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# A Systems Integration Approach to an Instrumented Tidal Energy Converter within an Open-Source Testbed

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**Abstract**—*System integration involves the combination of various subsystems, assemblies, sub-assemblies, components, and parts into a unified, cohesive system. Herein, we detail the system hierarchy, workflow and tasks to integrate and test subsystems, assemblies, subassemblies and components of an Open-Source Tidal Energy Converter (OSTEC) system, which includes rotor, blades, power takeoff, turbine yaw mechanism subassemblies as well as the data acquisition subsystem and turbine deployment platform. The turbine system includes a nacelle, a 2.5 m diameter rotor with hub and blades, motor/generator, gearbox, tower with a yaw drive, many sensors, and power/data cables. The turbine system integration is a critical task prior to subsystems testing and deployment. Blades are machined, equipped with sensors, and calibrated before assembly. Motor control and instrumentation is integrated into a custom data management strategy and acquisition system. The OSTEC testbed will undergo several stages of system verification and dry testing prior to being integrated onto the floating open water deployment platform for long term testing at the AMEC-UNH Tidal Energy Test Site. With the system integration, the goal is to provide a unified system that comprises different subsystems, assemblies and subassemblies that can provide data on inflow conditions, power performance, mechanical loads, and health monitoring of the overall system. This work will provide an update on the OSTEC system integration.*

**Keywords**—**System Integration; Marine Hydrokinetic Turbine; Tidal Energy; Renewable Energy; Research & Developments.**

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## I. INTRODUCTION

Tidal currents, known for their predictability, reliability, and higher energy density than wind, represent a largely untapped renewable energy source that can be captured using tidal energy converters (TECs). Among these, tidal turbines have experienced notable advancements in recent years, driven by extensive research and development efforts focused on design improvements, prototype testing at both lab and full scale, and real-world implementations.

The Open-Source Tidal Energy Converter (OSTEC), developed collaboratively by Atlantic Marine Energy Center at the University of New Hampshire (AMEC-UNH), Sandia National Laboratories (SNL), the National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL), serves as a versatile testbed for open-source research and development (R&D) in various aspects of tidal energy technology. With a 2.5-meter rotor and 26kW rated power, this axial flow tidal turbine will produce open-source data on recommended best practices given in international standards, including the International Electrotechnical Commission's (IEC) technical specification on design of marine energy systems (IEC TS 62600-2), mechanical load measurements (IEC TS 62600-3), power performance assessment (IEC TS 62600-200), tidal resource characterization and assessment (IEC TS 62600-201), and scale testing of tidal energy converters (IEC TS 62600-202) as well as enabling comprehensive model verification and validation [1] for digital twinning and numerical models. Fig. 1 illustrates the measurements capabilities of the OSTEC turbine.

Many studies in this field primarily focus on the design and deployment [2] of tidal energy converters (TECs), resource assessment [3], resource forecasting [4,5], often addressing the overall test results or design considerations of the proposed devices and concepts aiming to help this field to evolve toward commercialization. However, the system integration of TECs as first-of-kind devices are not properly addressed leaving uncertainties to the engineers and researchers. Effective system integration, which is the process of combining and coordinating a turbine's components, parts, subassemblies, and assemblies, is a crucial phase for creating a functional and operable system [6]. Often the studies conducted on system integration of TECs and wind turbines address the integration of a system to another system like a utility scale turbine to a grid.

However, this paper provides a comprehensive framework for the system integration of an instrumented

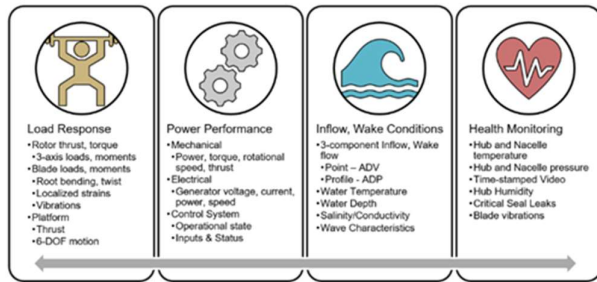


Fig. 1. Measurement purposes & list of sensors of the OSTE C testbed [1,10].

Tidal Energy Converter (TEC), specifically focusing on the OSTE C Testbed as a case study. It presents a structured approach to the development process, from design to deployment, offering a clearer understanding of TEC integration as a cohesive subsystem. The paper details the hierarchical integration of various subsystems, assemblies, and components, outlining the testing, operation, and pre-deployment preparations. By systematically organizing these processes, the authors aim to offer a methodological guide to streamline the integration of tidal turbine subsystems.

II. WHAT IS SYSTEM INTEGRATION

One of the most frequently used yet often overlooked concepts in the application of systems engineering in industry is integration. Much like the word “system,” “integration” carries multiple meanings and can be misunderstood. Therefore, it is carefully defined herein. Further, its importance in the development of marine turbine systems is demonstrated.

