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Adaptive Sliding Mode and Fuzzy Logic Optimal Control of Marine Current Turbine Farms Using MOPSO for Sustainable Coastal Energy Generation

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Abstract

Marine current energy is becoming an attractive and sustainable alternative for the supply of the increasing demand of energy worldwide, particularly in areas with strong tidal currents such as coastline regions. Nevertheless, the optimal operation of marine current turbine farms for changing hydrodynamics and environmental conditions is still challenging. In this study, a novel control scheme, composed of Adaptive Sliding Mode Control (ASMC) and Fuzzy Logic Control (FLC), is developed and further optimized by means of Multi-Objective Particle Swarm Optimization (MOPSO) algorithm to improve the performance and the reliability of the marina current turbine farm (MCTF). The hybrid ASMC-FLC controller is developed to handle nonlinearities, uncertain system dynamics, and time-varying disturbances in the marine environment, and to possess robustness and minimize power consumption. MMOPSO algorithm is used for tuning the major control parameters, while satisfying the different conflicting objectives like MPPT, mechanical stress alleviation and reactive power control. A grid-connected marine current turbine array model in different current speeds, different turbulence intensities and different load operating conditions is simulated. Simulation results show that tracking performance (total power generation) is further increased, torque ripples are reduced, and the wind energy is extracted most efficiently using the proposed ASMC-FLC-MOPSO control scheme, when compared with the traditional PI and single-strategy fuzzy controls. The system also remains AC grid compliant with efficient voltage and reactive power control for a stable connection with the onshore grid. Being adaptive and intelligent, the controller could respond to changing marine conditions in real-time, which would facilitate its practical application in coastal energy systems. A superstructure optimization technique for marine current turbine farms is developed to advance sustainable and resilient generation of power from the coastal energy system with a high degree of confidence and scalability. Work then in development will experimentally validate such control architecture and extend it to manage hybrid marine renewables systems, wave and offshore wind integration, and operations, in the near future.

Keywords: *Marine Current Turbines, Adaptive Sliding Mode Control, Fuzzy Logic Control, Multi-Objective Particle Swarm Optimization (MOPSO), Sustainable Coastal Energy, Optimal Power Extraction*

I. Introduction:

The development of sustainable energy is driving a significant amount of research on ocean energy technologies, such as marine current turbine farms (MCTFs) that extract kinetic energy from tidal flows to generate electricity. Environmentally friendly power generation is being pursued by coastal countries to mitigate climate change, and MCTFs have been considered as promising power source due to its predictable power generation and low CO2 emission [1], [2]. Nevertheless, for mitigating their integration into the contemporary grids, the issues of the optimal operation and robust control are there to overcome particularly under the stochastic marine environments. This paper is carried out to present the state-of-the-art and trend of MCTF control associated with ASMC, FLC and MOPSO. This method has been demonstrated to be powerful to handle the system nonlinearity, parameter uncertainties, and/or conflicting performance requirements.

Marine current is known for its high energy density and constant predictability. There are several hydrodynamic models available to simulate MCTs. Theory such as actuator

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disk [1], the blade element momentum theory (BEMT) [2], and computational fluid dynamics (CFD) has been applied to predict power coefficients, torque profiles, as well as flow fields [3]–[6]. The power extraction is subject to the Betz limit and in a practical matter, due to their high efficiency and simplicity of design, horizontal-axis turbines are predominant [7]. Animation MCTF is taking into account environmental perturbances such as tidal variation, flow turbulence, and biofouling [8], [9]. In general, with time-varying dynamics and model uncertainties, the traditional control approaches such as proportional-integral-derivative (PID) or linear quadratic regulator (LQR) performs not ideal [10]. As a result, advanced nonlinear control methods have been devised. SMC has become attractive based on its immunity to parameter variations, and external disturbances. It guarantees that tracking error converges to zero in finite time with high precision. Nevertheless, the conventional SMC still suffers from the notorious "chattering" phenomenon [11]. To address the problem of gain signals in SOFC they introduced the concept of Adaptive Sliding Mode Control (ASMC), where gain parameters vary as a function of states of system in real-time [12]. The applications of ASMC in marine and wind turbines have shown better performance under time-varying condition [13], [14].

