



Interoperability of the Power Electronics dominated grid by openness Inter-oPEn

Deliverable D4.1 Towards integration methods for a resilient and flexible power system - Status report

Dissemination			
Lead	Level	Type	Delivery Month
TU Delft	☒ PU (Public) ☐ SEN – Sensitive ☐ C-UE/EU-C - EU Classified	☒ R (Document, report) ☐ DEC (Websites, patent fillings, videos, etc.) ☐ DMP (Data Management Plan) ☐ OTHER	M29

Grant Agreement:	101119349
Project acronym:	Inter-oPEn
Project title:	Interoperability of the Power Electronics dominated grid by openness
Start of the project:	01.01.2024 (54 months)
Work package:	WP4
Deliverable number:	D4.1
Title of deliverable:	Towards integration methods for a resilient and flexible power system – status report
Deliverable due date:	31.05.2026
Date of submission:	29.05.2026
First Author:	Aleksandra Lekić (TU Delft)
Contributors:	A. Farshadi (TUBS, DC7), A. Obando Martínez (UPC, DC3), C. K. Gerald (KTH, DC5), M. Musa (RWTH, DC2), T. B. Hashfi (TU Delft, DC10)
Version:	1.2

DISCLAIMER

Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or REA. Neither the European Union nor the granting authority can be held responsible for them.

VERSION CONTROL

Version	Date	Author (Name, Institution)	Comments
1.0	07.05.2026	Aleksandra Lekić (TU Delft)	First draft
1.1	21.05.2026	Eduardo Prieto-Araujo (UPC) Melanie Hoffmann (TUBS)	Proofreading of the report
1.2	25.05.2026	Aleksandra Lekić (TU Delft)	Final version

Table of Contents

1	Introduction	4
2	Control Interoperability Assessment Considering Partially Open Converter Controls: A DC-Side Stability Perspective (DC2)	5
2.1	Topic summary	5
2.2	Outputs	5
2.3	Alignment and interactions with other PhD students.....	6
2.4	Publications.....	6
3	Data-driven control of power converters for modern power networks (DC3).....	6
3.1	Topic summary	6
3.2	Outputs	6
3.3	Alignment and interactions with other PhD students.....	7
3.4	Publications.....	7
4	Interoperability pathways and workflows for the power-electronics dominated electricity grid (DC5).....	7
4.1	Topic summary	7
4.2	Outputs	8
4.3	Alignment and interactions with other PhD students.....	8
4.4	Publications.....	8
5	Model-Based Systems Engineering (MBSE) for Protection System Development for HVDC grids with connected OWFs (DC7)	8
5.1	Topic summary	8
5.2	Outputs	9
5.3	Alignment and interactions with other PhD students.....	9
5.4	Publications.....	9
6	The Development of Advanced Strategy for Isolating and Controlling The fault in HVDC Network (DC10).....	10
6.1	Topic summary	10
6.2	Outputs	10
6.3	Alignment and interactions with other PhD students.....	10
6.4	Publications.....	11
7	Next steps	11

1 Introduction

The MSCA DN project titled Inter-oPEn started on January 1st, 2024 and will end on June 30th, 2028. Inter-oPEn is composed of 8 beneficiaries, 11 industrial associated partners and 10 doctoral candidates. The project offers a broad industry and transmission systems operator expertise for doctoral trainings, research, and secondments. In line with this, a unique doctoral training programme that integrates multi-sector knowledge, gathering electrical engineering and legal researchers, is implemented. The doctoral training programme is divided into three complementary parts: (1) Engineering components for swift interoperability; (2) Integration of a resilient and flexible power system and; (3) Enabling interoperability from a legal and regulatory view. Inter-oPEn follows an innovative approach by including two fundamental and new aspects: (1) The interplay of technical and legal perspectives is considered and; (2) Openness principles are heart of engineering and legal research, as well as training.

To briefly summarize, the accelerating deployment of power electronics in transmission and distribution networks is fundamentally reshaping how modern power systems are designed, operated, and controlled. Voltage Source Converters (VSCs) and Modular Multilevel Converters (MMCs) are increasingly displacing conventional synchronous generation, bringing with them considerable benefits in terms of controllability and grid flexibility, but also introducing new challenges related to stability, interoperability, and resilience. The Inter-oPEn project addresses these challenges through a coordinated Marie Skłodowska-Curie Actions Doctoral Network (MSCA DN), uniting doctoral candidates across leading European research institutions.