At its core, integration represents the final stage of a structured process that begins with breaking down intricate problems into smaller, interconnected challenges. These challenges are then addressed by specialized teams, and their solutions are ultimately synthesized into a cohesive resolution to the original problem. System integration is both an art and a science—it serves as the intellectual and technical marketplace where individual solutions converge into a unified system. As a crucial element of the systems engineering process, integration ensures that product components and process elements function harmoniously. It guarantees that hardware, software, and human-system interactions align to fulfil the system’s intended purpose or meet customer requirements. This coordination is fundamental to what some refer to as concurrent development.

The systems engineering approach begins by translating customer needs into specific functions that the system must perform. These functional requirements are further decomposed and allocated to distinct components within the system [6]. Once assigned, they are transformed into performance specifications and combined with design constraints, forming a comprehensive set of minimum design attributes—requirements that must be met for the component to seamlessly integrate into the overall system.

A team of engineers synthesizes these requirements into one or more design concepts. If multiple concepts are proposed, they are systematically evaluated through trade-off analyses to determine the optimal solution. The selected design is then refined into preliminary and detailed designs, interspersed with periodic reviews to ensure alignment across teams and adherence to technical and functional objectives.

Specialists from various disciplines collaborate with the principal designers, ensuring that all specialty

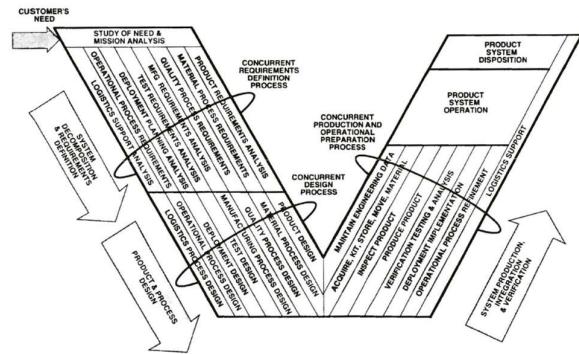


Fig. 2. The “V” model of system development [6]

requirements—which the core design team may not be fully acquainted with—are properly accounted for. Once finalized, designs transition into manufacturing planning and procurement, leading to production and sourcing activities. Prototype or test versions of the product components undergo rigorous evaluation to verify their performance and qualify them for implementation in the final system solution.

Numerous models exist to represent the system development process, but the authors find that the “V” model—depicted in Fig. 2—effectively captures the essence of TEC system integration. Representing such a multi-dimensional process in a two-dimensional format poses challenges, particularly given the hierarchical nature of the system [7]. As the process moves top-down, it involves repeating similar steps over time. This repetition unfolds in an expanding pattern during the phases of decomposition and definition, and in a contracting pattern during integration and verification. The interplay between these cyclical actions and the linear progression of time adds complexity to clearly visualizing the process.

III. WHY SYSTEM INTEGRATION IS NECESSARY

A. The Role of System Integration in the Design Process

The seeds of system integration begin to take root during the design phase, where engineers synthesize project requirements into one or more design concepts. At this stage, trade-off analyses are conducted to determine the optimal solution. The initial impact of system integration becomes evident during the preliminary and detailed design phases, as various critical aspects—such as feasibility, operability, equipment requirements, and other key integration factors—come into play.

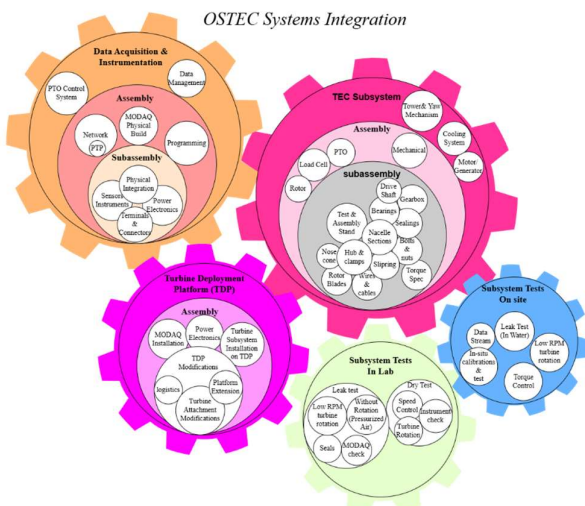


Fig. 3. Schematic of system integration for OSTEC testbed

While it may seem straightforward, one cannot simply assume a design is flawless, build the full system, and deploy it in the water. Prototype designs often diverge from the initial design intent due to unforeseen practical challenges. Such changes require design adjustments, thorough checks, and verification steps to ensure the system remains functional and well-integrated. Even in cases where no design changes occur, verification is crucial to confirm that subcomponents, assemblies, and subsystems fit together seamlessly and perform their intended functions.

