POWER DISPATCH AND VOLTAGE CONTROL TOOL FOR HYBRID AC/DC DISTRIBUTION GRIDS

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Abstract

As the deployment of DC segments in existing AC distribution grids becomes more common, network operators face a critical gap: the lack of planning tools capable of calculating feasible dispatch and voltage setpoints across both AC and DC domains. This paper presents how the Horizon Europe funded HYNET project aims to tackle the operational coordination of these tightly coupled sub-grids, where voltage limits and converter interactions must be managed simultaneously. We introduce a unified Optimal Power Flow tool designed to be able to handle hybrid AC/DC architectures. A key innovation of our solution lies in its practical implementation - the solver is embedded as a Python-based user defined tool within DIgSILENT PowerFactory, ensuring compatibility with the HYNET project toolchain. Validation is performed using modified Stagg's 5-bus and IEEE 33-bus systems. The proposed tool provides Distribution System Operators with technically consistent operating points, allowing them to assess emerging control strategies and architectures before real-world deployment.

1 Introduction

The transition toward hybrid AC/DC distribution networks requires new operational paradigms to manage the increasing penetration of power-electronic-interfaced devices. This section outlines the specific industrial context of this challenge and reviews the current state-of-the-art in hybrid optimal power flow (OPF) methodologies.

1.1 Project Context and the French Demonstration

The work presented in this paper is conducted within the Horizon Europe-funded HYNET project [1]. The project's primary objectives are to facilitate the European energy transition, establish standardized methodologies for multi-terminal medium-voltage direct current (MVDC) interoperability, develop innovative technologies for the cross-border design of hybrid grids, and enhance overall system resilience. To validate these technologies, HYNET features four distinct pilot demonstrations across Europe.

Our work is associated with the French demonstration (demo #1), which includes specific use cases focused on integrating hybrid AC/DC systems for congestion management in distribution grids. The examined scenarios address the challenge of integrating high-power applications, such as electric vehicle (EV) charging stations, on networks not originally designed for such demands. This evaluation, eventually validated by EDF Lab Les Renardières is conducted within a simulated environment. This provides a controlled environment for the evaluation of computational coordination tools under high grid stress conditions without reliance on physical hardware. The proposed evaluation architecture can be seen on Fig 1.

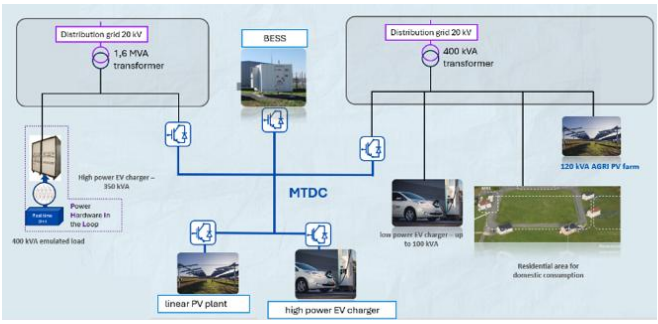

Fig. 1 Multi-terminal MVDC Grid in the planned validation of the French demonstration [2]

Within this demonstration, the proposed optimal power flow framework (Tool #1 of the 13 tools utilized in HYNET) serves as the primary congestion analysis engine. To evaluate the operational benefits of DC grid reinforcements, Tool #1 operates through a highly specific, iterative workflow. It initially establishes a base case by importing an AC network topology alongside varying time-series data for loading and generation provided by EDF. Tool #1 then calculates the OPF utilizing Tool #5 (a Python-based steady-state power flow solver) as an embedded black box module in the optimization. If increased loading scenarios cause network congestions that cannot be managed by the grid's existing controllable devices, Tool #1 calculates specific congestion indicators and exports them to Tool #7 (the project's network planning tool). Tool #7 subsequently designs a reinforced hybrid AC/DC topology and returns it to Tool #1. Finally, Tool #1 re-evaluates this new hybrid architecture to verify that the newly embedded DC links successfully alleviate the thermal and voltage constraints.

In this paper, we demonstrate the technical and computational considerations taken into account for the framework formulation, including the underlying modelling assumptions, constraint definitions, data exchange mechanisms, and integration aspects required for operation within a multi-tool demonstration environment.

1.2 Existing Hybrid AC/DC OPF methodologies

To properly contextualize the hybrid AC/DC OPF framework proposed in this paper, it is necessary to examine the evolution of grid optimization techniques and their limitations in practical deployment. The following subsections review the historical progression of the OPF problem, the specific mathematical challenges introduced by hybrid AC/DC architectures, the existing analytical solution strategies, and finally, the operational gap that necessitates the black box approach adopted for the HYNET demonstration.