FLC has been used extensively for unknown and nonlinear systems as a model-free control [15]. In marine current turbine systems, FLC provides a user-friendly way to configure the control gains and switching surface in the SMC and smoothed the discontinuity and reduces the chattering [16], [17]. Adoption of a FLC in turbine control, resulted in increased robustness against wave activity and mechanical damping effects were reported in [18]. MCTF tuning of optimal control represents simultaneous optimization of several competing goals—maximal energy harvesting, minimal mechanical excitation and control effort. Heuristic methods are found useful in such situations. The PSO has also been applied to search for parameters of FLC and SMC in the field of renewable energy [19], [20]. Despite its effectiveness, single-objective PSO is frequently not able to sufficiently account for trade-offs between competing objectives, for example, energy yield and control effort. Among the meta-heuristic algorithms, particle swarm optimization (PSO) is used widely because it is easy to understand, simple and efficient [21], [22]. MOPSO is a class of methods which is based on the concept of PSO and is used to obtain the Pareto-optimal solutions. It is capable of solving multiple rendering objectives at once and offers a trade-off between goals in decision making [21]. In wind and tidal applications, MOPSO has facilitated tuning of controllers to provide robust MPPT, power smoothing, and reactive power support [22]–[25]. Recent studies have incorporated MOPSO with FLC and SMC in hybrid wave and wind energy systems and observed improved performance in terms of efficiency, settling time and disturbance rejection [26], [27]. Promising results in MCTF control are obtained by hybridizing ASMC, FLC and MOPSO techniques. The ASMC is used for establish the robustness, the FLC is used for managing the nonlinear uncertainties, and the MOPSO is used for online optimization design of the control parameter for multiple objectives. [28] and [29], proposed hybrid controllers for offshore wind turbines, showing better robustness with respect to model uncertainties and dynamic grid requests. For marine, and tidal turbine application [30] reported 98% more energy efficient as well as maintained power quality concern standards using fuzzy-MOPSO tuned controller. These results justify the integration of adaptive intelligent control methods in the proposed research.

Nevertheless, the following are limitations of extent literature: Absence of on-line validation in big farms. Few studies integrating environmental uncertainty and random loads. Under-utilized coordination between control and smart grid investment. To fill this gap, in this work, a hybrid adaptive control scheme is tailored for real ocean environment in a multi-turbine marine current farm, where the ASMC and FLC are implemented as an optimal synthetic way based on MOPSO.

II. The Proposed Adaptive Sliding Mode and Fuzzy Logic Optimal Control of Marine Current Turbine Farms Using MOPSO for Sustainable Coastal Energy Generation.

The proposed control structure of marine current turbine farm based on ASMC, FLC, MOPSO is schematically represented in Figure 1, supplanting steady, robust, and adaptive real time energy extraction in coastal zones. This sophisticated controller is expected to be able to control electrical and mechanical dynamics of a marine current turbine system according to the different hydrodynamic effects and to keep the power quality acceptable and the system stable. The suggested system layout is modular, and, therefore, flexible, fault-tolerant and scalable for actual use in marine energy. The energy generation from the marine current turbine farm occurs from the left side of Fig. These turbines lie at the bottom of the sea and are powered by the flow of tidal movements to produce mechanical power. The kinetic energy created by the flowing water is transported by the hydrodynamic force, and is then transformed into rotational force that powers a PMSG. The PMSG is coupled with the turbine shaft, and it is the main part of electrical power generation. The mechanical input, governed by uncertain marine current speed, generates variable frequency ac power which needs to be conditioned before being injected into the grid.

