

Title: Coordinated Control and Energy Management of a Hybrid Marine Energy System

The accelerating global demand for sustainable and low-carbon energy sources has intensified research into marine renewable energy systems, particularly tidal and wave energy. These marine resources offer considerable advantages, including high predictability, vast availability, and minimal visual or land-use impact. However, their inherent variability, especially in wave energy, introduces significant challenges for reliable integration into islanded or weakly connected grid systems. Moreover, the dynamic and nonlinear nature of marine loads, coupled with the harsh offshore environment, demands robust and flexible energy management systems. To address these challenges, this study presents a coordinated control and energy management framework for a hybrid marine energy system integrating tidal and wave energy converters with a Battery Energy Storage System (BESS) and a Supercapacitor Energy Storage System (SCESS).

The proposed architecture exploits the complementary characteristics of individual resources. Tidal energy, characterized by its cyclical and highly predictable nature, is utilized as the base energy contributor, ensuring a consistent supply. In contrast, wave energy is more stochastic but provides additional harvesting potential during high-energy periods. To smooth the variability of these inputs and ensure consistent power delivery, the hybrid system employs a two-tier storage strategy. The BESS is used for medium-duration energy balancing and steady-state load support, while the SCESS is optimized for short-duration, high-frequency power fluctuations caused by load transients or abrupt changes in wave input.

A hierarchical coordinated control algorithm is developed, combining droop control principles with state-of-charge (SOC)-aware strategies for optimal energy sharing. Both tidal and wave converters operate under Maximum Power Point Tracking (MPPT) control to ensure optimal energy extraction under varying environmental conditions. The energy management system differentiates between long- and short-term power needs using a multi-time scale approach: the SCESS responds rapidly to sudden transients, while the BESS is engaged for sustained power support based on SOC levels and load forecasts. This coordinated response improves the dynamic performance of the system, reduces battery stress, and extends its operational lifespan by minimizing high-frequency cycling.

The effectiveness of the proposed strategy is validated through a comprehensive simulation model developed in MATLAB/Simulink. The model includes realistic tidal and wave energy input profiles, converter dynamics, and detailed storage system characteristics. Multiple operational scenarios are evaluated, including variable tidal speeds, irregular wave heights, sudden load changes, and combined disturbances. Simulation results demonstrate the capability of the hybrid system to deliver high-quality, stable power with reduced voltage and frequency deviations. The coordinated control mechanism ensures smooth transitions between power sources, efficient use of storage, and robust operation even under challenging marine conditions.

This research highlights a promising pathway toward resilient, efficient, and autonomous marine microgrids suitable for islanded or remote coastal applications. By leveraging the strengths of tidal

and wave energy in conjunction with advanced storage technologies, the system offers enhanced flexibility, reliability, and grid compatibility. Future work will involve real-time validation through Typhoon HIL-based testing, integration of fault detection mechanisms, and exploration of adaptive control strategies using machine learning and predictive analytics.

This work is supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Water Power Technologies Office (WPTO) Award Number DE-EE0009450.