1.2.1 Classical OPF and Active Distribution Networks: The OPF problem has been a cornerstone of power system analysis since its mathematical formulation in the 1960s [3]. Traditionally applied in high-voltage transmission networks, classical OPF seeks to optimize generation dispatch while respecting the physical constraints of the network, such as the thermal limits of the equipment or the power quality requirements [4]. However, the rapid deployment of distributed energy resources (DERs) has fundamentally transformed passive distribution grids into active networks, necessitating the adaptation of OPF frameworks for DSOs. In these modern contexts, the operational objective frequently shifts from classical economic dispatch to the minimization of active power losses and the mitigation of voltage deviations [5].

1.2.2 Modelling Hybrid AC/DC Grids and VSCs: The emerging integration of DC links through Voltage Source Converters (VSCs) into traditional AC infrastructure has introduced profound mathematical complexities to the OPF problem [6]. Unlike conventional AC networks, hybrid AC/DC distribution grids require the simultaneous resolution of highly coupled voltage and power flow equations across both domains [7]. The accurate representation of VSCs is critical, as standard lossless converter assumptions are insufficient for hybrid OPF, requiring accurate quadratic models to capture switching and conduction losses, as well as specific control strategies [8].

1.2.3 Analytical Solution Strategies: Algorithmically, the literature is divided into two approaches for solving hybrid AC/DC power flows: simultaneous and sequential methods. Simultaneous methods integrate both AC and DC state variables into a single, massive Jacobian matrix, offering robust convergence for tightly coupled multi-terminal DC networks [9]. Sequential methods, on the other hand, decouple the AC and DC equations, iteratively passing boundary conditions between distinct solvers [10]. To handle the non-convexity introduced by these hybrid constraints, recent literature has explored options for mathematical relaxation, such as Second-Order Cone Programming (SOCP) and Semidefinite Programming (SDP), to guarantee global optimality [11]. Modern open-source frameworks, such as the one presented in [7] provide a unified mathematical representation of AC and DC subgrids, allowing direct generalization of AC relaxation techniques to hybrid architectures. Additionally, metaheuristic optimization techniques, such as Particle Swarm Optimization (PSO), are increasingly employed to handle the non-linearity of multi-objective AC/DC optimizations without relying on complex analytical derivatives [12].

1.2.4 Operational Gaps: Despite the methodological strength of both simultaneous and sequential analytical models, a significant operational gap remains for DSOs. The development, maintenance, and solution of custom analytical state matrices are computationally demanding and pose significant integration challenges for grid-management software environments. A possible solution is the use of a multi-layered black box optimization frameworks where the power flow solver is embedded as a function [13]. By wrapping high-level optimization algorithms around industry-standard power flow engines, network operators can calculate feasible dispatch setpoints without needing to analytically derive the underlying hybrid grid equations. This black box approach, which bridges the gap between theoretical OPF mathematics and practical network operations, forms the primary focus of the framework proposed in this paper.

2 Methodology

To address the operational gaps identified in hybrid distribution networks, we propose a unified optimization framework. The following subsections detail the mathematical objective of the algorithm, the software architecture utilized to bypass complex analytical derivations and the standardized benchmark systems used for pre-demonstration validation.

2.1 Objective Function

The primary goal of the proposed framework is to optimize the steady-state dispatch of the hybrid distribution networks while alleviating branch congestions in high EV penetration scenarios. The objective function of the proposed OPF tool is defined as the minimization of the total active power loss $(\boldsymbol{P_{loss,tot}})$ across the entire examined grid model.

Unlike traditional AC-only OPF formulations, this objective function must explicitly aggregate the losses occurring in the AC branches, the DC links, and the internal conversion losses of the interfacing converters. The objective function is formulated as follows:

$$\mathbf{min}\, P_{loss,tot} = \sum_{ij\in E_{ac}} \boldsymbol{P_{loss,ij}^{ac}} + \sum_{mn\in E_{dc}} \boldsymbol{P_{loss,mn}^{dc}} + \sum_{k\in N_{vsc}} \boldsymbol{P_{loss,k}^{vsc}} \quad (\mathbf{1})$$

Where $\boldsymbol{E_{ac}}$ and $\boldsymbol{E_{dc}}$ represent the sets of all AC and DC branches respectively, $\boldsymbol{N_{vsc}}$ represents the set of all VSCs connecting the AC and DC sub-grids, $\boldsymbol{P_{loss,ij}^{ac}}$ and $\boldsymbol{P_{loss,mn}^{dc}}$ denote the ohmic active power losses in the AC branch connecting nodes $\boldsymbol{i}$ and $\boldsymbol{j}$, and the DC branch connecting nodes $\boldsymbol{m}$ and $\boldsymbol{n}$ respectively, $\boldsymbol{P_{loss,k}^{vsc}}$ denotes the total internal active power loss (including both switching and conduction losses) of the $\boldsymbol{k}$-th converter. By minimizing this unified loss function, the optimization algorithm inherently seeks to route power through the most efficient, least-congested pathways, thereby leveraging the DC links to relieve heavily loaded AC corridors.