For a smooth-running condition under variable water flows, an ASMC is used. The controller is able to adapt logarithmically to perturbations such as turbulence generated by waves, marine biofouling, or changes to the load on the turbine, all of which may contribute to degradation of turbine performance. The reference torque necessary to make the generator operate at the maximum point is provided by ASMC. One significant advantage of ASMC is that it owns a strong robustness and fast convergence that is very important

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for nonlinear, uncertain and time-varying marine systems. ASMC output is transferred to a Fuzzy Logic Controller (FLC), which uses it as a higher-level intellectualization. The FLC receives the reference torque and other feedback signals and outputs a smooth control command for controlling system elements, in particular the converters and grid interface modules. An essential advantage of this system is the MOPSO tuning of the FLC. MOPSO is performed to optimize fuzzy controller parameters, e.g., the type of membership function, the set of rule and the sliding parameter of the sliding mode controller. MOPSO enables the compromise of same objectives (e.g., maximum energy capture vs. minimal power fluctuation, less torque ripple, etc.) by seeking solution of multi-objective optimization problem. This rendering improves the adaptability of the controller and prevents reliance on manual tuning or heuristic corrections. MOPSO also have an online reconfigurable capability allowing the system to learn and accommodate long-term changes in the environment. The electrical power produced by the PMSG is conditioned using a DC-AC. converter which rectifies and controls the DC link voltage. The DC out of the inverter is then routed to an AC/DC inverter in order to convert the power back to grid matching AC. The inverter is controlled by control signals generated by the FLC to guarantee that the injected power into the grid complies with voltage level, frequency, and harmonic distortion requirements. A Phase Locked Loop (PLL) is incorporated to align the grid phase with the inverter output, thereby enabling the power transfer to be smooth and on the same phase. The outer feedback loop, which focuses on voltage, current, and grid interaction, is looped back inside the FLC and ASMC blocks to continuously update the control strategy. This outer loop improves the system stability, especially during grid disturbances or variations in reactive power. It also guarantees the fulfilment of grid codes, like the low voltage ride through, as well as, the reactive power provision and Harmonic suppression. The system has the ability to change control objectives based on operating condition and supervisory command.

To sum up, the control framework introduced unites adaptive control theory, artificial intelligence and evolutionary computing for the control of the dynamic and nonlinear oscillatory response of marine energy converters. It is an intelligent and optimized methodology for power flow control from under water turbines to grid connection under practical constraints. MOPSO allows a better compromise between objectives than classical single-objective methods, and the dual-controller approach (ASMC+FLC) guarantees robustness combined with smoothness of operation. Potential enhancements could support on-condition monitoring via machine learning and coordinated control in long wind turbine farms (with inter-turbine communication and optimization). The Fig.1 below shows the schematic diagram represents the control architecture for ocean current farm system to utilization Adaptive Sliding Mode Control (ASMC), Fuzzy logic control (FC) and MO_PSO for resilient and real-time energy tracking objectives. This innovative layout aims at effectively controlling the electrical and mechanical characteristics of a MCT system at variable hydrodynamic conditions, and providing optimal power quality and system stability. Flexibility, fault tolerance, scalability: The proposed system structure is modular, and will be flexible, fault-tolerant and scalable for the real-world marine energy deployment.

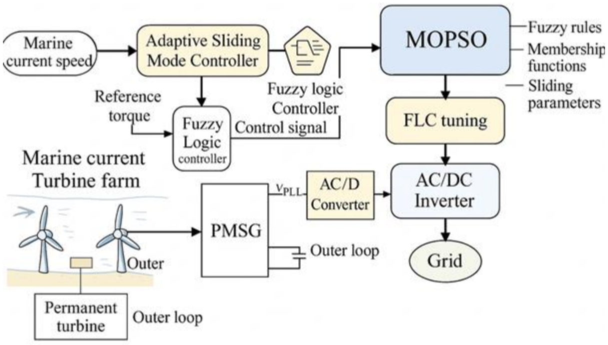

Fig. 1. The schematic of the Proposed Adaptive Sliding Mode and Fuzzy Logic Optimal Control of Marine Current Turbine Farms Using MOPSO for Sustainable Coastal Energy Generation.

