Subtask 4.4 SBU Smart Mobile Grids and Power Conversion:

D 4.4.2 Instruction manual and report on operation and maintenance strategy

Contents

Atlantic Marine Energy Center

Continuing Application for Budget Period 2

[D 4.4.2]

Summary

This report provides a summary of the methods used to develop and validate software models for marine energy conversion systems. Step-by-step instructions using flowcharts and examples are also provided to help the users to run and validate the simulation models in real time. The report involves three key components: modeling, optimization, and hardware-in-the-loop (HIL) validation of Tidal Energy Conversion System (TECS), operational procedure and updating /maintenance of developed software platform.

The first phase involves optimizing the design and operation of the power converter devices for marine renewable energy sources. Optimization techniques employed to identify the most efficient power converter devices and architectures with the goal of maximizing power output and minimizing costs. These converter models serve as the foundation for subsequent energy conversion system. The second phase focuses on creating accurate and comprehensive models of tidal energy conversion systems, considering various parameters such as tidal patterns, turbine characteristics, and environmental factors.

The final phase validates the optimized system through HIL simulation. HIL validation enables real-time testing and evaluation of the system's performance under various operating conditions. It provides a reliable and cost-effective way to verify the effectiveness of the optimized design before implementing it in real-world settings. By combining modeling, optimization, and HIL validation, this project aims to pave the way towards achieving optimal tidal energy conversion systems. The outcomes of this research will contribute to the development of more efficient and economically viable solutions for harnessing tidal energy, supporting the transition towards sustainable and renewable sources of electricity generation.

[D 4.4.2]

1. Model Based Optimization (MBO) Algorithm

1.1 Motivation

- Growing demand for clean and sustainable energy sources, driving the need for efficient power conversion systems in marine renewable applications.
- Marine renewable technologies, such as tidal and wave energy, hold significant potential, but efficient power electronics converters are crucial for effective energy conversion.
- Existing challenges in marine renewable power electronics converters include maximizing power extraction efficiency, adapting to variable operating conditions, addressing the harsh marine environment, ensuring system reliability, and optimizing cost-effectiveness.
- Model-based optimization techniques offer a promising solution by leveraging accurate and dynamic models of power electronics converters.
- By utilizing optimization algorithms with these models, we can explore and identify optimal converter designs, control strategies, and operational parameters, leading to higher conversion efficiencies, improved power quality, increased system reliability, and reduced maintenance costs.
- Advancements in power electronics converters for marine renewable applications will contribute to unlocking the full potential of marine energy resources and accelerating the transition to a more sustainable and environmentally friendly energy future.

1.2 Model Based Optimization (MBO) operational Flow Chart

General block diagram of power converter with different elements is given in Fig.1. Optimization of the performance of these elements is the key behind the model-based optimization algorithms. Flowchart in fig. 2 gives the step-by-step method used in developing the Model Based Optimization algorithm. MBO begins with selection of appropriate switching devices, leading to comparison amongst candidate topologies and optimization of the device combination. Towards the end, the impact of passive components and thermal considerations on volume and power density of the entire system is included. The process gets finished by offering the optimal switching frequency, number and type of devices required, and combination of the filter components.

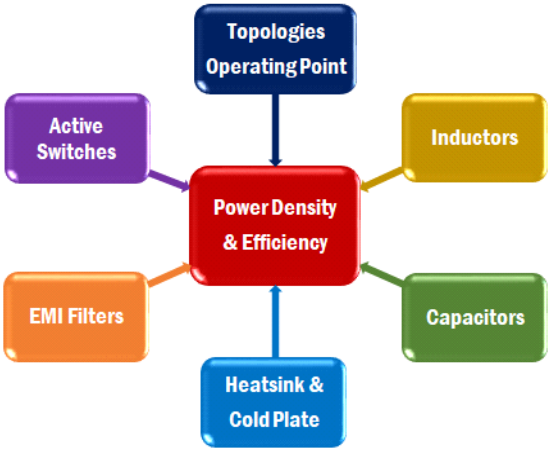


Fig 1. General Block Diagram of an Inverter

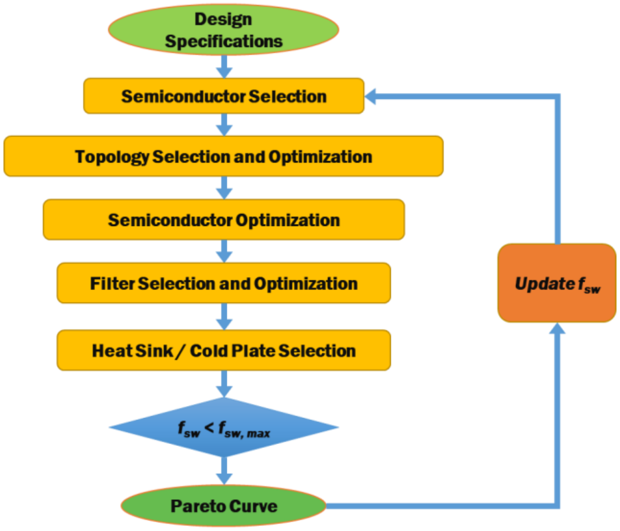


Fig.2 Model Based Optimization (MBO) Flow Chart

1.2.1 Selection of semiconductor devices

One of the critical aspects in the design of a converter is appropriate device selection. It requires a device to be capable of handling the rated current and blocking the rated voltage. The loss model essentially comprises of two major types of losses: conduction and switching losses, which can be modelled from datasheet provided by manufacturer.