2.2 Operational Constraints

To guarantee feasible dispatch and actively manage grid congestion, the generalized OPF objective function must be subject to a comprehensive set of equality and inequality constraints. The tool is designed to handle diverse and evolving hybrid topologies seamlessly. These constraints are enforced modularly depending on the specific network configuration and the available assets:

- Equality Constraints: The framework implicitly enforces fundamental active and reactive power balance at all applicable AC and DC nodes through the use of the black box power flow solver module.

- Inequality Constraints: To prevent congestion, the optimization framework enforces constraints on key operational state variables according to operator requirements. For example, AC and DC node voltages are bounded within limits set by power quality standards, and power exchanges between sub-grid can be limited by predefined capacity thresholds. The algorithm is also designed to enforce the physical limitations of the specific active, controllable assets connected to the grid. Depending on the topology, this includes the ability to bound the active and reactive power setpoints of DER units, such as EV chargers, controllable loads, PV plants, and battery energy storage systems. Furthermore, the operational setpoints of any integrated VSC can also be confined by their nominal ratings, as well as their specific active and reactive power capability limits.

2.3 The Proposed Layer Architecture

To circumvent the computational burden of developing a unified analytical state matrix, the proposed tool employs a black box architecture. The core optimization logic, which manages the constraints and drives the objective function, is programmed in Python. Rather than the full mathematical problem formulation internally, Tool #1 is directly interfaced with Tool #5, which serves as the dedicated hybrid AC/DC power flow solver engine. In this decoupled, multi-layer setup, Tool #1 acts as the master controller, adjusting the control variables (active/reactive power and DC voltage setpoints) and commands Tool #5 to execute the hybrid power flow calculations. Tool #5 then resolves the non-linear AC/DC matrices and returns the resulting state variables (nodal voltages, branch flows, and total system losses) back to Tool #1. This architecture ensures high fidelity to the physical constraints of the grid while maintaining the modularity required for integration into the broader HYNET toolchain.

2.4 Algorithmic Flow of the Hybrid OPF

The interaction between Tool #1 and the power flow solver Tool #5 is structured through a closed-loop iterative process. The execution follows these sequential stages:

- Initialization: Tool #1 imports network topology (including the control capabilities of controllable network elements), generator set-points, load profiles.

- Model Construction: Tool #1 builds the operational constraints and defines the initial decision variables based on the objective function.

- Domain-Specific Optimization: Tool #1 runs domain-specific optimization to generate preliminary setpoints. During the development of the tool, we will compare different optimization methods to determine which algorithm matches the requirements of the demonstration best.

- Feasibility and Constraint Checks: The algorithm verifies if the converter power balance is feasible and checks for any constraint violations. If violations occur, Tool #1 iteratively updates converter flows, adjusts slack bus parameters, and tightens or relaxes limits.

- Final Validation via Tool #5: Once the optimal setpoints are mathematically identified by Tool #1, a final validation run is executed by passing these setpoints to Tool #5. Tool #5 performs the rigorous hybrid AC/DC power flow. If the results returned by Tool #5 fall within acceptable tolerances, the optimal setpoints are finalized and exported for secondary control execution.

2.5 Benchmark Validation Networks

Prior to deployment in the demonstration, the algorithmic robustness of Tool #1 will be validated against standardized grid models. The algorithm is first applied to a modified Stagg's 5-bus system [14], which provides a heavily constrained environment for VSC limit testing. Subsequently, to evaluate scalability, the framework will be tested on a modified IEEE 33-bus radial distribution network [15]. The AC system is extended with DC links connected via VSC, creating a highly meshed environment that accurately replicates the anticipated operational challenges of the HYNET demonstration use cases.

3 Challenges and Future Work

The work conducted thus far has primarily centred on positioning Tool #1 within the context of the demonstration and laying the methodological groundwork for its deployment. This phase involved defining the tool's functional scope, integration interfaces, and operational role within the broader coordination architecture. These steps ensured compatibility with the demonstration objectives and partner systems. The activities performed thus far have validated the conceptual approach and identified key implementation requirements. This provides the basis for the development of a scalable framework that can be progressively extended and deployed in later project stages under more realistic operational conditions.