#### B. Challenges in System Integration

One of the key challenges in system integration is the inherent difficulty of testing every aspect of the system before field deployment. While extensive checks are performed to mitigate risks within practical and economic constraints, full validation ultimately requires real-world operation.

A prime example of this challenge is the planned testing of the OSTEC turbine's Power Take-Off (PTO) subsystem under both speed and torque control. While speed control can be effectively tested in a laboratory setting during the system integration process, torque control presents a significant limitation. Since the turbine must be subjected to actual load conditions for proper torque control assessment, conducting such tests in the lab poses a high risk of damaging the PTO and drivetrain. In theory, a dynamometer could enable torque control testing under controlled conditions; however, due to budget limitations and the project timeline, the OSTEC team is unable to incorporate this facility.

This limitation highlights the critical need to consider feasibility and equipment availability during the design phase. Proper planning for system integration should account for potential constraints, ensuring that the necessary infrastructure and resources are available to validate key operational parameters before full-scale deployment.

## IV. SYSTEM INTEGRATION OF THE OSTEC

### A. Definition for OSTEC turbine

With the definition of general system integration established, we can now extend this concept to the application of a TEC. In this context, TEC is considered a system that, when incorporated with other systems—such as the deployment platform or grid—forms a fully functional device. This integration involves the seamless combination of software, hardware, and data systems to facilitate efficient collaboration and information exchange.

Over the years, significant research and development efforts have been dedicated to advancing TEC to a commercial stage. Achieving this requires an industrial framework that enables TECs to transition into mass production. However, this is only possible through extensive research and prototype development of this complex subsystem. The OSTEC turbine serves as a prime example of a research turbine whose system integration provides the critical insights needed for scaling TECs to commercial viability.

Building on the definition of system integration outlined in the previous section, the primary industry demand here is for a detailed understanding of the integration and assembly processes required to develop TECs capable of generating renewable energy to meet high energy demands. During the system integration phase, the TEC subsystem undergoes structured decomposition into various subsystems, assemblies, sub-assemblies, components, and individual parts, which collectively form a unified and cohesive (sub)system.

For the OSTEC instrumented turbine, the key objective is to systematically coordinate the testing, connection, and assembly of each component, sub-assembly, and the overall system. This ensures that every element functions correctly on its own and integrates seamlessly with others, fulfilling the intended design specifications and performance objectives.

The integration process is carefully planned to verify performance across multiple levels, ensuring both reliability and efficiency. The schematic provided in Fig. 3 illustrates the sequence and interdependencies of the testing, assembly, and system integration activities for the OSTEC turbine, emphasizing the structured approach required to achieve successful system integration.

### B. System Hierarchy

The hydrokinetic turbine subsystem [8] is divided into three main subassemblies: the nacelle [9] with its subassemblies including the powertrain and power take-off, the rotor (hub, nosecone, and blades), and the tower with a yaw drive. The assembly sequence was carefully planned during the design process [10]. The nacelle houses a permanent magnet synchronous motor/generator, a gearbox, drive shaft and bearings, a slip ring for power and data transfer to/from the hub, seals, various health monitoring sensors, and penetrations for power and data cables. The 2.5-meter diameter rotor includes a hub, three instrumented blades each measuring 1.05 meters in length, an optical

interrogator for fiber optic strain gauges, a data acquisition system, blade-hub attachments, and seals. Fig. 4. shows a cross-sectional view of the nacelle and rotor, including the hub and blades, as well as the arrangement of the nacelle components [11]. This figure also presents an overview of the turbine mechanical assembly process, which is planned to be carried out in the lab using a custom-built test and assembly stand.

### C. Project Management

Successfully navigating the system integration phase demands meticulous coordination and cross-functional collaboration. Effective project management is essential to ensure that weekly, monthly, quarterly, and annual objectives are met consistently. This phase involves key activities such as procurement of components, lead time estimation, logistics coordination, and regular scheduling of inter-team meetings.

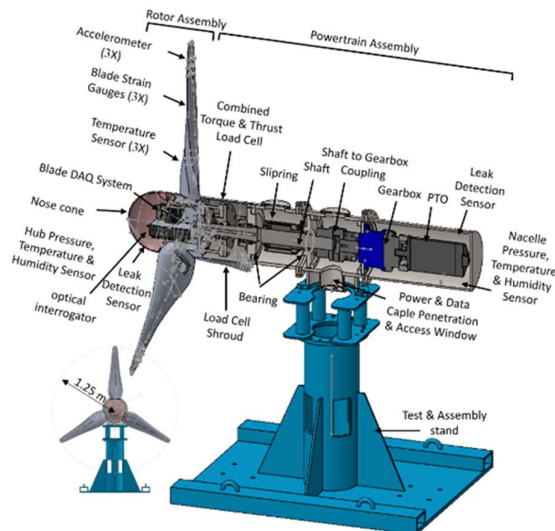


Fig. 4. System hierarchy for OSTEC testbed

In large and complex projects, tasks are often distributed across multiple teams, each with its own area of expertise. It is critical that these departments and individuals communicate effectively and meet regularly—especially when pivotal decisions require input from different domains. Such collaboration ensures that choices align with project requirements and do not conflict with other ongoing tasks or departmental goals.

