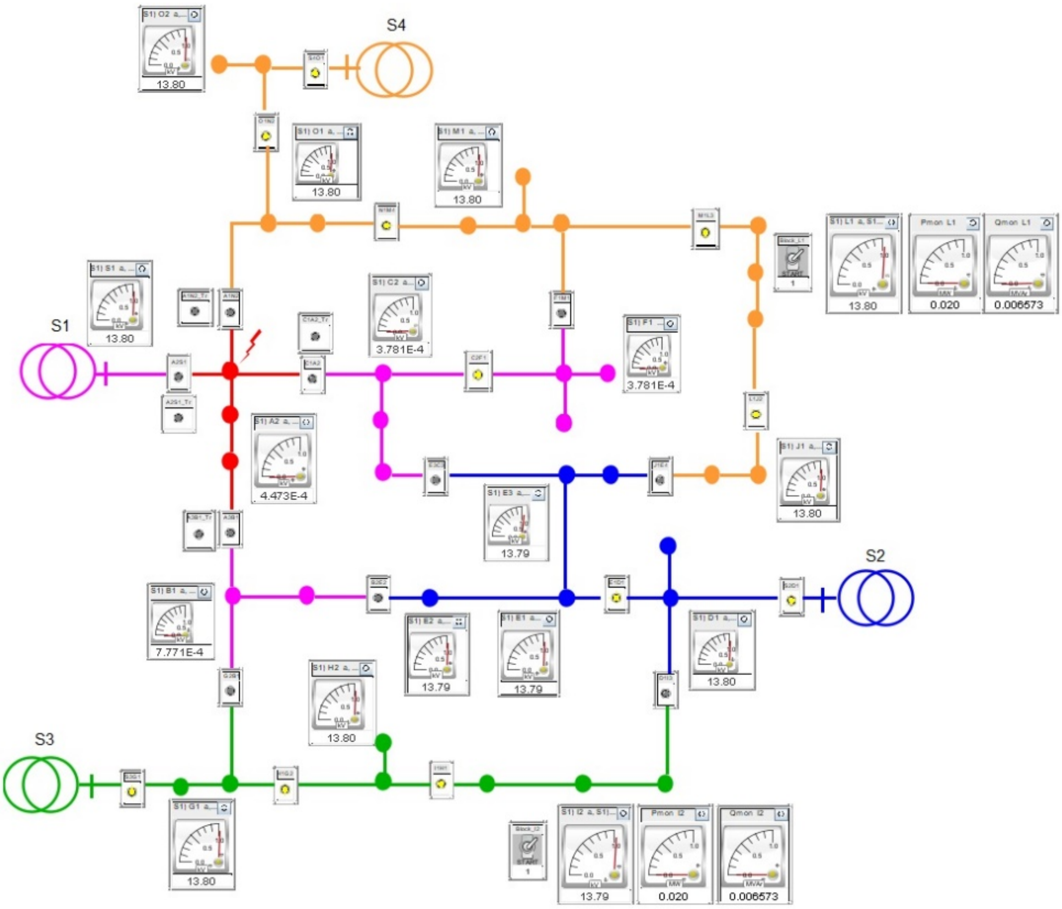

Figure 22: RTDS network model for service restoration.

The algorithm has been implemented as middleware in the FISMEP platform (cloud, FIWARE-based) and tested on a 13.8 kV distribution grid model with the Real-Time Digital Simulator (RTDS), shown in Figure 22: in the radially managed grid four primary substations are present, whose actual feeders are related to specific colours; due to the fault, the buses in the purple feeders are disconnected and need to be reconnected.

However, currently, the presented algorithm has been tested uniquely on AC distribution grids and it requires specific modifications in order to be applied to hybrid ACDC networks. Firstly, reliable estimations of electrical quantities need to be obtained; this is also related to the validation of candidate restoration schemes, for which the respect of electrical constraints needs to be ensured. Hence considering the ACDC grid configuration, it is necessary to analyse the modelling of power converters, particularly with respect to its power losses, and the implementation of dedicated AC/DC power flow algorithms. In HYPERRIDE, a strict relationship will be kept with the implementation of the ACDC state estimation solution: similarly to the AC service restoration, also in the ACDC case the state estimation algorithm will be implemented to verify the electrical constraints and compute the criteria parameters. Moreover, the inclusion of DC grid portion in the distribution networks, in the form of DC interlink or MTDC sub-system, will allow to investigate and numerically demonstrate the role of DC technology in the fault management and, particularly, in the restoration phase. In fact, the specific role of the AC-DC converter station, together with the RES, introduce new possibilities in the topology reconfiguration solutions. Additionally, the current algorithm starts considering the priority of the disconnected loads and, then, providing a local optimal solution. Besides the existing criteria for the selection of the restoration scheme, the updated algorithm is being integrating the computation of the global optimal solution and the inclusion of additional criteria. The complete development of the service restoration for ACDC grids is related to the Task T4.5 of the project, led by the project partner RWTH Aachen. The solution will be integrated in the HYPERRIDE ICT platform, developed in the WP5 of the project, as middleware component, and tested according to the German pilot test, to demonstrate the benefits in real grid conditions.

Target TRLs and responsibility for the solution can be seen in Table 25.

Table 25: Responsibility and TRL target for fault location, identification, service restoration solutions for hybrid AC/DC grids.

Lead partner	RWTH
Start TRL	5
End TRL	7

Main roles for tool development and demonstration are as follows:

- RWTH: responsible for the development and integration in HYPERRIDE ICT platform. Test and validation at German pilot.

A general specification of the solution can be seen in Table 26.

Table 26: Functional specification for fault location, identification, service restoration solutions for hybrid ACDC grids.

Function	Description
Initiation of service restoration	Notification of fault occurrence, by circuit breakers tripping
De-energized loads priority	Determination of rank for de-energized loads, to determine the most critical loads to be firstly reconnected
Candidates of reconfiguration topology	Closing of switching devices, variation of power setpoints for AC/DC converters and DG
State Estimation	To check the constraints respect and criteria values
Multi-Criteria Decision Analysis	To measure the candidate solutions and implement the most optimal one

4.5 FIWARE-Compliant Solution for Grid Asset Monitoring

The adoption of FIWARE is proposed inside WP4 and in general the HYPERRIDE project basically to address the need of interoperability of the different components in the ACDC grid, at both sensing and control levels. This is also a key aspect of the Open ICT platform which we are going to study and propose. The availability of widely adopted information models is key for creating a global digital single reference of interoperable and replicable smart solutions in multiple domains, including ACDC grid which fall under the umbrella of the general topic of the smart energy management. Such models provide an essential element in the common technical ground needed for standards-based open innovation and procurement. Data models play a crucial role because they define the harmonised representation formats and semantics that will be used by applications both to consume and to publish data.

The FIWARE Foundation is leading a joint collaboration program to support the adoption of a reference architecture and compatible common data models that underpin a digital market of interoperable and replicable smart solutions in multiple sectors, starting with smart cities. The reference architecture and data models use the FIWARE NGSI API and TM Forum Open Application Programming Interface (API)s for interoperability and scalability of smart solutions. The FIWARE Context Broker technology, implementing the FIWARE NGSI APIs, provides the basis for breaking information silos in organizations aiming at becoming smart. Actually, it enables a real-time view and foundation for the development of governance systems at global organization level.

FIWARE is a curated framework of open source platform components which can be assembled together with other third-party platform components to accelerate the development of smart solutions. The FIWARE Orion Context Broker is the core component of FIWARE: it gathers, manages and provides access to the information coming from different sources that describes what is going on in an energy ecosystem. The main goal of a smart grid implementation is the creation of an automatic process. It is critical to define for every possible data exchange, both the semantics of the information as well as the communication protocol. A number of data standards are available and many data exchanges are already formalised.

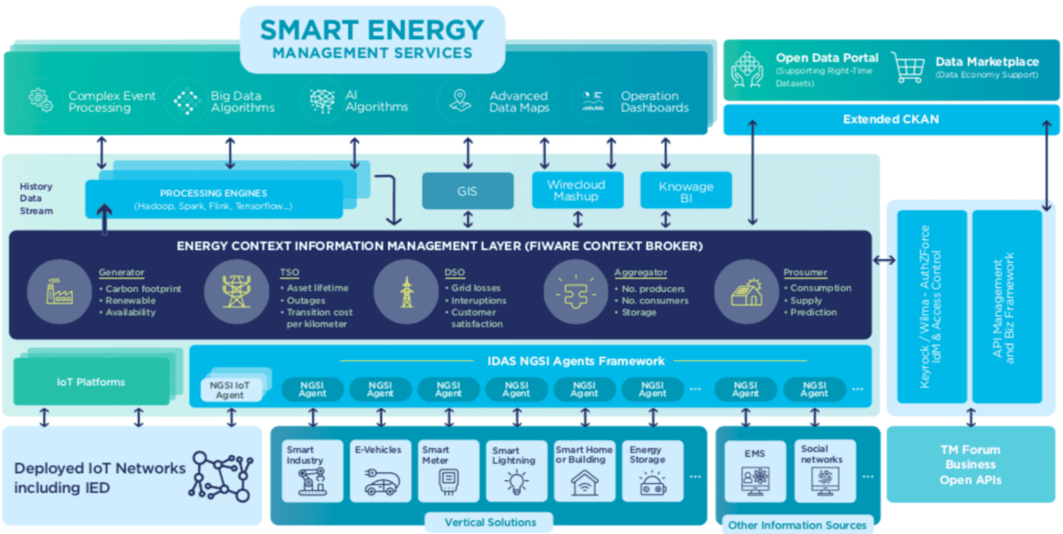

Figure 23: Reference architecture for smart energy management solutions "powered by FIWARE" https://www.fiware.org/community/smart-energy/.

As reported in Figure 23, the FIWARE architecture, in the picture even tailored only to the Smart Energy segment, is composed of a number of modules and services, called Generical Enabler (GE), whose description is out of the scope of the current template description. Nevertheless, not all the GEs must be implemented, inside any custom "powered by FIWARE" application, giving the modular nature of the framework. In HYPERRIDE, we will select the GEs we intend to exploit, and we may also extend the existing set proposing new ones, in terms of data models or new software artefacts, such as new Internet of Things (IOT) agents, and propose them with pull requests to the FIWARE community to contribute to its growth and increase our project visibility.

IOT agents are (e.g, the Context Broker), essential tiles of the general architecture: they allow to interact with the hardware by means of standard protocols, such as Message Queuing Telemetry Transport (MQTT) or Open Platform Communications Unified Architecture (OPC UA), and integrate them into the Orion Context Broken using the common NSGI structure. In this way, the Orion Context Broker manages context information and its availability. It is possible to create context elements and manage them through updates and queries. In addition, notifications are provided when context elements are modified. The data can be visualised using the open software like Grafana, which interacts with the Orion Context Broker. Specific alerts can be deployed (e.g., in case a measurement quantity overcomes the assigned limit) or a better understanding of the system with respect of the time evolution. Big Data Analysis – Cosmos is the third FIWARE GE that we may include in the Open ICT Platform. It allows the evaluation of both batch and/or stream data. Batch data do not need immediate processing and they can be stored; as an example, they can be related to the electrical load condition. On the other hand, the stream data require the instantaneous analysis. As an example, they can be associated to voltage level on the two sides of each converter, in order to detect their excessive variation, or the status of components (connected and operative).

So, FIWARE includes open source components, which can be assembled together with other third-party platform components to accelerate the development of smart solutions. Its application is perfectly suitable in the energy sector. In addition to the FIWARE components, other software elements may be included: for example, instead of the standard MongoDB installation, or besides it, for the storage purposes we may test the adoption of a time series database, like InfluxDB, which are particularly suitable in case of high amounts of monitoring data to read and to write. Of course, the inclusion of specific HYPERRIDE components like the smart circuit breaker, which will be developed in WP3, will be evaluated to implement the specific Open ICT platform criteria.

The proposed services will be implemented in the ICT platform developed in WP5, which will be based on software components from FIWARE technology, will exploit also the results from other EU projects like Wisegrid (https://www.wisegrid.eu/), FINESCE (http://www.finesce.eu/) and FISMEP (https://fismep.de/): as an example, the former uses FIWARE for building a cloud-based, service-oriented open source software platform to facilitate an efficient, automated and sustainable energy supply for single buildings as well as municipalities. RWTH will have an important role in the definition of the FIWARE implementation, as leader of the task T5.2 in which this technology will be analyzed, adapted and integrated.

A key outcome of WP5 will be a technology independent specification of the ICT platform and the tools it includes. The sensing and monitoring layer specification will be technology-independent, but a reference implementation will be developed by extending existing DC and AC monitoring infrastructures by adopting and upscaling FIWARE compliant solutions. As reference implementation of platform and tools, a FIWARE-compliant version will be developed, tested and validated. The development of both specifications and reference implementation will be lead by ENG.

The goal is to provide a tailored interface for the data collection from Hybrid ACDC networks and the transmission of commands/setpoints for the safe and reliable operation of the system. The data collected by the field instruments will be provided to the Open ICT platform according to a specific data model, based on NSGI powered by FIWARE. The acquired data will be leveraged for the energy services developed in WP4, such as Hybrid ACDC state estimation, OPF and fault location, isolation and restoration services. On top of the monitoring layer reconciliation and harmonization tools are necessary to support all the key functionalities that the ICT platform will integrate (state estimation, fault detection or optimal power flow management, or detection and prediction of technical and cyber-contingencies). A strict collaboration will be necessary with task 5.4 that provides data models for AC and DC parts of the hybrid network, necessary to develop tools for reconciliating, harmonising and analysing monitoring data. This task will release the deliverable D5.2 FIWARE IoA Agent based Sensing and Monitoring infrastructure layer.

Within the project, the performance of automation energy services are defined and implemented in the FIWARE-based ICT automation architecture of the demo-site. Further, it will be verified in real operating conditions.

Target TRLs and responsibility for the solution can be seen in Table 27.

Table 27: Responsibility and TRL target for FIWARE-compliant solution for grid asset monitoring.

Lead partner	Engineering
Start TRL	5
End TRL	7

Main roles for tool development and demonstration are as follows:

- Engineering: responsible for definition and implementation in ICT architecture, test and validation at Italian pilot;
- ASM Terni: provision of specifications, support with pilot demonstration.