This status report, Deliverable D4.1, presents the current research progress of five doctoral candidates whose work collectively addresses the integration challenges facing power electronics-dominated grids. The research spans five complementary themes: DC-side stability assessment in multi-vendor HVDC systems (DC2), data-driven control methodologies for power converters (DC3), interoperability pathways and workflows for grid-connected power electronics assets (DC5), Model-Based Systems Engineering (MBSE) for HVDC protection system development (DC7), and advanced fault isolation and control strategies for multi-terminal HVDC networks serving offshore wind farms (DC10).

A central concern across all doctoral projects is the multi-vendor nature of future HVDC grids. As point-to-point HVDC links evolve into multi-terminal DC (MTDC) networks, equipment from different vendors must coexist and cooperate on a shared DC bus. Proprietary control logic and technology-specific design assumptions create barriers to transparency and interoperability, making it difficult for system operators to perform stability assessments, verify compliance with grid codes, or develop vendor-agnostic protection schemes, all without full disclosure of intellectual property. The doctoral research reported here develops frameworks and tools that work within these practical constraints, enabling stability analysis, control synthesis, protection design, and interoperability verification using partial or openly available information.

A particularly distinctive contribution within this report is the application of MBSE to the structured design of HVDC protection systems. By enforcing a clear separation between stakeholder requirements, architectural decisions, and implementation details — in line with the V-model design procedure — this research addresses a methodological gap in how

protection functionalities are allocated across devices in multi-vendor environments. This work complements the stability and control threads by providing a formal, traceable design process that spans from high-level stakeholder needs to technology-specific implementation, while preventing premature lock-in to any single vendor solution.

Beyond stability and control, the network investigates how resilience can be improved under fault conditions, including AC and internal converter faults in offshore MTDC applications. Power-Hardware-In-the-Loop (PHIL) experimentation is used to bridge the gap between simulation and physical validation, offering a rigorous basis for assessing converter control performance under realistic conditions.

The doctoral candidates operate in an interconnected research environment, with active cross-institutional collaborations covering HVDC control design, protection coordination, simulation workflow automation, contract-based subsystem specification, and standardisation. These interactions reflect the ethos of the Inter-oPEn network: advancing the technical foundations for an open, interoperable, and resilient power electronics-dominated grid through coordinated doctoral research across Europe.

Sections 2 through 6 present the individual research summaries of each doctoral candidate, including topic overviews, outputs achieved to date, collaborations within the network, and publications. Section 7 outlines the planned next steps for the coming period.

2 Control Interoperability Assessment Considering Partially Open Converter Controls: A DC-Side Stability Perspective (DC2)

2.1 Topic summary

As point-to-point HVDC links transition to MTDC networks, the system is expected to naturally integrate components from different vendors, leading to multi-vendor MTDC networks. In this configuration, converters from different vendors will share a single DC network, with each vendor's control logic being proprietary and independently tuned. The interaction between differently tuned converter controls could introduce the risk of unwanted oscillations and DC-side stability uncertainty. Ensuring DC-side stability requires access to converter control information, however, full model disclosure is not feasible due to IP constraints.

This research focuses on DC-side stability assessment in multi-vendor MTDC systems under partial openness. It aims to develop a framework enabling TSOs to assess DC-side stability and size DCCB inductors without requiring full vendor IP disclosure. The approach is based on impedance-based small-signal stability analysis, using the Generalised Nyquist Stability Criterion applied to a MIMO admittance matrix assembled from individual converter station impedances and the DC network admittance [1].

2.2 Outputs

To carry out the DC-side stability assessment under partial openness, a systematic review of DC-side stability assessment methods for VSC-HVDC systems was conducted to identify a suitable method applicable to a multivendor HVDC system.

This research will deliver the following outputs:

- A frequency-domain perturbation-based impedance scanning toolbox for extracting DC-side terminal impedance of MMC converter stations on EMT simulation.
- Framework for DC-side stability assessment in a multivendor HVDC system using impedance stability analysis.
- A stability-informed DCCB inductor sizing methodology that jointly satisfies protection and stability constraints without full IP disclosure.

2.3 Alignment and interactions with other PhD students

This research sits at the intersection of converter control, DC-side stability, and protection coordination, which aligns with other doctoral candidates within the Inter-oPEn network. An ongoing collaboration with DC4 at KU Leuven focuses on HVDC control design and stability investigations to highlight protection-driven constraints and dynamic requirements.