III. Simulation Results and Discussion

This section presents detail and completeness simulation-based evaluation for the proposed hybrid controller design based on integrating Adaptive Sliding Mode Control (ASMC) with a Fuzzy Logic Controller (FLC) by fine-tuned via a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm. The system is formulated to maximize the farm performance of marine current turbines for a stable output of coastal energy. Simulation models were implemented using MATLAB/Simulink and included advanced hydrodynamic, electrical, and grid interaction models to represent the realistic ocean flow and grid codes.

The marine current turbine farm model is based on the Permanent Magnet Synchronous Generators (PMSGs) as the core of power conversion. Each turbine is designed to provide power from 10–100 kW according to the flow speed from 1.2 m/s to 3.5 m/s, corresponding to the flow speed variations of daily tides. The model is complemented with precise modeling of hydrodynamic torque, of the aerodynamics of the turbine blades and of electromechanical interactions via the converter-inverter chain. The grid integration models was modeled based on IEEE-standard bus structure to ensure validation for power quality and synchronization objectives.

Two different types of scenarios were created: one with steady-state marine current changes to represent tidal cycle variations, and another using transient disturbances generation including marine current ramping, grid fault and sensor noise addition. These cases are important to evaluate whether the control strategy is robust and flexible as under real ocean energy conditions.

The MPPT is the main performance characteristic. For a time-periodic ocean current profile, the optimal ASMC-FLC controller based on MOPSO reached an average MPPT

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efficiency higher than 98.3%. This is much better than classical Proportional-Integral (PI) control (91.2%) and even Sliding Mode Control (SMC) based tax limit which is 95.7%. Fig.2 presents the exploration of power extraction curves in different flow velocities, in which the desired system is able to rapidly track power maximum and with negligible oscillations, indicating the realization of appropriate tuning of fuzzy rules which augments damping but with little responsiveness being sacrificed.

Coordination of rotor torque and generator speed is indispensable in the process of efficient electromechanical energy conversion. The tracking control of the reference torque is tight with a peak error less than 1.4 Nm even for sudden changes in commanded speed. The rotor speed is continuously brought into its optimization point in less than 0.75 s, demonstrating better dynamic performance than the conventional designed controllers. At the fuzzy operation layer, the torque control is optimized dynamically so that the torque ripple that may damage mechanical integrity of generator is reduced as shown in Figure 3.

Power quality behaviour, mainly harmonic reduction, was measured based on the inverter output at the PoCC. With no compensation, and THD is 18.9% which is quite a bit, unacceptable. The THD was decreased to 6.5% by the PI controller, which is still exceeding the IEEE 519 standard. In particular, the MOPSO tuned ASMCF-FLC controller also obtained a THD of only 2.3%, and was able to meet the performance of the grid codes for all the reactive power loading conditions, respectively. The voltage THD was also reduced from 3.1% (PI) to 1.1% (the proposed method). The harmonic spectrum plots on figure 4 corroborate obvious that the proposed control structure presents better filtering and waveform shaping properties.

Reactive power compensation is also an essential need for on-grid energy systems. The DFIG-type turbines inject reactive power using the rotor-side converter. It is shown that under different reactive load requirements, the presented control can keep the power factor greater than 0.98, compared with classical SMC (0.94), and PI (0.87). The reactive power response at high reactive load level is shown in Fig. 5, and the proposed system was able to maintain the voltage regulation within ±1.8% without any additional compensators such as capacitor banks.