4.6 Electric Vehicle and Charging Station Monitoring and Management

EMOT will provide EV and charging station real-time monitoring and remote management services for the Terni pilot demonstration activities. EMOT charging stations will exchange data through a Teltonika RUT230 modem connected to a single-board computer, a Raspberry Pi 3; charging station protocols will be Open Charge Point Protocol (OCPP) (application protocol for communication between charging stations and EMOT central management system) and Websocket (computer communications protocol, providing full-duplex communication channels over a single Transmission Control Protocol (TCP) connection). Charging station data format will be JavaScript Object Notation (JSON) and the sampling rate will be one second. Regarding EV monitoring, EMOT will use an On-board Diagnostic (OBD) device to retrieve data from the EV; OBD is a IOT component, based on a Raspberry Pi 3 and Carberry; Carberry represents the link between car electronics and Raspberry Pi, which allows the development of end-user applications. OBD will utilize a TCP/IP communication to a TCP/IP server. The network connectivity of the OBD device will be via data SIM (Universal Mobile Telecommunications System (UMTS)), thanks to a Raspberry module that works as a modem, and the server will be a python software; OBD protocol will be MQTT and the sampling rate will be 5 seconds. The OBD will connect to the car diagnostic interface from which it will be able to extract the information from the electric vehicle control unit using the CAN-bus protocol. The output data format of the OBD will be an ASCII string; when the data will be sent to the server, it will be reorganized into a wrapper, thus obtaining a grouping of the data in JSON format. EMOT network topology for HYPERRIDE demonstration activities is shown in Figure 24.

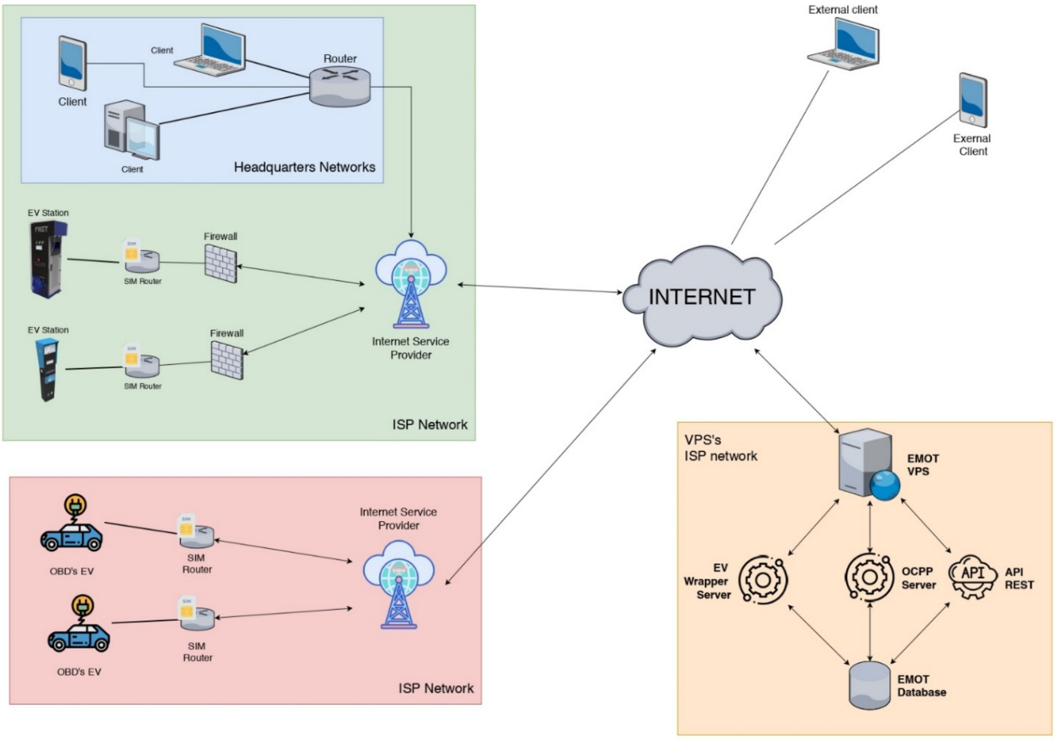

Figure 24: EMOT network topology.

Figure 25: EMOT charging station already deployed in Terni pilot site.

Electric vehicle and charging station monitoring and management service will make it possible to exploit the e-mobility in order to offer energy flexibility to a hybrid ACDC grid: in the Terni pilot the problem of managing hybrid ACDC grid in a high penetration condition of distributed renewable energy plants will be tackled; this situation entails system instability which can be avoided by using charging stations as electricity grid balancers. In fact, EMOT service has the ability to remotely start&stop charging sessions, as well as modulate the power output according to power grid needs. Thanks to this ability, the DSO (ASM) will be able to send commands to charging station managers in real-time, obtaining immediate results on grid balancing.

Target TRLs and responsibility for the solution can be seen in Table 28.

Table 28: Responsibility and TRL target for electric vehicle and charging station monitoring and management.

Lead partner	Emotion
Start TRL	6
End TRL	8

Main roles for tool development and demonstration are as follows:

- EMOT: responsible for definition and implementation of solution, test and validation at Italian pilot;
- ASM Terni: provision of specifications, support with pilot demonstration.

A general specification of the solution can be seen in Table 29 and Table 30.

Table 29: Functional specification for electric vehicle and charging station monitoring and management.

Function	Description
Charging Station Real-Time Monitoring	Emotion will provide real-time monitoring service for the charging stations deployed in Terni pilot
Charging Station Remote Management	Emotion will provide remote management service for the charging stations deployed in Terni pilot (Start&Stop, Power Modulation, etc.)
Electric Vehicle near Real-Time Monitoring	Emotion will provide real-time monitoring service for the electric vehicles deployed in Terni pilot

Table 30: Value based specification for electric vehicle and charging station monitoring and management.

Parameters	Values	Unit
Charging Station Real-Time Monitoring	Charging Station ID	Integer
	Power Output	kW
	Socket ID	Integer
	Socket Status	String
	Charging Session ID	Integer
	Start Time	YY-MM-DD hh-mm-ss
	End Time	YY-MM-DD hh-mm-ss
	Cost	Rational
Charging Station Remote Management	Power Output Modulation	kW
	Cost Modulation	Rational
Electric Vehicle near Real-Time Monitoring	Electric Vehicle ID	Integer
	Electric Vehicle Model	String
	Connector Type	String
	Battery Capacity	kWh
	Battery Power	kW
	Timestamp	YY-MM-DD hh-mm-ss
	SoC	%
	Latitude	Rational
	Longitude	Rational
	Speed	km
	Kilometers Autonomy	km
	Odometer	km

5 Protection

Circuit breakers are playing a crucial role in novel DC grids. Due to lack of zero current crossings as seen in AC grids, arcing is not self-extinguishable. Therefore, AC solutions are not suitable for this task and new applications with extinction mechanisms need to be developed. Though there are solutions available for DC railway systems, mass market products need to be optimised with respect to price, interoperability and other aspects. The proposed solutions focus on MVDC circuit breakers with resonant circuits and the simulation method for arc detection.

5.1 MVDC Hybrid Circuit Breaker

Circuit breakers and switchgear are essential parts of power grids. The problem of power system protection is typically regarded as solved for AC grids, where acceptable solutions have existed for over 100 years, but above a few kilovolts in DC systems, feasible circuit breaker technologies have only recently surfaced.

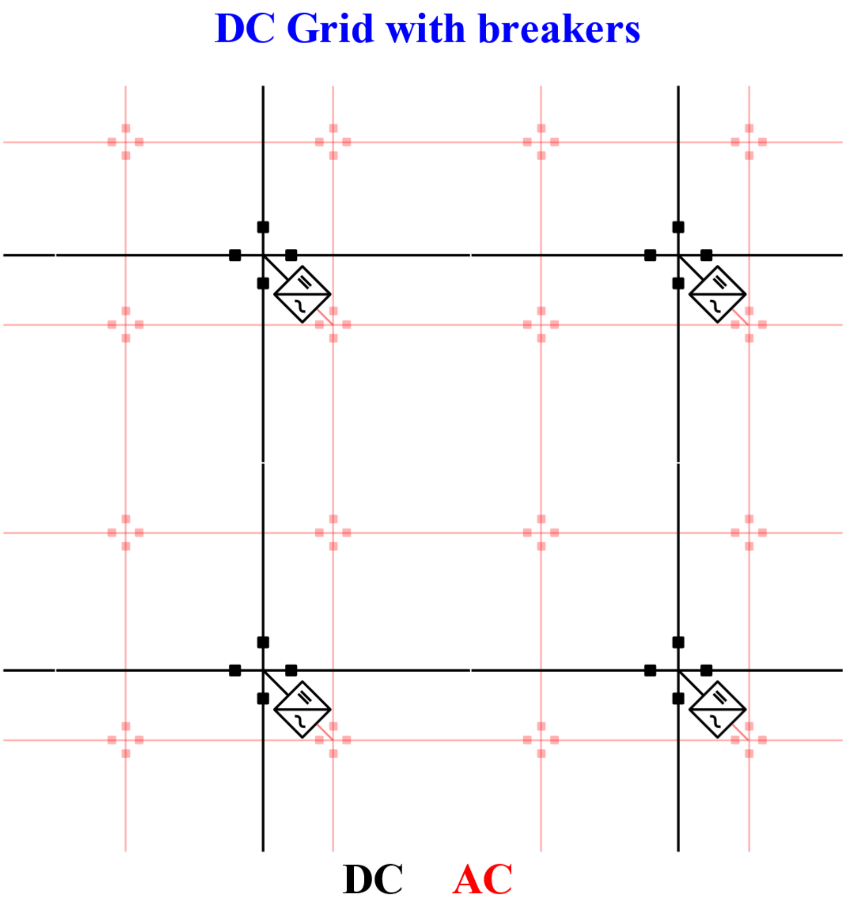

Figure 26: Meshed DC grid with circuit breakers (black squares) and interconnections with an underlying AC grid.

DC circuit breakers are required for in grids that need to be able to clear faults without de-energising the system. Such grids are expected to constitute a large part of the future DC grids targeted by the HYPERRIDE project. The VSC Assisted Resonant Current (VARC) breakers developed in the HYPERRIDE project will provide a high-performing and cost-effective solution for grid protection, suitable for mass deployment in future meshed DC grids. The VARC circuit breaker solution relies on a vacuum interrupter as its main switching element. The vacuum interrupter is also the only component of the breaker that carries the normal load current, which makes for negligible losses in a VARC circuit breaker in the on-state. In order that the vacuum interrupter be able to switch, it needs to be provided a current zero. For this purpose, the circuit breaker includes an auxiliary circuit driven by a low voltage converter, that in a forced manner provides such a current zero crossing in the vacuum interrupter. Energy resulting from the interruption is absorbed by a surge arrester, also integral to the circuit breaker. In addition to capabilities to make and break current, the circuit breaker will also be able to detect faults, measure and log currents and voltages and communicate with other equipment, both in the same substation and elsewhere, over a variety of communication protocols. Two types of circuit breakers are developed in the project: a 5/2.5 kV model, that also will be demonstrated in the German pilot (WP7), and a 14 kV model, that will be tested in a laboratory environment. These two circuit breakers models will together cover a large range of applications relevant for both distribution system owners and businesses who desire an MVDC grid in a factory or in an offshore auxiliary power application. Another, perhaps less obvious, application for fast bidirectional DC circuit breakers is as current limiting circuit breaker in AC systems with excessive fault current levels.

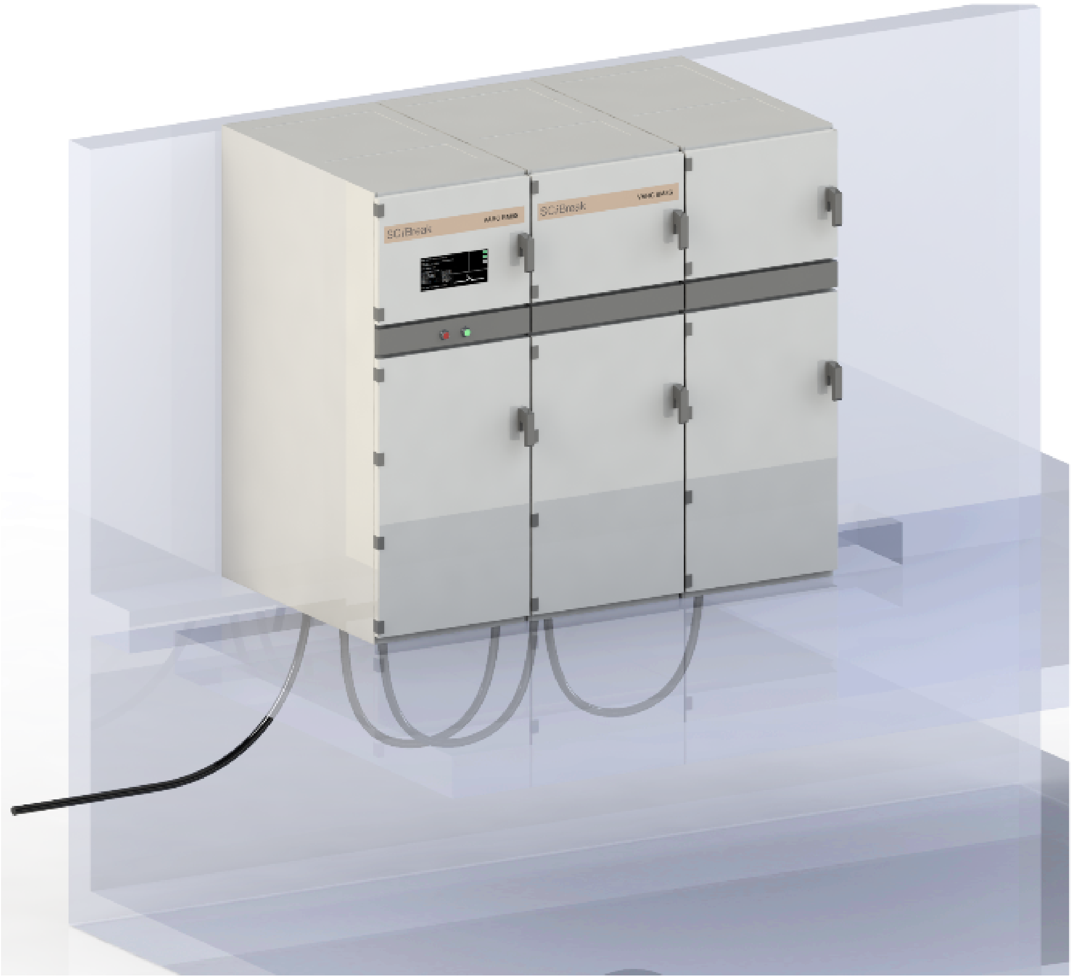

Figure 27: Envisioned appearance of 14 kV DC circuit breaker (leftmost cabinet).

 doi:10.5281/zenodo.4772129

The 2.5/5 kV circuit breaker demonstrator

The 2.5/5 kV circuit breaker demonstrator will be developed by SCiBreak and tested in the German Pilot installation at RWTH Aachen over the course of several months. Hardware requirements on the circuit breaker will be derived in a collaboration between SCiBreak and RWTH Aachen. During the demonstration period, the circuit breaker will be kept in steady state operation under various conditions, as well as subjected to induced short-circuit faults. Communication of measurement data, event logs etc., between the circuit breaker and the substation will also be tested during the demonstration period. Arc faults inside the switchgear cabinet will also, as a preparation for type tests, be analysed with Finite Element Analysis (FEA) software in T3.3 (AIT) as a part of the HYPERRIDE project. Software requirements for the demonstrator will be developed together with EMOT as part of T3.5.