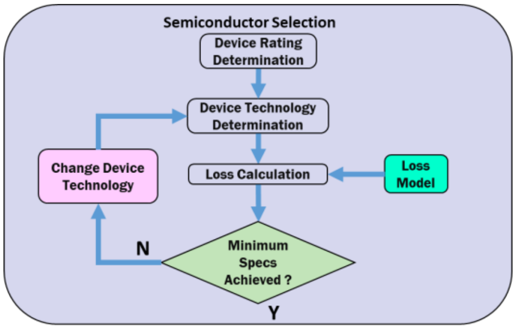
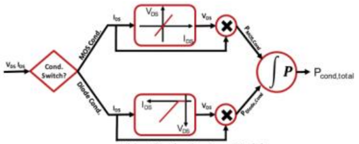
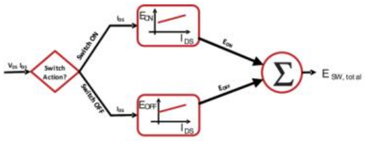


Fig 3. Flowchart for device selection



(a) Conduction Loss Model



(b) Switching Loss Model

Fig 4. Loss model of device

1.2.2 Topology Selection

In the design of any power electronics converter, the most important and integral part is the choice of converter topology. Converter topology not only influences the input output voltage relation and efficiency, but also the spectrum of output voltage and current and hence the output filter size, leading to lower or higher volume, and better or poor specific power density accordingly. Fig. 5 gives a detailed flowchart for topology selection and optimization.

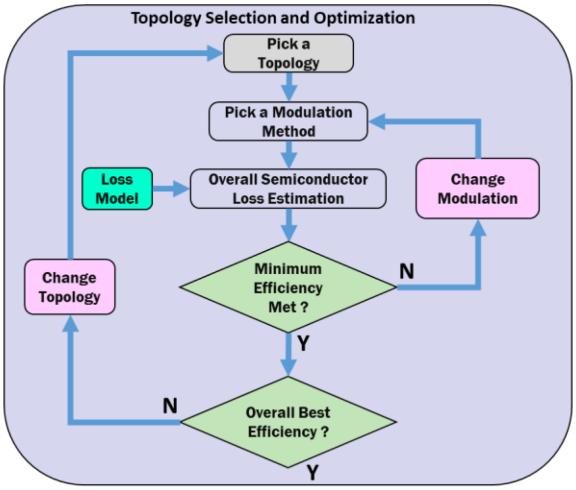


Fig 5. Flowchart for Topology selection and optimization

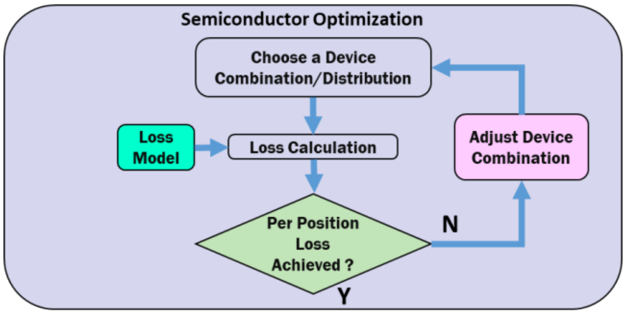


Fig 6. Flowchart for Topology selection and optimization

1.2.3 Semiconductor Optimization

Having selected device type and topology, an important aspect in converter design is finding the most suitable combination of paralleling of devices (Fig.6). Paralleling of devices of different types e.g., IGBTs and MOSFETs and similar types e.g., all SiC has been reported in literatures. Finding their optimal combination not only affects the gate driving capability but can also influence the overall semiconductor efficiency. Although paralleling more devices may offer reduction in conduction losses, switching losses may increase and lower the overall efficiency.

1.2.4 Filter Size Determination and Optimization

Since 30 % of the volume of any converter is occupied by passive filter components, comprising inductors and capacitors, it is important to have an appropriate estimate of their magnitude, power loss and volume. An estimate about input direct current (DC) link capacitors based upon ripple current can be made from, however actual values may be limited by the current rating. Similarly output filter inductors can also be estimated.

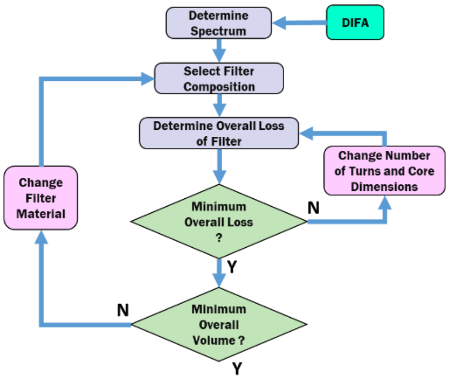


Fig 7. Flowchart for filter sizing and optimization.

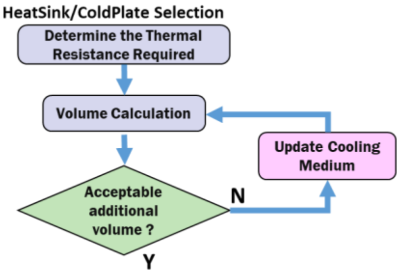


Fig 8. Flowchart for Heatsink/Cold plate selection.

1.2.5 Step 5 Cold Plate Selection: To have all the active devices operate below the maximum junction temperature Tjunc, heat generated is removed through a heatsink or a cold plate. A typical thermal equivalent circuit for a cold plate and heat source comprises of numerous elements having non-zero thermal resistance. Fig. 8 details the flowchart for heatsink/coldplate selection.

1.2.6 Pareto Curve As per the flow chart, an efficient converter is selected for further optimization and a pareto curve was obtained including the weight, and efficiency of components defined in the flow chart.