At the next development stage, the primary objective is to verify the mathematical feasibility, constraint handling, and software interoperability of the black box approach. To achieve this, the tool is subjected to controlled testing across two distinct mathematical benchmark models.

3.1 Framework Construction and Functional Testing: Modified Stagg's 5-Bus System

The first test environment will be a modified Stagg's 5-bus system, adapted into a hybrid AC/DC topology as seen on Fig. 2. This compact, heavily constrained network serves as a highly controlled platform to isolate and investigate specific converter interactions and the tight voltage coupling between the AC and DC domains. Initial software trials on this system confirmed the optimizer's ability to seamlessly manage different converter control modes. Initial results of functional tests demonstrate that the black-box framework accurately penalises operational violations, preventing the dispatch of setpoints that would breach converter capability limits.

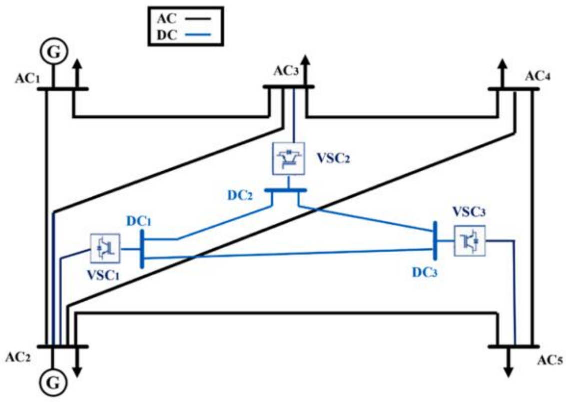

Fig. 2 Architecture of the modified Stagg's 5 bus system [16]

3.2 Scalability and Adaptability: Modified IEEE 33-Bus System

To evaluate the tool's scalability and its adaptability to realistic distribution challenges, a second benchmark test will be conducted using a modified IEEE 33-bus distribution grid. To mirror the anticipated HYNET use cases, this standard medium-voltage AC network is extended with integrated DC links and converter-interfaced DERs as it is displayed on Fig. 3. This highly meshed system provides a neutral platform to assess dispatch quality and voltage regulation capability under heavy load scenarios.

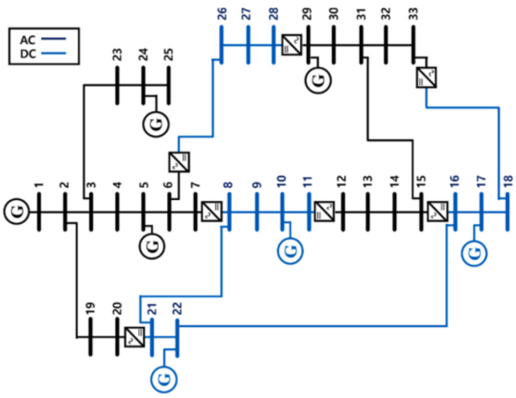

Fig. 3 Architecture of the modified IEEE 33 bus system [16]

3.3 Software Interoperability and Computational Robustness

A critical milestone achieved during this validation phase is the successful initialization of the OPF algorithm. The embedding of the Python optimization module directly within the DIgSILENT PowerFactory environment proved highly stable. The continuous read/write execution loop between the Python optimizer and the PowerFactory load flow engine operates efficiently, confirming that the tool can directly ingest and process detailed distribution-grid models. This validates the tool's readiness for integration with other software components within the broader HYNET toolchain ahead of the next stages of the tool development.

4 Conclusion

The integration of hybrid AC/DC segments into traditional distribution networks demands advanced operational planning tools capable of managing the complex interactions between AC and DC domains. This paper introduced a unified OPF framework developed within the HYNET project, specifically designed for hybrid AC/DC distribution grids, employing a black-box architecture that leverages external power flow solvers. By offloading the detailed grid physics to an embedded solver, the proposed Python-based optimizer circumvents the computational and integration challenges traditionally associated with unified analytical formulations. Validation on modified benchmark systems demonstrated the framework's ability to produce technically consistent and feasible operating points that respect converter constraints, voltage limits, and network security requirements.

While the black-box approach offers significant flexibility and seamless integration within the HYNET project toolchain, future work will focus on mitigating computational overhead from iterative solver calls and enhancing interoperability with other project modules. Ultimately, this framework provides a robust foundation for DSOs to evaluate emerging hybrid grid architectures, test control strategies, and prepare for real-world deployment in upcoming demonstration phases scheduled for 2026.

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