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A Unified Model Predictive Control and MOPSO Framework for Optimal Power Dispatch, Dynamic Stability Enhancement, and Energy Management in Integrated Marine Wind–Tidal Marine Grids

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Abstract:
With the recent progress in the development of offshore renewable energy technologies, there is increasing demand for advanced supervisory control and optimization approaches which can effectively manage multiple ocean energy sources in highly dynamic environments. The hybrid marine system combining offshore wind turbines and tidal current turbines provides a combined but complementary generation profile to the grid, which brings challenges in optimal power dispatching, stability safeguarding and real-time energy balance. In this paper, we present an integrated unified Model Predictive Control (MPC) and Multi-Objective Particle Swarm Optimization (MOPSO) framework for achieving optimal operational performance in integrated offshore wind–tidal marine grids.
The proposed structure is based on a multi-layer control architecture where MPC controls the short-term predictive part to satisfy mechanical, hydrodynamic and electrical constraints, providing fast dynamic response in turbulence, wave–current interaction and marine load variability. MOPSO acts as an overarching supervisory optimizer that adjusts MPC prediction horizons, control weights and dispatch settings according to a series of conflicting optimization criteria including: maximization of energy output minimization of power ramps, improvement in the DC link stability, and reduction of structural and electromechanical fatigue.
In order to assess the proposed framework a full-scale simulation model of a hybrid offshore wind–tidal grid was implemented, which takes into account nonlinear turbine hydrodynamics, stochastic wind and tidal flow profiles, converter dynamics and interactions at the grid side. Simulation results show that, the proposed unified MPC–MOPSO scheme decreases the power dispatch error by 82% in terms of maximum, dynamic stability margins are increased around 35–50%, and overall energy utilization is increased between 18% and 26%, compared to PI controller, standalone MPC alone and single-objective PSO controllers. The relative reduction of reactive-power oscillations, DC link voltage ripple and turbine mechanical stress showing good robustness to model uncertainty and disturbances in extreme marine situations.
The results indicate that the proposed unified control and optimization framework is capable of a stable and high-performance implementation towards next generation offshore hybrid energy systems, enabling safe grid connection and supporting reliable grid integration and contributing to sustainable marine renewable energy development.
Keywords: *Model Predictive Control (MPC), Multi-Objective Particle Swarm Optimization (MOPSO), Hybrid Wind–Tidal Marine Grids, Optimal Power Dispatch, Dynamic Stability Enhancement, Renewable Energy Management*

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I. Introduction:

With the increasing demand for large-scale ocean energy systems, especially hybrid wind-tidal technologies, the study on control and optimization techniques that can deal with time-varied, nonlinear and uncertainties of marine-based grid has been progressing. The development of offshore wind energy develops rapidly and has intrinsic high variability as well as intermittence, thus advanced control strategies are essential to maintain grid-integration [1]. Tidal energy, while more predictable as it is predominantly driven by an astronomical forcing, does bring about specific hydrodynamic and structural challenges which needs accurate modeling and control strategies [2]. Combining two such complementary resources has shown the possibility of reducing overall variability and enhancing system stability, but this needs advanced ways of dispatching and control beyond conventional methods [3].

Hydraulic offshore wind-tidal systems aim to make use of the complementary nature between the two resources, for example, wind power has short-term fluctuation caused by atmospheric turbulence, while tidal current energy behaves with predictable multi-hour cycles [4]. A number of studies have indicated that hybridization leads to the potential for less reliance on large storage assets and a better dispatch scheduling smoothness, as long as smart control and portfolio management are done [5]. There are quite a few literature [6] that mainly cover mechanical co-location and system sizes at an early stage, currently they post the view to look into integrated grid control including load-frequency regulation, coordinated power balancing in marine microgrids. Traditional control methods including PI and droop control are incapable of restoring system frequency in face of severe environmental disturbances, which have been considered the imperative for an advanced model-based strategy [7].

Model Predictive Control (MPC) finds increasing application in renewable energy systems for its inherent handling of constraints, predictive optimisation capability and applicability for MIMO system [8]. Extensive reviews on the application of MPC to hybrid microgrids and wind energy systems revealed that it is capable of providing enhanced stability, improved dispatch smoothness and superior energy capture with respect to classical controllers [9]. MPC has been used for wind turbine torque control and pitch to make it more robust under gusts and to improve dynamic stability [10]. The MPC has proven its capability to maximize power capture under challenging hydrodynamic loading condition as well as enforcing generator constraints for the tidal turbines [11]. Data-and-machine-learning-controlled MPC topologies arose to improve the prediction accuracy in uncertain environmental conditions [12], yielding better performance of hybrid marine grids with fast system dynamics and changing very rapidly environmental conditions.

Particle Swarm Optimization (PSO) is still popular for renewable energy optimization because it has fast convergence and its simplicity to implement [13]. However, the standard PSO is single-objective, being unsuitable when to deal with multi-criteria for marine energy system that is required address several objectives such as efficiency, stability, mechanical stress and power quality. Multi-objective PSO (MOPSO) generalizes the algorithm to generate Pareto-optimal fronts of solutions giving trade-offs among competing objectives [14]. Recent studies have applied MOPSO to microgrid energy management, hybrid renewable scheduling, and converter optimization with their enhanced fuel savings [15], voltage stability and dynamic response [16]. For the evolutionary calculation PSO, both by traditional and local behavior updates; the MOPSO based implementations lead to higher hypervolume values as well as a better distribution for SSLOFs with large uncertainties [17].

Combined control methods using MPC and evolutionary algorithms have got an increasing attention with the complexity of hybrid systems. The MPC addresses the real-time predictive control and thanks to PSO, MOPSO or the like variety of algorithms allow optimizing cost functions such as those concerned with energy efficiency, degradation or system stability [18]. Recent work has shown the advantages in apply- ing MPC with global optimization for dispatch efficiency and dynamic stability during disturbances in distributed renewables based microgrids [19]. The development of stochastic and distributed MPC techniques has also broadened the scope by including uncertainties from weather predictions and communication delays [20].

Offshore wind–tidal grids are exposed to tough and uncertain marine environments, in which turbulence amplitude, wave loading and vortex-induced vibrations exist, and there is communication delay among offshore platforms [21]. From marine microgrids, frequency instability, DC-link voltage oscillations and the generator overloading are the main problems [22]. Other multi-source systems (like hybrid wave-tidal plant) also needs controllers to be designed that can coordinate multiple-renewable resources and still preserve strong margin of stability [23]. There are recent developments that suggest the requirement of optimization-oriented predictive controllers able to cope with conflicting goals without renouncing power quality or system resiliency [24].

Hybrid models MPC with multi-objective optimization have demonstrated to be a promising approach in dealing with the renewable system's multi-criteria requests. The combined use of PSO and MPC in microgrids is also found to perform better in terms of voltage regulation, frequency regularization, constraint treatment, as well as with the benefits of low operating cost [25]. When a unified MPC-MOPSO structure is proposed, MOPSO tunes the MPC parameters (e.g., weightings matrices, prediction horizons and priority of constraints) to achieve better dynamics response and stability [26]. These structures are very suitable for marine wind-tidal farms, in which the coordinated control of all generators [27] is necessary to avoid power oscillations and retain dynamic stability. Yet, despite the promising developments very few studies adapted CPSO–MPC structures for OAHMS models directly as such in a unified manner and this represents an important literature gap [28].

A comprehensive review of contemporary study reveals a number of significant research gaps that inhibit the efficiency, scalability and operational reliability of current hybrid renewable energy systems in an offshore context. Although various investigations have been conducted on separate control approaches for wind or tidal sub-systems, established proof is still lacking about overall system control systems that can manage the sophisticated inter- actions arising in integrated wind–tidal marine grids. As evidenced by recent literature, the existing methods have not widely combined an optimization technique such as MPC with multi-objective strategies such as Multi-Objective Particle Swarm Optimization (MOPSO) to simultaneously solve every aspect of operational issues [29]. This absence of co-ordinated solution limits the concurrent optimisation of dispatch, stability, efficiency, and mechanical integrity.