2.4 Publications

[1] M. Mathew, L. Osterkamp, C. Klein, T. Heynen, M. Kuhn, W. Leterme, “DC-Side Stability Assessment Methods for Multi-Vendor VSC-Based HVDC Systems: A Review and Applicability Analysis” IET International Conference on AC and DC Power Transmission (ACDC 2026), Berlin. *In press*.

[2] M. Mathew, M. Kuhn, W. Leterme, “Impact of DCCB Inductor Sizing on DC-Side Stability in Multi-Vendor MTDC Systems” – Manuscript. *In preparation*.

3 Data-driven control of power converters for modern power networks (DC3)

3.1 Topic summary

The classical model-based control approaches are accurate and efficient when used with an exact system model. However, these approaches are restricted by model uncertainties.

The utilisation of overly intricate controllers has the potential to result in challenges or expenses related to their application, and faulty performance can occur too readily. In this context, data-driven control (DDC) represents an alternative to tackle the challenges that arise in controlling power converters. The aim of this research is to develop a methodology for the synthesis of DDC for implementation in VSC-based power converters. This will be achieved by a comprehensive study of existing control schemes, including optimisation-based, predictive, and direct data-driven controllers and the analysis of their integration into power network applications.

3.2 Outputs

The primary outcome is a systematic study of control theory using a simplified and structured approach, aimed at facilitating its integration across disciplines, particularly bridging control

engineering, power systems, and regulatory frameworks. A general taxonomy of control strategies was established, together with a specific taxonomy for DDC.

In the research of modern control strategies, a methodology was developed for the integration of optimisation-based and predictive control techniques into power electronics applications, leveraging symbolic modelling within the open-source framework CasADi (symbolic framework for numerical optimal control).

Finally, ongoing work focuses on the implementation of the OSQP solver¹ to reduce computational overhead and improve execution times relative to symbolic optimisation approaches. The results comprise a detailed description of the proposed methodology and its validation through simulations on a three-phase power converter.

A comprehensive description of these methodologies, along with the benchmark model of the three-phase power converter simulation, is intended for publication on the CRESYM website upon acceptance of the associated scientific publication.

3.3 Alignment and interactions with other PhD students

During interactions with other PhD candidates, we exchanged technical literature on control strategies and interoperability aspects with DC1 and DC7. We aim to align our research activities with DC4 to evaluate advanced control strategies, particularly Model Predictive Control (MPC), on a three-bus HVDC grid. We are considering a collaboration with DC6 focused on HVDC control methodologies during their academic stay at UPC. With DC9, during the PhD Candidates Workshop in Barcelona, we discussed the fundamental components of control systems and their integration within the Smart Grid Architecture Model (SGAM) framework.

3.4 Publications

- Review on Data-driven Controllers for Power Electronic Systems, IEEE Access or Renewable and Sustainable Energy Reviews, *ongoing*.
- Optimal Tuning of Conventional Converter Control Structures Following an MPC like Formulation, *ongoing*.

4 Interoperability pathways and workflows for the power-electronics dominated electricity grid (DC5)

4.1 Topic summary

Most likely, the future power grid will be power electronics dominated. Grid-connected converters take over the role of the traditional grid control components such as synchronous generators. A vital question is how to achieve interoperability at all levels, both distribution and transmission. The interplay between technology, standardisation, grid codes, verification methods, and openness will be investigated in the project. In particular, the collaborative workflows to be used by the different stakeholders (equipment vendors, TSOs, DSOs) for adapting and integrating new assets in a grid should be proposed and researched. Future flexibility with respect to evolving technology solutions should be sought with consideration of risk management.

¹ More information can be found here: <https://osqp.org/docs/>

4.2 Outputs

The initial phase of the research focused on developing a comprehensive literature review on multi-vendor interoperability in HVDC grids, thereby establishing the foundation for subsequent research directions. Building on this, preliminary studies have investigated a simplified approach for constructing a test-case operating envelope for a single modular multilevel converter (MMC), based on the functional requirements for interoperability defined in InterOPERA D2.1 (EU funded project, GA no.101095874). The objective is to reduce the effort required to assess whether a converter satisfies interoperability criteria.

To this end, an MMC simulation model was developed in PSCAD. Subsequently, a sensitivity analysis using Sobol indices was performed with the aid of a metamodel of the converter, constructed using Bayesian sparse polynomial chaos expansion. These methods form the basis for reducing the number of simulations required to evaluate the converter's performance with respect to interoperability requirements.