1.3 Results: Different converter topologies are simulated, and comparative result analysis is given in fig. 10.

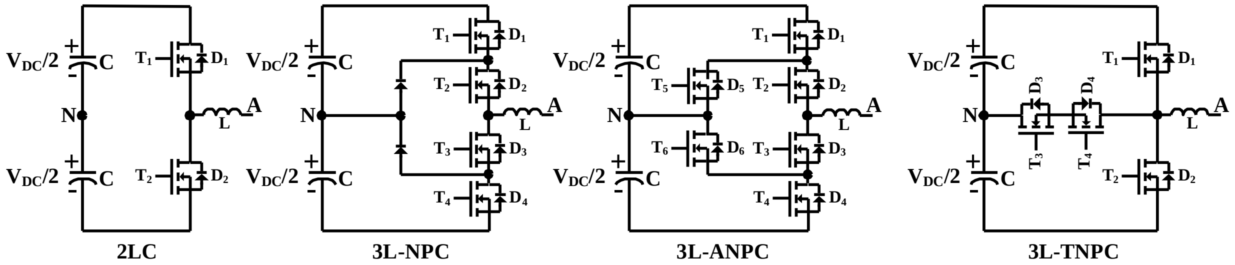


Fig 9. Candidate converter topologies

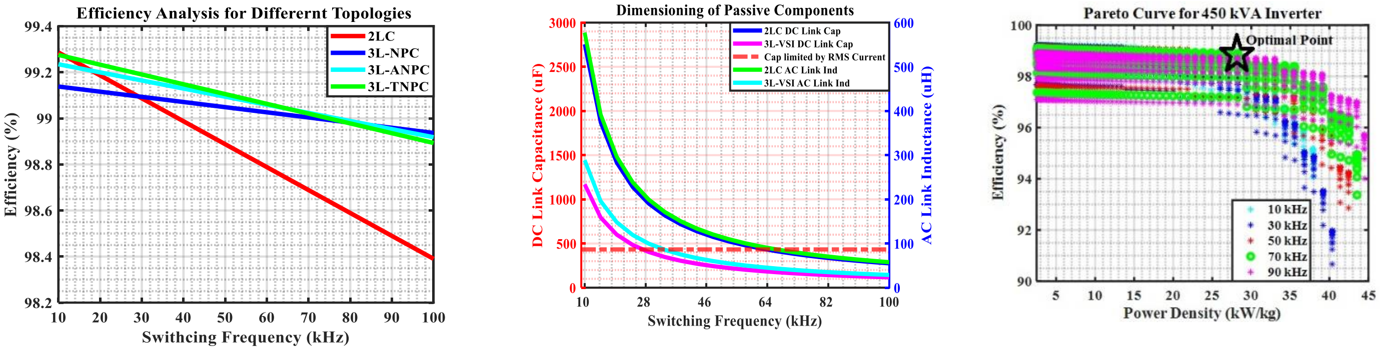
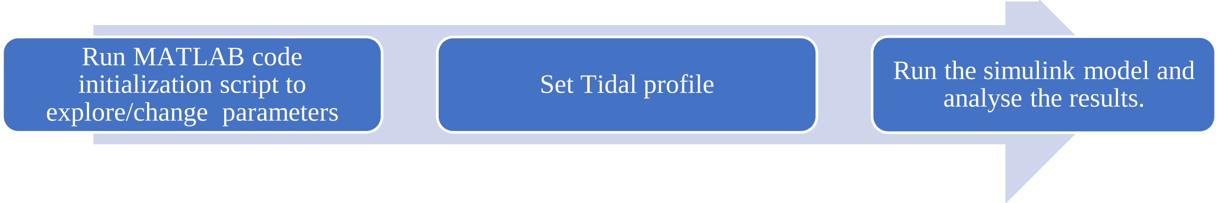


Fig 9. Simulation results

2. MATLAB/ Simulink based benchmark models for Tidal Energy Conversion System (TECS).

MATLAB/ Simulink based model of direct drive PMSG tidal turbine model is developed to investigate various aspects and challenges in developing scalable modular framework for high-performance power electronics converter design/optimization in MRE applications. The Simulink model is validated for both constant and variable tidal speed to understand the impact of variability and intermittency of tidal energy systems.

Flowchart for running MATLAB/Simulink based models.


Run MATLAB code initialization script to explore/change parameters

Set Tidal profile

Run the simulink model and analyse the results.

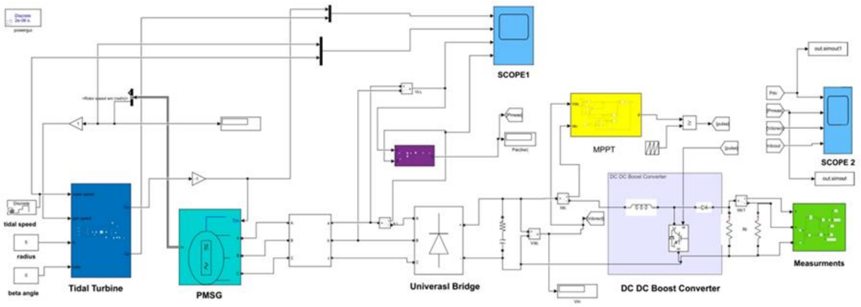


Fig 10. Simulink Model of PMSG based variable speed Direct Drive TECS

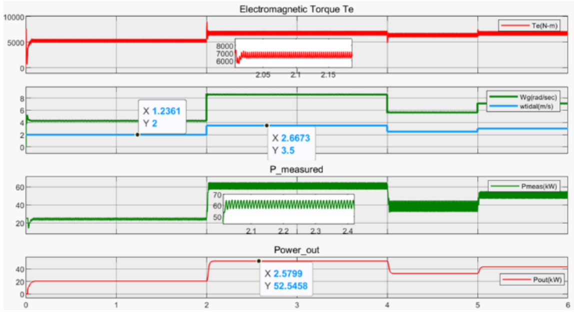
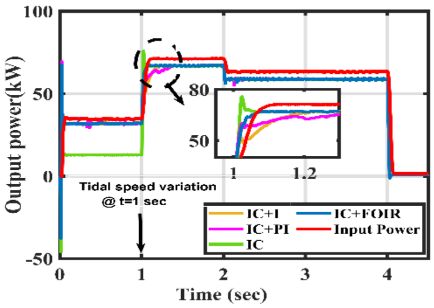


