Power Take-Off Design, Integration, Commissioning and Test of an Instrumented Open-Source Tidal Energy Converter Testbed

P. Sedigh, R. Cavagnaro, A. Bharath, M. Bichanich, V.S. Neary, and M. Wosnik

Abstract—[1]**The Open-Source Tidal Energy Converter (OSTEC) project aims to design, construct, and deploy an instrumented tidal turbine in a real marine environment, serving as a versatile testbed for research and development. With a 2.5-meter rotor diameter and 26 kW rated power, the OSTEC turbine operates at meaningful Reynolds number scales and generates open-access datasets on power performance, mechanical loads, and tidal inflow conditions. A key focus of this project is the power take-off (PTO) subsystem, which plays a critical role in the energy conversion process of tidal turbines. This article outlines a structured methodology for designing and selecting a suitable PTO subsystem, using the OSTEC turbine as a case study. It emphasizes the main factors affecting PTO integration in marine energy devices and presents findings from the laboratory-based development, integration, commissioning, and testing of the PTO within the broader turbine system. The insights gained are intended to streamline future design and prototyping efforts, enabling more efficient and informed PTO subsystem selection in tidal energy applications.**

Keywords—**Axial-Flow MHK Turbine, Power Take-Off system, R&D, Scaled Prototype, Tidal Energy Converter.**

I. INTRODUCTION

Tidal currents, with their predictable nature [1-3], reliability, and higher energy density compared to wind, offer a vast and underutilized source of renewable energy that can be harnessed through tidal energy converters (TECs). Among these, tidal turbines have seen significant advancements in recent years, with extensive research and development efforts driving innovations in design, lab-scale [4-6] and full-scale prototype testing, and real-world deployments [7-12].

The Open-Source Tidal Energy Converter (OSTEC), developed collaboratively by UNH-AMEC, SNL, NREL, and PNNL, serves as a versatile testbed for open-source research and development (R&D) in various aspects of tidal energy technology [13-15]. A critical component of any TEC is its power take-off (PTO) subsystem, which enables the conversion of rotor mechanical power into electrical power.

Many studies in this field primarily focus on the design and deployment of tidal energy converters (TECs), often addressing the overall application of power take-off (PTO) systems in proposed devices and concepts [4, 16-23]. This paper provides a comprehensive analysis of the PTO subsystem in a TEC, presenting a structured framework for its design, assembly, and integration. Using the OSTEC turbine as a case study, it outlines a methodical workflow that ensures proper planning and adherence to industry standards. The paper details the end-to-end development of the OSTEC-PTO subsystem, from conceptualization and design to integration and commissioning, while highlighting key technical considerations and challenges encountered throughout the process.

II. POWER-TAKE-OFF (PTO) SYSTEMS IN TIDAL ENERGY CONVERSION SYSTEMS

Hydrokinetic turbines are inherently complex machines that convert energy in flowing water to electricity through several subsystems that must be integrated. Mechanical power is transmitted from flow to blades and then typically to a rotating shaft, gearbox (typically), generator, power conversion and control electronics, and eventually the end use or transmission of electricity [4,14-16,18]. Here, we consider the PTO to be the subsystem responsible for converting mechanical power into electrical power at the generator terminals.

The efficiency, reliability, and durability of the PTO system are critical factors influencing the overall feasibility of any candidate TEC design. Unlike conventional power generation technologies like wind turbines, TEC systems must operate in harsh marine environments with limited access for maintenance [12].

This work is supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) through the Waterpower Technologies Office (WPTO).

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Digital Object Identifier: https://doi.org/10.36688/ewtec-2025-1095

High servicing costs and logistical challenges make it essential to improve the durability and reliability of PTO systems to reduce the levelized cost of energy [23]. In tidal energy converters (TECs), the PTO system is critical for converting mechanical energy from the primary converter—typically a three-bladed axial flow rotor—into electrical power. Its design directly influences energy efficiency, structural dynamics, and overall system size and mass.