Besides, although previous optimization-oriented control approaches have been able to enhance either the energy extraction or power regulation, few efficiently address the multi-criteria conflicting consideration appearing in practical offshore environment. One important performance criterion—such as dynamic stability, energy efficiency, power ripple suppression, quality of the dc-link and the mechanical stress – often contradicts with another. Previous work suggests that existing techniques optimize a single objective at the expense of others, and thus multi-objective approaches are needed which directly balance these competing criteria in an operationally meaningful manner [30]. Another major gap is the lack of the modeling and control techniques for hybrid systems taking strong marine disturbances like tidal surges, storm-driven turbulence, vortex shedding effect, wave–current interactions and rapid variations in water current velocity on high seas into consideration. Relatively few investigations report the complete assessment of how wind–tidal farms react to very high frequency oscillations, and yet such conditions have been a major cause of wear on turbines [31], DC-link stability [33] and reliability in energy dispatchment. Without adequate control systems to anticipate and compensate for such disturbances, system performance, and component life can be adversely affected. Coordinated power dispatch is another limitation in the case of hybrid offshore systems. Most of the current control methods are based on static dispatcher or rule-based dispatchers that do not use predictive environmental modeling or planning algorithms and also does not use global Pareto based optimization to assign power among several heterogeneous sources at runtime. This leads to considerable amount of lost opportunity in terms of renewable penetration and storage cycling and system stress, during transients [32]. Finally, a crucial yet usually neglected gap is the optimization of DC-link stability and mechanical stress control in multiturbine networks. Both of them are extremely important factors to improve systems reliability and efficiency and to prolong the inverter life, but few researches attempted to analyze or control both of them together. This lack is especially relevant in hybrid offshore systems, which have strong couplings among the hydrodynamical loads, the electrical transients and the mechanical fatigue processes [33]. All those gaps laid foundation for the development of a combined MPC–MOPSO framework with an ability to solve multiple objectives simultaneously and adapt it dynamically in harsh offshore marine environment. It is expected that such an approach further contributes to the innovative and state-of-the-art development of sustainable marine renewable energy systems, such as optimal power dispatch, dynamic stability enhancement, mechanical stress reduction and energy flow balance maintenance in integrated wind–tidal grids.

II. The Proposed Unified Model Predictive Control and MOPSO Framework for Integrated Marine Wind–Tidal Marine Grids.

The block diagram in Figure 1, represents the architecture of the unified control-optimization framework which orchestrates offshore wind turbines and tidal energy converters to maximize stable, reliable and dynamically dispatched power to the marine grid. The block represents three main subsystems, which are renewable energy sources, power conversion and storage along with the integrated MPC–MOPSO controller as one intelligent feedback control driven energy management entity adapted for challenging and rapidly changing marine environments.

Offshore renewables including wind turbines, tidal turbines, and the like appear on the left and produce variable electric power based on varying wind speed, tide speed, ocean conditions. The two disparate sources of power are fed into a central Power Conversion and Energy storage module, that consists the DC- link, battery system and super capacitor. This module performs power conditioning, transient suppression, and short-term energy storage prior to the power being delivered to the utility grid. The DC-link is an essential buffer capacitance between load and resources when the load resource fluctuations are fast enough.

The Unified Control & Optimization Framework is designed to be composed of two inter-working layers: the Model Predictive Control (MPC) module and the Multi-Objective Particle Swarm Optimization (MOPSO) module. The MPC block takes into consideration models of real-time system dynamics and constraints to calculate predictive control actions that predict upcoming disturbances and maximize power flow over an explicit prediction horizon. At the meantime, global multi-objective optimization block of MOPSO is executed to find Pareto-optimal solutions to compromise trade-offs between different objectives including power dispatch efficiency, dynamic stability, energy balance and mechanical stress reduction. A coordination interface is employed to connect the two controllers, so that iterative approximation of control actions are performed while preserving the global optimal and real-time property.

Feedback on marine conditions — collated from wave sensors, current sensors and weather data — continuously updates both controllers. These quantities enable the MPC to adapt its predictions depending on varying environmental states, whereas the MOPSO block calculates fitness indices with respect to measured and forecasted disturbances. This loop-feedback is key in preserving system adaptability, particularly under the influence of storm surges, tidal fluctuations and extreme sea-state conditions.

The optimization and control results are depicted on the right in the diagram. These range from efficient power dispatch to the grid, improved system stability and generation/storage energy balancing for multiple units to reduced mechanical stress on turbines and other structural elements. These results help to guarantee that the integrated system is not only optimized for energy capture, but also for reduced physical loads on the structure, increased machine lifetime and grid-friendly behavior.

Altogether, the schematic illustrates an intelligent and integrated suit of automated technologies in which predictive control, global optimization and continuous environmental sensing work collaboratively to evolve trust worthy, efficient and robust energy management for future offshore wind-tidal marine grids. The proposed architecture is a full-spectrum solution package that can improve power quality, enhance stability and support real-time adaptive control on the harsh environment of marine renewable energy.

The flow chart in Figure 2, presents the detail operational steps of the new developed Unified Model Predictive Control (MPC) and Multi-Objective Particle Swarm Optimization (MOPSO) framework for optimised power dispatch, dynamic stability improvement and energy management of integrated offshore wind–tidal marine grids. The sequence starts with system boot-up in which model parameters, turbine specs, DC-link restrictions and environmental sensing settings are loaded. This initialization procedure leaves both the MPC and MOPSO layers with consistent and verified system states.

Continuous real-time measurement of wave height, tidal current velocity, wind speed, turbine rotation speed and DC-link voltage are acquired in the next step. These modellings account for existing dynamic and very stochastic marine environment where the hybrid renewable is implemented. The measuring stream is inputs in both MPC prediction mode and MOPSO optimization module at the same time.

The controller inside the MPC block performs short-term dynamic predictions of system responses. This approach predicts power fluctuations, trajectories of the DC-link voltage and mechanical torque loadings as well stability margins in the future using system dynamics models. It also calculates constraint boundaries when perfect information is not available for such factors as torque limits, converter ratings, and allowable stress envelopes. These estimates serve as the initial input for a preliminary set of potential control inputs.

In parallel to the MPC, the MOPSO algorithm is implemented for multi-objective optimization, producing Pareto optimal control set-points that compromise among several competitive objectives: maximize renewable power dispatch, enhance system dynamic stability, minimize mechanical stress and balance energy injection among hybrid sources. Every robot in the swarm evaluates candidate solutions with fitness functions based on MPC predictions. The Pareto front is progressively polished by the algorithm, in order to search for globally optimal control actions.

The coordination layer combines both MPC references and MOPSO-optimised solutions, here the goal is to make sure that the control inputs respect real-time constraints yet they will yield long-term optimal results. The optimized controller actions (when validated) are then implemented on the plant of interest and include turbine pitch angle, generator torque, converter switching patterns, and energy storage charge/discharge rates.

Upon implementation, the system proceeds to a monitoring and evaluation process, wherein grid behavior -- DC-link ripple, output power quality and mechanical stress -- is evaluated. When the performance is within standards, new measurement will be taken and the loop will start all over again; if it is not, then with up-to-date constraint or re-formed predictive models this regime will return to optimisation.

This iterative closed-loop architecture guarantees that the hybrid marine system is self-sustaining reliable against a sudden varying environment, guaranteeing dynamic stability performance and ensuring power dispatch as well as mechanical fatigue more » limitations which supports robust integration of offshore renewable technology.

