POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Modelling and Optimal Power Flow Analysis of Offshore Wind Power Plants from HVAC to HVDC Transmission

LAUREA MAGISTRALE IN ELECTRICAL ENGINEERING - INGEGNERIA ELETTRICA

Author: MATTIA GIACOMO AIROLDI

Advisor: PROF. MARZIO BARRESI

Co-advisor: DIONYSIOS MOUTEVELIS, JORDI BÉJAR RABASCALL

Academic year: 2024-2025

1. Introduction

The progressive increase in rating and offshore displacement of modern offshore wind power plants (OWPPs) shifts the dominant technical constraint from energy conversion to long-distance transmission. Electrically long HVAC export corridors become reactive-dominated systems: cable-generated reactive power, voltage regulation limits, and phase-angle divergence progressively constrain feasibility. Although shunt compensation and coordinated reactive dispatch enlarge the admissible region [2], they do not modify the structural dependence of synchronised AC transmission on corridor length and grid strength. Offshore distance therefore acts as a feasibility-defining parameter, not merely as a loss-scaling factor. Converter-based HVDC transmission fundamentally alters this constraint topology. By decoupling active transfer from distributed reactive phenomena, voltage regulation is localised at converter terminals and transmission distance primarily affects resistive losses and converter limits rather than steady-state solvability [1]. Within this context, this thesis develops a comprehensive steady-state modelling and optimisation study for multi-cluster OWPPs under both HVAC and VSC–HVDC export architectures, implemented in *VeraGrid* [6]. Since native AC–DC OPF functionality is unavailable, a dedicated DC-side inequality-enforcement methodology is introduced for hybrid steady-state operation.

1.1. Case study: Hornsea One multi-cluster OWPP

The case study considers a 432 MW nominal capacity OWPP inspired by Hornsea One, representative of large-scale North Sea developments. Figure 1 depicts the baseline HVAC export scheme.

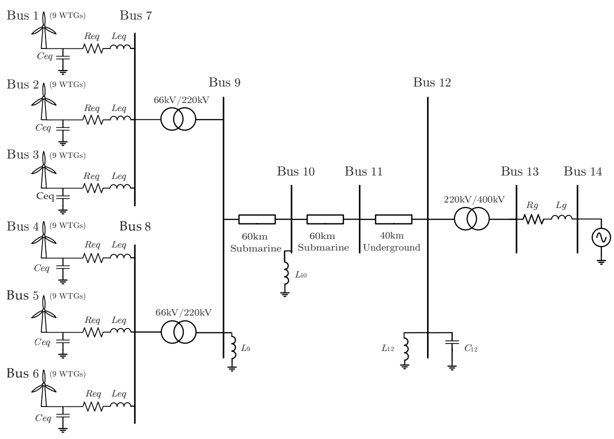

Figure 1: OWPP single-line diagram – HVAC.

The plant (432 MW nominal) comprises 54 Siemens Gamesa 8.0–167 DD WTGs, arranged in six 9-turbine clusters. Power is collected at 66 kV, stepped up offshore through two 66/220 kV transformers, and exported via a 220 kV HVAC corridor composed of two 60 km submarine sections and a 40 km onshore underground cable, terminating at the PoC through a 220/400 kV grid interface. The onshore network is represented by a Thévenin equivalent to parametrically vary SCR and X/R ratios. The multi-cluster structure is explicitly preserved to capture distributed reactive capability, intercluster voltage sensitivities, and angular dispersion along electrically long corridors, which ultimately govern export feasibility under binding voltage [4] and reactive constraints.

2. Modelling framework

A unified per-unit steady-state framework is developed to consistently represent both HVAC and VSC–HVDC export architectures within a single non-linear formulation. The modelling philosophy is plant-level and constraint-oriented, capturing the dominant mechanisms governing export capability—cable charging circulation, voltage regulation limits, device capability saturation, and transmission losses—while remaining suitable for systematic distance scaling and constrained optimisation [1, 2].

WTGs are modelled as converter-interfaced generators with jointly controllable active and reactive outputs constrained by apparent power capability, ensuring physically consistent tradeoffs between reactive support and active export under binding limits.

Transformers are represented through π-equivalents, with OLTC regulation treated as an admissible control variable in OPF studies, enabling coordinated voltage shaping along electrically long corridors.

HVAC cables are modelled via π-equivalents including series impedance and shunt capacitance, explicitly capturing charging-current-driven reactive circulation as the structural driver of AC export limitations. Shunt compensation is considered either as fixed design elements or as controllable resources within coordinated optimisation.