Unlike wind turbines, TECs operate under lower input speeds and higher mass flow rates [18], requiring mechanical designs tailored to the unique and variable loads of marine environments. Optimizing PTO systems for efficiency, reliability, and cost-effectiveness is therefore key to advancing the viability and scalability of tidal energy technologies.

III. POWER TAKE-OFF SYSTEM AND DRIVETRAIN CONFIGURATION OF THE OSTEC TURBINE

A PTO system for tidal energy converters consist of a drivetrain, a motor/generator, and a control system. However, the PTO configuration of the OSTEC turbine differs from conventional devices due to its primary function as a research turbine [13-15]. Drivetrain components leading up to the PTO include a driveshaft, two bearings, a coupling, a slip ring, a multi-axis load cell, flanges, dynamic seals, and a dedicated cooling system. A cross-sectional view of the OSTEC turbine's drivetrain is illustrated in Fig. 1. In operation, a portion of the kinetic energy of tidal currents acting on the rotor's projected area, *aka*, the energy extraction plane (EEP), is converted to mechanical power by the rotor as the prime mover. This mechanical power is then transmitted through the drivetrain to the PTO system. Here, the mechanical power undergoes conversion into electrical power before being relayed to the control cabinet. Within the control cabinet, the electronics regulate the electrical output to ensure grid compatibility. Additionally, the control system manages the turbine's operation (i.e., enabling speed or torque control), ensuring optimal performance. Details of the turbine's control logic are not included herein.

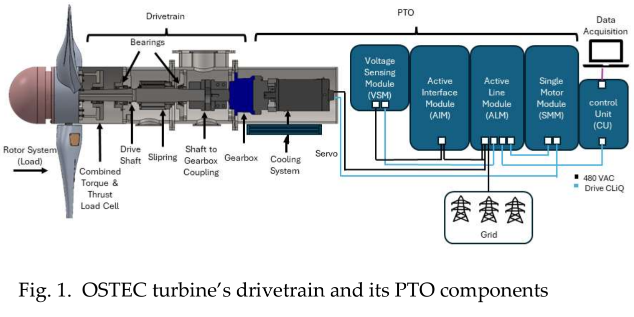

Fig. 1. OSTEC turbine's drivetrain and its PTO components

IV. DESIGN CONSIDERATIONS FOR GENERATOR AND GEARBOX SELECTION IN PTO SYSTEMS

The selection of a generator and gearbox for the PTO system must be guided by several critical design criteria to ensure efficient operation within the turbine's speed and torque limits while maintaining a reasonable factor of safety. The OSTEC turbine design basis, methodologies and specifications are detailed in reference [13,14]. Given that the OSTEC turbine is primarily designed as an instrumented research test bed and is deployed from a surface-mounted platform, the design process must account for multiple interdependent factors.

One of the primary considerations is that the rated speed, torque and power conversion efficiency of the selected components should closely align with the turbine's maximum power production point. Electrical machines and gearboxes tend to be more efficient when operating near their optimal range, which ensures energy is converted efficiently without excessive loads that could lead to performance degradation or mechanical failure. The required gearbox ratio also plays a crucial role, as higher ratios can lead to increased size, weight, and cost implications, making it essential to strike a balance between efficiency and practical constraints. The selected PTO must not only meet the required power performance but also conform to the spatial and structural constraints of the turbine system design.

Additionally, the heat generated as a byproduct of friction and electrical losses within the system must be managed effectively. Without proper thermal regulation, the efficiency and longevity of the components could be compromised. To address this, PTO components may incorporate features to enhance cooling efficacy, utilizing air or liquid cooling systems. However, the complexity of these cooling mechanisms must also be considered, as more advanced systems may introduce additional maintenance requirements and design constraints.

An essential mechanical aspect is the integration of a braking mechanism. Electrical machines with built-in brakes offer improved safety and control, often eliminating the need for additional external braking components.