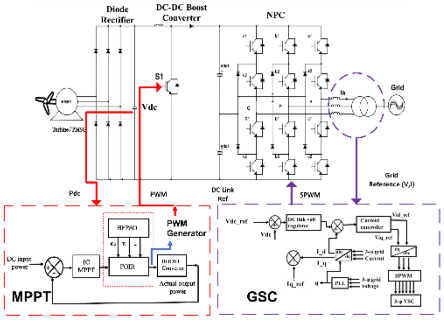
Figure 11. Simulation Results

2.1 Upgrading MATLAB/ Simulink based benchmark models for tidal energy conversion system.

2.1.1 Grid tied TECS: Tidal Energy Conversion Systems (TECS) are Highly non-linear and working in complex and fast varying oceanic environment. Hence, it requires advanced control algorithms to clinch efficient integration of TECS. Hence,

- ❖ Incremental Conductance based MPPT algorithm with Fractional Order Integral Regulator (FOIR) is developed.
- ❖ FOMCON toolbox is used to integrate FOIR.
- ❖ Parameters of FOIR (*KP*, *KI* and λ) are optimized using the hybrid of Bacterial Foraging and Particle Swarm Optimization (BFPSO).
- ❖ The grid side controller is a PLL based double loop control.





2.1.2 Simulation of Multiturbine Multi-converter tidal microgrid.

- ➢ Modeling of droop control-based grid forming inverter for islanded operation of tidal microgrid.
- ➢ Simulation based comparison of different power converter architectures.

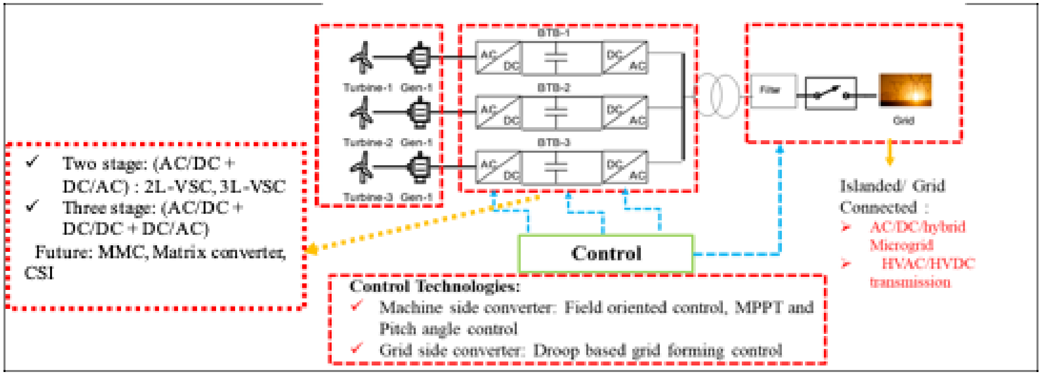


Fig 12. Simulink model for multiturbine multi-converter based tidal microgrid to study the impact of different dynamics on islanded and grid tied mode.

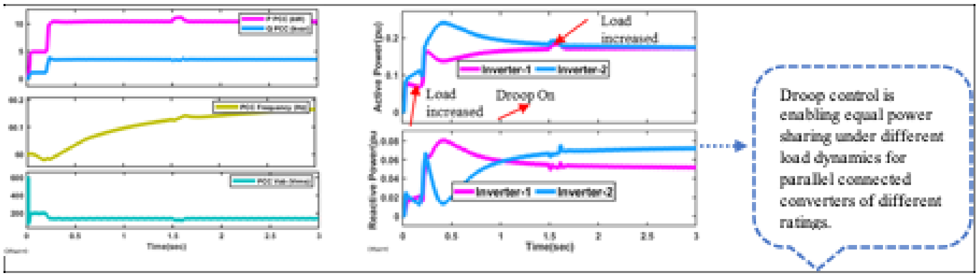
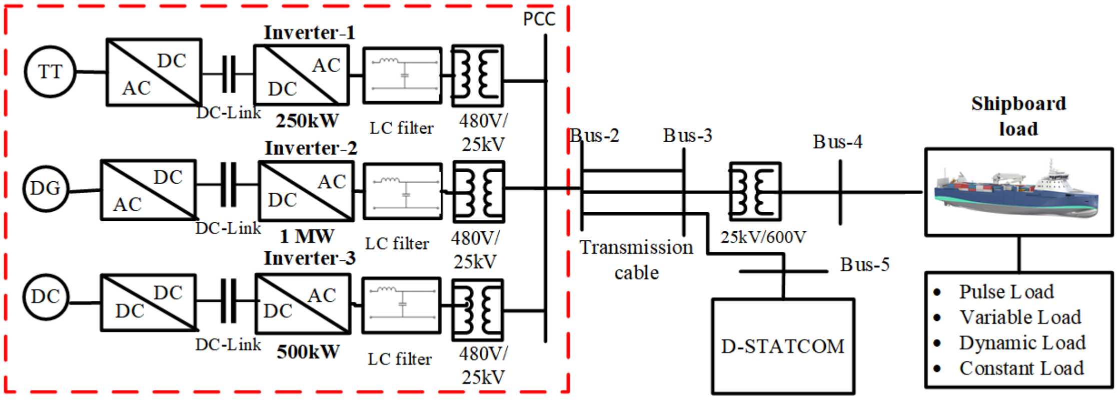
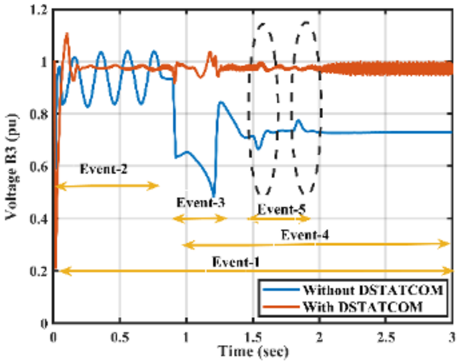