In the HVDC configuration, each VSC is represented as a steady-state AC–DC interface enforcing power balance between domains, with converter losses described through a current-dependent quadratic model consistent with MMC abstractions [1].

The DC cable is represented in steady state by its equivalent series impedance, rendering transmission predominantly resistive-loss-dominated.

3. Operational performance of HVAC-connected OWPPs

Electrically long HVAC export corridors are reactive-equilibrium-dominated systems. Steady-state admissibility is governed by the non-linear balance between voltage-driven capacitive generation ($\propto BV^2$) and current-driven inductive absorption ($\propto XI^2$), with shunt capacitance scaling with distance and progressively biasing the equilibrium toward capacitive dominance. Shunt compensation and generator reactive capability extend—but do not alter—this equilibrium. As compensation saturates, voltage constraints bind and the admissible manifold contracts: active power becomes limited not by turbine availability, but by the existence of a feasible steady-state solution.

3.1. AC power-flow formulation

The steady state of the HVAC export system is defined by the non-linear nodal active and reactive power balance equations:

$$P_i = \Re\left\{ V_i \sum_{j=1}^{N} Y_{ij}^* V_j^* \right\}, \tag{1}$$

$$Q_i = \Im\left\{ V_i \sum_{j=1}^{N} Y_{ij}^* V_j^* \right\}. \tag{2}$$

The system is solved via Newton–Raphson. Steady-state feasibility requires the existence of a solution of (1)–(2) satisfying voltage bounds and device capability constraints. Feasibility loss thus reflects the *structural disappearance* of admissible operating points of the non-linear power-flow manifold, rather than a numerical artefact.

3.2. Fixed shunt compensation

Fixed shunt compensation is a conventional mitigation strategy; however, static devices optimise voltage around a predefined operating point and do not alter the corridor's reactive equilibrium. Building on the baseline configuration [3], this work introduces a reactor-sizing methodology to quantify the trade-off between nominal export maximisation and robustness under realistic operation. Three paradigms are examined—baseline sizing, nominal-oriented optimisation, and probabilistic sizing based on wind statistics—with configurations ranked by the RMSE of voltage deviation from 1.0 p.u. At nominal loading (72 MW per cluster), the reference case delivers 402.909 MW at the PoC with $\mathrm{RMSE}_V = 0.033$. A search over **14,642** feasible configurations within a ±50 MVAr space identifies a nominal-oriented solution achieving $\mathrm{RMSE}_V = 0.0138$ and 400.23 MW at the PoC, improving voltage flatness without increasing export due to redistributed reactive flows and losses. Using a Weibull model ($k = 2.5$, $\lambda = 10.5$ m/s), probabilistic sizing at the most probable operating condition achieves $\mathrm{RMSE}_V = 0.0113$, ensuring robust voltage behaviour in the 20–60% range while reducing nominal export to 394.436 MW. These results demonstrate that active power maximisation and voltage deviation minimisation are structurally conflicting objectives under fixed compensation.

3.3. Structural limits of static compensation

Static shunt devices may locally reshape voltage profiles, yet they do not alter the reactive equilibrium and thus cannot prevent the distance-driven contraction of the admissible steady-state region. Figure 2 shows the evolution of worst-case generation-bus voltages under distance scaling.

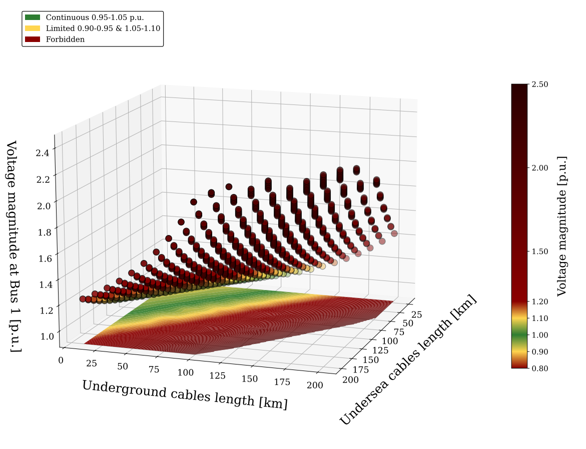

Figure 2: Generation-bus voltage vs. distance.