Project management plays a central role in maintaining momentum by tracking completed tasks, forecasting timelines for pending work, and offering timely feedback. This ongoing oversight supports smooth progression through the integration process. Ultimately, strong project management is the backbone of successful system integration, driving timely milestone completion and ensuring alignment with the overall project vision.

### D. Mechanical integration

Mechanical integration is a critical phase in the system integration process, where finalized designs are fabricated, and components are procured. This step is especially vital for tidal turbine subsystems, as they will

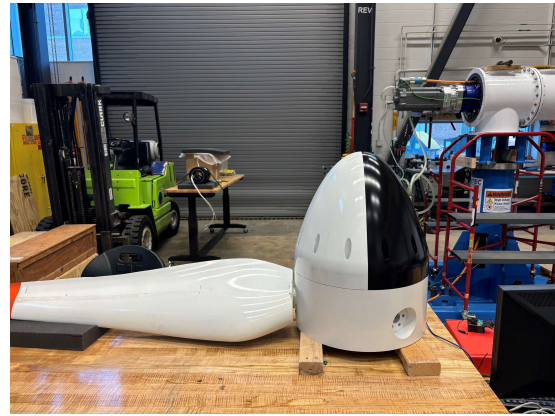


Fig. 5. In-progress OSTEC build and laboratory tests  
be submerged in water and must adhere to strict tolerances for seals and other structural elements to ensure durability and performance.

A custom-built test stand (blue structure in Fig. 4) offers a stable and efficient platform for system integration, supporting mechanical assembly,

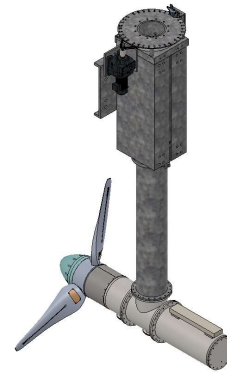


Fig. 6. Turbine, Tower and yaw mechanism for OSTEC testbed  
subassembly, component-level evaluation, and dry operational testing. It plays a critical role in maintaining the structural integrity of turbine components throughout these processes. It is important to note that the turbine will later be rotated 180 degrees for installation onto the turbine tower and yaw mechanism during deployment as depicted in Fig. 6. The test stand is used exclusively for in-lab integration, testing, and transport to the deployment site.

Moreover, drivetrain compatibility and structural considerations play a pivotal role in seamless system integration. The drivetrain—including the gearbox, shaft, and bearings as shown in Fig. 8—must be precisely aligned to minimize excessive wear and mechanical stress.

### E. Control, Instrumentation and data acquisition

One of the key objectives of this project is to deliver a comprehensive, open-source dataset across multiple categories, as outlined in Fig. 1. To accomplish this, a



Fig. 8. Drivetrain assembly and integration in the lab

suite of sensors, instruments, and devices will be integrated into the turbine subsystem to capture essential performance parameters. A custom data management strategy will be employed, centered around NREL's Modular Ocean Data Acquisition (MODAQ) system.

The MODAQ system is critical for acquiring high-fidelity performance data during both laboratory testing and operational deployment. It enables real-time monitoring, control, and in-depth analysis, all of which support system optimization. The architecture of the MODAQ-based data acquisition subsystem for the OSTEAC turbine is depicted in Fig. 7.

Originally developed by NREL [13-15], MODAQ will serve as the core data acquisition platform for the OSTEAC Testbed, with a custom implementation of the MODAQ framework, called UNH-MODAQ. In addition to data logging, the MODAQ system will monitor turbine health,

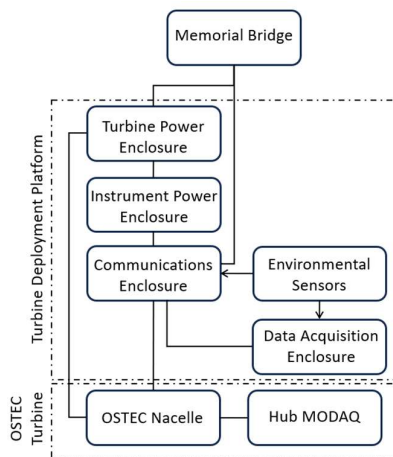


Fig. 7. System overview of the OSTEAC data acquisition system

interface with the power take-off (PTO) system for synchronized data collection and execute control functions such as turbine setpoint adjustments. Remote accessibility via VPN will enable seamless data transfer to the cloud for automated processing and analysis. A high-precision GPS receiver will support the Precision Time Protocol (PTP) network, ensuring sub-microsecond clock synchronization of all data across the entire system.