Potential open or shareable outputs for the CRESYM COLib repository include:

- MMC model suitable for interoperability studies

4.3 Alignment and interactions with other PhD students

Publication [1] was prepared in collaboration with DC7. Ongoing joint efforts focus on automating simulation and modelling workflows for EMT studies of HVDC grids.

4.4 Publications

[1] C.K. Gerald, A. Farshadi, I. Jahn, M. Hoffmann, M. Kurrat, S. Norrga “Review of Multi-vendor Interoperability in HVDC Grids” – published at the 22nd IET ACDC conference. *Not yet online*.

[2] C.K. Gerald, I. Jahn, S. Norrga “A PSCAD-Based Open-Source Average Model of a Modular Multilevel Converter for Interoperability Testing Procedures”. *Manuscript under preparation*

5 Model-Based Systems Engineering (MBSE) for Protection System Development for HVDC grids with connected OWFs (DC7)

5.1 Topic summary

The transition from single-vendor point-to-point HVDC links to multi-vendor multi-terminal HVDC grids introduces fundamental challenges for protection system design. In such environments, protection can no longer rely on technology-specific assumptions, and specifying required behaviour without constraining proprietary implementations becomes a central difficulty. A less visible but equally important challenge is methodological: existing research on individual components lacks a consensus on how to systematically allocate protection functionalities across devices. Requirements, behaviours, and device capabilities are frequently mixed at inconsistent levels of abstraction, leading to premature technological lock-in. This research applies MBSE to address these challenges through a structured framework that enforces a clear separation between stakeholder needs, architectural

decisions, and implementation details, while maintaining formal traceability across design layers in line with the V-model design procedure.

5.2 Outputs

In [1], a comprehensive literature review on multi-vendor interoperability in HVDC grids has been conducted, and as part of it, the MBSE approach as a multi-stakeholder procedure for achieving interoperability has been investigated. Publication [2] illustrates how stakeholder-derived requirements can serve as boundary conditions for protection system design at the concept level. In [3], a contract-based design methodology is introduced to capture interdependencies between subsystems that can be used the MBSE framework. Building on these foundations, [4] presents a structured, model-based method to define and document HVDC protection concepts at a level of abstraction that prevents premature device-level assumptions. The MBSE model is developed in Enterprise Architect and is integrated with a conceptual protection design module developed at KU Leuven, demonstrating the link between MBSE and model-based design (MBD).

5.3 Alignment and interactions with other PhD students

Publication [1] is a collaborative work with DC5. Publications [2] and [3] were produced in collaboration with PhD students at TUBS, and [4] is an ongoing collaboration with the KU Leuven team during the academic secondment. Additionally, a joint effort with DC4 is underway to connect the MBSE framework with control–protection interaction analysis, linking formal system-level design with EMT-based studies.

5.4 Publications

[1] C.K. Gerald, A. Farshadi, I. Jahn, M. Hoffmann, M. Kurrat, S. Norrga, “Review of Multi-vendor Interoperability in HVDC Grids”. *Presented at ACDC Europe 2026 Conference (Berlin)*.

[2] F. B. Witt, A. Farshadi, G. Chaffey, T. Jelden, M. Hoffmann and M. Kurrat, “Conceptualizing the protection properties of DC networks: Requirements engineering and system design,” *DC-IN; Industrial and Sustainable Direct Current Grids*, Lemgo, Germany, 2025, pp. 140–149, doi: 10.30420/566654019.

[3] F. B. Witt, A. Farshadi, G. Chaffey, M. Van Deyck, and M. Kurrat, “Compositional Specification of DC Protection Subsystems with Interface Contracts”. *Presented at ACDC Europe 2026 Conference (Berlin)*.

[4] A. Farshadi, F. B. Witt, G. Chaffey, M. Van Deyck, M. Hoffmann, D. Van Hertem, and M. Kurrat, “HVDC grid protection concept-level design using an integrated MBSE and MBD framework”. *Manuscript under preparation*.

6 The Development of Advanced Strategy for Isolating and Controlling The fault in HVDC Network (DC10)

6.1 Topic summary

The work focuses on MMC-based multi-terminal HVDC (MTDC) networks for offshore wind farm integration, with particular attention to grid-forming capability in offshore wind farms (OWFs). It investigates how OWFs and HVDC converters can establish and regulate offshore AC voltage and frequency, support isolated offshore grids, enable black-start operation, and improve coordinated power sharing among multiple terminals. By adopting grid-forming control strategies, the MTDC network can become more suitable for future offshore energy systems.