The 14 kV circuit breaker prototype

The 14 kV circuit breaker prototype is aimed at set of DC distribution applications, from which requirements will be developed by Eaton. The circuit breaker will be developed in a collaboration between SCiBreak and Eaton. Testing of the circuit breaker will be performed at several laboratories, among which are SCiBreak's high power lab, the planned AIT high power laboratory and an Eaton testing facility.

Target TRLs and responsibility for the solution can be seen in Table 31.

Table 31: Responsibility and TRL target for MVDC hybrid circuit breaker.

Lead partner	SCiBreak, Eaton
Start TRL	5
End TRL	7

Main roles for tool development and demonstration are as follows:

- SciBreak: responsible for definition development of 2.5/5 kV prototype, collaboration with 14 kV prototype;
- Eaton: responsible for definition development of 14 prototype, test and validation in test laboratory;
- AIT: test and validation in test laboratory;
- RWTH Aachen: provision of specifications, support with pilot demonstration.

5.2 Arc Detection Simulation

Developing ACDC grids to higher power level, where they can compete conventional medium voltage AC grids (rated power » 300kW), makes the arc fault security theme mandatory. This is because in arc fault scenarios electric power greater 1 MW is converted for durations up to 1s into pressure waves and hot gasses. Note that for arcing considerations the short circuit current or power at the considered point of the grid is relevant. Without protection this can be not only destructive for equipment, but also hazardous or lethal for human (Figure 28).

Figure 28: Exploding cabinet.

Obeying this danger several normative regulations were established in the AC world: AC low voltage as well as medium voltage systems have to withstand normative arc fault tests according to IEC/TR 61936 or IEC 62271-200/-202. In cases where (transformer-)stations are incorporated in buildings and experimental arc fault tests are not possible any more, EN 61936 section 7.5 have to be fulfilled: Buildings have to withstand pressurisation by arc faults. This is typically shown by calculations using the Room Average (RA) or the Continuous Fluid Dynamics (CFD) methods. If active arc protection systems are installed, typically both is shown:

- The active arc fault security of the Arc Mitigation System (AMS) is proven experimentally;
- The passive arc fault security of the cabinets is proven experimentally with not installed AMS.

This is necessary, because the AMS have some disadvantages:

- Fail positive or fail negative events can occur;
- Proper functionality is not guaranteed for decades;
- The current limiting device itself (pyrotechnic shortcutter, fuse, etc.) can explode and become the place of arc fault.

These aspects hold also for active DC overcurrent protection systems in converters, where e.g. diodes, thyristors or Insulated Gate Bipolar Transistor (IGBT)s itself can explode and be the place of an arc fault. These arc faults must be recognized and switched off by the feeding grid.

The physics of 3-phase AC arc faults shows jumping arcs (Figure 29) and is therefore different to the physics of DC arcing. The footprint of the voltage (Figure 29 b) is one possible indicator for AMS. It will be analyzed with standard mathematical tools.

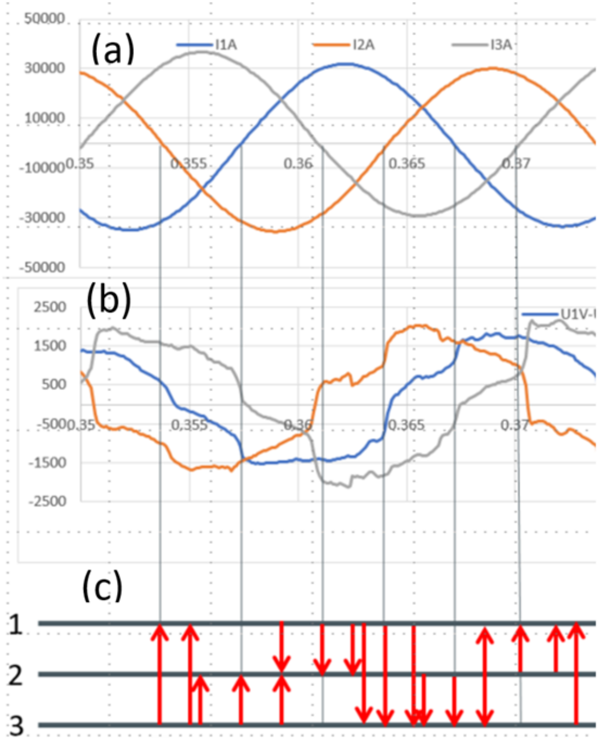

Figure 29: 3phase-AC-arcing: (a) current [A], (b) voltage [V], (c) bus-bars with jumping arcs.

Table 32 compares the different physics and the different measurement technique at AIT's lab of 3-phase AC versus DC arc faults tests.

Table 32: Comparison between 3-phase-AC- and DC-arc-fault-tests.

Parameter	3-phase-AC-arc fault	AC-arc fault
Physics		
Location	jumping arcs	continuous burning
Pressure waves	6 per 20 ms	only at ignition
Extinction due to current zero passings	sometimes observed	not expected
Rising of short circuit current	slow, e.g. large inductances	fast, e.g. large batteries, capacitances
Correlation with partial discharging	investigated for decades	not explored
Measurement		
Current	current-converter	shunt and isolation amplifier
Voltage	v.-converter (inductivities →large errors possible)	isolation amplifier
Experience	several decades	no data available
Duration of arc fault test	250 ms (LV), 1 s (MV)	5...500 ms

Summarizing, there is a lack of knowledge in simulation and experimental results on DC arc faults.

The developed and validated simulation models (RA and CFD methods) can be applied to existing as well as in the planning phase for future ACDC systems. Further knowledge like design-rules and comparison-rules ACDC will be gained by initial calculation of pressure and hot gas exhaust in arc fault scenarios.

This tool will provide planners of ACDC grids, manufacturer of ACDC systems and components, ACDC grid provider, HYPERRIDE partners and HYPERRIDE pilots access to the theoretically challenging theme of passive arc fault security.

Partners of Task 3.1 (Requirement and Specification) will give input like short-circuit-currents, powers and duration of HYPERRIDE pilots and future grids. Within the project, Eaton will provide cabinets for performing 3-phase AC and DC arc fault tests. These tests will serve for experimental validation of the RA and CFD models. Eaton and Scibreak can test components against DC short circuit and DC arc fault withstand at AIT's lab. Zelisko will develop DC current and DC voltage sensors. These Sensors can feed AMS and can be tested at AIT's lab.

Target TRLs and responsibility for the solution can be seen in Table 33.

Table 33: Responsibility and TRL target for ARC detection simulation.

Lead partner	AIT
Start TRL	6
End TRL	8

Main roles for tool development and demonstration are as follows:

- AIT: responsible for definition and tool development;
- Eaton, SciBreak, Zelisko: support with requirements and specification;

A general specification of the solution can be seen in Table 34.

Table 34: Functional specification for ARC detection simulation.

Function	Description
DC arc simulation tools for component validation	Workflow for utilizing COMSOL for performing DC arc fault simulations, physical modeling utilizing the room average model
Calculation of pressure and gas exhaust	The Calculation of pressure in the enclosure and gas exhaust
Real-time simulation	No, no demand on real-time simulation, typically several hours computation time in COMSOL
Possibility of communication between simulators	Yes, direct implemention of Pspice- and MATLAB-modells in COMSOL
Validation of computed DC-results with Experiments	Yes, direct implementation of Pspice- and MATLAB-models in COMSOL
Comparison of computed DC-results with computed and measured 2phase- and 3phase AC-results	Yes
Modelling of Arc Extinction	No
Modelling of stress in enclosure	No, but in principle possible
Modelling of moving arc	No, but in principle possible

6 Safety and Security

Aspects of safety and security became increasingly important throughout the last decades. Though this is a common topic throughout the ICT area there is still research needed for implementations in the specific field of application. For the case of electricity DC infrastructures threat detection can benefit from AC solutions. However, the signs of power system anomalies differ due to variations in control algorithms as well as due to the overall system approach. For assumed microgrid structures and connected communities potential affects of fault cascades also need to be addressed. The availability of a toolbox with countermeasures in the case of fault occurrence is equally important as means of mitigation upfront. This also includes aspects of asset reliability as a base of ageing detection and preventive maintenance to decrease the risk of asset malfunctions. The solutions provided in HYPERRIDE address all of the mentioned domains.

6.1 Solutions for Threat Detection

The solutions that are being proposed in the HYPERRIDE project involve increased amounts of ICT being deployed. The benefits of the introduction of this ICT will be explored in the project. However, the introduction of ICT in power systems introduces an increased risk of cyber-attacks. On the one hand there is a larger attack surface introduced, which can be exploited by an adversary, on the other hand, the consequences of these attacks can be operationally significant. In recent years there have been cyber-attacks that have resulted in physical consequences, such as the attack in Ukraine in December 2015 that resulted in a regional blackout. It is important to detect these cyber-attacks so that an appropriate response can be initiated; hopefully, prior to a negative consequence occurring. To this end, in the HYPERRIDE project an investigation into suitable threat detection methods will be performed for the project's use cases. This will leverage existing solutions that have been developed at AIT. Depending on the use case, several detection capabilities can be deployed that are monitoring different aspects of a target system. In cooperation with HYPERRIDE partners, a suitable configuration will be proposed and evaluated for hybrid ACDC networks.

AIT is experienced in the development of threat detection capabilities that can be applied in this context. For example, one of the ways cyber-attacks can be identified is via unusual behaviour (anomalies) that is exhibited in system log data. To detect these anomalies, AIT has developed a log-based anomaly detection system, called AMiner. This detection tool can employ different forms of detectors to be used to learn the normal behaviour that is exhibited in log data. After a learning phase, a trained detector can subsequently identify anomalous (and potentially malicious) behaviour in the log data. In addition to this form of detection, AIT has extensive experience with various deep learning methods to detect and classify attacks in communication network traffic (Teuffenbach, Piatkowska, & Smith, 2020). AIT has also developed approaches that are specifically targeted at detecting cyber-attacks that manifest in the telecontrol protocols (IEC 104 or IEC 61850) in power systems (Jung, Smith, Magin, & Reuter, 2019). Finally, if an adversary can compromise a system and manipulate Operational Technology (OT) systems (Intelligent Electronic Device (IED), smart breakers, etc.) there will be observable consequences in the power system. AIT has experience in detecting anomalies in this domain, for example, using lightweight statistical methods and residual-based anomaly detection approaches that leverage state estimation algorithms (Paudel, Smith, & Zseby, 2018).

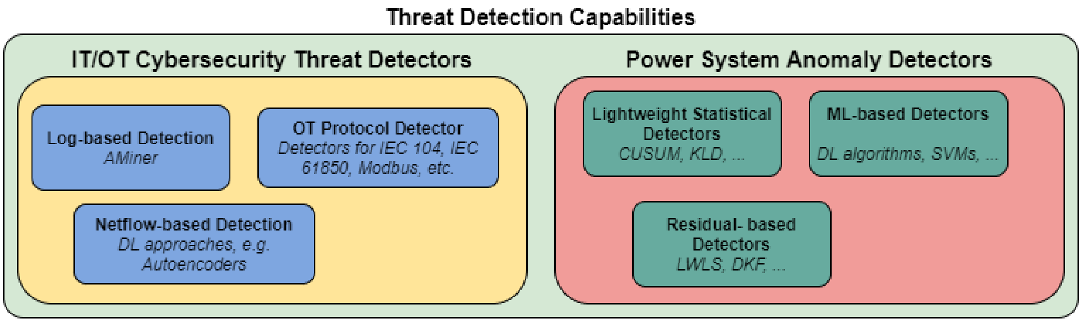

Figure 30: Summary of potential threat detectors that can be applied in HYPERRIDE.

It is intended that operators of hybrid ACDC networks will benefit from the threat detection solutions that are applied in the project. Many larger operators are developing operating Security Operations Centre (SOC)s whose purpose is to address cyber security incidents; they will be the primary benefactor of the solutions proposed in HYPERRIDE. It is intended that the threat detection modules introduced into the project will be integrated with the REASENS framework to, for example, understand their root cause and manage the number of false positives that are generated by detectors. This work shall be conducted with ENG and incorporated into the extended SUCCESS toolbox.

Target TRLs and responsibility for the solution can be seen in Table 35.

Table 35: Responsibility and TRL target for solutions for threat detection.

Lead partner	AIT
Start TRL	5
End TRL	7

Main roles for tool development and demonstration are as follows:

- AIT: responsible for tool definition and implementation;
- Engineering: collaboration for tool integration in SUCCESS toolbox.

A general specification of the solution can be seen in Table 36.

Table 36: Solution description of threat detection tools.

Solution	Description
REASENS	A framework to enable root cause analysis based on events that are generated by distributed sensors, such as intrusion and anomaly detection systems
Threat Detectors	Software components that are intended to detect malicious behaviour that is targeting a system.

6.2 Solutions for Fault Mitigation and Cascading Prevention

To support situation awareness and decision making in the case of cyber-attacks or faults within a hybrid ACDC grid, solutions are proposed to automatically process output from various sen-

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sors, such as anomaly and intrusion detection systems. These solutions are developed to address the following challenges in systems, such as those proposed in HYPERRIDE:

- There are large quantities of heterogeneous data and events that need to be processed for situation awareness. It is not feasible to perform this analysis manually since this requires tool support;
- In general, anomaly and intrusion detection systems can generate false positives, e.g. incorrectly identifying normal behaviour as anomalous or malicious. Processing potential false positives can take significant amounts of time; ideally, tools can be provided to support the management of false positives;
- In a distributed system, such as that proposed for HYPERRIDE, there are several heterogeneous sources of data that can be used to understand the system state or the potential root cause of problems that are occurring. A major challenge is to associate events from different sources that describe a situation.

To address these challenges, a substantial body of work has been proposed in the field of alert (event) correlation and sensor information fusion (Salah, 2013). The objectives of most event (alert) correlation techniques are to:

- reduce the number of false positives;
- improve understanding the situation through a more holistic approach, i.e. perform reasoning using different types of events to understand what they collectively mean;
- prioritize events – such that the most severe indicators can be addressed first; and
- connect current events with previous ones.

In the HYPERRIDE project we aim to leverage output from various anomaly and intrusion detection systems with the aim of determining their root cause for hybrid AC/DC networks. In what follows, we describe the REASENS framework that is intended to facilitate the integration of the anomaly detection tools with event-based reasoning. Subsequently, an approach is presented to integrate events from multiple data sources, i.e. evidential networks, which has proven to be applicable for handling unreliable data sources (and contradictory evidence).