The UNH-MODAQ subsystem will also undergo full turbine system integration. This process includes the physical assembly of power electronics, followed by comprehensive functionality, operability, and integrity testing during the system integration phase. In the second phase, individual sensors and components are first verified through standalone testing and then physically integrated into the UNH-MODAQ system.

The power electronics phase involves detailed planning and execution, including the creation of technical drawings, precise measurements, alignment procedures, and provisions for future upgrades. Once component-level testing and the full system build are successfully completed, a full functionality test of the integrated DAQ system is conducted to ensure it performs as intended. Programs developed by NREL for each instrument are deployed and thoroughly validated. Subsystem integrity checks are then performed to confirm readiness for higher-level system integration.

More details of the UNH-MODAQ will be provided in a separate paper [19].

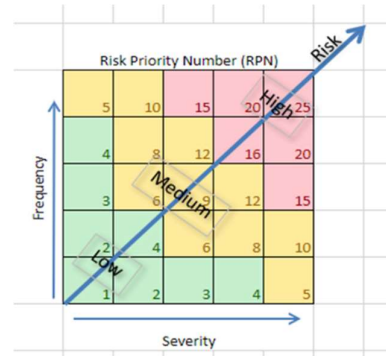


Fig. 10. Bottom-up Method for FMECA

#### F. Environmental and Operational Factors

The design and integration of the OSTEAC system were guided not only by performance metrics but also by environmental and operational resilience. Special attention was given to the durability and mechanical stability of the Power Take-Off (PTO) subsystem, ensuring its reliable operation in demanding marine environments.

To address environmental durability, all PTO components were selected and tested with consideration for exposure to temperature fluctuations, humidity, and saltwater-induced corrosion. In addition, mechanical robustness was assessed to withstand continuous vibrations and potential shock loading. Given the nature of offshore deployments, provisions were also made to ensure resistance to transient events such as lightning strikes, including appropriate grounding and surge protection measures.

To enhance longevity and resilience in marine environments, protective measures are implemented. Mechanical components, particularly those exposed to saltwater, undergo specialized treatments such as coating, painting, lubrication, and corrosion protection as depicted in Fig. 5. The hydrokinetic blades, hub, and nose cone (as shown in Fig. 5) are safeguarded with advanced ceramic coating technology, renowned for its superior resistance against corrosion. Additionally, the tower and yaw mechanism are galvanized to enhance their protection against harsh marine conditions.

Operational factors such as noise and vibration were also systematically evaluated [16]. Any new sources of mechanical or electrical noise introduced by the PTO subsystem could compromise the structural health of the turbine or interfere with sensor accuracy. To address this, motor-generator assemblies were operated under load during lab-based dry testing to assess vibration profiles and acoustic emissions. Where necessary, damping strategies and structural isolation methods were considered to minimize transmission of vibrations through the turbine frame.

To manage the excess heat generated by the generator during turbine operation, a liquid heat exchange device is integrated into the PTO assembly of the turbine subsystem as shown in Fig. 9. This involves assembling

and testing hoses, pipes, valves, the coolant pump, and the cooling subsystem, all of which are integrated into the aft nacelle section of the turbine.

These pre-deployment evaluations ensured that environmental stressors and operational disturbances were thoroughly accounted for, enhancing the long-term reliability and survivability of the OSTEC system under real-world marine conditions.

### G. Safety and Compliance

Safety assurance and regulatory compliance have been central to the integration and testing of the OSTEC system, encompassing both operational safeguards and adherence to international engineering standards. These efforts were critical to ensuring system integrity, personnel safety, and the long-term viability of the turbine in marine environments.

A key focus was verifying that the integration of the Power Take-Off (PTO) system did not interfere with essential safety mechanisms, including the turbine's braking and emergency shutdown systems. These features are vital for protecting both the equipment and its operators under fault or emergency conditions. During



Fig. 9. Cooling radiator installed on the generator housing at turbine back nacelle section.

laboratory testing, special attention was given to evaluating emergency response protocols. While replicating full-scale failure scenarios in a lab setting is inherently limited, simulated events such as emergency stop sequences, controlled load shedding, and PTO disengagement were performed to assess system responsiveness and validate fail-safe operation. A more detailed account of the PTO testing procedures is presented in a separate publication by the same author [21].

In parallel, the design and integration of the OSTEC system adhered to relevant international regulatory standards, including those established by the International Electrotechnical Commission (IEC) and Underwriters Laboratories (UL). Specific emphasis was placed on electrical safety, electromagnetic compatibility, and environmental robustness for both the turbine and the PTO subsystems. Compliance with these standards not only ensures operational safety and reliability but

also facilitates future scalability and deployment in commercial and regulated markets.