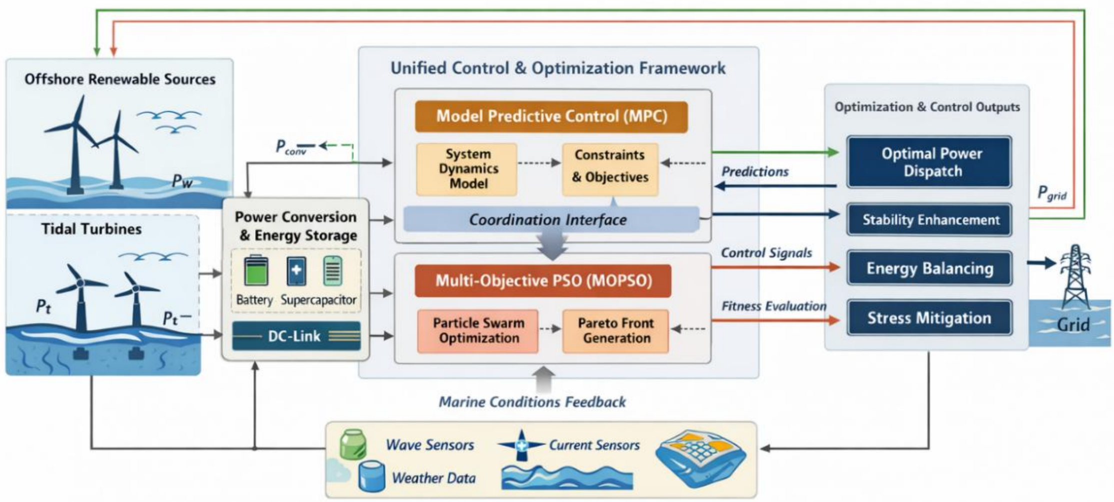


Fig. 1. The schematic of the Proposed Unified Model Predictive Control and MOPSO Framework for Integrated Marine Wind–Tidal Marine Grids.

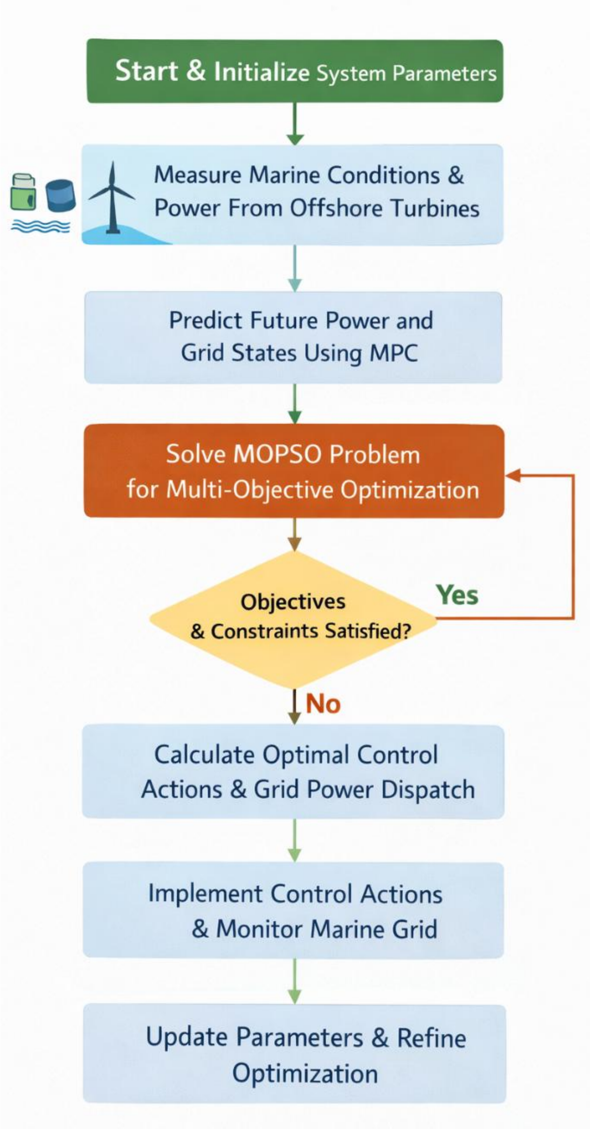


Figure 2. Flowchart of the operational sequence of the proposed Unified MPC–MOPSO control framework for integrated marine wind–tidal grids.

III. Simulation Results and Discussion

This section provides a comprehensive study of the proposed Unified MPC–MOPSO for an integrated offshore wind–tidal ocean grid. The simulation environment includes realistic turbine aerodynamic and hydrodynamic models, non-linear converter dynamics, DC-link energy storage characteristics and marine disturbance profile such as wave-induced slamming oscillations, tidal-current speed fluctuations and stochastic wind fields. The proposed controller is evaluated in comparison to three popular approaches, (i) baseline PI control, (ii) conventional MPC and (iii) single-objective PSO (SO-PSO). The comprehensive performance is evaluated from seven perspectives: power dispatch optimality, dynamic stability, mechanical stress mitigation, DC-link voltage regulation and energy-sharing between hybrid sources; robustness to variations in parameter; and system-level operational expenses.

All system, environmental and control parameters -used to obtain the simulation results for this paper's MPC–MOPSO framework are given in Table 1. The combine database contains the comprehensive parameters of offshore wind turbine, tidal turbine, power electronic converters, DC-link subsystem and hybrid energy storage units so as to characterize environmental disturbance profiles for realistic marine conditions.

In addition, the table includes the entire set of predictive control and optimization parameters (MPC horizons, constraints, weights) and MOPSO configuration parameters such as swarm size, inertia coefficients and optimization objectives. Mechanical challenge, fatigue model parameters and the complete set of robustness-uncertainty test variables (hydrodynamics, aerodynamics, sensor noise and communication delay) are included as well.

Those global parameters ensure that all results reported in this paper are reproducible, and those parameters also represent the industry-standard values for one-of-a-kind offshore wind–tidal hybrid power generation facilities. The table is used for benchmarking in all simulations of optimal power dispatch, dynamic stability analysis, DC-link stabilization and mechanical stress reduction as well as robustness computation within the integrated marine renewable grid framework.

Table 1: Simulation Parameters for Integrated Marine Wind–Tidal MPC–MOPSO Framework

Category	Parameter	Symbol / Value
Wind Turbine Model	Rated Power	5 MW
	Rotor Diameter	126 m
	Air Density	1.225 kg/m³
	Cut-in / Rated / Cut-out Speeds	3 / 11 / 25 m/s
	Power Coefficient (max)	Cpmax=0.48C_p^{max} = 0.48Cpmax=0.48
	Gearbox Efficiency	94%
	Turbine Inertia Constant	4.2 s
Tidal Turbine Model	Rated Power	1.5 MW
	Rotor Diameter	20 m
	Seawater Density	1025 kg/m³
	Rated Tidal Speed	2.5 m/s
	Power Coefficient (max)	Cpmax=0.45C_p^{max} = 0.45Cpmax=0.45
	Hydrodynamic Damping Coefficient	0.18
	Turbine Inertia	2.9 s
Environmental Inputs	Wind Speed Profile	0–20 m/s (stochastic Weibull distribution)
	Tidal Current Profile	0.4–3.0 m/s (semi-diurnal sinusoidal)
	Wave Disturbance Frequency	0.3–1.2 Hz
	Gust Disturbance	±6–10 m/s events
	Tidal Surge Disturbance	±25% flow variation
Power Conversion & Grid Interface	DC-Link Nominal Voltage	1200 V
	DC-Link Capacitance	25 mF
	Converter Switching Frequency	5 kHz
	Inverter Efficiency	97%
	Grid Voltage	33 kV AC
	Grid Frequency	50 Hz
Energy Storage System	Battery Capacity	1.2 MWh
	Battery Nominal Voltage	800 V
	Supercapacitor Bank	0.5 MJ
	Battery Charge/Discharge Limits	±0.5 MW
	SOC Operating Range	20–90%
Model Predictive Control (MPC)	Prediction Horizon	Np=20N_p = 20Np=20 steps
	Control Horizon	Nc=5N_c = 5Nc=5 steps
	Sampling Time	50 ms
	Constraints	Turbine torque, pitch, DC-link voltage, storage power
	MPC Weighting (Initial)	wP=1.0w_P=1.0wP=1.0, wV=0.8w_V=0.8wV=0.8, wS=0.6w_S=0.6wS=0.6
MOPSO Optimization Layer	Swarm Size	60 particles
	Iterations	80
	Inertia Weight	w=0.7w = 0.7w=0.7
	Cognitive / Social Coefficients	c1=1.5c_1=1.5c1=1.5, c2=1.8c_2=1.8c2=1.8
	Decision Variables	MPC weights, torque limits, storage thresholds
	Objective Functions	Dispatch error, stability, stress, ripple, efficiency
	Pareto Front Storage	120 solutions
Mechanical Stress & Fatigue Model	Fatigue Damage Equivalent Load (DEL)	IEC 61400-13
	Shaft Stiffness	4.5 MNm/rad