The REASENS Framework is a hierarchical reasoning system that enables the collection of events from distributed and heterogeneous sensors. It is based on micro-service and event-driven architecture, which integrates different security sensors and enables more holistic reasoning about the monitored system state (situation awareness). A microservice architecture facilitates the integration of independent (standalone) applications, written in different programming languages, etc. The event-driven architecture enables the system to be dynamically (automatically) updated whenever something changes without the need to periodically query the state of all subcomponents.

The figure below depicts an outline of the framework architecture. Applications, such as sensors, are distributed across the strategic critical points in the infrastructure to monitor the system's health (behaviour). The framework has been developed to support cyber-physical system awareness hence to incorporate sensors which monitor both the ICT infrastructure (hosts, applications, net-work) as well as the underlying physical processes.

Example sensors include host- and network-based anomaly detection systems, and host and network intrusion detection systems to check if there is adversarial behaviour present. In addition, sensors for ensuring system safety could be deployed locally to check physical process

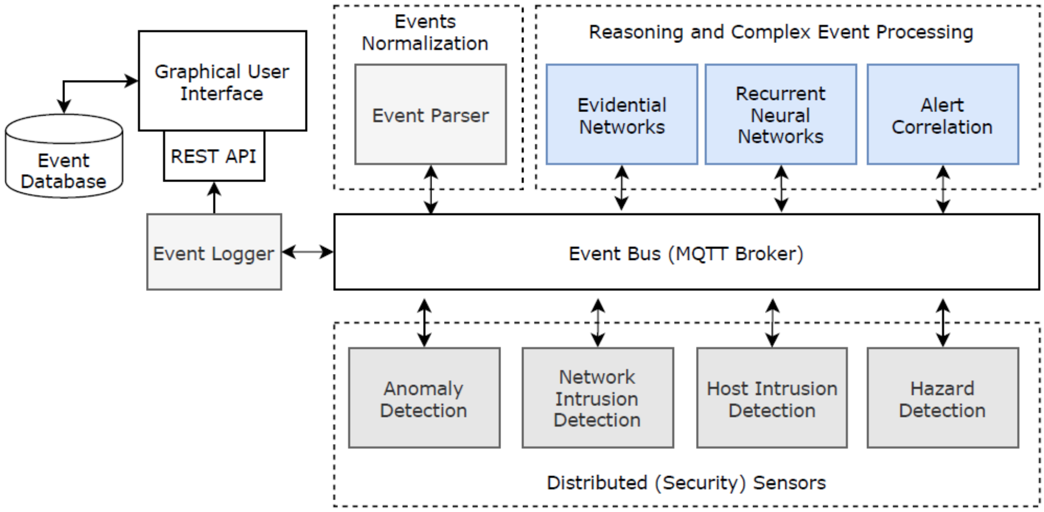

Figure 31: Overview of the REASENS Framework.

sensor measurements (anomaly detection) or to check whether control commands are safe, given the current system state (hazardous control detection).

Target TRLs and responsibility for the solution can be seen in Table 37.

Table 37: Functional specification for solutions for threat detection.

Lead partner	AIT, Engineering
Start TRL	5
End TRL	7

Main roles for tool development and demonstration are as follows:

- AIT: responsible for tool definition and implementation;
- Engineering: collaboration for tool integration in SUCCESS toolbox.

6.3 Reliability and Maintenance Database

The goal of this solution will be an open reliability information database to provide a common platform for storing and sharing component reliability information. The shared data will consist of system and subsystem reliability and maintenance statistics, information on system structure and operation conditions as well as estimations on data quality. The data will be used in quantitative reliability and availability assessments. Successful examples of such concepts can be found in oil, nuclear and wind power industries and this existing knowledge shall be used.

What is the typical situation that we are facing today? Failure data are recorded in various data sources for various purposes and separated by each organisation. The statistics about failure probabilities are only interpreted locally. Thus smaller business segments do not have the chance to get a representative overview on reliability properties for the components they are using.

The idea is to share information. A solution could be to share basic data on events and maintenance activities and costs. A neutral provider collects the data for each organisation and calculates Probability Density Function (PDF) for characteristic environmental and usage conditions.

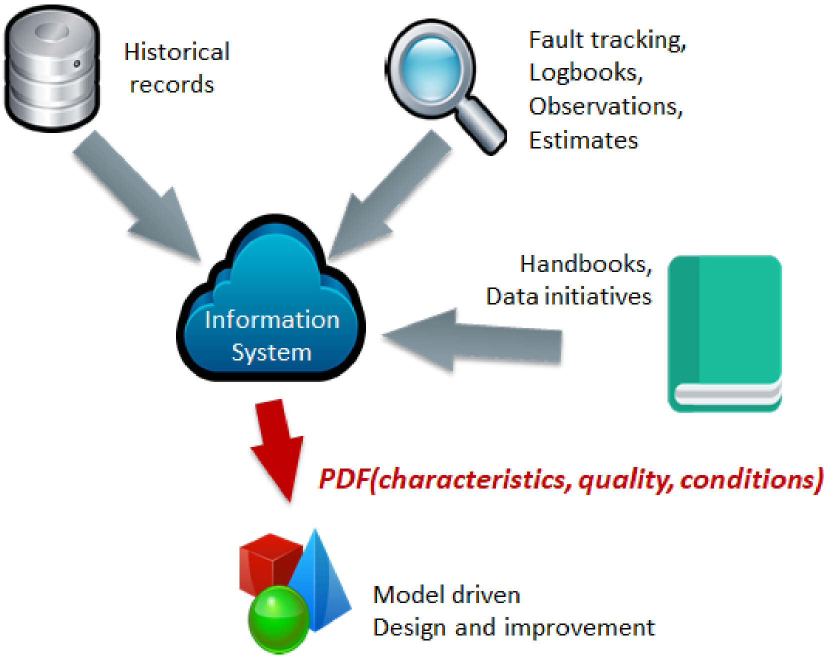

Figure 32: Proposed structure of the reliability database.

Detailed information for each organisation will be kept in a private area and will not be forwarded to the other organisations. Combined statistics for components over different organisations will be shared and will result in better estimations of probability parameters, like mean time of failures or typically maintenance cost. These parameters can be used for a better planning of redundancy and maintenance activities. As already mentioned, these approaches are implemented other industrial segments. Thus, the methods are already described in different norms like ISO 14224 and ISO 6527 industry standards.

Target TRLs and responsibility for the solution can be seen in Table 38.

Table 38: Responsibility and TRL target for reliability and maintenance database.

Lead partner	AIT
Start TRL	6
End TRL	8

Main roles for tool development and demonstration are as follows:

- AIT: responsible for tool definition and implementation.

6.4 H2020 SUCCESS Countermeasures Toolbox

In a smart grid environment, security is a crucial aspect for the stability and reliability of power system operation in contingency situations due to the failure of any critical power system component. The lack of proper security measures could cause major blackout. Furthermore, in a smart grid, the electric power infrastructure is modernised to incorporate advanced functionalities to its consumers. The introduction of new types of load in the grid, including plug-in hybrid electric vehicles, and the increasing adoption of green technologies to make the grid more sustainable are making the grid more complex to analyse. Consequently, the introduction of new technologies in the grid is making the cyber-physical system more vulnerable to cyber threats. Even if the adoption of cyber systems has made the grid more efficient and modern, it has also introduced cyber-attack issues that can degrade the performance of the physical system and even could cause a critical cascading failure of the power grid. In recent years, significant research and development effort has been put into cybersecurity for the smart grid. Mostly, it focused on smart metering and non-hybrid systems and architectures for the smart grid. For example, H2020 SUCCESS project developed solutions that are targeted at next-generation smart meters and smart AC grids; this effort provides a good starting platform to be applied to the hybrid AC/DC grids that are considered in the HYPERRIDE project. The ambition is to enable integrated data exchange of detected and predicted cyber-threats over AC grid branches (Security Manager) and to operate in an automated way under HYPERRIDE control also supporting dynamic reconfiguration from an AC to DC microgrid, if necessary.

The SUCCESS Security Solution is based on the consideration that different critical infrastructures, even if they are showing different characteristics, have common architectural features and common cyber-security vulnerabilities. Field equipment, although varied for different utility critical infrastructures, is monitored and controlled through similar sensors and actuators, which must communicate with data acquisition and control systems such as SCADA through similar communications networks. These similarities in field equipment, communications networks and SCADA imply that cyber-attacks to which the different critical infrastructures are vulnerable and are also comparable. Furthermore, the critical infrastructures have mutual dependencies, especially where critical infrastructures depend on electricity. As a consequence, cyber-attacks could target more than one critical infrastructure and an attack on one critical infrastructure can result in damaging other critical infrastructures. Hence, in order to address the cyber-security threats, the approach adopted by the SUCCESS Security Solution acts on a cross-critical infrastructure and pan-European basis.

This SUCCESS Security Solution addresses the problem of detecting hacker attacks on the Smart Grid and mitigating the attacks by applying countermeasures to mitigate this kind of threats.

The SUCCESS Security Solution Architecture proposes a two-level Cyber-Security Monitoring Solution as depicted in Figure 33.

The first level of the the SUCCESS system is designed for the individual Critical Infrastructure operator, typically a DSO business actor considering energy business. Meanwhile the second level is set at a regional level to integrate and share knowledge among operators. The two levels are interconnected through the so-called SUCCESS API. Firstly, security monitoring is performed at the Critical Infrastructure level. A Critical Infrastructure Security Operations Centre (CI-SOC) monitors the field equipment, communication infrastructures and any other relevant data sources of a Critical Infrastructure, trying to detect security threats. For any detected threat proper countermeasures are initiated by the CI-SOC. Secondly, the monitored information regarding identified threats and related countermeasures, is sent by CI-SOC to the second level in the SUCCESS Security Monitoring Framework. This level, called the Critical Infrastructure Security Analtyics Network (CI-SAN), serves as a regional network for exchanging security incidents and countermeasures information. CI-SAN is an infrastructure capable of monitoring the cyber-security of the various Critical Infrastructures present in different coun-

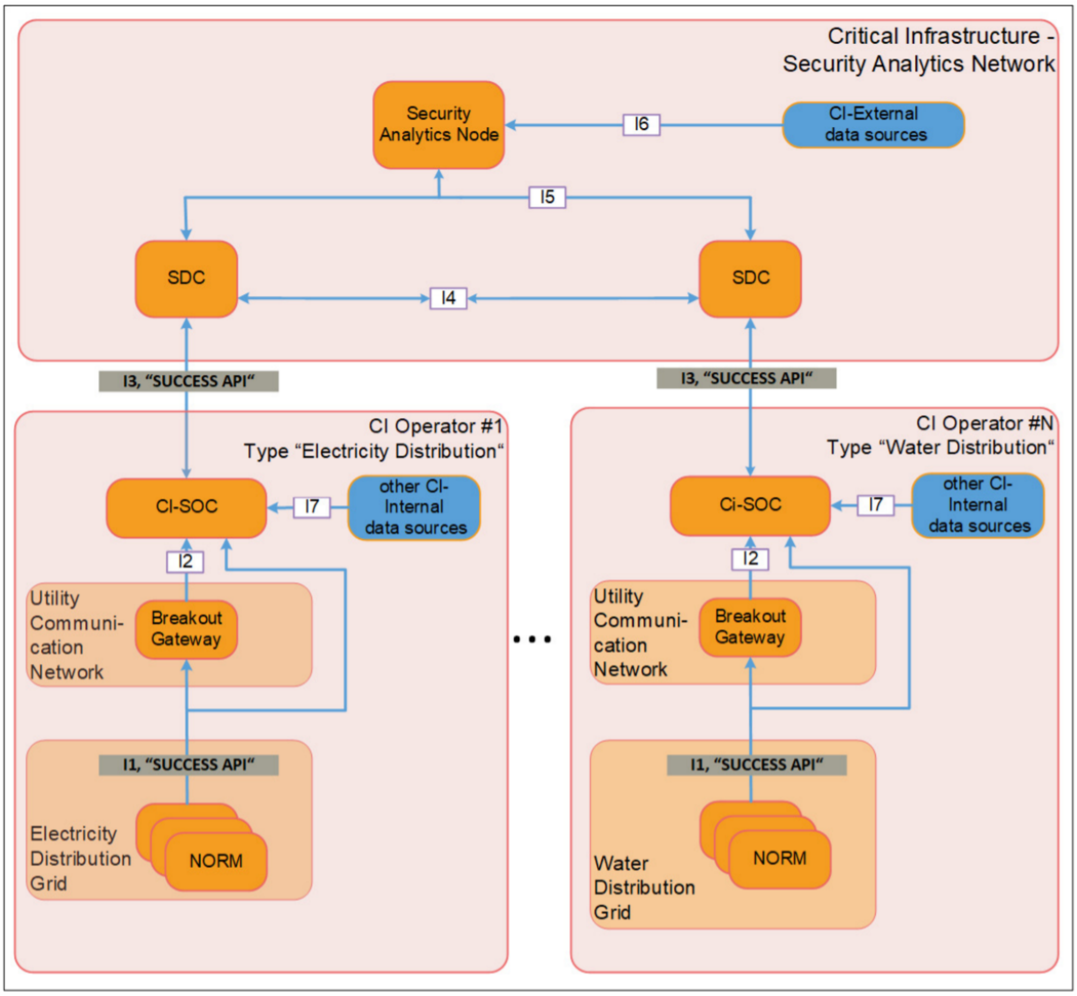

Figure 33: SUCCESS Security Solution Architecture (Padraic McKeever, 2018).

tries, thus providing an extensive view of the Critical Infrastructure (CI) security status. CI-SAN is designed as a system with two hierarchical levels, which consist of distributed instances: the Security Data Concentrator (SDC) represents the lower level which carries out information gathering across local instances, the Security Analytics Node (SA Node) represents the upper level analysing the information coming from instances at regional, national or international levels. The SDC instances are collecting information coming from the Critical Infrastructures in the local areas where they are located. Moreover, each SA Node instance on the upper level of the CI-SAN collects information from the SDC instances related to its area and from other sources. The information collected by each SA Node instance is used to identify security incidents by analysing those data, looking for patterns related to cyberattacks or physical attacks. Then, the information about the security incidents is both shared, through the SDCs, between the SA Nodes and alert Critical Infrastructure operators.

CI-SAN, by analysing data provided by DSOs and Transmission System Operator (TSO)s across Europe, has a comprehensive view of the security status of critical infrastructures; thus, the scope of its analytics is wide regarding the geographical span and, moreover, it is not limited to a particular type of critical-infrastructure but ranges across different CI types (electricity, water, gas). By the identification of common patterns, CI-SAN is able to characterize cyber-attacks; these patterns are shared with the DSOs and TSOs, which obtain information that cannot be derived locally.

In the context of task T5.3, with the support of RWTH and EMOT, ENG will tailor the H2020 SUCCESS framework to hybrid AC/DC networks, AIT will provide solutions for threat detection and reliability and the maintenance database, both AIT and ENG will provide solutions for fault mitigation and cascading prevention.