Fig13. Simulation results for droop controlled multiturbine multi-converter based tidal microgrid under different load dynamics.

2.1.3 Integration of Distribution Static Synchronous Compensator (D-STATCOM)

To enhance the dynamic voltage stability and resiliency of tidal energy-based system under different load dynamics D-STATCOM is integrated in tidal energy integrated hybrid seaport microgrid.



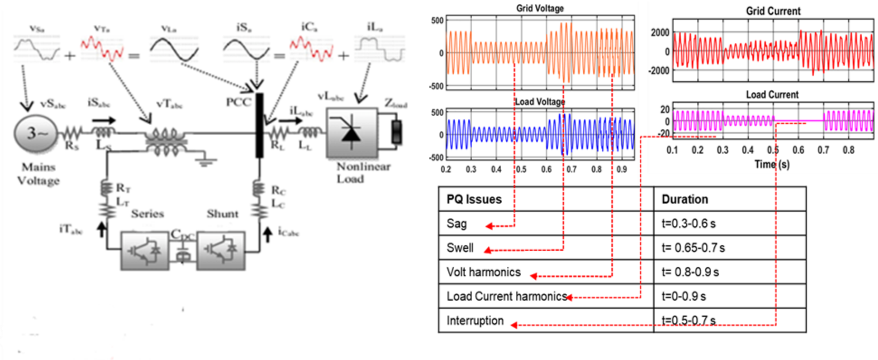


Events	Loading conditions
Event 1	Constant Z load on
Event 2	Variable load on
Event 3	Pulse load on
Event 4	Dynamic load on
Event 5	Variation in tidal speed

Fig 14. Simulation results for D-STATCOM integrated tidal energy conversion system under different dynamics.

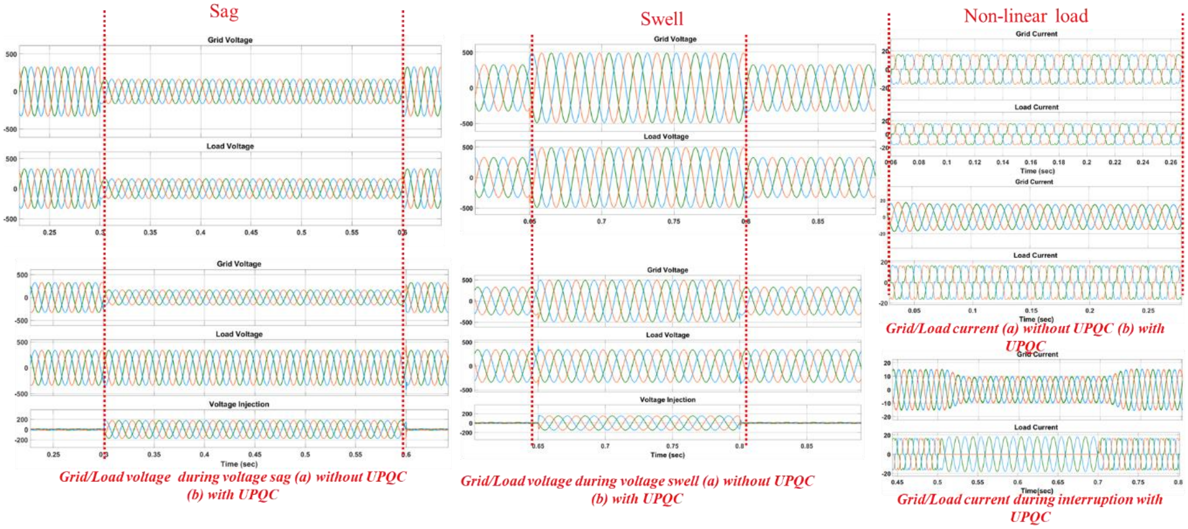
2.2 Assessing PQ issues and mitigation strategies

- Simulations to evaluate Power Quality issues for tidal integrated distributed network under different source/load dynamics.
- Comparative analysis of different compensating Custom Power Devices (CPDs).



PQ Issues	Duration
Sag	t=0.3-0.6 s
Swell	t= 0.65-0.7 s
Volt harmonics	t= 0.8-0.9 s
Load Current harmonics	t=0-0.9 s
Interruption	t=0.5-0.7 s

Fig15. Functional block diagram of hybrid compensating device (UPQC) and major PQ issues in MRE based power plants.