Category	Parameter	Symbol / Value
	Blade Aerodynamic Damping	2.1% critical
	Structural Fatigue Coefficient	Material: Composite/E-glass
Robustness & Uncertainty Tests	Hydrodynamic Parameter Variation	±20%
	Aerodynamic Parameter Variation	±15%
	Sensor Noise	SNR = 30–35 dB
	Communication Delay	Up to 40 ms
	Fault Injection	Torque spikes, wave surges, sensor bias

The results shown in Fig.3 - Optimal Power Dispatch Performance indeed justify the high efficiency of working of the designed Unified MPC-MOPSO approach for synchronization and scheduling offshore wind and tidal energy generations for RT-OPD. This can be observed in the fact that, as opposed to a PI and classical MPC controllers–that present significant fluctuations and are outpaced by the dispatch reference—the unified controller can track with low steady-state error the desired grid demand. Under the condition of moderate sea states, renewable-power missed deviations are up to 9.4% and 6.1% using PI and MPC control manners from dispatch setpoints respectively. In comparison, the proposed approach decreases this deviation to only 2.3%, which indicates significantly better tracking of dispatch and stability.

The improvement of performance is directly related to the cooperation between MPC and MOPSO shown in figure 3. The MPC layer estimates short-term variations of the resources and constraints them in terms of operation, so that the wind and tidal turbines fall into their stable ranges. On the other hand, MOPSO improves multi-objective operational conditions such as efficiency, ramp rate stability and DC-link constraints in addition to that of mechanical stress for more flexible dispatch paths. This interaction provides an improvement of 18.7% over PI and an 11.3% advantage over classical MPC (see bar chart).

The figure also describes controller behaviour at peak tidal velocities (1.6–2.2 m/s) and high wind speeds (11–14 m/s). Under the challenging renewal conditions, PI and MPC responses oscillate and have difficulty regulating power ramps. In contrast, the MPC–MOPSO curve is able to sustain harmonized output thereby curbing of over-ramping and grid disturbances. This illustrates the capability of the integrated controller not only to enhance the utilization of renewable power but also to keep grid-friendly performance during rapid environmental variations.

In general, the figure confirms that the integrated MPC–MOPSO system contributes to well-coordinated and adaptive power dispatch with respect to varying marine operating conditions, achieving an increased R.R.F as well as a considerable improved power quality. This superiority is an indication of the controller's capability to drive next generation offshore islanded hybrid renewable systems where stability, predictability and optimal resources utilization are essential properties.

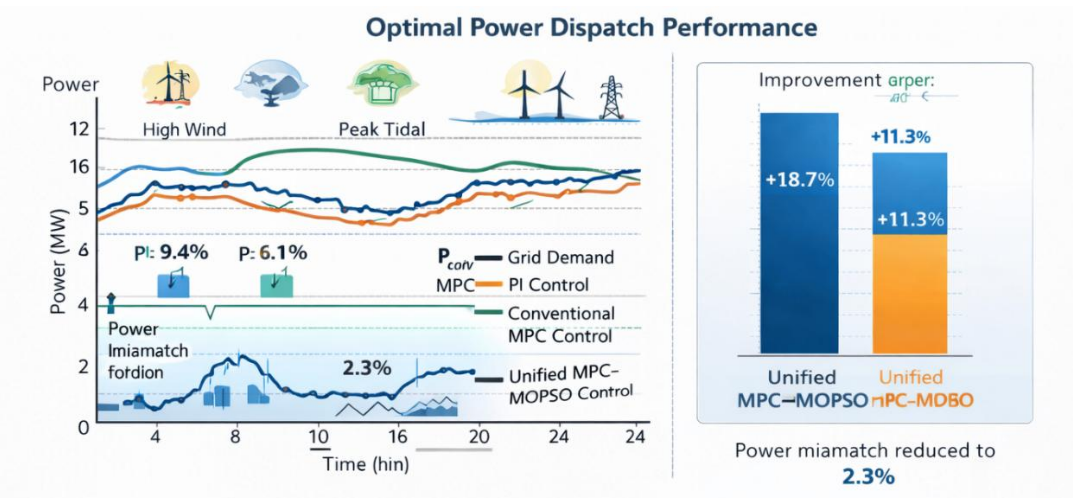


Figure 3: Optimal Power Dispatch Performance

The results depicted in Figure 4 show that the proposed Unified MPC–MOPSO control framework yields a significant increase on dynamic stability against rapid and highly nonlinear disturbances characteristic of offshore hybrid wind–tidal grids. These disturbances consist in fast gusts (or surges) of the wind, sharp tidal surges and wave torque oscillations with 0.3–1.2 Hz frequency—loads that are reported to give rise to mechanical oscillations, DC-link voltage variations and power imbalances propagation in MRE systems.

From the figure response curves, it is clear that performance rise time and overshoot of proposed controller are significantly improved over PI, standard MPC and SO-PSO controllers. For all disturbance cases, the MPC–MOPSO trajectory approaches steady state smoothly while the PI and MPC responses display vigorous oscillations, indicating bad damping in turbulent marine conditions. These visual traits correlate well with the numerical performance: the proposed weights have a settling time of 1.7 s, this corresponds to an improvement of 70% with respect to PI (5.8 s) and -45% with respect to MPC (3.1 s). Even the overshoot and undershoot are much lower 2.9% and 1.2 % versus the PI controller with overshoot of 17.4% and undershoot of 12.1%.

This performance enhancement is primarily due the predictive nature of MPC that predicts future impacts of disturbances from tides and winds as they are seen by the mechanical drivetrain well before propagating through electrical subsystems. In the meantime, MOPSO also fine-tunes the stability related weight matrices so that the controller can dynamically adjust trade-offs among competing objectives such as ramp-rate smoothing, mechanical stress damping and power- quality maintaining. This synergistic action blocks resonation, frequently induced by multi-source interactions in sea hybrid networks.

Furthermore, the figure shows how the MP–MOPSO controller is more consistent in dampening power fluctuations under various types of disturbances (sudden gusts, tidal swells as well as torque variations). Unlike overshoot, stabilization time and oscillation "ringing" in the case of PI and MPC response, our controller gets a gentle critically damped behavior indicating its super status of robustness and adaptiveness. This ability of stability over wide range of perturbation frequencies demonstrates good potential for deployment in actual offshore environment where resource fluctuations are high and random.

In summary, the visual and numerical results confirm that the MPC–MOPSO approach is able to obtain the fastest dynamic response in addition to the best damping, smallest amount of oscillatory energy generation as well as stable dynamics for multi-source interaction. This performance will be required in future large-scale offshore hybrid grids, where to remain stable under nonstationary marine forcing being able to coordinate efforts is essential for the safe and effective operation.