Finally, the overall cost of acquiring PTO components plays a significant role in the selection process. While high-performance components may offer improved efficiency and durability, they must also be economically viable within the project's budget constraints. The optimal choice of generator and gearbox should therefore strike a balance between performance, durability, cost-effectiveness, and ease of deployment, ensuring that the system meets the intended research and operational objectives.

V. METHODOLOGY

A. *Adaptive PTO Design for the OSTEC Research Turbine: Performance Matching and Gearbox Integration*

A crucial aspect of Power Take-Off design for a TEC is ensuring that its operating envelope aligns with the available energy resource. This requires a comprehensive resource assessment of the test site or deployment location, which helps define the dimensional operating space—a range of rotations per minute (rpm) and torque (Nm) as a function of inflow velocity. This operational framework provides valuable insight into the range of PTO systems that can effectively function within the given environmental conditions. Conversely, the performance characteristics of a turbine indicate the types of environments where it can achieve optimal operation.

The OSTEC research turbine has been specifically designed for deployment at the AMEC tidal energy test site located at Memorial Bridge, Portsmouth, NH, UNH, with its PTO configuration tailored to the site's energy potential. As shown in Fig. 2, the designed power performance of the OSTEC rotor closely matches that of the MHKF1 reference rotor [4], despite featuring a larger hub diameter and modified blade geometry. Both simulations and experimental data demonstrate similar power characteristics within the operational tip-speed ratio (TSR) range of $3 < \lambda < 5$, with the OSTEC rotor exhibiting a slightly lower peak power coefficient (C_P = 0.43 vs. 0.45). The torque and thrust coefficients are also slightly reduced due to differences in hub size and blade thickness. Nevertheless, these modifications do not overly compromise performance, as the OSTEC rotor maintains high efficiency in power capture and a broad performance curve, validating its effectiveness.

Among the most critical performance factors influencing PTO component selection are rotor shaft speed and torque. By leveraging the projected performance curve and accounting for flow speeds up to 0.5 m/s above the rated design velocity of 2.5 m/s, a defined dimensional operating space can be established in rpm and Nm. While these higher flow conditions are expected only during transient turbulent gusts, their consideration ensures the PTO system remains robust across varying conditions.

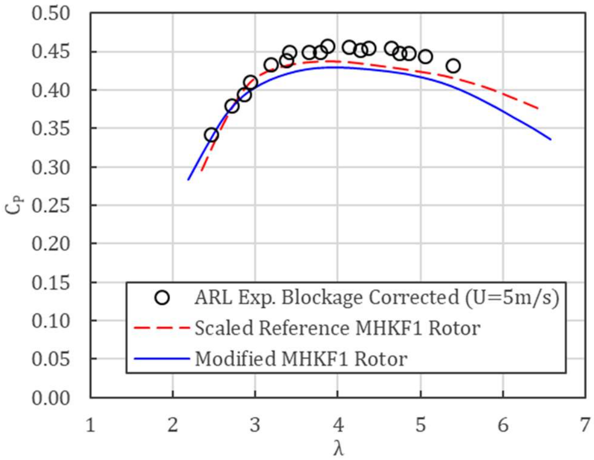

Fig. 2. Predicted power for scaled reference MHKF1 and modified OSTEC rotor model with the water tunnel test results for the reference rotor model [13].

Typical of performance curves for lift-based turbines, peak power occurs at a higher rpm than peak torque (Fig. 3). The shaft speed range is expected to be 0–160 rpm, with a maximum torque of 3,500 Nm at peak performance under 3.0 m/s flow conditions (0.5 m/s above the rated speed). This low-speed, high-torque profile is characteristic of both hydrokinetic and wind turbines, yet it is not inherently compatible with most electrical machines, which are typically optimized for high-speed, low-torque operation.