Target TRLs and responsibility for the solution can be seen in Table 39.

Table 39: Responsibility and TRL target for H2020 SUCCESS countermeasures toolbox.

Lead partner	Engineering
Start TRL	5
End TRL	7

Main roles for tool development and demonstration are as follows:

- ENG: responsible for tool definition and implementation;
- EMOT: collaboration with Engineering for DC transfer;
- AIT: provide subtools;
- RWTH: support AC/DC tool transfer.

7 Metrology

A prerequisite for successful grid operation based on automation technologies is the availability of reliable measurement data. Depending on the type of sensor, DC can either use synergies with existing AC solutions or it requires new methods and technologies to acquire the needed current and voltage values. Especially for inductively couples probes new methods are needed. The proposed solutions involve LV as well as MV solutions.

7.1 DC Measurement Units

DC Measurement Unit (DMU)s are devices specifically designed for monitoring currents and voltages in DC grids in a similar way to what Phasor Measurement Unit (PMU)s do for AC grids. The goal of PMUs is to perform synchronised measurements so that the time coherence of the data delivered to the automation layer supports efficient evaluation of the power flows. DMUs therefore are intended to extend the concept of synchronised measurements to DC grids, providing similar time accuracy to support widely distributed synchronisation actions.

However, beyond the abstraction of the concept of synchronised measurement, there still do not exist real specifications nor literature for DMUs. While PMU specifications are clearly defined in the international standard IEEE C37.118, describing standards for measurement, methods to quantify the measurements, testing & certification requirements for verifying accuracy, and data transmission formats and protocols for real-time data communication, there are no such specifications defined within the context of DC grid measurements. To cope with the lack of a standardised measurement framework, an approach can be adopted based on the analogy between the two domains in first instance with the goal to define homogeneous tools.

The main difference between AC and DC measurement devices consists in the reported values. PMUs do not report direct voltage and current measurements, but rather the estimation of the respective associated phasor, which is obtained by linear transformation of the measured waveforms from time to frequency domain via Discrete Fourier Transformation (DFT). This operation involves an implicit integration over a specific time-window in relation to the fundamental signal period. Conversely, because of the absence of a fundamental AC signal in DC grids, the concept of phasor does not find application in DMUs, whereas the integration over a time-window is still essential to reduce both the random noise components and the required reporting rate, although this is still to be defined in the extension.

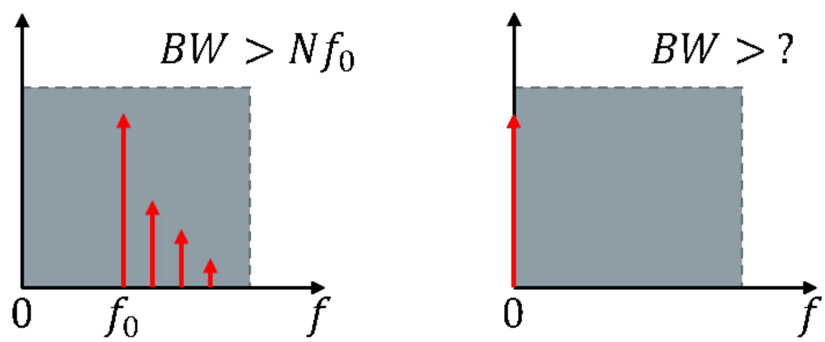

Figure 34: Simplified spectrum of AC (left) vs DC (right) grids.

Additionally, the fundamental frequency in AC grids allows the definition of a subset of harmonics suitable to define the minimum required signal bandwidth (Figure 34), whereas in DC grids

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all the power is expected to be centered around zero-frequency, posing in turns a significant unknown in the design requirements. To complicate the matter, the interaction between AC and DC grids might result in an inter-modulation of the AC grid harmonics with the AC-DC converter switching frequency, leading to the paradoxical condition of a small information content spread over a very wide frequency range.

Figure 35: Embedded solution for PMU applications.

To tackle such uncertainty in transient and evolving scenarios, RWTH Aachen already developed an embedded solution for synchronized grid measurements able to provide performance in line with the standard and at the same time showing great versatility and reconfigurability (Angioni, Lipari, Pau, Ponci, & Monti, 2017)(Carducci et al., 2019)(Carducci, Lipari, Giaquinto, Ponci, & Monti, 2020). The device, based on the RaspberryPi single-board computer, was previously developed for PMU applications in distribution grids, where monitoring requirements are expected to be more stringent than in transmission grids, but still not formalised separately in the standard C37.118. The developed device, now at the 2nd generation (Figure 35), is already able to perform simultaneous sampling of 8 channels with a resolution of 16 bits up to 10 kS/s, but in HYPERRIDE this limited range is intended to be further increased. The electronic front-end will be also adapted to meet the specifications of the voltage and current sensors developed by the partner Zelisko GmbH. The clear advantage of using this solution consists in a low-cost hardware based on open-source components, that is able to cover both AC and DC grid monitoring in one hardware solution and with a plugin-based software architecture well suited for new application scenarios.

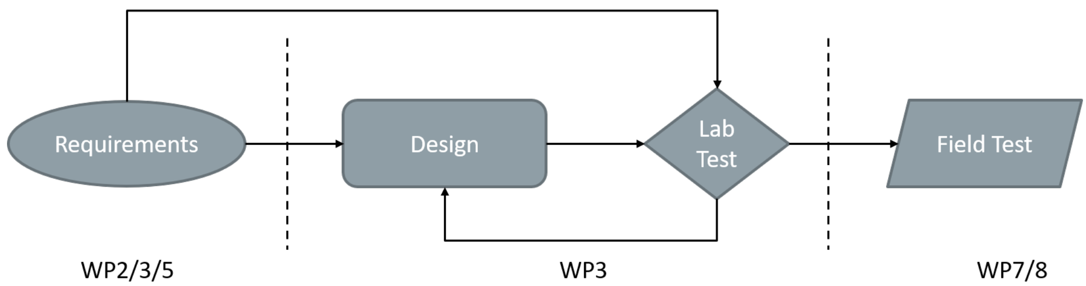

Figure 36: Embedded solution for PMU applications.

The complete development (Figure 36) of the DMU for ACDC grids will be carried out in Task T3.10 of the project, led by the project partner RWTH Aachen. The solution will undergo field test activities in Task T7.3 of the German pilot to validate its performance under real grid con-

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ditions and at the same time in Task T8.4 of the Italian Pilot.

Target TRLs and responsibility for the solution can be seen in Table 40.

Table 40: Responsibility and TRL target for DC measurement units.

Lead partner	RWTH
Start TRL	5
End TRL	7

Main roles for tool development and demonstration are as follows:

- RWTH: responsible for tool definition and implementation, test and validation in German pilot;
- ASM Terni: provide access to Italian pilot for demonstration.

A general specification of the solution can be seen in Table 41 and Table 42.

Table 41: Functional specification for DC measurement unit.

Function	Description
DMU - M	Provides UTC synchronized accurate measurements for monitoring purposes
DMU - P	Provides UTC synchronized fast measurements for protection purposes

Table 42: Value based specification for DC measurement unit.

Parameter	Values	Unit
Grid measurements	Node voltage (waveform)	kV
	Node voltage (RMS)	kV
	Branch current (waveform)	A
	Branch current (RMS)	A
	Branch current rate of change	dA/dt
	Harmonic content	dB

7.2 MVDC Voltage Sensors

Nowadays, knowledge about energy fluctuations in the voltage grid becomes more and more important. This entails a remarkable extension of the renewable energy production by means of e.g. PV and windmill-powered plants. Furthermore, the extension of renewable energies goes hand in hand with a decentralisation of power generation systems. Moreover, the decentralised power generation systems are feeding into the low voltage, medium voltage and high voltage grids, respectively.

The relevant nodes in the medium voltage grid are network substations in urban, rural and industrial areas. Actually, in these network substations of the MVAC grid, cf. Figure 37 are implemented more and more sensors made by Zelisko GmbH. These sensors are based on the principle of a resistive divider, cf. Figure 38. The implementation of sensors, e.g. medium

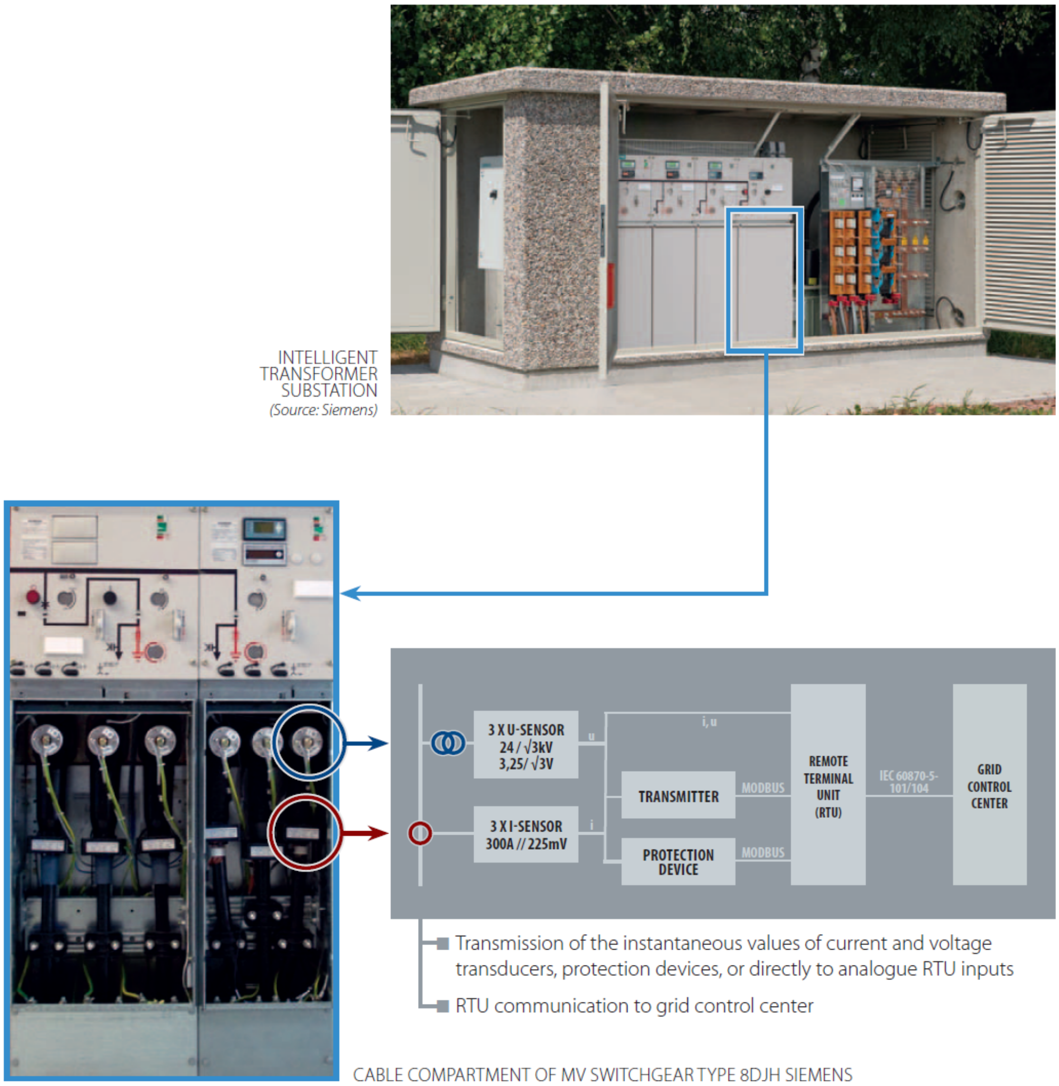

Figure 37: Voltage and Current Sensors in a MV Switchgear Type 8DJH by SIEMENS.

voltage sensors, enables highly accurate measurement of voltage without on-site calibration. Additionally, the mentioned voltage sensors show a good transfer behaviour regarding harmonic waves, regarding power quality management.

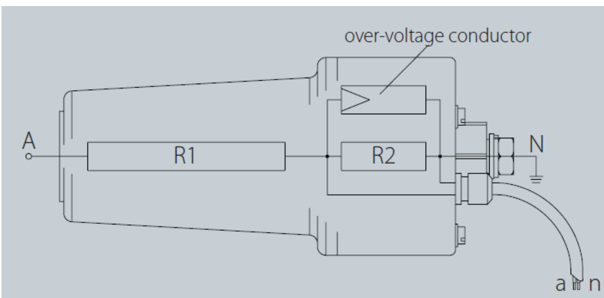

Figure 38: Medium voltage sensor for T-connectors, for symmetric plug according to EN 50181 © Dr. J. Zelisko GmbH.

In HYPERRIDE it is planned to work out a sensor concept for accurate measurement of MVDC voltage. Therefore, in a first step, research will be done in order to define and predict the requirements of the DC grid and especially of the MVDC switchgear. Furthermore, the parameters occurring in a grid fault case must be defined, e.g. over voltage and parasitic frequencies. In addition, the requirements referring to the transfer function must be defined. Finally, the goal is to find a solution for the implementation of voltage sensors into MVDC grids.

Target TRLs and responsibility for the solution can be seen in Table 43.

Table 43: Responsibility and TRL target for MVDC voltage sensors.

Lead partner	Zelisko
Start TRL	7
End TRL	8

Main roles for tool development and demonstration are as follows:

- Zelisko: responsible for development of sensor;
- Pilots: provide access for demonstration.

A general specification of the solution can be seen in Table 44.

Table 44: Value based specification for MVDC voltage sensors.

Parameter	Values	Unit
Insulation level	36	kV
Rated voltages	max. $30/\sqrt{3}$	kV
Voltage factor	1.2 U_N and 1.9 U_N 8h	
Accuracy class	0.5/1/3	
Rated secondary voltage	$3.25/\sqrt{3}$	V (or defined by customer)

7.3 MVDC Current Sensors

Like the arguments presented in section 7.2 the actual circumstances in MVAC grids require “intelligent” transformer substations, especially in the secondary distribution grid. Furthermore, the latter must be integrated into the power system management, in order to enable an intelligent, “smart” power grid and active load management. This “smart” power grid and active load management is assured by installing current and voltage measurement at the relevant points in the medium voltage AC grid. As mentioned, voltage and current measurement in intelligent transformer substations, especially in the secondary distribution grid, is indispensable to enable an intelligent, “smart” power grid and active load management. Therefore, analogously to voltage sensors, different measuring principles may be suitable.