As reactive circulation intensifies with increasing corridor length, device capability limits approach saturation and the operating point shifts toward voltage-constrained, ultimately infeasible domains. The resulting limitation is structural rather than numerical: beyond a critical distance, no operating point simultaneously satisfies the non-linear PF equations, voltage bounds, and reactive capability constraints. This structural contraction of the admissible region motivates the transition from static sizing to coordinated, constraint-aware optimisation.

4. Coordinated optimisation of HVAC-connected OWPPs

4.1. AC–OPF formulation

Coordinated operation is formulated as an AC optimal power flow (AC–OPF) problem in canonical non-linear programming form:

$$\min \ f(x) \quad \text{s.t.} \quad G(x) = 0, \qquad H(x) \le 0, \tag{3}$$

where x collects network states and control variables (shunt setpoints, WTG reactive dispatch, OLTC tap ratios). Equality constraints ($G(x) = 0$) enforce the full non-linear AC power balance, while inequalities ($H(x) \le 0$) encode operational limits (voltage bounds, capability constraints, tap ranges, branch limits). In *VeraGrid*, the default objective (4) minimises a quadratic generation cost augmented by penalised slack variables.

$$\begin{aligned} \min_{P_g,\, sl} \ f &= c_2^\top (P_g \circ P_g) + c_1^\top P_g + c_0^\top \mathbf{1} \\ &\quad + c_s^\top sl_s + c_v^\top sl_v. \end{aligned} \tag{4}$$

Here, P_g denotes the vector of generator active power outputs, while sl collects the slack variables associated with soft constraint violations. Given the negligible marginal cost of offshore wind, the objective is reformulated through *virtual cost coefficients*: WTGs are assigned zero cost, while the PoC slack bus carries a positive linear term. Under the adopted sign convention, minimisation is thus equivalent to maximising exported active power while preserving the full nonlinear AC–OPF structure. With WTG active power fixed at each operating point, export improvements arise from loss reduction and coordinated reactive and voltage control within binding constraints.

4.2. Optimised performance at baseline distance

At rated operation and 120 km offshore export length, coordinated AC–OPF based on reactive dispatch (shunt compensation and WTG reactive capability) increases delivered active power by +0.93% (+4.12 MW) relative to the non-optimised base case. The maximum generation-bus voltage angle is reduced from nearly 29° to approximately 26°, indicating reduced steady-state angular stress and improved corridor utilisation. When OLTC regulation is embedded, the maximum delivered power increase rises to +1.18% (+4.75 MW). Tap optimisation modifies transformation ratios and voltage distribution, improving alignment between offshore and onshore levels and enhancing the effectiveness of available reactive resources. These gains show that part of the baseline export limitation is *control-induced* and can be recovered through coordinated optimisation.

5. Distance sensitivity: structural limitation of HVAC

A systematic distance analysis is conducted by proportionally scaling the HVAC export corridor while preserving architecture and compensation structure, thereby delineating the feasibility frontier and associated regime transitions.

5.1. Constrained shunt compensation

Under the baseline HVAC configuration with limited compensation, steady-state feasibility is lost beyond approximately 217 km. The dominant mechanism is the escalation of capacitive reactive generation with length: beyond a critical distance, cable charging exceeds the maximum absorptive capability of reactors and controllable resources, making voltage limits unsatisfiable together with reactive capability bounds.

5.2. Incremental shunt compensation

When compensation capability scales proportionally with corridor length, feasibility extends to a structural threshold at approximately 470 km. Up to this frontier, coordinated AC–OPF preserves the full 432 MW nominal generation within voltage and device limits. Beyond ∼470 km, voltage and reactive constraints become simultaneously binding and cannot be relieved by further control reallocation; active power curtailment becomes structurally necessary to prevent overvoltage at the critical internal node (Bus 12). Curtailment reduces line current and thus the inductive absorption term ($\propto I^2$), while capacitive charging remains predominantly voltage- and length-driven. Active power export therefore becomes subordinated to reactive feasibility constraints. Figure 3 quantifies this degradation: delivered power decreases from 405.4 MW at 120 km to 231.8 MW at 600 km. At 600 km, generation must be curtailed to 273.9 MW.

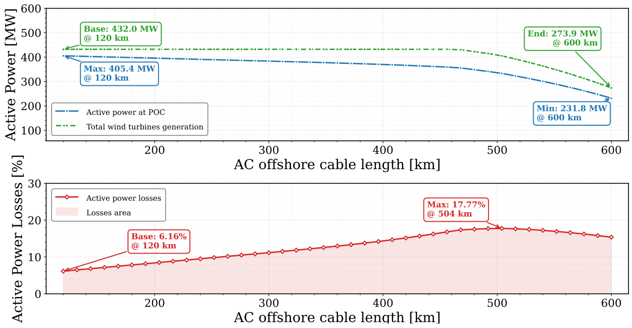

Figure 3: Nominal active power delivered at the PoC under optimised HVAC operation.

