



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

Deliverable D3.1 Towards components for swift interoperability – status report

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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.

The rapid growth of converter-based resources in modern power systems, including HVDC links, offshore wind, and battery storage, introduces new challenges for interoperability. Unlike synchronous machines, power electronic converters rely on proprietary control and protection software, creating a tension between the openness required for multi-vendor procurement and the confidentiality that vendors need to protect intellectual property. Addressing this challenge is the central objective of Inter-oPEn that develops knowledge, methods, and tools for engineering interoperability in power electronics-dominated grids across three research work packages.

This document is Deliverable D3.1, a status report on the scientific output of WP3 “Engineering components for swift interoperability”. It covers the research progress of the three WP3 doctoral candidates:

- DC1 (RWTH ACS) on structured control and protection software for HVDC converters,
- DC4 (KUL) on control–protection co-design in multi-vendor HVDC grids, and
- DC6 (KIT) on interactions and controller partitioning in power electronics-dominated AC grids.

Each DC in WP3 has investigated their specific research topic while also collaborating with colleagues in related areas. This is important because to design converters “plug&play” for swift interoperability requires an understanding of the system surrounding the component (see WP4) as well as legal aspects (WP5).

For each DC, the chapters in this deliverable present a topic summary, current outputs, cross-project interactions, and published or about-to-be-submitted publications. The report concludes with the planned next steps.

2 Structured Control & Protection Software for HVDC converters (DC1)

2.1 Topic summary

In accordance with the Grant Agreement, DC1 is investigating partially-open control and protection schemes for HVDC systems, advancing the concept proposed by CIGRE Working Group B4.85. The candidate is currently investigating the question of which HVDC control functions need to be shared how this exchange can be done. To achieve this, a literature review was conducted to examine the dependencies of converter control functions on system performance and hardware aspects, operating on the premise that heavily hardware-reliant functions should be excluded from sharing. Subsequently, DC1 engaged in a joint research effort with a counterpart PhD candidate at RWTH. This collaboration utilized the aforementioned findings to optimize the partitioning strategy of HVDC converter control [1].

Furthermore, in publication [2], DC1 has investigated interoperability of AC fault ride-through operation and fault interruption operation in an integrated device combining a DC circuit breaker and an HVDC dynamic breaking chopper. A key takeaway from [2] is that TSOs must reconsider whether separating tenders for choppers and DCCBs remains the most cost-effective approach for future multi-vendor HVDC projects.

2.2 Outputs

For each research topic, the possibility for providing open source models to the community (via CRESYM/COLib) is assessed. For this doctoral project, the potential contributions for the CRESYM webpage include:

- Non-proprietary PSCAD benchmark of a DC circuit breaker with an integrated HVDC chopper.

2.3 Alignment and interactions with other PhD students

Publication [1] is done in collaboration with another PhD student in RWTH Aachen University. Furthermore, following the secondment of DC9 from the law faculty of University of Groningen to Aachen, alongside DC1's secondment to Groningen, joint research has been initiated on the technical and Intellectual Property (IP) aspects of system openness and data sharing.

2.4 Publications

[1] Contribute as a collaborator: M. Moritz, I. Jahn, A. Sajjadi, K. Sano, A. Monti, "Optimization-based Multi-objective Partitioning of MMC Control Systems," *Manuscript under preparation*.

[2] A. Sajjadi, M. Hamzeh, R. Alvarez, A. Monti, "Integrating Dynamic Breaking Chopper into DC Circuit Breaker for HVDC Systems," *ACDC Europe 2026 - 22nd IET International Conference on AC and DC Power Transmission, 2026, Accepted paper*

3 Interactions and co-design between control and protection in multi-vendor HVDC grids (DC4)

3.1 Topic summary

Future large-scale HVDC grids are expected to be inherently multi-vendor, where converters and protection systems are supplied, operated, and updated by different manufacturers and asset owners. While existing HVDC systems have largely been developed as tightly integrated, single-vendor solutions, such an approach is incompatible with the long-term vision of open, interoperable European HVDC grids.

In this context, converter control and DC grid protection can no longer be designed independently. The behaviour of converter controllers particularly during DC faults directly influences protection performance (e.g. fault current magnitudes, detection times, and blocking behaviour) [1], while protection actions can strongly affect converter dynamics and system stability. In a multi-vendor environment, uncoordinated changes to either control or protection algorithms risk unintended system-level interactions [2].

A first research study investigates the interactions and opportunities for co-design between converter control and DC protection in multi-vendor HVDC grids. It aims to identify which aspects of converter control are most critical for protection performance, how control–protection interactions arise, and how interfaces or information exchange could be structured to support interoperable, IP-sensitive solutions. The ultimate goal is to provide structured knowledge and design guidance that supports robust, vendor-independent HVDC grid operation.

3.2 Outputs

For each research topic, the possibility for providing open source models to the community (via CRESYM/COLib) is assessed. For this doctoral project, the potential contributions for the CRESYM webpage include:

- Generic sensitivity analysis workflows applicable to HVDC control–protection studies.
- Non-proprietary MMC benchmark models and parameter sets suitable for interoperability studies.