To complement these safety efforts, a comprehensive Failure Modes, Effects, and Criticality Analysis (FMECA) was conducted to identify and prioritize potential risks throughout the system. A qualitative Risk Priority Number (RPN) approach was employed, using standardized severity and likelihood scales to ensure consistent evaluation across all components and subsystems.

A bottom-up methodology, illustrated in Fig. 10, was adopted—beginning at the component level and assessing how individual failures could propagate to affect broader system performance. This approach is particularly effective when evaluating detailed failure scenarios, especially for systems combining new and legacy technologies. It also avoids relying on assumptions about complex or opaque subsystems. FMECA tables were developed during the turbine integration phase to document risks, guide mitigation strategies, and support evidence-based design decisions. This structured process provided critical insights into system vulnerabilities, ultimately contributing to the enhanced safety, reliability, and operational lifecycle of the OSTEC platform.

### H. Testing & Validation

To ensure the reliability and performance of the Open-Source Tidal Energy Converter (OSTEC), a structured system integration and testing protocol was developed, comprising three major phases: early stages, laboratory testing and field testing [22]. This progressive approach allowed for iterative validation of components, assemblies, and subsystems, ensuring readiness for full-scale deployment under real environmental conditions.

#### 1) Early Stages

Prior to the full-scale integration and deployment of the OSTEC system, early-stage development focused on prototyping and simulation-based validation. These efforts were critical in identifying potential integration challenges and informing design decisions at both subsystem and system levels.

A scaled physical model of OSTEC was tested at the University of New Hampshire's tow tank facility [18]. This controlled environment allowed for preliminary validation of mechanical stability, hydrodynamic response, and system interaction under variable flow conditions. Complementing the experimental work, numerical simulations were conducted using Sandia National Laboratories' OpenFAST framework.

TurbSim and OpenFAST were employed to perform a detailed and comprehensive mechanical loads assessment on the PTO system. These simulations provided high-resolution insights into dynamic loading profiles, enabling the project team to optimize mechanical configurations and control strategies before proceeding with full-scale system integration. This combined experimental-simulation approach played a foundational role in de-risking later phases of the project and ensuring

the OSTEC system was prepared for real-world conditions.

### 2) Laboratory Testing Phase

The laboratory phase focused on validating the mechanical, electrical, and control subsystems of the turbine in a controlled environment. Each component underwent rigorous quality control and performance verification prior to system-level integration. Mechanical components were first inspected for manufacturing quality and proper fitment during assembly. Once assembled, moving parts were operated to verify mechanical alignment and to anticipate potential wear and tear under dynamic loading conditions. For example, the SNL Smart Sensor MHKF1 blades [12] equipped with fibre optic strain gauges, as shown in Fig. 11 were tested at Sandia's ACME lab. Due to their sensitivity, the gauges were carefully installed in pre-cut grooves on the blades, sealed with epoxy, and sanded to preserve the blade profile. The factory-calibrated sensors were verified before rotor assembly and DAQ system integration.



Fig. 11. Bending moment and torsion testing of blades

Data acquisition (DAQ) systems played a central role during this stage. All available sensors and instruments were checked for calibration and compatibility with the DAQ interface. The real-time data stream was validated, and the DAQ software was evaluated to ensure alignment with operational protocols. Subsystems integrated into the DAQ—such as the Power Take-Off (PTO) unit—were individually programmed and tested for performance. In particular, the OSTEC project required commissioning of a servo motor, where control parameters were carefully defined to establish a speed control scheme. This approach allowed the turbine to be operated in a motorized mode within the lab environment, simulating real-world rotational speeds and providing confidence in the overall functionality of the system. Notably, this control strategy mirrors techniques commonly used in the wind turbine industry, and a similar approach is planned for OSTEC to ensure operational consistency and robustness.

Leakage prevention was also a critical part of the laboratory phase, given the harsh marine conditions in which the turbine would operate. The internal housing of the turbine was slightly pressurized above atmospheric

conditions, and pressure retention was monitored over time using the system's onboard health monitoring unit. This testing aimed to identify any sealing deficiencies and rectify them before deployment. The culmination of the laboratory phase involved a system-level dry test. The fully integrated turbine was operated at a range of rotational speeds, verifying both structural stability and data acquisition capabilities. This final check was essential to expose any unforeseen integration challenges. In addition, system balancing was performed based on operational data collected from multi-axis load cells and the PTO control system, ensuring compliance with dynamic balancing standards prior to field deployment.

### 3) Field Testing Phase

Following successful lab validation, the OSTEC system progressed to the field-testing phase involved full deployment in a real aquatic environment. The turbine was transported to the University of New Hampshire's research pier and installed on the dedicated turbine deployment platform. Project logistics and operational sequencing were meticulously planned to allow for a smooth transition from lab to field.