In addition, the work addresses MTDC resilience under external and internal fault conditions. AC faults are also critical because they affect the wind farm collection grid, reduce offshore converter power transfer capability, and create power imbalance between wind generation and the HVDC system. Therefore, coordinated control among grid-forming wind turbine converters, offshore MMCs, and onshore DC voltage-regulating stations are investigated to maintain voltage stability, limit DC-link overvoltage, enable OWF power curtailment, and support fast post-fault recovery. The work also includes power-hardware-in-the-loop (PHIL) testing using real-time MTDC simulation, a downscaled MMC prototype, IEDs, and a power amplifier to evaluate converter control, fault ride-through, and internal MMC fault-tolerant operation.

6.2 Outputs

The expected outcomes of this research are directed toward improving the stability, resilience, and practical implementation of MTDC networks for OWF integration. RTDS simulators and MATLAB are used to cover the research studies and experimental validation through PHIL testing.

This research will deliver the following outputs:

- Enhancing failure management of the converter stations by having internal MMC fault tolerance and AC-FRT performance with minimal disruption between AC/DC grids connection
- Increasing system resilience, scalability and making MT-HVDC system more suitable for future grid technology.
- Increasing the competence of the research through validating and investigating the MT-HVDC system through PHIL technology.

6.3 Alignment and interactions with other PhD students

This research focuses on the intersection of converter control, stability, and handling the faults, which aligns with other doctoral candidates within the Inter-oPEn network. Namely, DC impedance scanning tool will include grid-forming control developed as the part of DC10.

6.4 Publications

- [1] T. B. Hashfi, H. Vahedi, P. Palensky and A. Lekić, "Internal Power Flow Control For Modular Multilevel Converter During Submodule Failure," 2025 IEEE Kiel PowerTech, Kiel, Germany, 2025, pp. 1-7, doi: 10.1109/PowerTech59965.2025.11180269.
- [2] T. B. Hashfi, Rahul Rane, Arjita Pal, and A. Lekić, "Grid-Forming Offshore Wind Farm Integration Through MMC-HVDC Network" IEEE Transactions on Power Electronics. *Submitted*.

7 Next steps

Building on the foundations established in this status report, the doctoral candidates will advance their respective research threads towards more complete frameworks, experimental validation, and peer-reviewed publications. The following activities are planned for the next reporting period.

In the area of DC-side stability (DC2), the impedance scanning toolbox will be finalised and validated on a multi-vendor MTDC test system in electromagnetic transient (EMT) simulation. The stability-informed DCCB inductor sizing methodology will be extended to multi-terminal configurations, and a journal manuscript on the combined stability and protection framework is being prepared. Collaboration with DC4 at KU Leuven on protection-driven control constraints will continue.

For data-driven control (DC3), the integration of the OSQP solver into the MPC-based converter control framework will be completed and benchmarked against symbolic optimisation. Joint activities with DC4 targeting a three-bus HVDC grid demonstration are planned, alongside a potential collaboration with DC6 during their academic visit. A review article on data-driven controllers for power electronic systems is under preparation for IEEE Access.

Within the interoperability pathways theme (DC5), the operating envelope methodology for MMC interoperability testing will be further developed, with a focus on reducing simulation effort through Bayesian sparse polynomial chaos expansion and metamodeling. An open-source average MMC model suitable for interoperability studies will be prepared for release via the CRESYM platform. Joint work with DC7 on automated EMT simulation workflows will proceed in parallel.

For MBSE-based protection design (DC7), the integrated MBSE and model-based design framework developed in Enterprise Architect will be extended and further validated in collaboration with the KU Leuven team. The ongoing joint effort with DC4 to link the MBSE framework with control-protection interaction analysis will be advanced, and the manuscript on HVDC grid protection concept-level design is being finalised for journal submission. Collaborative work with TUBS colleagues on contract-based specification of DC protection subsystems will also continue.

In the MTDC fault control domain (DC10), PHIL testing campaigns are planned to experimentally validate grid-forming control strategies and AC fault ride-through performance. The manuscript on grid-forming offshore wind farm integration through MMC-HVDC is currently under review, and a further paper on coordinated fault management in MTDC systems is in preparation. Network-wide dissemination activities, including contributions to the Inter-oPEn PhD Candidates Workshop and open-access publication of simulation models and datasets, will be pursued across all doctoral projects.