In AC grids, the current measurement is based on the induction principle, for example in the split core sensor from Zelisko as shown in Figure 39. As this principle cannot be applied for DC current measurements, it is planned to develop a MVDC current sensor based on the Hall effect. More precisely, it is planned to implement an adequate Hall effect sensor into a block type transformer. Here again, in a first step, the influence of operating and ambient conditions on the functionality of the sensor and the parameters occurring in fault case in MVDC grids, e.g. over current, response function, etc., must be defined. Thus, for both current and voltage

Figure 39: Split core sensor for earth fault detection of type GAE120/SENS, © Dr. J. Zelisko GmbH.

sensors the partners in WP2 and the demo sites are strongly integrated in the definition of the requirements for the sensors. Additionally, Scibreak and Eaton, mainly involved in WP2, are also part of the development, as the operating conditions and the parameters occurring during MVDC grid fault are the same for the circuit breaker as for the MVDC sensors.

Target TRLs and responsibility for the solution can be seen in Table 45.

Table 45: Responsibility and TRL target for MVDC current sensors.

Lead partner	Zelisko
Start TRL	7
End TRL	8

Main roles for tool development and demonstration are as follows:

- Zelisko: responsible for development of sensor;
- Pilots: provide access for demonstration.

A general specification of the solution can be seen in Table 46.

Table 46: Value based specification for MVDC current sensors.

Parameter	Values	Unit
Insulation level	36	kV
Rated short time thermal current	5	kA (1 s)
Accuracy class	1& 5P10 . . . 5P20	
Output signal	tbd.	

8 Power Electronics Converters

Power electronics converters are considered key enablers for DC grids. This involves coupling of renewable energy sources such as PV, electric energy storage etc. via DC-DC converters. Further, ACDC systems are needed to couple hybrid installations (bidirectional) and to purely supply DC subgrids (unidirectional) from AC sources such as MVAC grids. Potential solutions involve, among others, a set of topologies such as MMC, DAB etc. for MV as well as two and three level topologies for LV couplings.

8.1 MVDC-LVDC Power Conversion Technologies Based on DAB and MMC Topologies

Since AC-DC converters, whether as grid-following or grid-forming, can be considered as the state-of the-art technology, those are not discussed here. On the other hand, various DC-DC converters are available, but as DC grids are in the infancy phase, their figures of merit are not yet completely quantified. This is especially true for MVDC grids, currently restricted to special applications where DC power distribution networks are considered to be a justifiable and beneficial choice. Regarding DC-DC converters, DAB and Resonant Converters are among the most popular choices for galvanically isolated DC-DC conversion. EPFL demo site will incorporate only low voltage version of both of these converters into the hybrid ACDC microgrid (Figure 40).

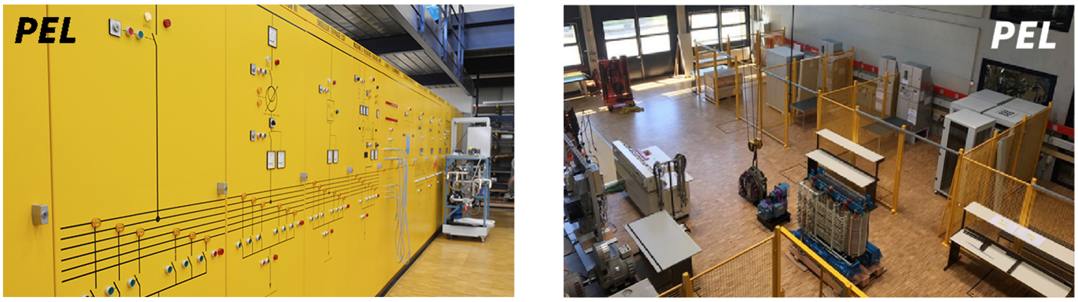

Figure 40: Infrastructure at EPFL for MVDC-LVDC converter design.

The DAB converter topology, as depicted in Figure 41, will be used with IGBTs as switching devices. The reason for this converter topology is that it enables full and bidirectional power control (Krismer, 2010). Because DAB operate at Zero Voltage Switching (ZVS) turn-on, it enables low switching losses and hence, a higher efficiency and higher ratings with respect to the switching devices capabilities. Furthermore, using IGBTs as switching devices enables high power ratings of the converter and a 50 kW converter is totally in the range of the converter capability. With the DAB topology, the power across the converter is fully controlled, enabling full power flow control at the microgrid level. In this case, the DAB DC-DC converter needs to receive references from the upper layer controller.

Resonant DC-DC converters, on the other hand, will be used to emulate DC transformers. Stepping-up and stepping-down voltage is very important in a power grid since this simple method enables significant loss reduction by lowering the current in the power lines. In a DC power grid, direct use of a transformer is not possible but instead, the concept of DC transformer has been introduced. It has the same feature as an AC transformer, with an isolating transformer at its centre but surrounded by two semiconductor-based AC-DC converters, generating high-frequency AC voltage applied to the high frequency transformer. In order to prop-

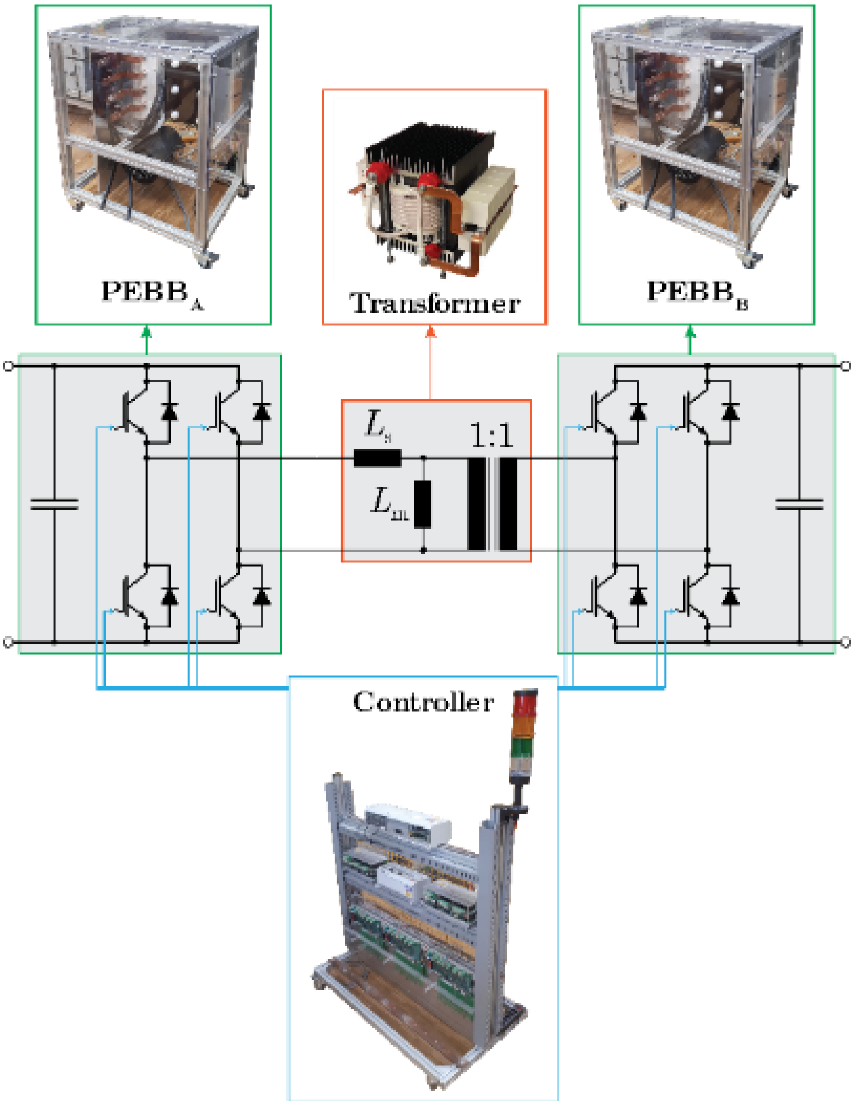

Figure 41: DC Transformer using the DAB converter topology.

erly integrate the DC transformer in the grid, two steps are crucial: modelling of the transformer and voltage control at each end of the DC transformer to avoid excessive power flowing through the DC transformer. The DC transformer topology used in this research is the LLC converter topology (Kucka & Dujic, 2021) since, with its ZVS turn-on and Zero Current Switching (ZCS) turn-off properties, low switching losses and high efficiency are expected (Figure 42). In this case, the LLC DC-DC converter does not receive any references from the upper layer controller, but works completely independently and behaves as AC transformer.

Protection is another important topic in DC grids. While the DC part of EPFL demo is available for deployment of commercial technologies, this will depend on the industrial partners. A Solid-State Bus-Tie Switch (SSBTS) is one of the devices we intend to test. When a fault occurs in the grid, there need to be ways to isolate the faulty section to avoid damages on the grid components such as converters and to maintain operation of the grid on the healthy grid sections (Figure 43). Restoring the voltage and power on the faulty section without impacting the grid quality on the healthy sections is also challenging. Bus-tie switches and circuits breakers are typically adapted to isolate a faulty grid section in case a fault has occurred (islanding mode). AC circuit breakers are easy to operate but DC circuit breakers, due to the non-zero crossing of

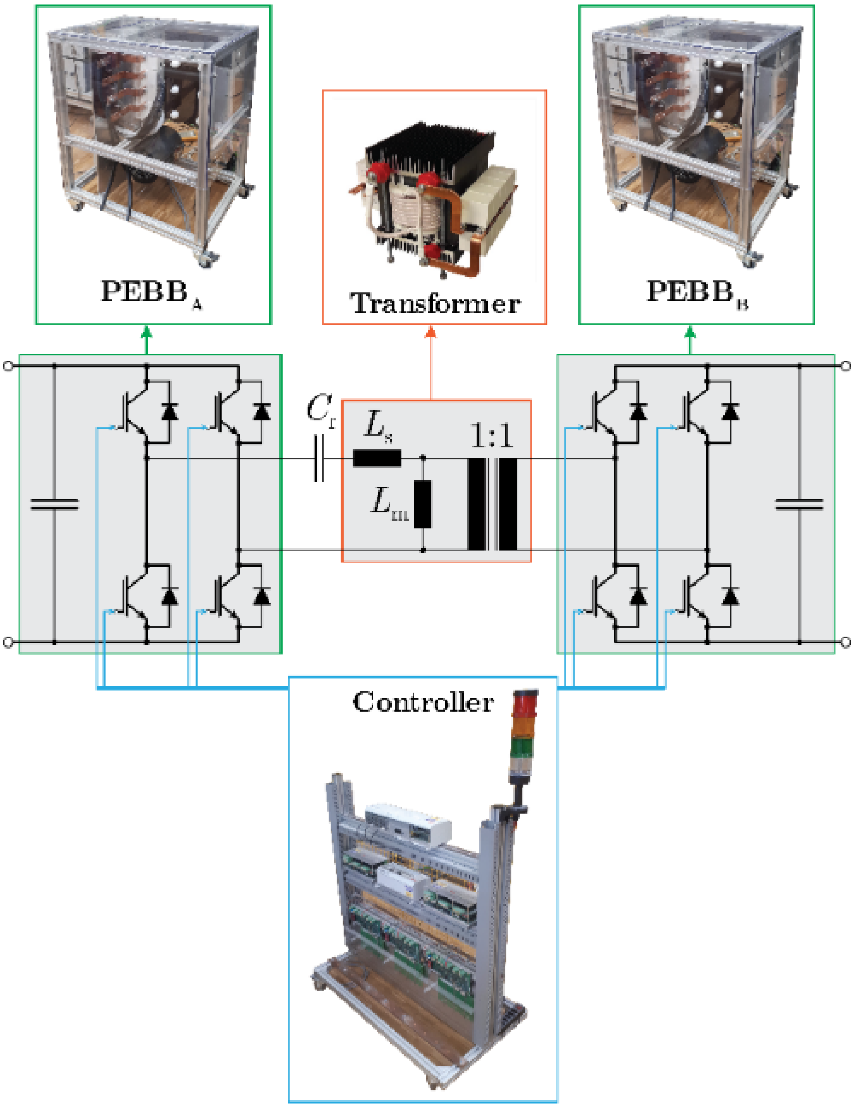

Figure 42: DC Transformer using the LLC topology.

the DC voltage, are a more challenging technology and have therefore been subject to intense research recently (Ulissi, Lee, & Dujic, 2020). Properly integrating circuit breakers and bus-tie switches into the grid is a very interesting subject of research and a prerequisite for building proper DC power grid. SSBTS, developed within previous activities related to marine DC grids, will be deployed between different DC lines to aid system reconfiguration and fast separation in case of faults. Yet, this device is not a replacement for the circuit breaker.

While power electronics converters can contribute in manifold ways, two main aspects are:

- **Power flow optimisation:** By controlling the power flowing in each converter supplying the DC lines and through DAB and DC transformer (indirectly through control of DC voltage level of the line), it is possible to optimise the overall grid power flow depending on the needs of different prosumers. Hence, power flow optimisation enables significant grid losses reduction and is therefore a core element of power grid control;
- **Protection coordination:** Isolating a faulty section requires proper coordination of the circuit breakers and bus-tie switches; (Kim, Ulissi, Kim, & Dujic, 2020) and it needs to be investigated in detail in the case of an ACDC microgrid. Isolating a faulty grid section can

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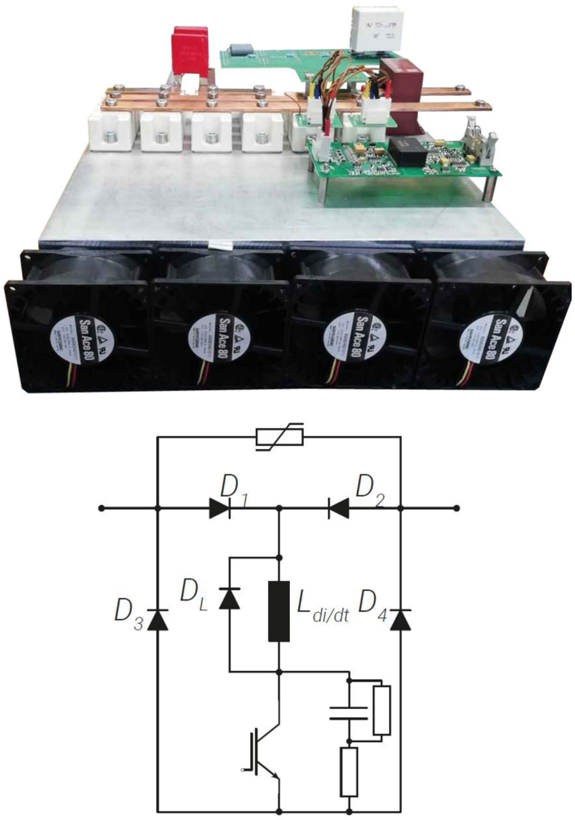

Figure 43: Solid-State Bus-Tie Switch.

also lead to other grid sections being islanded, meaning completely disconnected from the rest of the grid. This islanding mode of a grid is an important mode to handle in a grid but it is challenging because the islanded section is much weaker.