Prior to submersion, an additional sealing step was taken: the turbine housing was first vacuumed and then purged with nitrogen gas. Nitrogen is a dry gas, and it will greatly reduce the condensation inside the nacelle. Also, Nitrogen molecules are larger than air/oxygen, that enhances sealing efficiency at micro-interfaces, reducing the likelihood of leakage once submerged. The turbine was then deployed at slack tide at the test site as illustrated in Fig. 12 to minimize hydrodynamic disturbances during initial testing. Health monitoring systems closely observed internal pressure, and no leakage was expected given the thorough sealing process completed in the laboratory.

In-situ calibration and performance checks were conducted for sensors that could not be adequately validated in the lab. These included Acoustic Doppler



Fig. 12. AMEC-UNH Tidal Energy Test Site at Memorial Bridge, Portsmouth, NH, USA [18]

Velocimeters (ADV), Acoustic Doppler Current Profilers (ADCP), and Conductivity-Temperature-Depth (CTD) sensors. The full DAQ system was also tested to confirm the integrity of data streaming and overall operational functionality under marine conditions.

A key objective of field testing was the evaluation of torque control within the PTO system. Since dynamometer testing was not feasible in the laboratory, this scheme was defined and tested in real-time using the

natural resistance imposed by water flow. This approach provided a realistic assessment of the turbine's performance under load. Torque control strategies, commonly employed in wind energy applications, were directly adapted for OSTEC to ensure effective and adaptive system response in dynamic marine environments.

## V. SUMMARY & CLOSING REMARKS

System integration for an axial flow tidal turbine, such as the Open-Source Tidal Energy Converter (OSTEC), is a multifaceted process that brings together mechanical, instrumental, and electronic components into a cohesive and functional system. This paper presented a comprehensive framework for the system integration of the OSTEC testbed—an open-source platform designed to advance marine renewable energy research.

The integration process involved hierarchical decomposition and assembly of subsystems including the nacelle, rotor, power take-off (PTO), drivetrain, yaw mechanism, and the Modular Ocean Data Acquisition (MODAQ) system. These components—designed, fabricated, and independently tested—were assembled on a custom-built test stand, enabling controlled motorized rotation and in-lab validation. Leak tests confirmed waterproofing integrity, and performance verification was conducted through laboratory dry runs prior to full deployment. The UNH-MODAQ system, adapted from NREL's MODAQ framework, served as the core of the data acquisition and control infrastructure, enabling high-resolution monitoring, diagnostics, and control during both lab and field testing.

The deployment site for the OSTEC turbine is the AMEC-UNH tidal energy test site located at Memorial Bridge on the Piscataqua River in Portsmouth, NH. A structured integration and testing protocol—spanning early-stage simulations, lab-scale validation, and open-water deployment—ensured that each subsystem was robust, interoperable, and aligned with project specifications. Key aspects such as drivetrain alignment, blade sensor instrumentation, torque and speed control strategies, and environmental resilience were verified through rigorous processes.

A major focus of the system integration phase was to verify the turbine's integrity, operational reliability, and lifecycle performance. This required a confluence of expertise in mechanical and electrical engineering, control systems, instrumentation, and project management. The OSTEC testbed's successful integration will also enable testing, demonstration, and improvement of recommended best practices in international standards, including the IEC's technical specifications on marine energy converters (TC 114), including IEC TS 62600-2, -3, -200, -201, and -202.

Importantly, the OSTEC project serves as a crucial learning platform. Many lessons have been and will continue to be learned during and after its integration

phase, informing future system improvements, reducing uncertainty in deployment, and guiding the scale-up of tidal energy converters (TECs) toward commercial viability.

In conclusion, the OSTEC testbed represents a significant advancement in tidal energy technology and system integration methodology. It not only provides a replicable roadmap for assembling and validating TECs but also delivers valuable open-source datasets to support the marine renewable energy research community. Through its structured design, thorough validation, and real-world deployment, OSTEC paves the way for more resilient, efficient, and scalable tidal energy solutions.