To bridge this gap, a gearbox has been integrated into the PTO system to adjust the turbine's operating conditions, making them compatible with a broader range of generators. As illustrated in Fig. 3, a gear ratio of 20:1 has been applied, effectively increasing the maximum shaft speed to approximately 3,000 rpm. This gearbox implementation allows for greater flexibility in generator selection, ensuring the torque and speed requirements remain adaptable within the range of available gear ratios.

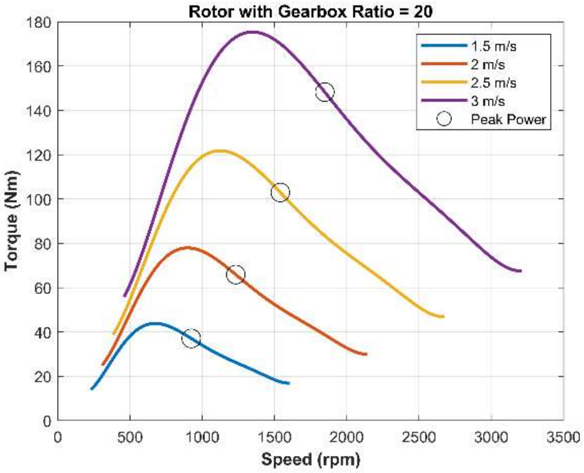

Fig. 3. Dimensional power curves for rotor [13], adapted from Fig. 2 with a 20:1 speed increasing gearbox

B. *Generator Selection and Specifications*

To identify the most suitable generator from the wide range of options available in the market, a Pugh decision matrix was employed. This method allows for a systematic comparison by assigning weighted criteria and qualitatively evaluating alternatives against a baseline selection (datum). Key selection criteria were weighted to prioritize compact size, low weight, minimal heat generation (high efficiency and effective cooling), inclusion of a holding brake, and an appropriate power rating for integration with the OSTEC turbine.

Given the turbine's rated flow speed of 2.5 m/s, numerous combinations of electrical machines and gearboxes could meet the system's requirements. The emphasis on minimizing weight and size guided the selection toward a compact generator with a moderate gearbox ratio and a closed-loop cooling system to manage the high current density efficiently. The specifications of the selected generator are detailed in Table I [13].

Table I
OSTEC selected generator specifications

Category	Units	Value
Mfg.	-	Siemens
Model	-	SIMOTICS S-1FT7
Type	-	PM Servo
Rated Speed	rpm	2000
Max Speed	rpm	3400
Rated Torque	Nm	125
Rated Power	kW	26.2
Max Torque	Nm	330
Rated Efficiency	-	0.95
Eff. Diam	mm	278
Length	mm	504
Has Brake	-	Yes
Has Encoder	-	Yes
Rec. Gear Ratio	-	20
Cooling	-	Water

The chosen generator [26], a Siemens SIMOTICS permanent magnet servomotor, is rated at 26.2 kW and requires a 20:1 gearbox to align with the turbine's expected performance envelope. To maintain low weight and compactness, the generator relies on an active fluid cooling system to manage heat dissipation under peak operating conditions.

A notable advantage of the Siemens servomotor is its flat torque response across varying speeds, ensuring reliable and predictable performance. Fig. 4 illustrates the motor's torque-speed characteristics, including operational constraints. The generator is designed for continuous operation with acceptable temperature rises above ambient, with a 100 K (relative temperature) operating limit set as the baseline threshold. While the OSTEC turbine is expected to experience transient gusts exceeding the rated speed, brief excursions beyond this limit are acceptable, provided they remain within the current and torque constraints managed by the generator-side inverter.

As shown in Fig. 4, continuous operation at the maximum power point of the turbine at an inflow velocity of 2.5 m/s should induce a temperature rise below 100 K, ensuring stable and safe performance. Additionally, the generator is capable of short-duration operation above the rated conditions, with the system retaining control authority to halt the rotor at 3 m/s, leveraging a 20% torque/current buffer as a built-in safety margin. All specifications assume the integration of a 20:1 gearbox between the turbine rotor and generator shafts, ensuring proper alignment of the system's mechanical and electrical performance.

