*Subtask 3.7.0 R&D: Reliability Modeling, Health Monitoring, and Predictive Maintenance*

Power electronics (PE) circuitry and control are essential components of a WEC or CEC (current energy converter) drivetrain, serving to convert and regulate variable power from the mechanical-side generation to useful stable grid-side power. Consisting of multiple power semiconductor devices, passive and active electronics, and energy storage, the power conversion stage is vulnerable to failure, where one malfunctioning device can shut down the entire WEC/CEC operation. Given the harsh environment, any maintenance and repair service is costly, not only due to the labor cost but also due to the downtime. The vulnerability stems from the 10k+ times of power cycling a day with average power levels nominally less than 1/5th the peak rating, imposing frequent and high-amplitude electro-thermal stress on the circuitry. The PE degradation pattern, aging behavior, and health monitoring require a comprehensive reliability-oriented study. Although the related reliability work has been performed in other renewables such as solar and wind, the unique high-power-cycling mission profile for WEC/CEC demands new study. The success of this research will result in novel methods to lengthen WEC/CEC service time and to reduce maintenance/repair visits, eventually lowering the levelized cost of energy (LCOE).

We will use multiphysics (electro-mechanical-thermal-hydro) models to predict the power semiconductor device and PE circuit stress under a mission-profile-based long-duration cycle. Conventional IGBT and emerging SiC MOSFET power semiconductors at commercial ratings suitable for WEC’s will be the main study focus. Successful modeling requires various air- or liquid-cooling and commercially available supercapacitor modules. The integrated multiphysical system will be built on a generic basis, formulating from a library of a variety of user input options and applicable to a wide range of WEC/CEC applications. We will pay particular attention to the unique WEC low-speed high-torque operations, since the current/thermal stress stemming from the nonlinear torque ripples can be an additional area of investigation.

We then use rainflow counting and Markov chain methods to estimate the degradation and lifetime. Multiple fault modes are considered, including open and short circuits and thermal stressed failures. Condition monitoring uses a physical signal such as vibration, temperature or electrical signals, to detect patterns or variations that correspond to the degradation or failure of a component or device. Often the change in measured signals due to device degradation is difficult to distinguish from changes anticipated during normal operation. Machine learning offers a solution, since hard-to-discern changes in multiple variables can be a recognizable signature of failure or degradation to a correctly trained algorithm. Since the performance of different machine learning algorithms is highly dependent on the specific use case and data input, multiple algorithms should be considered as possible candidates.

The data used for the machine learning algorithm may be the original measurements or derived from the measurements through calculation or model-based methods. The training and testing data must be acquired through simulation or experimental testing. Experimental testing is preferable, since the measurements include noise. Hence, in this project's second half (Year 3-4), we will dedicate significant efforts to building a lab-scale AC-DC-AC converter hardware prototype for WEC applications. Once the test data has been acquired, each algorithm can be optimized by an iterative train, test, and evaluation process in which the algorithm parameters are fine-tuned. The PE circuitry data will train the model to evaluate the system's state of health and further allow a model predictive controller to intelligently adapt to environmental conditions for power generation curtailment or to signal upcoming maintenance.

**Final Products/Outcomes:** 1) a multiphysics-based reliability model uniquely designed for PE within the WEC/CEC drivetrain; 2) a real-time PE health monitoring tool under a deployed mission profile, against time, wave/current amplitude, temperature, etc.; 3) a machine learning based algorithm controller to elongate device lifetime and optimize maintenance/repair intervals; 4) a lab-scale PE hardware prototype (AC-DC-AC) validating the model and controller.

Dr. Yue Cao (OSU) will lead this subtask with support from co-PI Dr. Ted Brekken (OSU); Dr. Cao and Dr. Brekken will co-supervise a dedicated Graduate Research Assistant at OSU. Dr. Cao has previously researched extensively on reliability, fault-tolerance, condition monitoring, and predictive maintenance for electric aviation and hydro turbine-powered energy generation [6][7][8][9]. The team will leverage previous knowledge and apply to WEC’s.

[6] A. Thurlbeck and Y. Cao, “A Mission Profile Based Reliability Modeling Framework for Fault-tolerant Electric Propulsion,” *IEEE Transactions on Industry Applications*, vol. 58, no. 2, pp. 2312-2323, 2022.

[7] A. Thurlbeck and Y. Cao, "An Online Peak Shaving Controller for Optimized Power-electronic Converter Lifetimes in Turbine Array Generation Systems," *IEEE Trans. on Energy Conversion*, vol. 38, no. 2, pp. 1325-1337, 2023.

[8] P. Li and Y. Cao, "Fault-Tolerance MPPT Design and Analysis for Hydrokinetic Turbine Systems," in *Proc. IEEE Energy Conversion Congress and Expo (ECCE)*, 2023.

[9] A. Thurlbeck\* and Y. Cao, "Machine Learning based Condition Monitoring for SiC MOSFETs in Hydrokinetic Turbine Systems," in *Proc. IEEE Energy Conversion Congress and Expo (ECCE)*, 2022.

*Subtask 3.7.0 Reliability Modeling, Health Monitoring, and Predictive Maintenance*

This subtask seeks to develop novel methods to lengthen WEC/CEC service time and to reduce maintenance/repair visits, focusing on power electronics (PE) based drivetrains. In the first half of the project, we will use multiphysics (electro-mechanical-thermal-hydro) models to predict the power semiconductor device and PE circuit stress under a mission-profile-based long-duration cycle. We then use rainflow counting and Markov chain methods to estimate the degradation and lifetime. In the second half of the project, significant effort will be focused on building a lab-scale AC-DC-AC converter hardware prototype for WEC applications. The hardware will generate testing data that will train the model to evaluate the system's state of health and further allow a model predictive controller to intelligently adapt to environmental conditions for power generation curtailment or to signal upcoming maintenance.

**Milestone 3.7.1** M12: Power electronics multi-physics reliability model developed and validated in simulation with historic data.

**Milestone 3.7.2** M24: Power electronics health monitoring tool designed and validated in simulation against data sheets or literature data.

**Milestone 3.7.3** M36: Control algorithm developed and validated in simulation and hardware-in-the-loop for steady-state and dynamic responses.

**Milestone 3.7.4** M48: Lab-scale AC-DC-AC converter built and used to validate the model and controller.

**Deliverable 3.7.1** M24: Release of open-source reliability model for WEC power electronics with lifetime prediction.

**Deliverable 3.7.2** M48: Demonstration of power electronics hardware with improved controller. Report documenting the testing results and data.