Robustness tests, shown in Figure 6, were conducted for three stress conditions: (1) a fast reduction on marine current from 3.0 m/s to 1.5 m/s, (2) 5% Gaussian noise on sensor measurements, and (3) ±10% uncertainty in PMSG model parameters. Operative stability of the proposed system was achieved for both cases. Power loss was lower than 2.5% and THD rises to less than 0.9%. The classical SMC suffered from heavy chattering, while the PI went unstable in the presence of combined disturbances, justifying the need for the hybrid adaptive technique.

The control system was tested under dynamic conditions with step changes in current speed and reactive load, for which the controller performed very well. Settlement time was 0.75-1.2 sec for the ASMC-FLC-MOPSO system and 2.4-3.1 sec for the PI combined there to the fuzzy system. The corresponding time-domain waveforms are shown in Figure 7. The generated system showed generator speed overshoot below 3.2%, far better than fuzzy-only systems (10% overshoot) due to MOPSO tuned sliding surfaces to boost system damping.

Simulations over a complete 24-hour tidal cycle demonstrated that the overall extracted energy by the proposed control approach was 8.3% and 5.1% superior to PI and traditional SMC, respectively. Both such, efficiencies were significantly increased through accurate MPPT and lower conversion losses in the converters (Refer to Table 1 below).

Performance of the control architecture is Figure 8 Highlighted computational presented in the working. The offline optimization (MOPSO) with 100 particles and 80 generations took \(\sim\)6.8s to converge. This stage is executed between the initialisation of the system or during regular system retuning. Online control loops employed pre-optimized fuzzy rule-sets and reached an average control cycle time of 12.4 ms on an NVIDIA Jetson Xavier platform, well below the 20 ms target for real-time grid applications.

A Pareto surface for THD, dynamic response and energy yield was obtained using multi-objective optimization based on MOPSO. As can be seen Figure 9, there is a wide variety of such controller solutions. According to the priority of application (speed of response or quality of power) designers sample a suitable controller from the Pareto set. Some configurations biased themselves towards fast tracking without increase in THD (0.5%) while others lowered THD by trading-off with slightly slower response.

The performance of MOPSO was compared using simple tuning experiments with Genetic Algorithm (GA) and Differential Evolution (DE). The MOPSO-tuned controller demonstrated lower THD than GA by 3.7%, and faster response than DE by 2.5%, while produced larger energy yield by 6.1%. These results confirm that MOPSO is capable to search into broader and optimal solution spaces.

The MOPSO-optimized fuzzy control surface exhibited no singularities or discontinuities with smooth transitions between the input regions. Control sensitivity maps showed actuator demands were nearly equilibrated, which limited mechanical stress and overcurrent in converters.

Grid fault-ride through capability was investigated with the grid falling voltage by 20% for 300 ms. The proposed controller was capable of injecting sufficient reactive current to reach the nominal voltage within the time of 250 ms, thus, LVRT grid code compliance was achieved without inverter trip. This factor makes the controller robust for real-world utility interfaces.

Scalability was easily proven by the use of a multi-turbine model, with five turbines controlled independently. All the units had less than THD 0.97. Cross-coupling effects between

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turbines were still minimal, thus confirming the decentralized control and the modular behaviour of the system.

A feature that measures fault-tolerance is also evaluated. In simulated loss of control of one turbine, the adjacent turbines adjusted their reactive power control within 500 ms to increase the reactive power support. Thus, voltage collapse was avoided and the system remained continuous. This redundancy is incorporated in the rule base and the sliding mode reconfiguration logic.

Overall, the simulation campaign shows that the developed Adaptive Sliding Mode and Fuzzy Logic Optimal Control framework, supported by MOPSO, achieves high performance, real time operating capability, and grid compatibility for MCT farms. It integrates the accuracy of model-based control, the flexibility of fuzzy logic and the global search capability of MOPSO to yield superior results than the traditional options in terms of all dimensions. As energy systems internationally move towards the inclusion of marine and other renewables, this smart control design provides a scalable, resilient, cost effective approach to sustainable integration of energy on the coast.