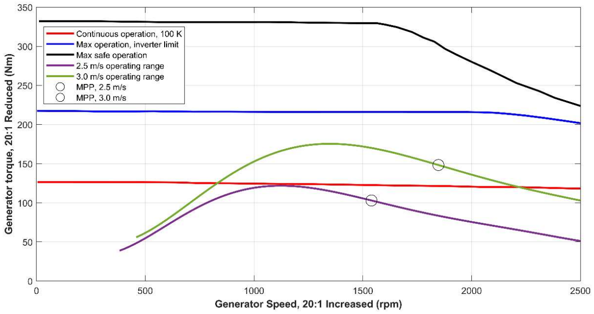

Fig. 4. Generator operating range with expected turbine operating envelopes for rated and above rated flow speeds [11].

C. PTO cooling system

Based on the manufacturer's recommendations, the generator requires a coolant flow rate of 5 litters per minute and an inlet temperature 5–30°C below ambient for effective thermal management. Given that the generator is housed within a submerged nacelle, where surrounding seawater temperatures range between 5°C and 21°C during the intended operational months (April through October), the cooling strategy must be both efficient and resilient to the marine environment.

To meet these requirements, the chosen cooling approach is "keel cooling," a well-established method in the marine industry depicted in Fig. 5. This closed-loop system circulates coolant through the generator before directing it through the nacelle's hull, where heat is dissipated as the tubes are cooled by the surrounding seawater. This passive cooling mechanism eliminates the need for additional heat exchangers or external radiators, leveraging the natural convective properties of seawater for efficient heat dissipation.

The selected keel cooler unit is designed for high thermal conductivity and corrosion resistance in marine environments. To ensure optimal seawater exposure, the cooling tubes are enclosed within a protective fairing,

Fig. 5. Keel cooler used for the OSTEC PTO cooling system.

which enhances heat transfer while safeguarding the system from debris and biofouling.

Coolant circulation is facilitated by a compact magnetic drive pump, which can be mounted in the aft section of the nacelle near the generator. The external cooling tubes are strategically placed on the flat aft bulkhead of the nacelle, ensuring efficient heat exchange while maintaining ease of access for maintenance and inspection. This integrated cooling solution provides a reliable, low-maintenance approach to managing the generator's thermal load in an offshore environment.

D. Gearbox Selection

The gearbox selection process was guided by the generator specifications, which helped streamline the design criteria. The chosen gearbox needed to provide seamless mounting compatibility, achieve the desired gear ratio, meet or exceed torque and speed requirements, and maintain a compact form factor to optimize space efficiency within the system. After evaluating various options, the Wittenstein SP+240 planetary gearbox was selected for its ability to effectively bridge the low-speed, high-torque characteristics of the rotor with the operational parameters of the generator. This gearbox ensures efficient torque transmission and speed alignment, enhancing overall system performance. Detailed specifications for the selected unit are provided in Table II [13].

VI. Power Take-Off Sub-System Integration For the OSTEC Turbine

Successful integration of a PTO subsystem hinges on harmonizing mechanical, electrical, and control systems while addressing efficiency, reliability, safety, and cost. Collaboration between the PTO and other turbine subsystem designers, as well as grid operators (voltage, frequency, power quality), is essential to optimize performance and ensure compliance with industry standards. The integration of components and subsystems is a crucial aspect of the overall system integration of the OSTEC turbine. As a key subsystem, the Power Take-Off (PTO) undergoes multiple levels of integration to ensure seamless operation within the turbine system. The first stage involves assembling and integrating all electrical and electronic components of the PTO. To facilitate this, a dedicated power and electronics cabinet has been constructed, as shown in Fig. 6. In this figure, the red-highlighted section manages power exchange between the grid and the PTO. The blue and yellow sections represent the drive system, while the green section supplies power to the auxiliary systems.