Grid/Load voltage during voltage sag (a) without UPQC (b) with UPQC

Grid/Load voltage during voltage swell (a) without UPQC (b) with UPQC

Grid/Load current (a) without UPQC (b) with UPQC

Grid/Load current during interruption with UPQC

Fig 16. Simulation results analyzing the impact of UPQC under different PQ issues.

3 Development of Hardware-in-the Loop testbed

A Control Hardware-in-the-Loop (CHIL) validation testbed is a system that combines real-time control hardware with a simulation environment to validate and verify the performance of control algorithms and systems. It serves as a powerful tool for testing and evaluating the effectiveness and robustness of control strategies before implementation in real-world applications.

3.1 **Motivation**

The motivation behind developing a CHIL validation testbed lies in the following factors:

1. Realistic Evaluation: The integration of physical control hardware with a simulation environment allows for realistic evaluation of control algorithms and systems. It provides a more accurate representation of the actual operational conditions, enabling comprehensive testing and validation.
2. Risk Mitigation: By using a CHIL testbed, potential risks and issues associated with control strategies can be identified and addressed before deployment in real world applications. This approach helps mitigate risks, improves system performance, and reduces the likelihood of costly failures or safety hazards.
3. Cost and Time Efficiency: Conducting experiments and tests in a controlled and repeatable virtual environment saves significant time and costs compared to conducting physical tests on the real system. The ability to simulate various scenarios and system conditions accelerates the development and optimization of control algorithms.
4. Hardware Integration: The integration of real-time control hardware, such as microcontrollers or programmable logic controllers (PLCs), allows for seamless testing and validation of control strategies that interact with physical components. It ensures that the control algorithms can effectively interface with the hardware and respond accurately to system dynamics.
5. Flexibility and Scalability: A CHIL testbed provides flexibility to modify and fine tune control parameters, algorithms, and system configurations rapidly. It also offers scalability, allowing for the testing of different control strategies and hardware setups to optimize performance and achieve desired system behavior.

3.2 Typhoon-HIL 402: Typhoon-HIL 402 is a real time simulator This compact, extremely powerful, 4-core HIL gives all the tools need to test power electronics controllers in a wide range of applications: solar and wind power generation, battery storage, power quality and motor drives. Controllers can be run in a closed loop with the high-fidelity power stage in real time, with a 1MHz update rate and an ultra-high PWM resolution of 6ns [2].

3.3 Hardware-in-the Loop testbed

To accomplish the intended project goals outlined in BP1 and to meet the milestones and deliverables HIL based testbed platform is developed to validate the developed control and power architectures [Fig 17].

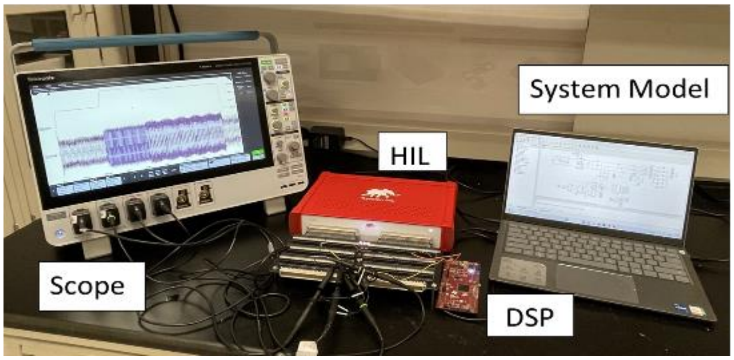


Fig 17. HIL based testbed to validate different control algorithms.

3.4 Interfacing with troubleshooting: For concept validation, we developed direct drive PMSG based tidal energy conversion system with MPPT and PID based output voltage controller using Control Hardware-in-loop (CHIL). The validation of simulations and parameter tuning for the PI control were conducted in HIL using the built-in signal processing blocks. In this case, the Typhoon HIL 402 device was utilized. C code is developed for the Simulink models including controller.

However, in order to implement CHIL and import the C code onto a DSP, a custom API needed to be constructed. Since the control algorithm is a direct translation of the block diagram, certain input values such as the output voltage data (Vout) of the boost converter and the reference voltage data (Vref) were lacking. To address this, a TI F28379D DSP was employed for concept validation, equipped with four onboard analog-to-digital converters (ADCs). One of these ADCs was dedicated to sampling Vout from the HIL device. The ADC's sampling rate was set to match the switching frequency at 20kHz.

It's worth noting that the HIL device is limited to outputting a voltage range of +20 to -20 V, while the ADC can only sample voltages within the range of 0 to +3V. For applications involving high voltages like the boost converter, Vout had to be scaled down on the HIL device to a value below 3V. After sampling, the DSP then applied a consistent multiplier to scale up the voltage, ensuring data integrity throughout the process. To accommodate the dynamically changing Vref, an UART communication channel was established utilizing the DSP's onboard FTDI chip. This allowed for seamless communication between the Typhoon HIL control panel (SCADA) and the DSP.

The SCADA incorporates a built-in feature that enables serial communication ports and facilitates bidirectional data transmission with the DSP using PySerial. Once the communication link was established successfully, the SCADA can change Vref data via widgets and send it to the DSP.

In order to minimize any interference with the control loop, the baud rate for communication was set at 3.125Mbps. However, it should be noted that the SCADA sends numeric values as ASCII characters, which are not recognized by the control loop as proper input values. To resolve this issue, a specific function was developed in C as part of the DSP's communication loop. This function effectively translates any incoming numeric ASCII characters into their corresponding integer representations, ensuring compatibility and accurate data processing within the DSP.