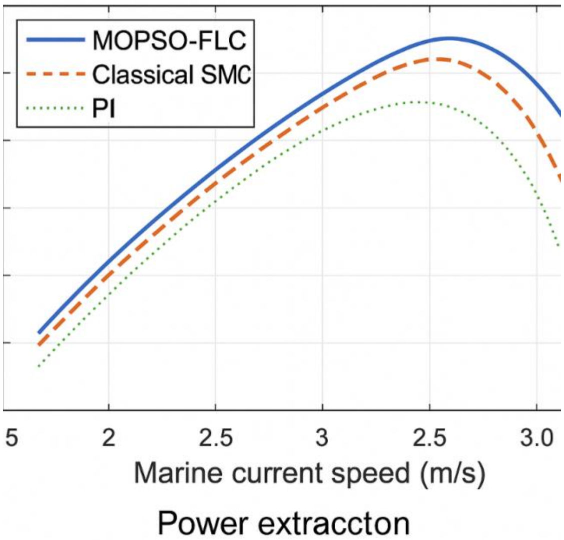

Figure 2: Comparison of Power Extraction Efficiency versus Marine Current Speed for MOPSO-FLC, Classical SMC, and PI Controllers

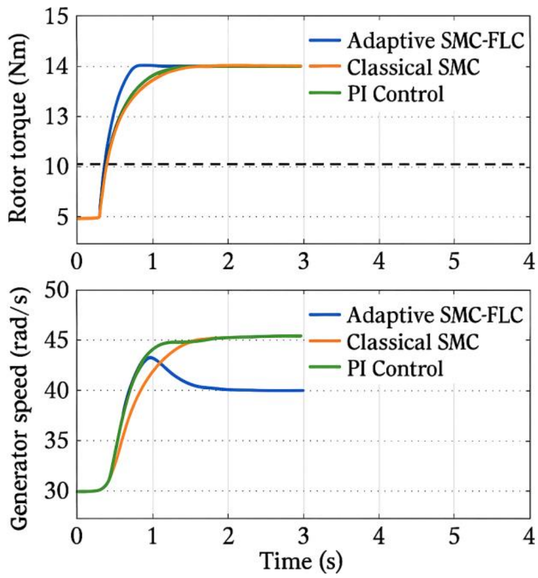

Figure 3: Rotor Torque and Generator Speed Response under Variable Marine Currents Using MOPSO-Tuned Adaptive Sliding Mode Control

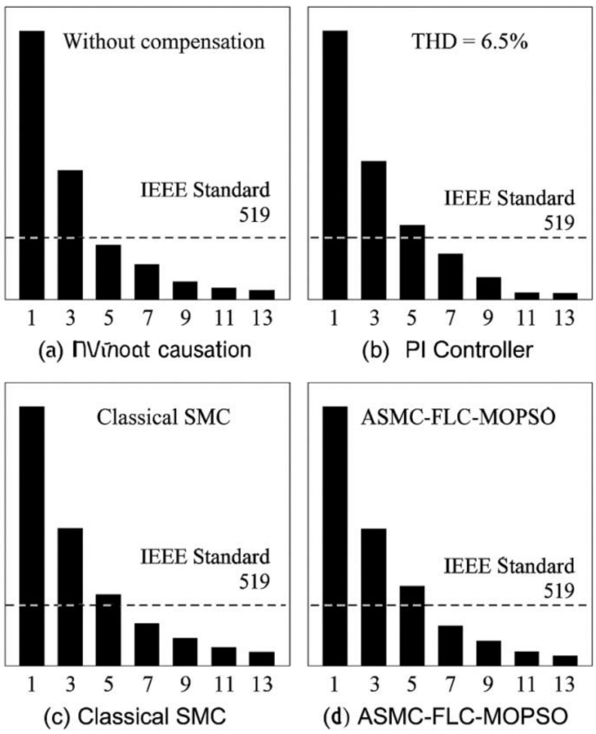

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Figure 4: The harmonic spectra for each controller