Table II
Selected gearbox specification for the OSTEC Turbine

Category	Units	Value
Mfg.	-	Wittenstein
Part #	-	SP240S-MF2-20-0M1-2S
Type	-	planetary
Gear Ratio	-	20
Stages	-	2
Nominal Torque	Nm	2658
Max Torque	Nm	5446
Emergency Stop Torque	Nm	8500
Nominal Speed	rpm	2300
Max Speed	rpm	4500
Backlash	arcmin	3
Max Axial Load	N	33000
Max tilting moment	Nm	5000
Rated Efficiency	%	94
Noise @ 3000rpm	dB	62
Weight	kg	76
Input Shaft Diam	mm	48
Moment of inertia	Kg-cm2	39.2
Eff. Diam	mm	290
Length	mm	467

A. Power Electronics and Drive System Integration

As depicted in Fig. 6. along with Fig. 1, the 480 VAC power input from the grid is connected to a Siemens Active Interface Module (AIM), which is designed to enhance power quality, mitigate harmonics, and ensure stable operation when paired with Active Line Modules (ALM). The ALM, a regenerative power supply module within the SINAMICS drive system, enables bidirectional energy flow to and from the DC bus. This feature is particularly beneficial for renewable energy applications requiring frequent acceleration and braking.

Following the AIM and ALM, the Siemens Single Motor Module (SMM) is integrated into the SINAMICS S120 drive system to efficiently control a single generator. The SMM provides the necessary power and control signals, ensuring precise motor operation under dynamic load conditions [25-27].

B. Test and Commissioning Setup

To support the OSTEC turbine system integration, a custom-built test and assembly stand has been built as shown in Fig. 7a. An attachment plate is utilized to mount the generator, enabling its commissioning, startup, and operational configuration (Fig. 7b).

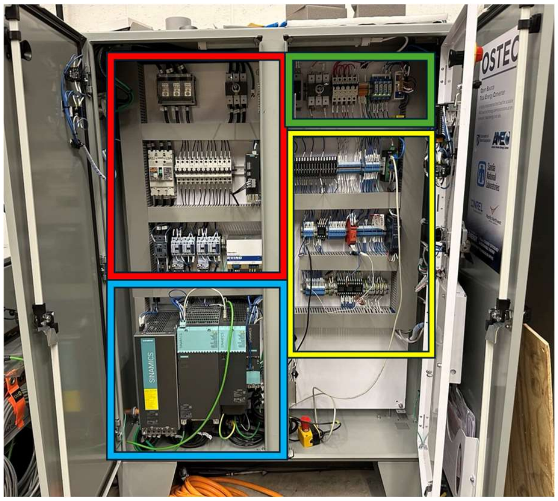

Fig. 6. Power electronics for the OSTEC power take-off subsystem.

Using a Siemens Starter S120 drive system, control parameters have been defined, and initial commissioning tests have been conducted. The motor was first spun at low speeds before ramping up through the full operational speed range under no-load conditions. For in-lab testing and operations, a speed setpoint control scheme has been implemented. However, a torque control scheme is also planned as part of future turbine testing.

C. *Torque Control Considerations and Pre-Deployment Adjustments*

While speed control is feasible in a lab setting, torque control requires an actual mechanical load on the turbine. As a result, in-lab torque control testing is not viable without a complete dynamometry test stand and will be postponed until the pre-deployment phase, where real-world loading conditions can be simulated and validated.

By integrating these commercial off-the-shelf components, power electronics, and drive systems, the OSTEC turbine's PTO is systematically configured for its role in enacting a high degree of control on turbine setpoint, providing feedback on key parameters to a data acquisition system, and performing reliably in real-world deployment scenarios.

Fig. 7. Siemens 26.2 kW permanent magnet servo drive installed on the custom build test stand for OSTEC turbine.