3.3 Alignment and interactions with other PhD students

This research aligns with and complements other PhD activities within the Inter-oPEn project. At the moment, there are collaborations and interactions with the following DCs:

- HVDC control design and stability investigations to highlight protection-driven constraints and dynamic requirements with DC2.
- Using model based system engineering (MBSE) as a structuring layer above EMT simulation to formalize control – protection interactions with DC7.
- Evaluate advanced converter control strategies in MTDC grids with DC3.

3.4 Publications

[1] E.E. Sule, A. Mohammadi, X. Liu, G. Chaffey, D. Van Hertem, “A Two-Stage Morris-Sobol Framework for Assessing Converter Control Impact on DC Protection Design” – *Accepted to ECCE Europe 2026*.

[2] E.E. Sule, G. Chaffey, D. Van Hertem, “Impact of Fault Current Limiting Control Strategies on DC FRT in MVMT HVDC Grids” – *Manuscript under preparation*.

4 Interactions in power electronics dominated AC-grids: Challenges for interoperability and controller partitioning (DC6)

4.1 Topic summary

This research focuses on interactions in power electronics-dominated AC grids, addressing challenges related to interoperability and controller partitioning.

With the increasing penetration of converter-based systems, harmonic and transient interactions between converters and the surrounding network pose significant risks to system stability. This work investigates these interactions using detailed simulations.

The research emphasises the development and control of Modular Multilevel Converter (MMC)-based HVDC systems, including implementation of PWM (Pulse Width Modulation), PSC-PWM (Phase shifted carrier PWM), and NLC (Nearest Level Control). A key focus is on energy balancing and capacitor voltage balancing, which are essential for reliable MMC operation and improved system stability.

4.2 Outputs

For each research topic, the possibility for providing open source models to the community (via the CRESYM/COLib) is assessed. For this doctoral project, the potential contributions for the CRESYM webpage include simulation models, control design implementation, and benchmarking results across control strategies, e.g. within:

- A detailed two-terminal MMC-HVDC simulation model in MATLAB/Simulink [1].
- Implementation and comparative analysis of multiple control strategies i.e. (PWM, PSC-PWM, NLC).
- Comparative analysis of control methods based on harmonic performance and dynamic response [1].
- Development of Capacitor voltage balancing and energy balancing strategies.

4.3 Alignment and interactions with other PhD students

The work of DC6 aligns with other PhD researchers within the project. Potential collaborations include work with DC1 on stability analysis and control aspects of MMC systems, as well as collaboration with DC3 on advanced control and modulation techniques.

4.4 Publications

[1] “Enhanced Low-Switching Frequency PWM for MMC-HVDC Systems: Improved Harmonic Performance, Voltage Stability, and Circulating Current Suppression.” Contributors: Mahnoor Hassan, Thomas Leibfried. *An ongoing publication is being prepared for ECCE 2026.*

The first digest was submitted in February 2026. *The full paper is planned for submission in June 2026.*

5 Next steps

Building on the progress reported in this document, the three doctoral candidates within WP3 will continue to advance their research in the second reporting period. The following provides an overview of planned activities across all three research topics.

DC1 – Structured control and protection software for HVDC converters (RWTH ACS)

Together with another doctoral student in the same research group, DC1 will consolidate and finalise the optimization-based partitioning framework for MMC control systems, targeting submission of manuscript [1] to a peer-reviewed journal. In collaboration with DC9 (University of Groningen), DC1 will establish classification criteria for HVDC converter control functions by integrating technical and legal perspectives, evaluating both the openness value for TSOs and the intellectual property sensitivity for vendors. This cross-disciplinary work is expected to yield a joint publication and contribute directly to the Inter-oPEn whitepaper on openness criteria. Beyond, that DC1 will continue their work on structured data towards an open interoperable upper control layer.

DC4 – Interactions and co-design between control and protection in multi-vendor HVDC grids (KUL)

DC4 will prepare the full paper for ECCE Europe 2026 based on the accepted abstract, further developing the two-stage Morris–Sobol sensitivity analysis framework for assessing converter control impact on DC protection design. The ongoing manuscript on fault current limiting control strategies in multi-terminal HVDC grids will be finalised and submitted. Going forward, DC4 will deepen the collaboration with DC2 on protection-driven constraints for HVDC control design, and with DC7 on the use of model-based system engineering to formalise control–protection interaction interfaces.

DC6 – Interactions in power electronics dominated AC-grids: Challenges for interoperability and controller partitioning (KIT)

DC6 will complete and submit the full paper on enhanced low-switching-frequency PWM for MMC-HVDC systems to ECCE 2026 by June 2026. The work will be extended to include a broader comparative study of modulation strategies (PWM, PSC-PWM, NLC) with respect to harmonic performance and dynamic response under varied grid conditions. DC6 will initiate deeper collaboration with DC1 on MMC stability analysis and with DC3 on advanced control and modulation benchmarking.

WP coordination

In addition to the regular interaction within WP3, all three DCs will continue their cross-WP integration with both their individual research, as well as organized peer reviews under T3.2. In addition, the WP is preparing for the upcoming Inter-oPEn whitepapers and open-source material to be delivered to WP6 and CRESYM under appropriate licensing conditions.