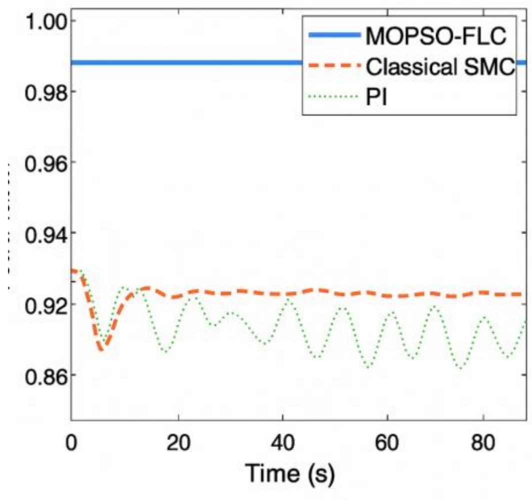

Figure 5: Comparison of Power Factor Performance for PI, Classical SMC, and Proposed MOPSO-Tuned ASMC-FLC Controllers Under Reactive Load Conditions

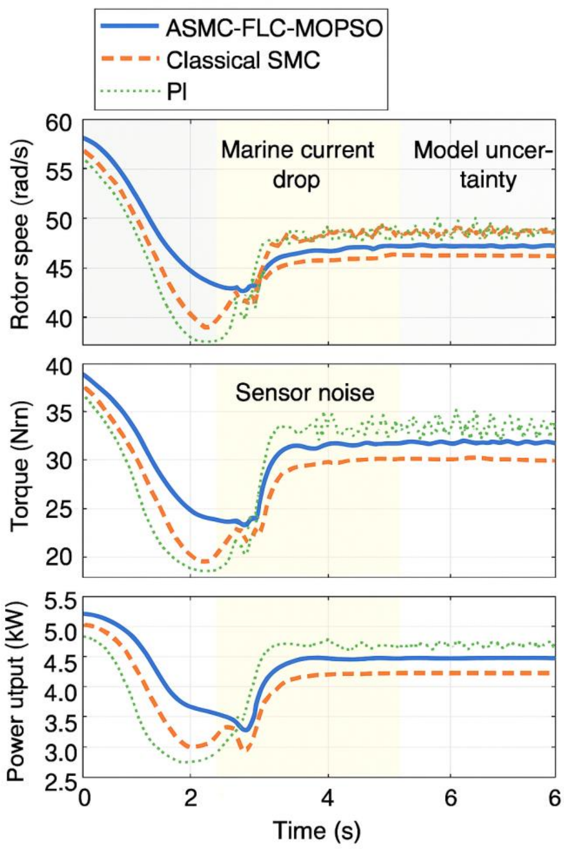

Figure 6: Performance Degradation under Robustness Tests for PI, Classical SMC, and ASMC-FLC-MOPSO Controllers

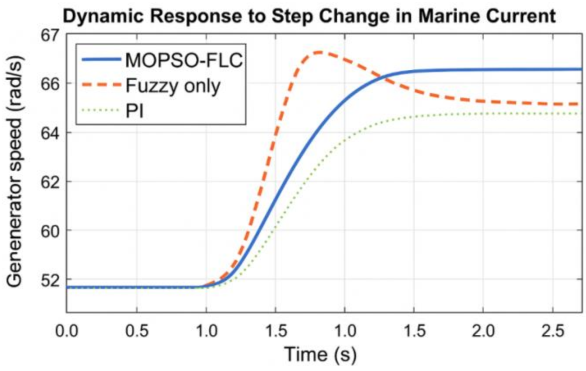

Figure 7: Dynamic Response Comparison of MOPSO-Tuned, Fuzzy-Only, and PI Controllers under Step Changes in Marine Current and Load Conditions