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## REFERENCES

- [1] V.S. Neary et al., "USDOE's Marine & Hydrokinetic Turbine System Test Bed for Model Verification & Validation," International Conference on Ocean Energy and Ocean Energy Europe 2022 (ICOE-OEE 2022), San Sebastian, Spain, 18-20 October 2022.
- [2] Z. Zhou, F. Scullier, J. F. Charpentier, M. Benbouzid, and T. Tang, "An up-to-date review of large marine tidal current turbine technologies," International Power Electronics and Application Conference and Exposition, pp. 480–484, Nov. 2014, doi: 10.1109/peac.2014.7037903.
- [3] Bichanich, M., Sedigh, P., Bharath, A., Neary, V., & Wosnik, M. (2023). Tidal Energy Resource and Turbulence Characterization at the Atlantic Marine Energy Center Tidal Energy Test Site at Memorial Bridge in Portsmouth, NH. Bulletin of the American Physical Society.
- [4] Barooni, M., Taleghani, S. G., Bahrami, M., Sedigh, P., & Sogut, D. V. (2024). Machine Learning-Based Forecasting of metocean data for offshore engineering applications. *Atmosphere*, 15(6), 640. DOI: [10.3390/atmos15060640](https://doi.org/10.3390/atmos15060640)
- [5] M. Barooni, D. Velioglu Sogut, P. Sedigh, and M. Bahrami, "Novel Hybrid Deep Learning Model for Forecasting FOWT Power Output," *Energies*, vol. 18, no. 13, p. 3532, Jan. 2025, DOI: [10.3390/en18133532](https://doi.org/10.3390/en18133532).
- [6] J. O. Grady, System integration. CRC Press, 2020.
- [7] J. O. Grady, System Requirements Analysis. Elsevier, 2013.
- [8] Neary, V.S.; Lawson, M.; Previsic, M.; Copping, A.; Hallett, K.C.; LaBonte, A.; Rieks, J.; Murray, D. Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies; Technical Report; Sandia National Lab. (SNL-NM): Albuquerque, NM, UEA, 2014.
- [9] Bichanich, M.; P. Sedigh; Wosnik, M.; Neary, V.; Cavagnaro, R.; Bharath, A.; Forbush, D.; Kim, D.; Gunawan, B.; Wakefield, K.; Harris, S. (2024). Design and testing of an open-source tidal energy converter to advance Marine Energy IEC standards [Presentation]. Presented at UMERC+METS 2024 Conference, Duluth, MN, USA.
- [10] Neary, V.S. et al., "Open-Source Tidal Energy Converter (OSTEC) Testbed: Design Basis Report. SAND2024-10839, Sandia National Laboratories, August 2024. 73 pages.
- [11] "How Two Rookie Engineers Expertly Designed a Tidal Energy Turbine | NREL." Accessed: Aug. 18, 2025. [Online]. Available: <https://www.nrel.gov/news/detail/program/2024/how-two-rookie-engineers-expertly-designed-a-tidal-energy-turbine>
- [12] Fontaine, A., Straka, W., Meyer, R., Jonson, M., Young, S., & Neary, V. (2020). Performance and wake flow characterization of a 1:8.7-scale reference USDOE MHKF1 hydrokinetic turbine to establish a verification and validation test database. *Renewable Energy*, 159, 451–467. <https://doi.org/10.1016/j.renene.2020.05.166>
- [13] Neary, V.S., et al., USDOE Instrumented Marine Turbine Testbed: Experimental Test Plan. 2023, Sandia National Laboratories, Water Power Technologies: Albuquerque, NM. p. 150.
- [14] Raye, R., Nichols, C., Bharath, A., Candon, C., & Baca, E. (2024). Data acquisition and control for marine energy Devices: Cost considerations. <https://doi.org/10.2172/2472815>
- [15] <https://www.nrel.gov/docs/fy21osti/78773.pdf>
- [16] <https://www.nrel.gov/water/open-water-testing.html>
- [17] Rotor Balancing ISO 21940-11:2016(E)
- [18] <https://livingbridge.unh.edu/>
- [19] Andersen, Megan Nicole, "Design of an Axial-Flow Tidal Turbine Test Bed and Initial Validation and Performance Testing with 1:5 Scale MHKF1 Rotor" (2024). *Master's Theses and Capstones*. 1875. <https://scholars.unh.edu/thesis/1875>
- [20] M. Bichanich, A. Bharath, P. Sedigh, C. Candon, R. Raye, and M. Wosnik, "UNH-MODAQ: An implementation of NREL's Modular Ocean Data Acquisition System for the Open-Source Tidal Energy Converter (OSTEC) Testbed", Proceedings of The 16<sup>th</sup> European Wave and Tidal Energy Conference, 7-11 September 2025, Funchal.
- [21] P. Sedigh, R. Cavagnaro, A. Bharath, M. Bichanich, V.S. Neary, M. Wosnik, "Power Take-Off Design, Integration, Commissioning and Test of an Instrumented Open-Source Tidal Energy Converter Testbed", Proceedings of The 16<sup>th</sup> European Wave and Tidal Energy Conference, 7-11 September 2025, Funchal.
- [22] P. Sedigh *et al.*, "System Integration of an Instrumented Open-Source Tidal Energy Converter (OSTEC) Testbed," presented at the University Marine Energy Research Community Conference (UMERC) 2024, Zenodo, Aug. 07, 2024. DOI: [10.5281/zenodo.14504027](https://doi.org/10.5281/zenodo.14504027).