At the component level, the DC-DC converter's function is to control or support the power flow between different DC lines, while the AC-DC converter's function is to control the voltage levels of each DC line or the power exchange with AC parts of hybrid microgrid. The role of the bus-tie switches and circuit breakers is to isolate a faulty grid section and to protect remaining parts of the system. At the grid level, two functions are developed specifically for the solution: power flow control and grid fault monitoring and management.

The power flow optimisation leads to loss reduction so the grid operation is less costly. Hence, the network owners and operators should recognise a reduction in operational costs when power flow optimisation is performed in a grid. The protection coordination leads to a higher grid robustness and hence ensures the quality of supply.

Both laboratories of EPFL: PEL and DESL are closely collaborating on the hybrid ACDC grid implementation. EPFL demo site is open for other partner's technologies and solutions.

Target TRLs and responsibility for the solution can be seen in Table 47.

Table 47: Responsibility and TRL target for MVDC-LVDC power conversion technologies based on DAB and MMC topologies.

Lead partner	EPFL, RWTH
Start TRL	5
End TRL	7

Main roles for tool development and demonstration are as follows:

- EPFL: responsible for development of power electronics converter, test and validation at Swiss pilot;

8.2 DC Front End for LV Grids

In any grid, generated and consumed power needs to be balanced. While this is done for AC via frequency control, DC grids need a different approach to stabilise. Common approaches involve droop control which is implemented in power supplies and loads. Control via ICT connection is also possible. In general there is a need for in DC installation since instabilities in the grid are always negatively affecting relevant KPIs.

The active front end solution not only acts as an AC connected power supply for the DC grid but also plays an important role to handle potential instabilities caused by e.g.:

- sudden changes in load and/or generation;
- malfunctions of loads and/or generation (short circuits);
- surplus or minus of generation with respect to loads.

Within the HYPERRIDE project the basis is an existing converter platform (AIT Smart Grid Converter) which provides full functionality towards the AC side including low voltage ride through and base functions towards the DC side. To serve as full functional AFE the droop functions need to be implemented to enable field demonstration (e.g. at Terni demo site). The main beneficiaries of such a solution are grid operators and generation plant owners as the DC interface can also be transferred either in a back-to-back setup with battery/photovoltaics or to a full DC-DC converter with the same connections. The control strategy can also be transferred to load converters and for testing purposes the AFE can also act as a generic load for test and validation setups.

With its controlled neutral line the AC connection is suitable to provide positive, negative and neutral sequence currents and hence it is capable of AC balancing functions in addition to the DC droop control. This includes all necessary means to act as a smart active front end in a hybrid ACDC grid.

Figure 44: AIT Smart Grid Converter as basis for 34.5 kW LVDC active front end.

The AFE will be developed in WP3 and further adapted and tested in the respective demo work packages.

Target TRLs and responsibility for the solution can be seen in Table 48.

Table 48: Responsibility and TRL target for Active DC Front End for LV grids.

Lead partner	AIT
Start TRL	6
End TRL	8

Main roles for tool development and demonstration are as follows:

- AIT: responsible for development of LV power electronics converter as active front end, test and validation at pilot;
- Pilots: provide access for demonstration.

The specification example in Table 49 is given for a 35 kW active front end unit and can be used as a guideline for other low-voltage AFEs. The values are based on the HYPERRIDE demonstration unit provided by AIT.

Table 49: Value based specification for active front end converter.

Parameter	Values	Unit
Power		
Power rating	34.5	kW
DC side		
DC nominal input voltages	-350, 0, +350	V
DC max. input voltage	1000	V
DC operating voltage range at nominal AC voltage	570 - 950	V
DC (full power) voltage range (PF=1)	570 - 850	V
DC max. short circuit current	75	A
DC max. operating current	60	A
AC side		
AC nominal output voltage	3 NPE 380 / 220V or 3 NPE 400 / 230 or 3 NPE 480/277	V
AC operating voltage range	$\pm$ 20	percent
AC nominal frequency / Frequency range	50 (45-55) or 60 (55-65)	Hz
AC max. continuous output current	50	A
AC output current surge capability	105	A
Power factor range	0 - 1.0	over/under excited
THD at max. power	< 3	percent
General data		
Peak efficiency / Weighted efficiency EU/CEC	> 98	percent
Enclosure type protection class (electronics/mags)	IP54/IP20	
Ambient air temperature for operation	-25 to +60	degC
Relative humidity	0 - 100	percent (non-condensing)
Audible noise	35 $\pm$ 3	dBA
Other		
Communications	ModBus TCP, IEC61850	
Safety and EMC	IEC 62477-1, IEC 62109, IEC 61000-6-2, IEC 61000-6-3	
Grid code compliance (examples)	VDE-AR-N4110, VDE-AR-N4105, IEEE1547-2018	

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9 ACDC Product Test and Validation

For a safe and reliable operation of DC grids it is important to provide access to certified products according to relevant standards. For AC products a wide range of standards is available, respective test procedures are in place, and necessary laboratory infrastructures are established. As the test and validation infrastructures are costly and can negatively affect the business model for DC grids, it is important to be able to lever on existing laboratories. Hence, the proposed solutions for MV and LV test capabilities are based on enhancements of existing AC test facilities. Control strategies for automation, as developed in this project, need to be validated in an environment which enables the assessment of the functionality of large scale installations. Here, virtual test labs based on Hardware-in-the-loop methods are seen as most promising test beds.

9.1 High Power Laboratory Test Services for Components (MV and LV)

MVDC and LVDC applications need to be tested with respect to standards regulations as a prerequisite for market introduction. A normative environment enables users to use interoperable products for safe and secure infrastructure instalments. To achieve this, extensive test facilities are needed either at certification bodies or affiliated test infrastructures. Especially for new concepts such as DC MV and LV grids it is important to be able to lever on existing AC test infrastructures to provide test services at reasonable costs to not negatively affect the system business case.

AIT currently enhances its infrastructure capabilities for new DC grids and grid components with a focus on short circuit capabilities. To achieve this, a configurable transformer/rectifier bench with high short circuit currents up to 120 kA is installed. Within the project HYPERRIDE it is planned to use the new infrastructure for test development for newly defined standards and to provide a test portfolio suitable for industry partners in need of accredited test facilities.

Main products to be tested are breakers, switchgear and converters with a focus on the short circuit performance.

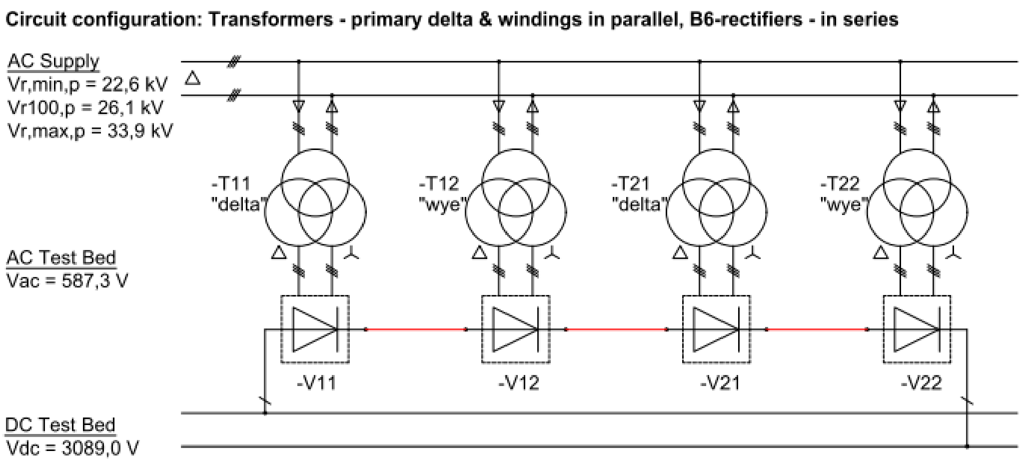

Figure 45: Schematic setup of DC source.

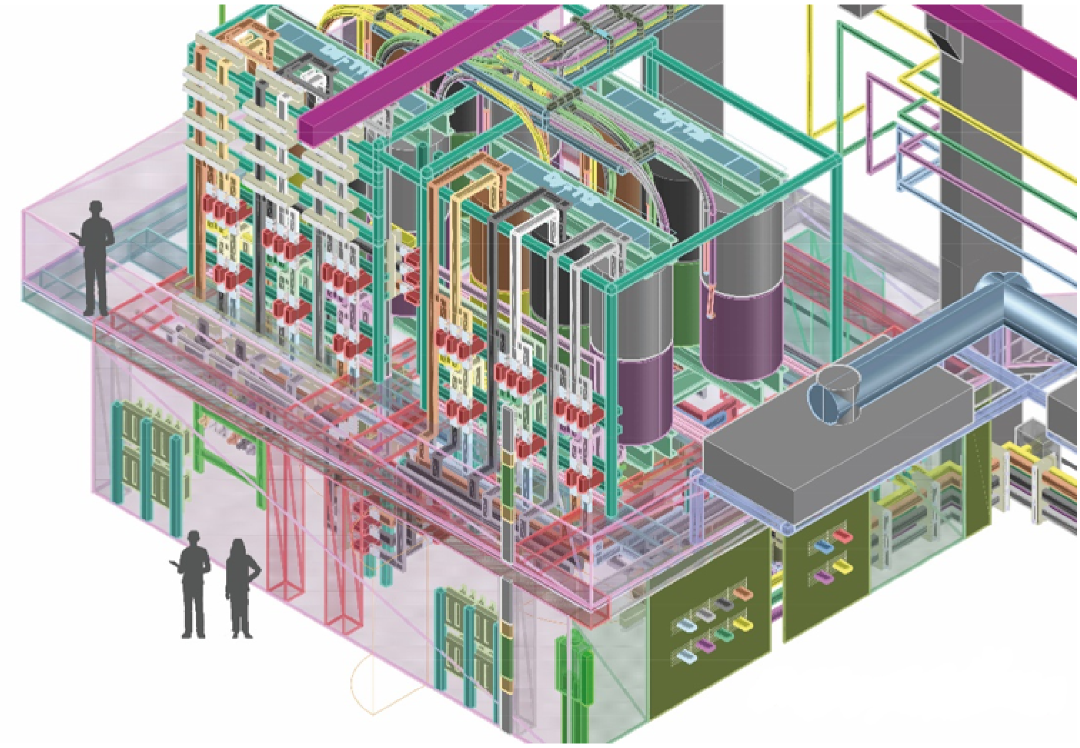

Figure 46: MVDC component test infrastructure - under construction at AIT.

Planners of ACDC grids, manufacturers of ACDC systems and components, ACDC grid providers and HYPERRIDE project partners will ultimately benefit from the test and validation services. Tests for SciBreak and/or Eaton are planned in HYPERRIDE. Intensive interaction with all tasks of WP3 (Hybrid grid solutions) is scheduled with further impact on all HYPERRIDE work packages.

Target TRLs and responsibility for the solution can be seen in Table 50.

Table 50: High power laboratory test services for components (MV and LV).

Lead partner	AIT
Start TRL	6
End TRL	7

Main roles for tool development and demonstration are as follows:

- AIT: responsible for test definition and implementation in laboratory;
- SciBreak, Zelisko, Eaton: provide solutions to be tested in laboratory environment.

A general specification of the solution can be seen in Table 51.

Table 51: Value based specification for LV/MV high current laboratory.

Parameter	Values	Unit
High Current AC		
voltage rating (3 s max)	0.1 - 40	kV
power rating (3 s max)	120	MVA
current rating (3 s max)	150	kA
High Current DC		
voltage rating (100 ms)	0.1 - 3.8	kV
power rating (100 ms)	160	MW
current rating (100 ms)	80	kA
permanent power	4	MW
High Voltage		
voltage rating	600	kV
current rating	1	A
voltage rating	600	kV
impulse voltage	1.2	MV

9.2 HIL Laboratory Test and Validation for Hybrid Grid Components (LV)

To enable a secure installation of new products (e.g. converters, breakers) into an existing grid infrastructure it is important to proof the operation according to relevant standards and grid connection requirements. This is state-of-the-art for AC components but not fully yet for DC or hybrid ones as those are partly under development. Hence, suitable test and validation procedures need to be developed, leveraging on existing procedures as well as infrastructures. The reason is that the respective infrastructure invest would add to development costs and would therefore negatively affect the business case of the whole infrastructure development.

The AIT SmartEST laboratory was originally designed as an AC infrastructure with DC sources for tests of PV inverters with intensive ICT backbones to be able to test and validate smart grid components with the respective interfaces. Within the last years the roll-out of storage solutions and Electric Vehicle Supply Equipment (EVSE) led to an increasing demand in the test of DC connected systems and components.

Component tests

Component tests can be based on current test procedures as they are already deployed for a wide range of applications such as PV inverters, battery storage systems or electric vehicle DC charging infrastructure. All of the before mentioned devices have at least one DC interface. Here the Device Under Test (DUT) is connected to the respective power amplifiers as well as ICT backbone and tested according to predefined test procedures. Depending on the test complexity this can also be combined with re-parametrization of certain functions. Within HYPERRIDE these kinds of test procedures will be developed using the AIT SmartEST laboratory (see Figure 47).

Figure 47: AIT SmartEST laboratory.

System tests

System tests are based on the simulation of a whole grid section and therefore it is important to be able to e.g. test control algorithm and scaling potential of solutions for smaller grids. Therefore a co-simulation of real installation with defined interfaces towards larger grids which are simulated in real-time systems enable the assessment of new functions in a potentially instable environment. To promote these test procedures a LVDC testbed will be conceptualised within the AIT laboratory infrastructure to showcase control and hardware solutions within a safe environment prior to field integration. For LV-applications it is also important to be able to use existing AC testbeds as a starting point for DC test development as newly built facilities would negatively impact the business case due to the large invest necessary.

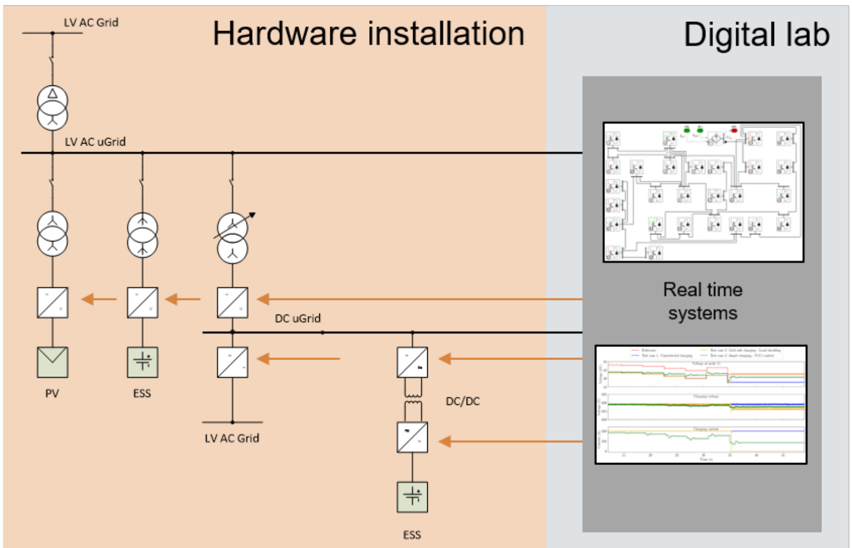

Figure 48: LVDC grid testbed.

