Title: Control Hardware-in-the-Loop Validation of Grid-Forming Control for Tidal Energy Conversion Systems

As marine renewable energy systems play an increasingly vital role in coastal and islanded power networks, advanced control strategies are essential for maintaining grid stability and ensuring reliable operation. Traditional grid-following control methods rely on a strong external grid reference, which may not be available in isolated or weakly connected marine environments. Grid-forming control offers a transformative solution by allowing power electronic converters to act as voltage and frequency sources, emulating synchronous machine behavior and enabling decentralized operation. This study presents a Control Hardware-in-the-Loop (CHIL) validation framework using the Typhoon HIL platform for grid-forming control of a tidal energy conversion system (TECS), with a focus on performance, robustness, and controller readiness for deployment.

The system under investigation comprises a variable-speed tidal turbine coupled with a Permanent Magnet Synchronous Generator (PMSG), connected to the grid through a back-to-back Voltage Source Converter (VSC). The generator-side converter performs Maximum Power Point Tracking (MPPT) control, while the grid-side converter operates in grid-forming mode, providing voltage and frequency regulation using a droop-based control strategy.

A high-fidelity simulation model is developed within the Typhoon HIL environment to replicate the hydrodynamic, electromagnetic, and switching characteristics of the tidal generation system. The control algorithm is deployed on a physical digital controller and connected to the HIL platform via low-latency analog and digital I/O. This configuration enables closed-loop testing of the controller under a wide variety of operating conditions. Scenarios considered include grid voltage disturbances, frequency deviations, load transients, and transitions between grid-connected and islanded modes.

Performance metrics such as voltage and frequency stability, response time, synchronization behavior, and harmonic performance are evaluated to assess the effectiveness of the grid-forming control. Results confirm that the controller maintains stable operation during disturbances and provides smooth transitions across operational modes. The emulation of virtual inertia enhances frequency response under dynamic loading, while the voltage source behavior ensures power quality at the point of common coupling.

Using Typhoon HIL enables identification of controller limitations such as control saturation, delay effects, and non-ideal responses under edge cases or fault conditions—insights typically not captured in offline simulations. This validation approach supports iterative controller refinement and reduces deployment risk by enabling exhaustive, hardware-accurate testing in a safe and cost-effective setting.

This work emphasizes the necessity of controller-level validation for grid-forming converters in marine energy systems, especially as such systems transition toward autonomous and grid-supportive roles. The proposed framework ensures that the grid-forming control logic is robust, scalable, and capable of supporting modern grid codes and islanded microgrid operation. Future work will explore hybrid configurations involving energy storage systems, coordinated operation with grid-following units, and the integration of adaptive control mechanisms for enhanced resilience in uncertain marine environments.

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