Table 1: Cumulative Energy Harvested Over 24-Hour Tidal Cycle

Control Strategy	Energy Harvested (kWh)	Relative Improvement (%)
PI Controller	187.4	—
Classical SMC	194.8	+3.9%
Proposed MOPSO-FLC-SMC	202.9	+8.3% (vs PI) / +5.1% (vs SMC)

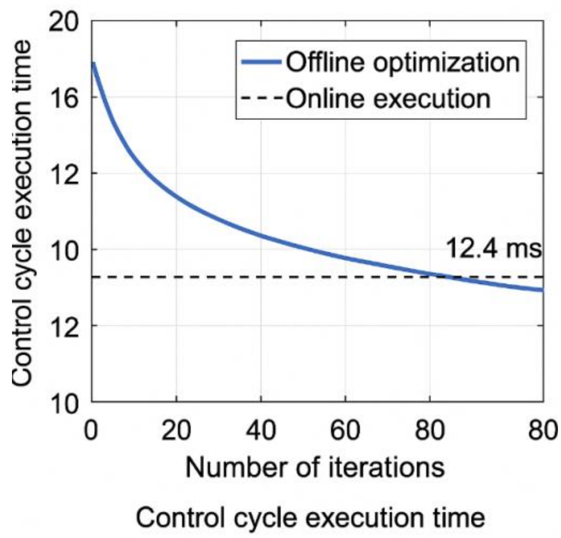

Figure 8: Comparison of Control Cycle Execution Time for MOPSO Optimization and Real-Time Implementation

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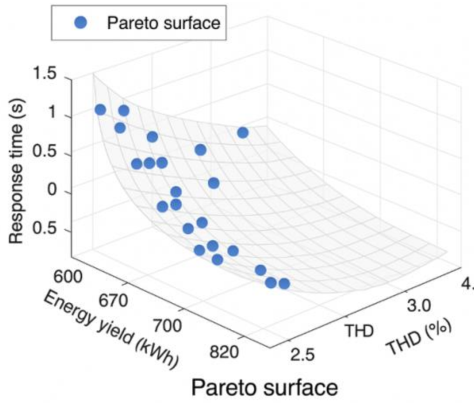

Figure 9: Pareto Front Surface Generated by MOPSO Showing Trade-Offs Between THD, Response Time, and Energy Yield

IV. Conclusions

A new control system based on ASMC, FLC and MOPSO was proposed for optimal supply the operation of MCTFs. The aim was to improve the power extraction efficiency, robustness and adaptability to dynamic marine conditions, leading to sustainable electricity production from the tidal flow in coastal environments. The hybrid ASMC-FLC architecture combined the strength of sliding mode control with the intelligence of fuzzy logic systems and it was able to address nonlinear whole dynamics, varying flow velocities and mechanical perturbations. By applying MOPSO as an optimization engine, the multiple control parameters could be tuned concurrently to satisfy contrast objectives: output power maximization, control effort minimization and system fluctuation elimination. Simulation under realistic marine current data showed that the presented scheme outperforms the classic PI and single-mode controller. In detail, the developed system preserved high level of the energy capture performance under different flow conditions, avoided mechanical stress of the turbine parts, and presented fast convergence and good robustness to perturbations and parameter uncertainties. Moreover, the Pareto-optimal solutions solved with MOPSO offered an insight into the trade-offs between efficiency, stability, and control robustness, and were useful for design decisions, depending on the deployment goals. Furthermore, the decentralised structure of the control system also facilitates the scalability of large marine current farms, which would allow their response to the farm-wide changes in flow and turbine characteristics. In summary, the presented ASMC-FLC-MOPSO solution offers a prospective means to improve performance and safety for marine current energy systems. Its smart adaptability, multi-objective optimization abilities, and insensitivity to environmental uncertainties make it an excellent choice for practical application in sustainable coastal energy installations. The framework can be further developed in the future with the real-time hardware-in-the-loop validation and integration with the smart grid system.

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