Target TRLs and responsibility for the solution can be seen in Table 52.

Table 52: HIL laboratory test and validation for hybrid grid components (LV).

Lead partner	AIT
Start TRL	7
End TRL	8

Main roles for tool development and demonstration are as follows:

- AIT: responsible for test definition and implementation in laboratory, setup of test environment for LVDC solutions;
- RWTH: provide solutions to be tested in laboratory environment.

The general specification in Table 53 is based on the existing SmartEST laboratory installation by AIT.

Table 53: Functional specification for HIL laboratory test for hybrid grid components (LV).

Function	Description
Grid Simulation	3 independent laboratory grids with variable network impedances for up to 1000 kVA, flexible star point configuration and grounding systems
	2 independent high bandwidth grid simulators: 0 to 480 V 3-phase AC, 800 kVA (AC and DC)
	5 independent dynamic DC array simulators: 1500 V, 1500 A, 960 kVA
	3-phase balanced or unbalanced operation
	Facilities for Low Voltage Ride Through (LVRT) and Fault Ride Through (FRT) tests
Line impedance emulation	Adjustable line impedances for various LV network topologies: meshed, radial or ring network configuration
	Freely adjustable RLC loads up to 1 MW, 1 MVAr (capacitive and inductive)
	Individual control of RLC components for performance testing of islanding detection systems
Environmental simulation	Test chamber for performance and accelerated lifetime testing
	Full power operation of equipment under test inside chamber
	Max. size of equipment under test: 3.60 x 2.60 x 2.80 m (Length x Width x Height)
	Temperature range: -40 degC to +120 degC
	Humidity range: 10% to 98% relative humidity
Real time PHIL simulation	Multicore Opal-RT real-time simulator
	Power Hardware in the loop (PHIL) and CHIL experiments at full power in a closed control loop
DAQ and measurement	Multiple high precision power analyzers with high acquisition rate
	Simultaneous sampling of asynchronous multi-domain data input
General	Indoor and outdoor test areas suitable for ISO containers

9.3 HIL Based Controller Validations for Automation Solutions

In the area of multi-megawatt converter systems, careful validation of the control algorithms and control hardware in a safe test environment is necessary. The purpose of real-time simulation is to simulate physical systems and to reproduce the output states (e.g. voltage and current) with the desired accuracy in order to map the behaviour of a real system in real time. To maintain real-time operation, the model equations must be solved and output within a time step that is below the real time step considered. The approach of Controller Hardware in the Loop (CHIL) in connection with the real-time simulation of power electronic converters makes it possible to test new control platforms and control algorithms easily and safely using special simulation hardware, without the risk of destroying the power section of a real converter system. Using a rapid control prototyping platform, new developments can be driven forward quickly and in a planned manner.

Depending on the complexity of the converter topology to be simulated, scaled laboratory prototypes for verification of the control hardware and control strategy can be avoided. In addition, the simulation approach allows various scenarios, such as various fault scenarios or grid faults (e.g. fault ride through) to be tested, which cannot be easily carried out in a scaled hardware structure. The areas of application of CHIL can be divided into the:

- Testing of control units;
- Testing of control hardware and the implementation of control algorithms;
- Testing of the control hardware and its interactions in large systems;
- Investigation of interactions between proprietary control systems.

In addition, operating states can be mapped in the real-time simulation that can only be reproduced with great effort in a laboratory environment using grid emulators. The accuracy of the simulation is directly related to the computation power and thus to the smallest time step of the simulator. Therefore, it makes sense to optimise the models. The basic structure of a CHIL real-time simulation system is shown in Figure 49. The control algorithm is executed on the control platform and then generates the control signals. These Pulse Width Modulation (PWM) signals are sampled and read in by the real-time simulator and used as an input for the simulation. The system statuses for the next time step are calculated and output on the basis of the switching signals. The input values required for the control, such as grids current, voltage, or intermediate circuit voltage, are output via analogue outputs and read in accordingly by the control platform. The behaviour of the converter is thus completely emulated from the point of view of the control platform.

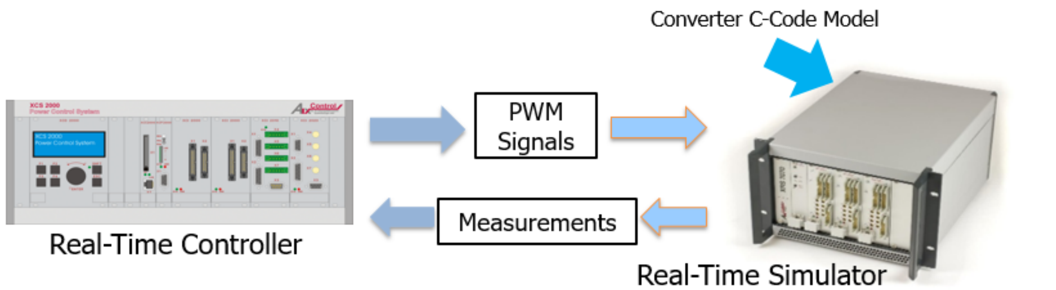

Figure 49: Structure of a Control-hardware-in-the-loop real-time simulation

Target TRLs and responsibility for the solution can be seen in Table 54.

Table 54: Responsibility and TRL target for hardware-in-the-loop based controller validations for automation solutions.

Lead partner	RWTH
Start TRL	7
End TRL	9

Main roles for tool development and demonstration are as follows:

- RWTH: implementation of the workflow and field test activities at German pilot site;
- Eaton: inputs on models and simulation tools;
- SciBreak: inputs on models for DC breakers.

A general specification of the solution can be seen in Table 55 and Table 56.

Table 55: Functional specification for hardware-in-the-loop based controller validations for automation solutions.

Function	Description
HIL Simulator	AixControl XRS system
Real-time converter model	2L-DAB, 3L-DAB, 3L-NPC
Possibility of communication between simulators	Yes
Software for model creation	PLECS

Table 56: Value based specification for hardware-in-the-loop based controller validations for automation solutions.

Parameter	Values	Unit
Time-step of real-time simulator	5	µs
Number of ADCs per real-time simulator	8	units
Number of DACs per real-time simulator	8	units

10 Open Issues and Research/Specification Needs

On basis the of enabling technologies descriptions above (overview) WP3 is preparing in co-operation with the other technical HYPERRIDE Work Packages 4-8 the detailed specifications for components and solutions considering additional demonstration requirements to setup the hybrid ACDC grid (see Figure 50).

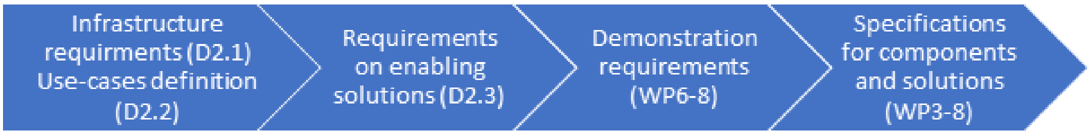

Figure 50: Process for components and solutions specifications.

Main interacting technical issues to setup the hybrid ACDC grid with focus on DC for every demonstration site (points 1-5 are essential for an initial setup):

1. Definition of a complete set of DC grid power hardware components on system level based on (AC) infrastructure requirements and DC grid KPI definition (D2.1), planned HYPERRIDE use-cases description (D2.2) and enabling technologies requirements (D2.3). Definition/adjustment of specifications for components/solutions in normal operation conditions considering planned applications and vice versa – choose grid topology/wiring (monopolar/bipolar), nominal voltage (band) and nominal currents/power ratings and (minimum) conversion stages based on available devices, starting with a single-line diagram and functions which were defined in use-case descriptions on system level (use standards if available, e.g. LVDC voltages and power quality: IEC TR 63282:2020). Break down these system requirements on component/solution level. Maybe several loops are necessary because of restrictions concerning available/existing devices. Definition on cable types/diameters (power rating, voltage drop, cable-laying, etc.). Efficiency optimisation with focus on system-level.

2. Definitions for protection coordination (incl. measuring) and insulation coordination for DC and AC grid side going along with system- and power converters (full bridge, half bridge,..) topology, specific grounding schemes (isolated or protective earth based on soil resistance) and needed galvanic insulation between AC and DC grid side. Failure Mode and Effects Analysis (FMEA) of transients (over- and short circuit current, over- and under voltage specifications) – higher system dynamics and dissipated fault transient energy (I^2t) values were reported in literature in case of DC compared with AC (discharging current from the capacitors), especially close to the source/point of common coupling, depending on the converter topology and external current limiting inductance (first 1-2 milliseconds and below). “Classical” and well-established protection schemes/standards using in this context “slow” electro-mechanical protection devices (circuit breakers, fuses with I/t-characteristics) which are based on AC dynamics and lead to oversizing/parallelization of converters because of their limited overcurrent capabilities. There is a trade-off with recent hybrid and solid-state circuit breaker concepts (prototypes, control and protection protocols) in isolated operated applications like labs, ships, buildings and lighting area allowing a faster clearing and selective feeder protection (zone concept) which enable thermal component ratings of power converters comparable to AC components. They show actually lower TRLs for DC utility distribution grid use-case.

3. Power quality requirements in context of voltage quality and electromagnetic compatibil-

ity - actually based on AC standards for the product "electricity" and immunity levels of relevant components (EN 50160, IEC 61000, CISPR,..) – esp. within the DC grid (DC customers) and also DC-AC interaction with the AC-grid (AC customers) shall be handled on existing standards/pre-standards like IEC TR 63282:2020 or best practice in case of lack of standards. DC topics: corrosion problem because of common mode currents depending on grounding schemes,..

4. DC grid automation: DC-Voltage control (node voltages and resistive network define power flows) as main parameter and stability assessment (local/global) because of interactions between different (active) converters and with the hybrid ACDC grid, incl. a grid management on system/component level to balance the generation and loads and to avoid grid congestions, especially when disconnected from (AC) main grid but also for grid optimisation in case of grid-connected mode – hybrid ACDC grids need a managed system and enough inertia (capacitance).
5. ICT-platform definition (esp. commands, monitoring & storage of relevant parameters for operational test phase) for each demonstration and interoperability assessment of control, protection, ICT interfaces and protocols (secondary technology). Considering measurement data/data interfaces for analysis of new services/business models (e.g. Terni use case for energy-communities, prosumers, D2.2).
6. Fault and cascade-effects mitigation based on hybrid ACDC concept with power converters – closely related to point 2. and considering cyber security issues.
7. Planning & testing demand (grid planning tools, simulation models, definition of test- and validation infrastructure/procedures for concrete HYPERRIDE solutions) for preparing demonstrations and general requirements for hybrid ACDC grids including actual standards.
8. Environmental factors and cooling (relevant environment for demos).

Relevant set of required LVDC and MVDC component- and system solutions (to be extended) can be found in Table 57 and Table 58:

Table 57: Relevant set of required LVDC component and system solutions.

LVDC component	demonstrated in WP (6-8)	technical issues (1-8)	specifications in WP (3-8)
Power converters	6, 7, 8	1-8	3, 6, 7, 8
Fuses	tbd.	1, 2, 7, 8	6-8
Arresters	tbd.	1, 2, 7, 8	6-8
Harmonic-Filters (AC-side)	6, 7, 8	1, 2, 3	6-8
Grounding equipment	6, 7, 8	1, 2, 3	6-8
Switching devices (disconnectors, breakers, residual current devices)	6, 7, 8	1, 2, 7, 8	3, 6, 7, 8
Power cables and accessories	6, 7, 8	1, 7, 8	6-8
Switchyard/compartments	6, 7, 8	1-8	6-8
Sensors, DC-MUs, meters	6, 7, 8	1-8	3
Secondary technology (Controls, protection relays, ICT)	6, 7, 8	1-8	3, 4, 5
Generation (photovoltaic plant)	6, 7, 8	1-8	6-8
Storage (battery, supercapacitor)	6, 7, 8	1-8	6-8
Loads (EV charging)	6, 7, 8	1-8	6-8
Grid planning and simulation	6, 7, 8	1-4, 6-8	4
AC/DC product test and validation	6, 7, 8	1-8	3
Mitigation of faults and cascade effects	6, 7, 8	1, 2, 4-8	5
Cyber security, thread detection	6, 7, 8	1, 2, 4-8	5

Table 58: Relevant set of required MVDC component and system solutions.

MVDC component	demonstrated in WP (6-8)	technical issues (1-8)	specifications in WP (3-8)
Power converters	6, 7	1-8	3
Fuses	tbd.	1, 2, 7, 8	6-8
Arresters	tbd.	1, 2, 7, 8	6-8
Harmonic-Filters (AC-side)	6, 7	1, 2, 3	6, 7
Grounding equipment	6, 7	1, 2, 3	6, 7
Switching devices (disconnectors, breakers, residual current devices)	6, 7, 8	1, 2, 7, 8	3
Power cables and accessories	6, 7	1, 7, 8	6, 7
Switchyard/compartments	6, 7	1-8	6, 7
Sensors, DC-MUs, meters	6, 7	1-8	3
Secondary technology (Controls, protection relays, ICT)	6, 7	1-8	3, 4, 5
Generation (photovoltaic plant)	6, 7	1-8	6, 7
Storage (battery, supercapacitor)	6, 7	1-8	6, 7
Loads (EV charging)	6, 7	1-8	6, 7
Grid planning and simulation	6, 7	1-4, 6-8	4
AC/DC product test and validation	6, 7	1-8	3
Mitigation of faults and cascade effects	6, 7	1, 2, 4-8	5
Cyber security, thread detection	6, 7	1, 2, 4-8	5

11 Conclusions

The deliverable provides detailed insight on the solutions to be developed within the HYPERRIDE project. For a better overview they have been clustered with respect to domain and each is described in terms of:

- Technology Readiness Level at the beginning and at the end of the project;
- A description of the solution answering the questions:
  - Why is there a need for the solution in ACDC grids?
  - How the solution will act in the system or for the system?
  - What are the basic functions of the solution?
  - Who will benefit of the solution and how?
  - Which partner will participate with which action and setup - simulation, validation/lab test setup, etc. - in HYPERRIDE (implementation)?
- A general specification prior to detailed work in WP3 in cooperation with WP4-8.

This report is to be used in context of D2.1 (Infrastructure Requirements) and D2.2 (Use Cases) to gain a full picture of the activities in the project.

Next steps will be the work in WP3 in cooperation with WP4-8 to gain a detailed specification, further realisation of the solutions and demonstration in one or more of the demonstration sites.

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