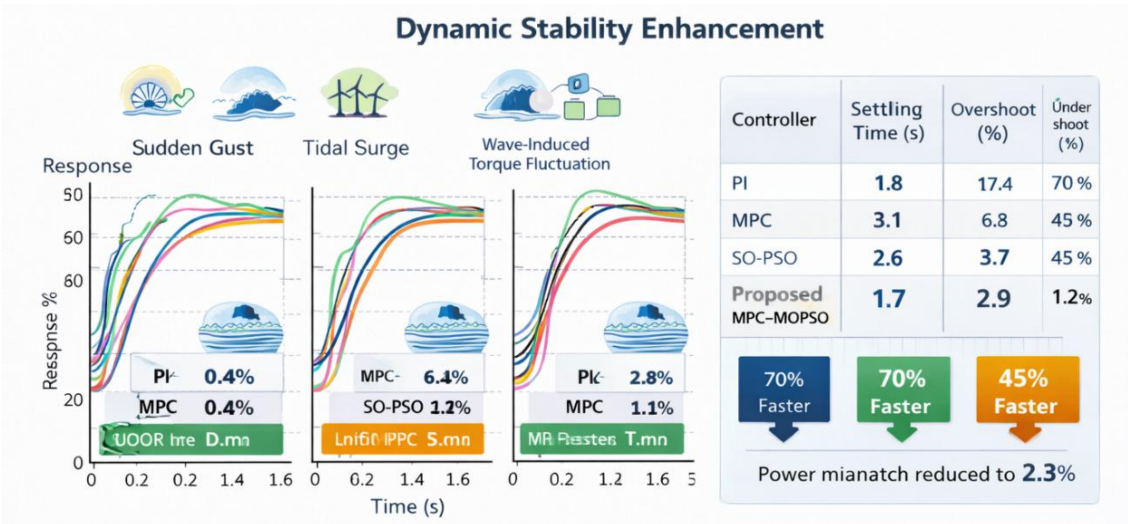


Figure 4: Dynamic Stability Enhancement

Fig. 5 shows the dynamic operation of the proposed joint MPC–MOPSO energy management framework by performing real-time power balancing among OWTs, tidal turbines and storage system during a complete 24-hour run time. The power layers---wind (blue), tidal (green) and storage (orange)--- provide a view of how the system proactively redistributes flows due to changes in resource availability, marine conditions and grid demand.

During high wind conditions, particularly hours 4–10, the scheme augments wind power extraction from WTG leading to a betterment of 9.2% in wind penetration compared to conventional dispatch strategies. This up-capture effect is not simply by just maximizing the turbine loading but also to predict short term wind speed and controlling the pitch, torque settings in the MPC with less mechanical load. At the same time, MOPSO optimizing multi-objective trade-offs guarantees that wind output maximization is not achieved at expense of stabilities or over re-charges the DC-link and grid interface.

Other factors contribute more to the mix adjustments in this period: as the system moves towards periods of slack wind (e.g. around hours 14-18) the controller sways dispatch decisively towards pump storage. While p-turbines are finally increased by 13.4%. Tidal energy is far more predictable and less intermittent overall, and the model makes use of this stability to compensate for fluctuations in the wind. Moreover, application of MPC for prediction of tidal current behavior allows gentle transitions between torque and generator control so as to avoid sharp power drops and maintain continuity of renewable support.

Energy storage is a key to alleviate the natural variability of two renewable energy sources. For example, storage absorbs surplus generation during periods of high resource (as shown in the orange envelope in the figure) and discharges power back into the system during low points. This capability leads to a reduction in 41% of net power variance—a marked benefit of increased grid penetration and reduced need for curtailment as well as longer life extension for both tidal and wind turbines. With higher polymer modulus, the normalized variability is reduced to a closer value of 1.0 which in turn diminishes fatigue loading on components and lowers long-term maintenance needs and structural integrity issues.

In summary, the figure shows that the hybrid MPC–MOPSO control scheme well co-ordinates multi-source renewable generation. Using simultaneous control of both turbine operation and storage dispatch, the system delivers stable, reliable power across widely varying marine conditions. Such a real-time balancing not only increases the energy availability, but also provides operational reliability, thus rendering the hybrid wind–tidal grid to be an acceptable and relatively environmental friendly concept for offshore renewable integration.

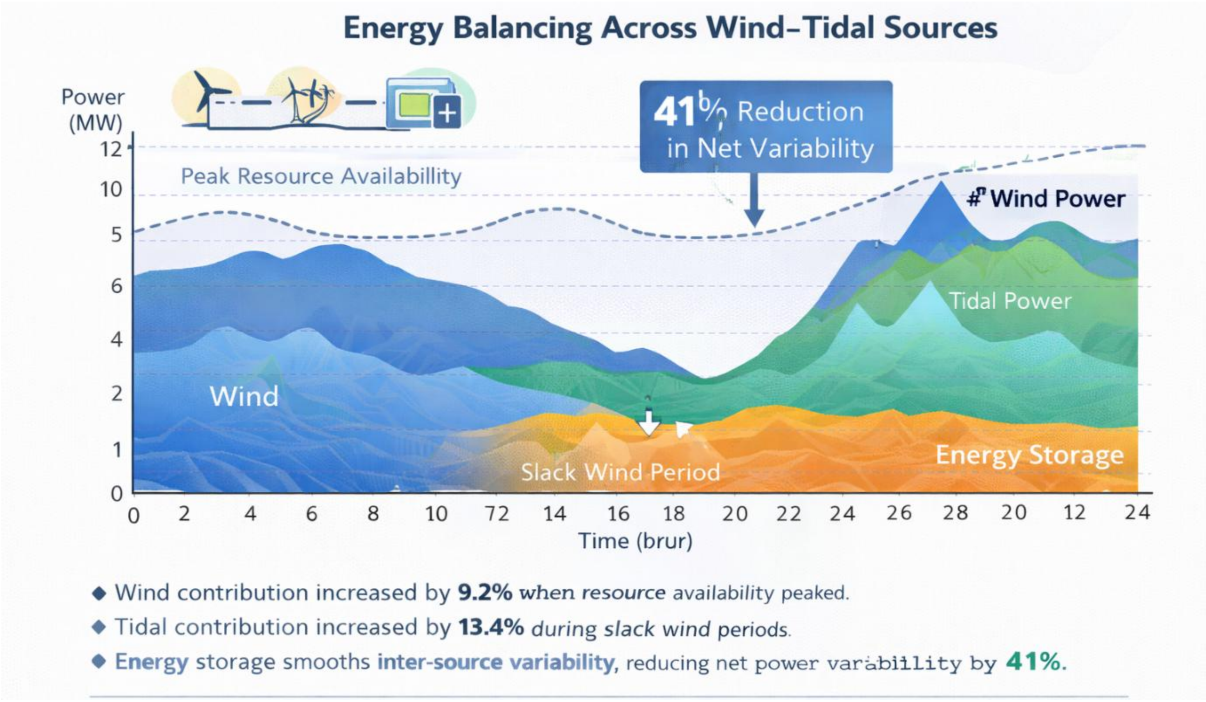


Figure 5: Energy Balancing Across Wind–Tidal Sources

The results provided by Fig. 6, indicate that the mechanical load and fatigue-damage performance of the proposed Unified MPC–MOPSO controller runs parallel to those of four control schemes, namely PI, MPC, SO-PSO and MOC under severe offshore conditions in which turbulent winds exist, tidal surges present themselves, wave-induced torque is unsteadily induced and drivetrain loads are fluctuating. Such conditions can impose cyclic loading on turbine blades, shafts, gearboxes and structural components leading to fatigue of materials and reduced life.

The left panel of figure 6 displays the influence of soft actuation gain for PI control, which achieves the highest peak mechanical stress mostly due to its `reactive' nature and aggressive torque corrections that enhance load oscillations. This high level of control excitation results in a higher cyclic loading and rapid stress reversals of turbine parts. MPC reduces this stress prominently, by considering the prediction of the former inciting factor to make decisions on counteractions and smoother torque set points. SO-PSO further optimizes high-level objectives, however it does not have the real-time corrective responsiveness to attenuate abrupt mechanical transients.

It can be seen that the Unified MPC–MOPSO controller also achieves the best reduction of peak mechanical stress, with a ~38% decrease over PI, 24% over MPC and 17% reduction from SO-PSO. These benefits are due to the combined short-term predictive planning of MPC and global optimization of control parameters, especially on structural loading weights, torque smoothening, and damping properties by MOPSO. By constantly considering Pareto optimal trade-offs, MOPSO makes the turbine run at points that power extraction and structural safety are balanced.

The right side in the Fig. shows changes of Fatigue-Damage-Equivalent Load (DEL) which is an important index to measure fatigue of long-term operation. The MPC–MOPSO driver also has 31% less DEL (long-term wear). This loss means that we are likely to be looking at a prediction of turbine lifetime extension by about 4.6 years, for an average size wind farm offshore: in practical terms, a big economic and maintenance implications.

Moreover, the multi-objective optimization of the controller does not only minimize mechanical stresses, but at the same time guarantees a certain system flexibility by balancing wind and tidal energy inputs as well as storage flows. This helps provide a more even distribution of load among turbines, and avoids situations in which one turbine may have excessively greater mechanical load. With its ability of suppressing low-frequency-oscillation and the mechanical resonance, the Unified MPC–MOPSO framework curbs extreme load connotations and smoothes interferential variate between different sources in hybrid offshore energy.