Transmission losses increase quasi-linearly from 6.16% at 120 km to 17.77% near 504 km, then decline as curtailment reduces current.

6. Integrated AC–DC operation of HVDC-connected OWPPs

The export system is reconfigured through a VSC-HVDC solution (symmetrical monopole [5]), shown in Figure 4.

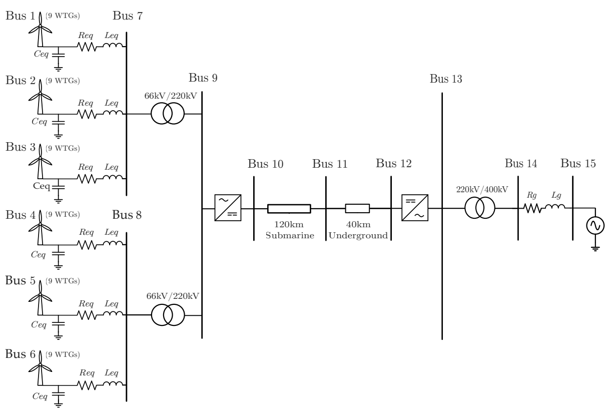

Figure 4: OWPP single-line diagram – HVDC.

This transition represents a structural redefinition of the steady-state transmission problem.
In synchronised AC corridors, active transfer and voltage feasibility are intrinsically coupled through distributed reactive phenomena and long-range phasor interactions. The HVDC interface suppresses long-range phasor coupling, replacing voltage-angle-driven power transfer with controlled DC current exchange, while confining reactive phenomena to the local AC terminals. Consequently, distance no longer contracts the admissible steady-state region but it acts primarily on efficiency via resistive dissipation and converter operating limits.

6.1. Unified AC–DC formulation

The hybrid network is solved within a fully unified non-linear algebraic framework in which AC states, DC variables, and converter coupling are embedded into a single Newton–Raphson scheme. Unlike conventional sequential AC/DC approaches, no artificial decoupling is introduced: all subsystems are solved simultaneously. This guarantees consistent treatment of the strong non-linear interaction imposed by VSC converters and preserves the physical coupling between voltage regulation and power transfer. From a graph-theoretic perspective, converter interfaces define topological boundaries between asynchronous AC subsystems, each endowed with an independent reference, thereby preserving Jacobian non-singularity and mathematical determinacy without artificial phasor coupling.

6.2. DC-side inequality enforcement

A critical practical aspect is enforcement of DC-side inequality constraints (e.g., rectifier-side DC voltage insulation limit).
Since native AC–DC OPF is not available in the adopted platform, constraint satisfaction is ensured through a PI-based enforcement loop embedded within the unified PF iterations.
The onshore DC reference voltage is iteratively adjusted to satisfy the DC voltage limit at the constrained Bus 10.
The embedded PI enforcement is seamlessly integrated within the unified Newton–Raphson framework, preserving numerical robustness across operating-point-dependent sensitivities over the investigated distance range and enabling extensive parametric analyses.

6.3. Distance behaviour and optimised HVDC performance

A distance sweep reveals smooth and strictly monotonic degradation of delivered active power at the PoC with increasing corridor length. Unlike synchronised HVAC transmission, no feasibility collapse nor structural frontier analogous to the 470 km boundary emerges within the investigated range: the admissible steady-state region does not contract and voltage feasibility remains preserved across the entire investigated range. Two operating regimes are distinguished to clarify the structural role of converter control.
In the *non-optimised configuration*, the independent control variables of the two VSC stations are assigned solely to ensure a well-posed AC–DC equilibrium. The offshore converter establishes the voltage magnitude and angular reference of the isolated collection grid, while the onshore station regulates the DC voltage and does not participate in reactive exchange.
Conversely, *coordinated VSC setpoint optimisation* systematically adjust the operating point within the internal control manifold defined by the converters. The offshore AC voltage magnitude, DC voltage level, and onshore reactive exchange are jointly tuned within admissible bounds, while the offshore angle remains the grid-forming reference. The physical infrastructure and network topology remain unchanged; only the equilibrium state within the admissible non-linear manifold is shifted.