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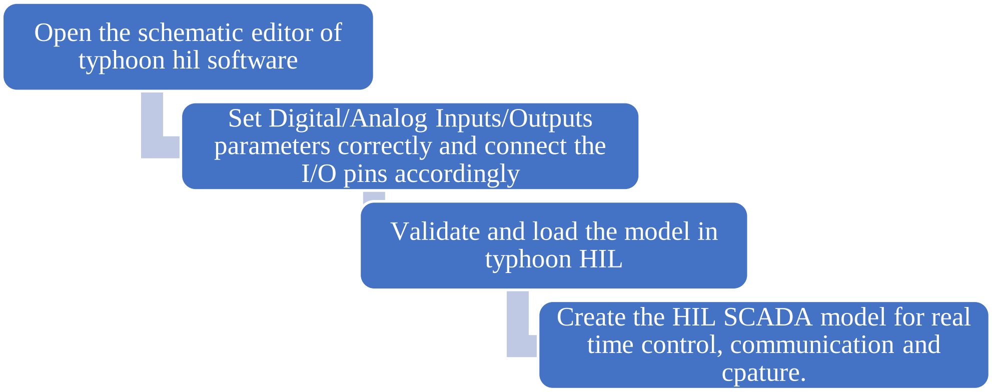
Flowchart for real time validation of Simulink models.



3.5 Validation Results:

3.5.1 Tidal energy conversion system with output voltage control: Output voltage regulation of a boost converter using a PID (Proportional-Integral-Derivative) controller is an effective method to achieve precise control over the output voltage. Fig. 18 shows the developed TECS schematic in typhoon HIL. The PID controller continuously monitors and adjusts the control signal to maintain the desired output voltage despite variations in load or input conditions, as evident from Fig. 19. By analyzing the error between the desired and actual output voltage, the PID controller dynamically adjusts the duty cycle of the boost converter to regulate the output voltage. This control technique ensures stable and accurate voltage regulation, enabling optimal performance and reliable operation of the boost converter in various applications.

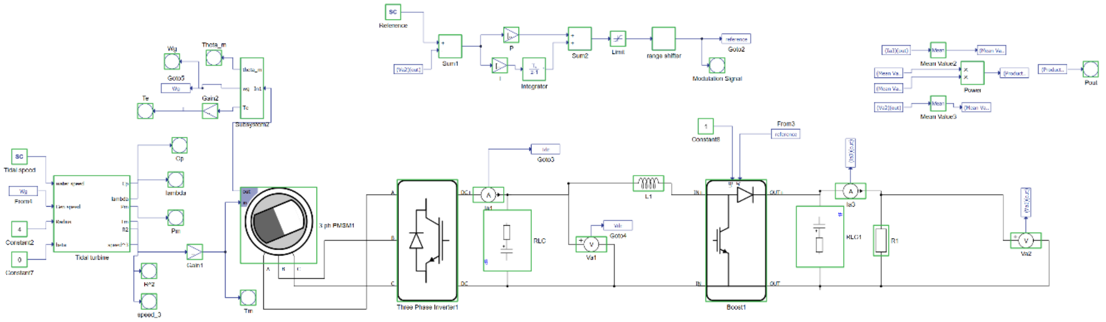


Fig 18. Schematic of TECS.

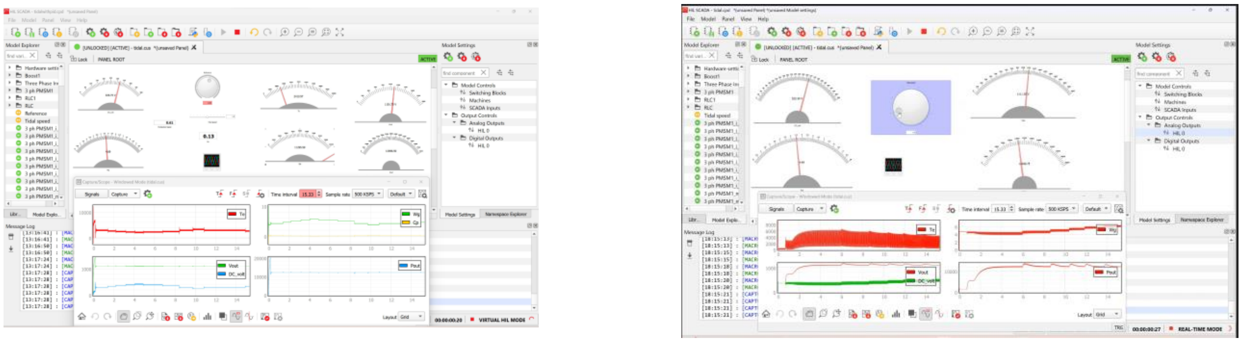


Fig 19. Results of simulation (Left) and real time validation (Right) of Voltage control.

3.5.2 Tidal energy conversion system with MPPT control

The tidal energy conversion system with Perturb and Observe (P&O) MPPT control is designed to maximize power extraction from tidal energy sources. By employing the P&O algorithm, the control system continuously adjusts the operating parameters of tidal turbines to track and maintain the maximum power point (MPP) of the energy resource. Fig. 20 shows the TECS interfaced with load using boost converter. The tidal speed varies between 0.5m/s to 3 m/s to validate the control performance. It is evident from both simulation and real time validation results that the MPPT controller ensures optimal power generation and efficiency in varying tidal conditions (Fig. 21). The P&O MPPT control enables the system to adapt to the changing characteristics of tides, resulting in improved energy conversion and increased overall performance. With its ability to optimize power extraction, the tidal energy conversion system with P&O MPPT control plays a crucial role in harnessing the renewable energy potential of tides for sustainable electricity generation.