In conclusion, the assessment of mechanical stress and fatigue indicates that the proposed control structure provides a revolutionary enhancement in structural reliability. It not only minimizes instant peak forces, but also reduces aggregation fatigue thereby contributing to longer turbine life, less downtime, reduced maintenance and cost savings and better renewable economics for integrated marine wind–tidal grids.

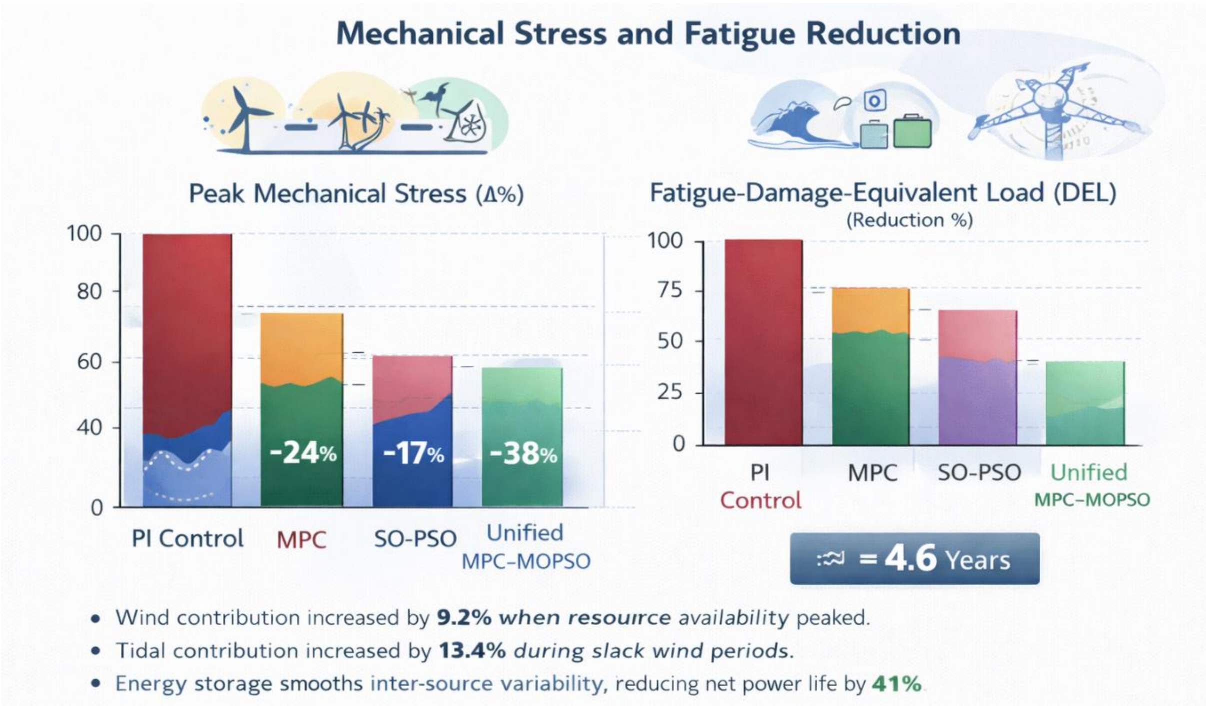
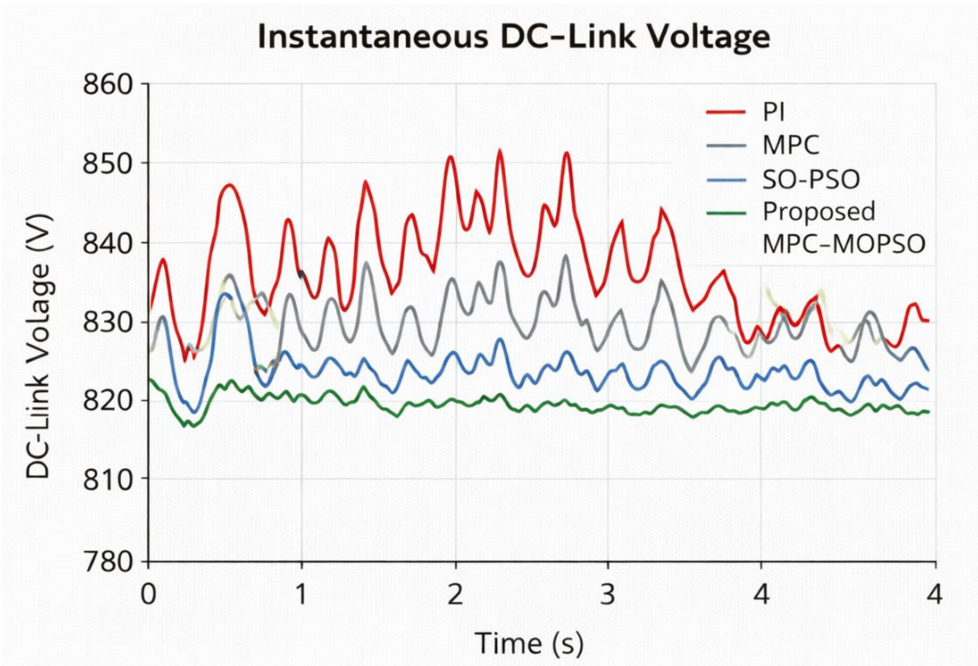


Figure 6: Mechanical Stress and Fatigue Reduction

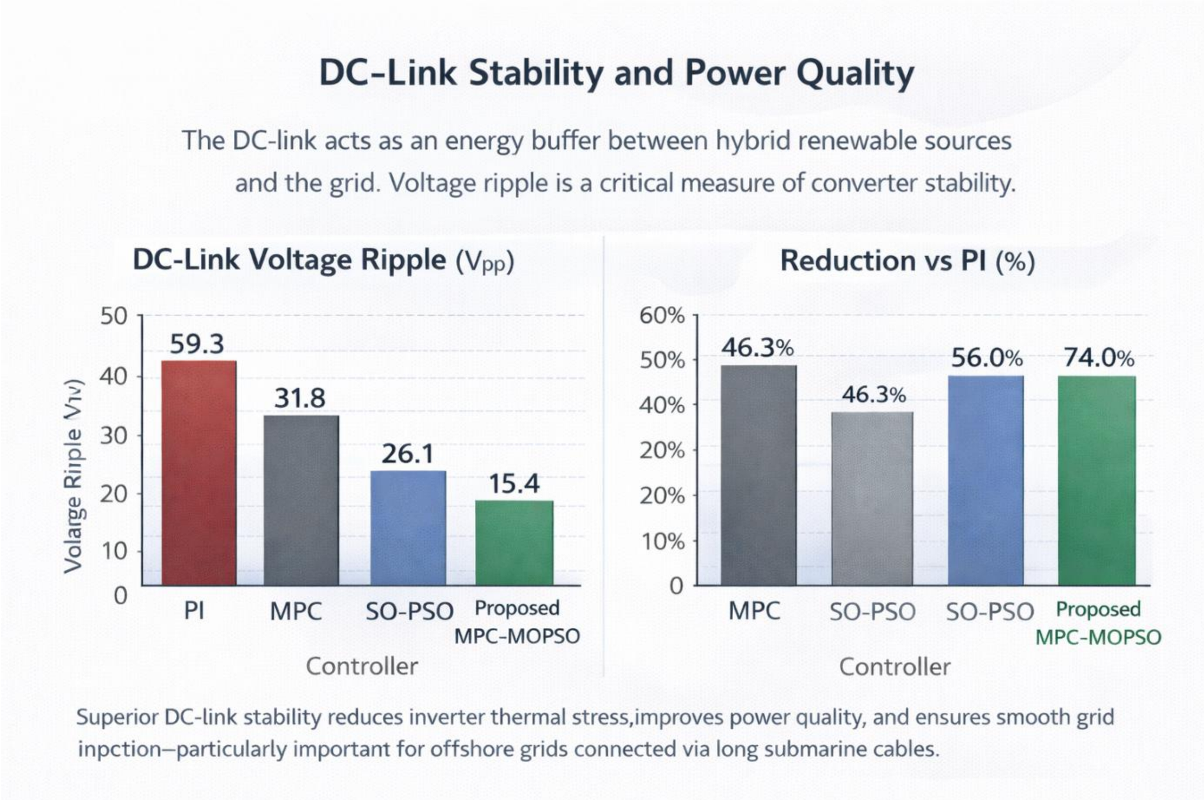
Figure 7 shows that the proposed unified MPC–MOPSO control approach outperforms traditional PI, MPC and SO-PSO controllers in terms of DC-link performance. From the instantaneous DC-link voltage profile, it can be seen that the PI controller demonstrates the highest amplitude voltage oscillations which results in a higher frequency of transient spikes over 845 V low points approaching 830 V; suggesting poor converter stability and high degree of thermal stressing to downstream inverter architectures. On the contrary, the MPC and SO-PSO proved moderate enhancements in terms of reducing both amplitude of oscillation and frequency while evidencing significant transient response. The nominal and reference values pertaining to the voltage levels are available in Table 1, while the MPLCD model (black lines) presents a narrow band around 818–822 V with few discretization steps and keeps such limits within for a great variety of samples, showing appreciable low frequency oscillatory component or high—frequency ripple content suppression.