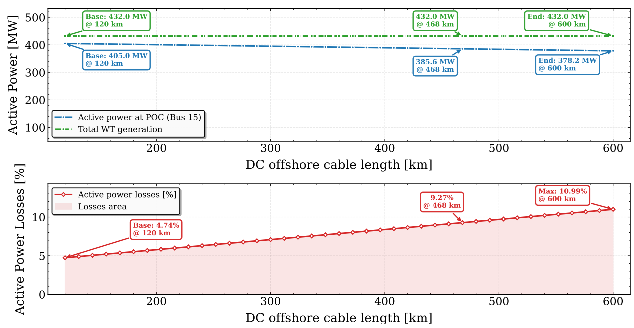

Figure 5: Nominal active power delivered at the PoC under optimised HVDC operation.

Under coordinated optimisation, delivered active power decreases from 405.0 MW at 120 km to 378.2 MW at 600 km, while the nominal

432 MW generation remains exportable across the investigated range. At 600 km, transmission losses are reduced from 11.46% (non-optimised) to 10.99%, recovering approximately 2 MW without structural reinforcement of the corridor. The absence of discontinuities confirms that, under VSC–HVDC export, offshore distance does not alter the admissible steady-state manifold. Performance degradation is governed by quadratic current losses, while optimisation geometrically repositions the operating point within a structurally preserved solution set.

7. Conclusions

This thesis demonstrates that the transmission limits of large-scale OWPPs are not merely consequences of component ratings or cable parameters, but arise from the intrinsic topology of the non-linear steady-state constraint structure governing the coupled generation–transmission system. By embedding multi-cluster offshore generation, reactive resources, and extended export corridors within a unified non-linear formulation, the analysis shows that offshore distance acts as a structural operator on the admissible solution manifold of the power-flow equations. In synchronised HVAC transmission, increasing corridor length progressively activates reactive and voltage constraints, as cable charging accumulates and absorptive capability saturates. The feasible steady-state region geometrically contracts, and the operating point shifts from an interior solution to a boundary-constrained regime in which active power becomes subordinated to reactive equilibrium. Offshore distance therefore emerges as a feasibility-defining parameter. The introduction of a converter-based DC interface fundamentally alters this constraint topology. By suppressing long-range phasor coupling and localising reactive phenomena to converter terminals, the VSC–HVDC architecture decouples transmission distance from steady-state solvability. Within converter operating limits, the admissible manifold remains structurally preserved; distance modulates efficiency through predictable resistive dissipation rather than governing existence of solutions. The offshore grid-forming converter is central to this transformation: by establishing the voltage magnitude and angular reference of the isolated collection network, it converts the offshore system into a controlled asynchronous subsystem and relocates stability from distributed passive compensation to actively regulated power-electronic control. The technology divergence observed at extended distances reflects two fundamentally distinct limiting regimes: reactive-equilibrium-constrained synchronised AC transmission versus converter-regulated, current-constrained DC transmission. Optimisation therefore plays fundamentally different roles: in HVAC systems it reshapes but cannot prevent manifold contraction, whereas in HVDC architectures it shifts the equilibrium within a structurally preserved admissible region. This contrast provides the physical and mathematical foundation for transmission architectures enabling far-shore offshore wind integration at continental scale.

8. Acknowledgements

I sincerely thank my supervisor, Marzio Barresi, and my mentors at the CITCEA research group, Dionysios Moutevelis and Jordi Béjar Rabascall, for their guidance throughout this work. I am especially grateful to my parents for their unwavering support and for making this educational journey possible.

References

[1] M. Cheah-Mañé. *Offshore Wind Integration through HVDC Systems.* PhD thesis, Cardiff University, 2017.

[2] J. Dakić, M. Cheah-Mañé, O. Gomis-Bellmunt, and E. Prieto-Araujo. Hvac transmission system for owpps including mid-cable reactive power compensation. *IEEE Trans. Power Del.*, 2021.

[3] A. Narula. *Grid-forming wind power plants.* PhD thesis, Chalmers University, 2023.

[4] National Grid ESO. The grid code: European connection conditions, 2018.

[5] B. C. Valerio, V. A. Lacerda, M. Cheah-Mañé, P. Gebraad, and O. Gomis-Bellmunt. Optimal power flow for ac/dc hybrid systems applied to offshore wind power plants. *IEEE Trans. Power Syst.*, 2020.

[6] VeraGrid. Veragrid software, 2025.