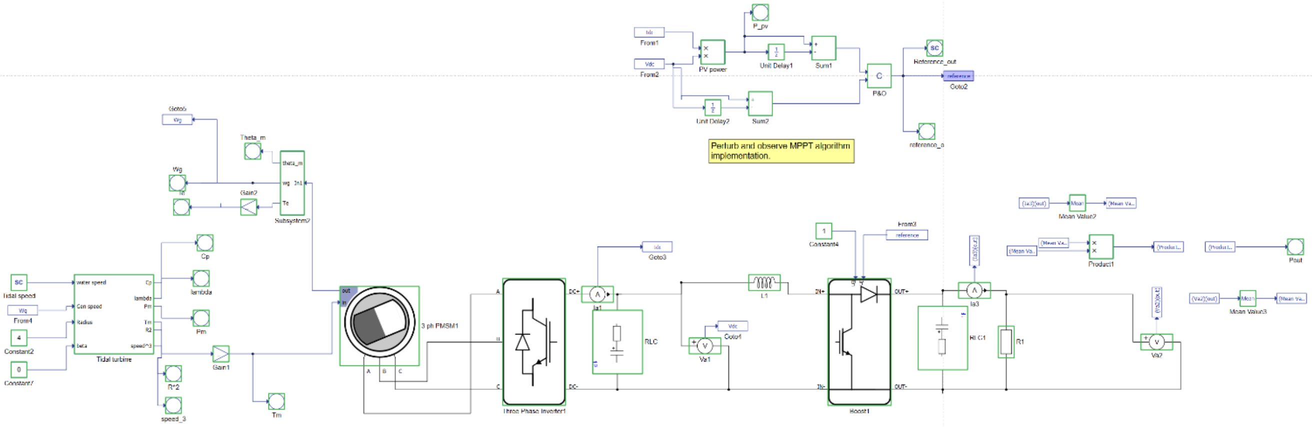


Fig 20. Schematic of TECS with MPPT control

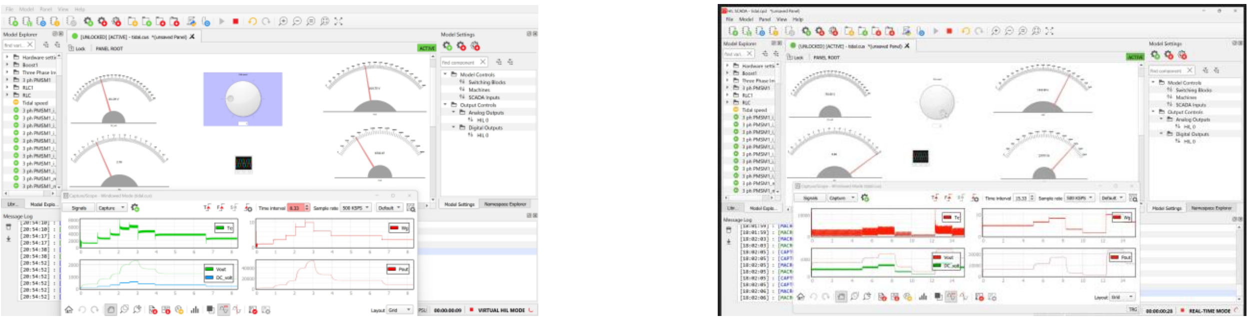


Fig 21. Results of simulation (Left) and real time validation (Right) of MPPT control.

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4. Hardware Validation results

Hardware validation of DC-DC-AC power converter Simulink model using SYNDEM converter kit and RS485 communication.

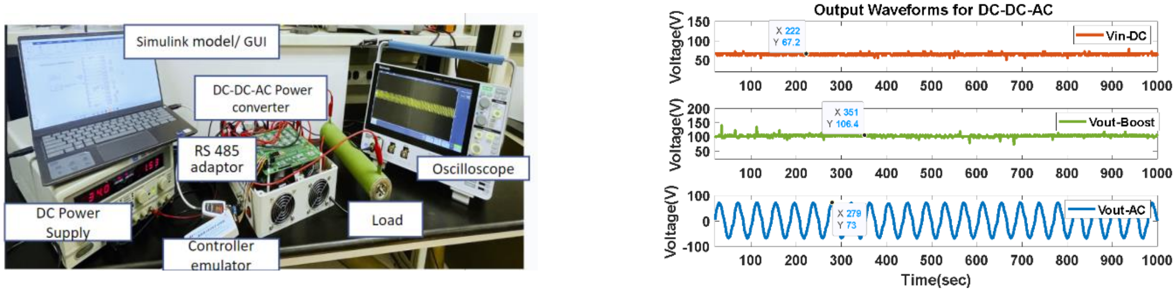

Fig 22. Hardware testbed platform (Left) and validation result of DC-DC-AC toplogy (Right) .

5. Maintenance/ Updating Software Platform

MATLAB/Simulink/ HIL based models and codes have been posted on PRIMRE. However, editing of data submissions by users is only allowed during submission and curation on PRIMRE. Additionally, once a submission has been published, any changes require republication. To make the updating procedure easy a GitHuB link is added on PRIMRE.

References:

[1] Mustafeez-ul-Hassan, Z. Yuan, A. I. Emon and F. Luo, "A Framework for High Density Converter Electrical-Thermal-Mechanical Co-design and Co-optimization for MEA Application," *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, Vancouver, BC, Canada, 2021, pp. 3120-3125, doi: 10.1109/ECCE47101.2021.9595516.

[2]https://www.typhoonhil.com/products/hil402/#:~:text=This%20compact%2C%20extremely%20powerful%2C%204,power%20quality%20and%20motor%20drives.