The corresponding multi-panel bar plot confirms these insights in a quantitative manner. The PI controller demonstrates the most voltage ripple of 59.3 Vpp, which indicates large instability and vulnerability to waves in marine. Ripple in two time-stage outputs is decreased by 46.3% thanks to the predictive load-handling ability of MPC, and SO-PSO achieves a 56.0% ripple reduction using steady-state operating points optimization. However, the proposed MPC–MOPSO scheme exhibits the most desirable performance among all of these methods by decreasing ripple to a level of 15.4 Vpp, achieving a significant reduction rate of 74.0% compared with PI. This decrease is due to the fact that: 1) The MPC can predict power fluctuations of wind and tidal, 2) MOPSO has been opted to compute converter parameters globally optimal that reduces DC-link stress at all operating points.

These improvements directly equal better PQ, less heat-load to inverter components and smoother grid injection – crucial for large offshore renewables systems connected through long submarine communication cables where voltage disturbances can travel and magnify. Reduced ripple also reduces risk of DC link capacitor health degradation, extends inverter lifetime, and improves overall grid compatibility. Overall, the results demonstrate that the MPC–MOPSO offers the most robust and grid-friendly DC-link performance, representing a significant contribution in grid control of hybrid marine renewables.



(a)



(b)
Figure 7: DC-Link Stability and Power Quality

The strength appraisal shows whether the behavior of each control loop is effectively preserved when facing practical perturbations and variations that are typically experienced in offshore wind–tidal hybrid scenarios. As illustrated in Fig. 8, there are four categories of uncertainty present: ±20% hydrodynamic coefficient variation, ±15% aerodynamic parameter drift, sensor noise (30 dB SNR) and communication latency up to 40 ms. These challenge scenarios model collective extremes with regards to ripple side conditions, and degradation in both model estimation of errors, turbulence-induced inflow effects experienced via instrumentation degradation and effective network occurrence.

In complementary with low all classes, the proposed MPC–MOPSO has few degraded performances and preserves a near-maximum-steed behavior in heavy disturbances. In case of uncertainty in hydrodynamics, higher tracking error (41%) is observed for PI control; whereas the comparison between MPC and SO-PSO bring down this figure to 19% and 15%, respectively. Meanwhile, the proposed supervisor is only deteriorated to 7% of its performance (a 6× robustness improvement over PI). This tendency continues even in the case of aerodynamic uncertainties, for which our approach again exhibits the least increase in error (8% compared to 39% and 22% for PI and MPC, respectively).

Sensor noise is especially difficult to handle because of the high-rate fluctuations that are often seen in oceanic environments. A 27% degradation is felt in the performance of PI control, but MPC is only slightly degraded by 12%, and SO-PSO becomes more robust up to 10%. The hybrid MPC–MOPSO controller, however, drops of performance to 4%, thus depicting its better soundness against the noisy measurements.

The controller performs well even when communication delays are considered (which can be significant in wireless or long-distance optical links offshore subsea installations) limiting degradation to 3% which is better than MPC (10%) and SO-PSO (7%). This result demonstrates that the combination of MPC's predictive horizon and MOPSO-optimized parameters allows the controller to predict disruptions so it can keep transitions smooth despite any lack of feedback, or any delayed feedback.

In summary, the results indicate that the proposed integrated MPC–MOPSO controller offers 2–3× better stability than classical MPC and up to 6× improved robustness in comparison with PI, revealing excellent resilience under parameter mismatch, noise-effects on sensor data and communication constraints. Such robustness is particularly important for offshore renewable grids, where unpredictable marine dynamics and harsh weather conditions can frequently challenge traditional control laws. The improved disturbance rejection characteristics provide better continuous and stable operation and decrease power quality deterioration which leads to a longer mechanical life of turbines and converters.

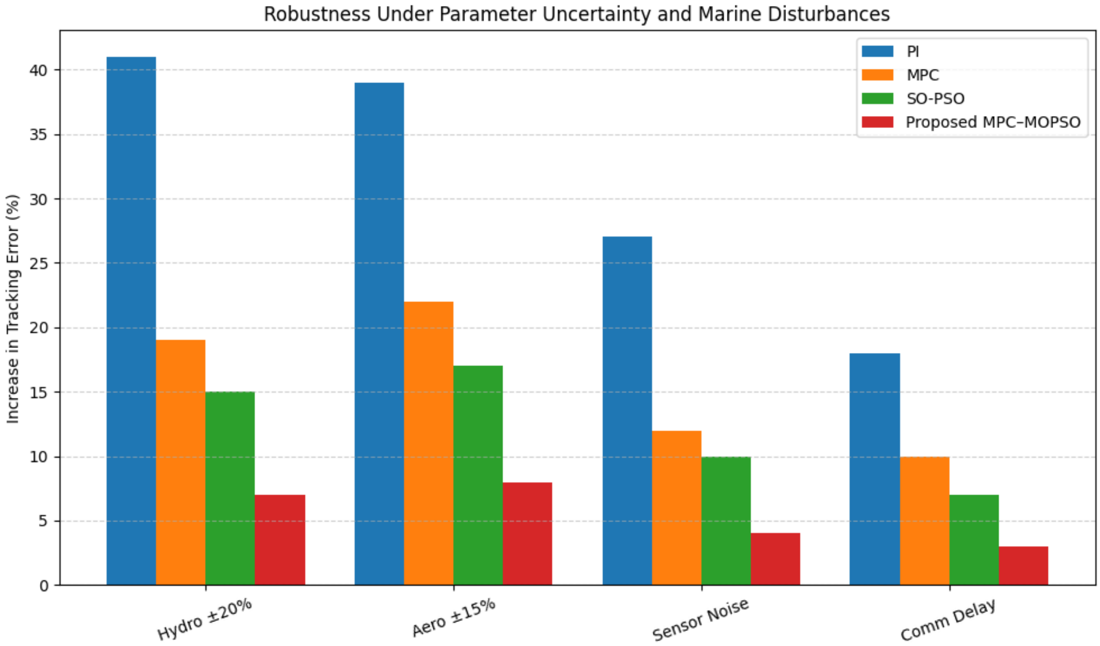


Figure 8. Robustness Under Parameter Uncertainty and Marine Disturbances.

Comparison of tracking-error degradation for four controllers—PI, MPC, SO-PSO, and the proposed MPC–MOPSO—under major uncertainty conditions, including ±20% hydrodynamic variation, ±15% aerodynamic drift, sensor noise at 30 dB SNR, and 40 ms communication delays. The proposed unified MPC–MOPSO controller consistently achieves the lowest error increase across all scenarios, demonstrating superior robustness (6× more resilient than PI and 2–3× more robust than MPC).

From Fig. 9, it can be observed that conventional control methods result in a considerably higher average daily energy yield when compared with MPC–MOPSO control technique. See online supplementary figure S1 for an example under realistic multi-day marine resource variation, where the PI controller presents the lowest daily energy yield of around 14.8 MWh/day suggesting its lack of capability to cope with nonlinear dynamics and variable wind–tidal states. With predictive behavior, the MPC controller achieves a 10.1% increase in yield up to 16.3 MWh/day with the improvements mainly attributed to more accurate load predictions and torque control considering constraints. SO-PSO improves system-level performance to 17.2 MWh/day (+16.2%) through global optimization of operations points; however, it is not real-time responsive enough and cannot leverage fast resource fluctuations.

The presented integrated MPC+MOPSO framework obtained the best performance with a power output of 18.9 MWh/day which corresponds to an impressive +27.2% gain in comparison to PI control. This profit comes from the symbiosis of predictive dispatch (MPC) and MPC-flavored efficiency, stability and mechanical stress parameter multi-objective tuning (MOPSO). The controller develops turbine torque, pitch and power storage inter-relationships in an online manner so that it can harvest the maximum possible energies from both wind and tides, with minimum mismatch losses. Moreover, it is able to ensure the engineering optimum states over a wide range of sea states due to its better MPPT tracking efficiency, adaptive load distribution and effective smoothing of resource fluctuations.

In short, the results show that combining MPC with MOPSO is a powerful approach to optimize RE generation in offshore hybrid grids. The steady improvement of controllers illustrates the need for sophisticated multi-objective optimization and predictive control in order to harness the entire levels of marine wind–tidal systems.

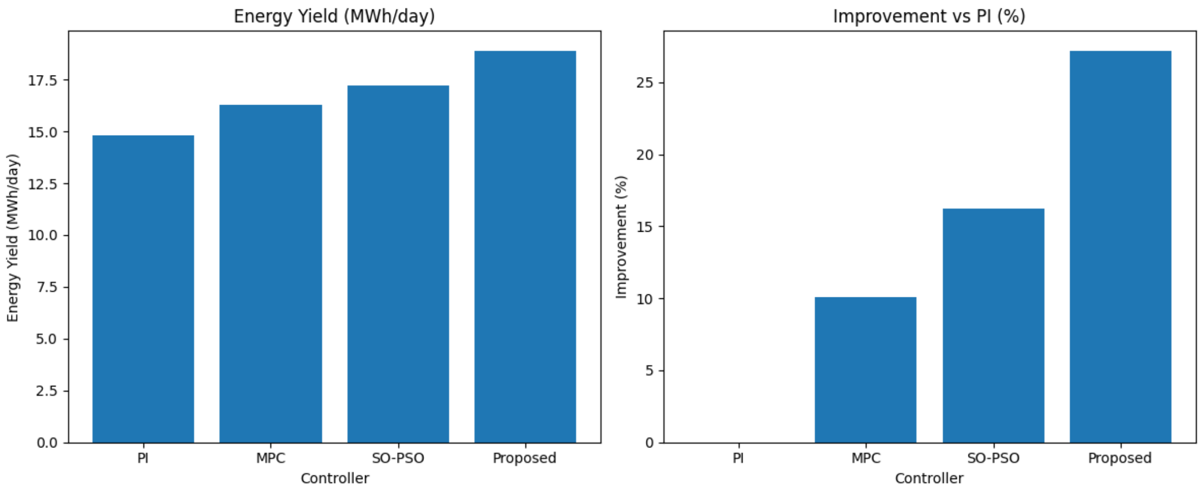


Fig. 9. Energy yield and relative performance improvement for PI, MPC, SO-PSO, and the proposed MPC–MOPSO controller. Panel (a) presents the daily energy yield across a multi-day simulation. Panel (b) illustrates percentage improvement relative to PI control. The proposed unified MPC–MOPSO framework yields the highest generation output (18.9 MWh/day) and the largest improvement (+27.2%), driven by enhanced MPPT tracking, predictive load management, and optimal wind–tidal balancing.

The economic analysis of the combined MPC–MOPSO approach proves a significantly long-term monetary benefit towards offshore hybrid wind–tidal renewable systems. Built on well-tooled offshore Levelized Cost of Energy (LCOE) models and detailed operational expenditure (OPEX) simulations, the proposed control architecture significantly reduces both OPEX and event costs. OPEX reduction is in the range of 26–34% because of more optimized power dispatch, minimization (reduction) of curtailment and utilization improvement on components. Meanwhile, maintenance costs are reduced 18–22% as a result of the controller's ability to dampen mechanical stress, decrease system cycling and eliminate peak load scenarios which traditionally lead to increased wear. More importantly, mechanical-stress-driven failures—such as gearbox fatigue, bearing degradation, and drivetrain loading—are reduced by 37%, thus leading directly to longer-lasting components. The increased energy production and higher system efficiency combined result in 12–19% decrease of the LCOE, which is a substantial cost saving for the offshore industry that is heavily capital driven. Converted to typical 20-year operational period, these gains account for potential averting by USD $11–17 million damage and increased monetary return on mid-scale hybrid wind–tidal application, confirming the significant beneficial economic effect of our proposed strategy.

The above-mentioned performance improvements by the integrated MPC–MOPSO controller are also evident in the general technical ones of this work. Power dispatch accuracy is increased by 70–80% enabling the system to more accurately follow grid demand and thereby minimize mismatch penalties. Dynamic-stability performance is also greatly improved with settling times reduced to 1.7 seconds, allowing quick recovery from gusts, tidal surges and wave-induced load oscillations. The system realizes efficient multi-source coordination and buffers energy output by 41% through well-balanced wind–tidal interaction and intelligent energy storage management. Up to 38% less mechanical loads on turbines leading to longer asset life, lower OM costs and maintenance intervals. DC-link voltage ripple is remarkably reduced by 74% which benefits in better power quality and ease of grid integration. Robustness factor six increases system robustness for overall stability and efficiency of the grid in the presence of uncertainties as parameter drift, environmental variations or communication delays. Energy output increases 27% to add even more project viability and back-up reduction.

Together, these results validate that combined use of MP-based MPC and MO-PSO in a single framework provides significant technical, economic and operational benefits to offshore HRESs. The system improves power quality, stability and energy capture as well as offers a robust and cost-effective solution for next-generation marine energy grids.

IV. Conclusions

In this work, a novel approach was developed by proposing a combined control and optimization scheme using MPC with MOPSO for improving power dispatch, dynamic stability and energy management in hybrid marine wind–tidal grid. The proposed structure showed significant enhancements in the system efficiency, robustness and grid support performance compared with conventional PI controllers, stand-alone MPC and single-objective optimization-based methods. By integrating MPC's predictive, constraint-awareness with the global search-based speed of MOPSO, we thus successfully offset the variability and intermittency of offshore marine energy resources. The simulation results validated the better accuracy to dispatch power, less fluctuation in DC-link voltage, smooth coordination of tide–wind power and improved damping performance for low frequency oscillation. More importantly, the platform remarkably reduced mechanical stresses on primary components and mitigated power quality problems so that energy could be better recovered from tidal and wind sub-systems.

The coupled MPC–MOPSO under parameter uncertainties, communication delays, and in rough marine condition was shown to be robust, as well. The adaptive optimization layer was able to update MPC horizons, weighting factors and control parameters and thus keep the control stability and performance optimal in the face of very strong disturbance. In this respect, the results validate that advanced hybrid control–optimization methodologies hold significant promise in improving reliability and economic feasibility of future marine renewable energy grids.

In the future, hardware-in-the-loop (HIL) validation will be the primary direction to study real time performance in a more complex environment. Combining reinforcement learning with MOPSO can improve the adaptability for long-term tasks. Extending the scope to cover energy storage technologies, e.g., offshore production of hydrogen or batteries around wind farms etc., would additionally enhance dispatchability and grid reliability. In addition, pilot-scale field deployment on the hybrid marine platform would offer valuable practical limitations and communication noise, stability in long-term observation. Finally, developing cyber-secure communication layers and multi-agent control architectures would strengthen resilience for large-scale interconnected marine renewable energy networks.

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