VII. CONTROL, COMMUNICATION, AND SAFETY SYSTEMS IN THE OSTEC TURBINE'S PTO INTEGRATION

The Siemens SINAMICS S120 is a high-performance, modular drive system designed for precise control in servo applications [25,27]. It provides flexibility, scalability, and advanced motion control capabilities, making it suitable for demanding industrial and research applications. One key feature of the S120 drive system is its position control function, which allows the user to jog, rotate, or set the drive shaft to a specified position with defined speed and displacement parameters. This functionality is particularly useful in the OSTEC turbine, as it enables precise rotor positioning after operational cycles.

It is important to emphasize that the OSTEC turbine is a research turbine, designed for short-term operational testing rather than continuous deployment. Its runtime is measured in weeks to months, rather than indefinite operation. Consequently, the ability to park the rotor in a designated position is critical for data acquisition (DAQ), storage, and maintenance.

A. *Communication and Data Acquisition: Integration of MODAQ with PTO Controls*

For a research turbine, real-time access to PTO control parameters and setpoints is crucial from a data acquisition perspective. Siemens drive components utilize the PROFIdrive network, a standardized drive profile for communication between motion control systems and drives over PROFINET and PROFIBUS [25-27]. PROFIdrive ensures seamless interoperability and real-time control in industrial automation systems. It supports various application classes, ranging from basic speed control to advanced servo applications, making it highly adaptable for different operational needs.

One of the key advantages of PROFIdrive is its ability to provide real-time communication, ensuring precise and synchronized drive operations. Additionally, it integrates with PROFIsafe, offering built-in functional safety features for secure operation. PROFIdrive also provides detailed diagnostics, enabling efficient troubleshooting and system maintenance, which is particularly beneficial for a research-oriented setup like the OSTEC turbine. To facilitate seamless communication between the PTO and the data acquisition system, the Modbus TCP network protocol has also been implemented.

Modbus TCP is a widely used industrial communication protocol that enables real-time data exchange over Ethernet (TCP/IP) networks, as opposed to traditional serial communication methods (such as RS-232 or RS-485). Within the OSTEC system, Modbus TCP enables efficient data transfer between the PTO and the Modular Ocean Data Acquisition (MODAQ), ensuring reliable monitoring and control.

MODAQ system, originally developed by NREL [27], has been adapted by UNH for the OSTEC turbine. This customized MODAQ implementation serves as the primary data acquisition platform, turbine setpoint controller (i.e., streams speed or torque commands to the Siemens controller), and a monitoring and health management system. Beyond standard DAQ functions, MODAQ continuously monitors critical turbine health parameters, including water intrusion, sensor faults, overload conditions, and other potential failure risks. By integrating these real-time monitoring capabilities, MODAQ enhances the turbine's operational reliability and safety. Further details on the MODAQ architecture and its role in OSTEC's field deployment will be provided in a separate publication.

B. *Safety System and Emergency Operation Conditions*

Ensuring safe operation is a fundamental consideration for the OSTEC turbine, as with any industrial system. The safety framework is designed to handle different operational scenarios, including normal operation, emergency shutdowns, and fast deceleration scenarios.

In normal operation, the system prioritizes the turbine's structural health and stability. To achieve this, a ramp function is incorporated into the control system, gradually adjusting the speed with a time-rated sequence. The ramp rate is carefully determined through dynamic simulations, considering the local inflow conditions to prevent excessive mechanical stress on the drivetrain [27]. However, in more critical situations, the turbine must be stopped immediately. For life-threatening emergencies, an Emergency Stop (E-Stop) function is implemented. This feature immediately disconnects the PTO power and activates the generator's internal magnetic brake, bringing the rotor to a full stop within a fraction of a second. While this rapid braking mechanism is effective in preventing catastrophic failure, it also has the potential to damage the generator due to the abrupt torque applied. To ensure accessibility, the E-Stop system can be triggered both physically, using a dedicated emergency stop button on the turbine deployment platform (TDP), and digitally, through software signals.

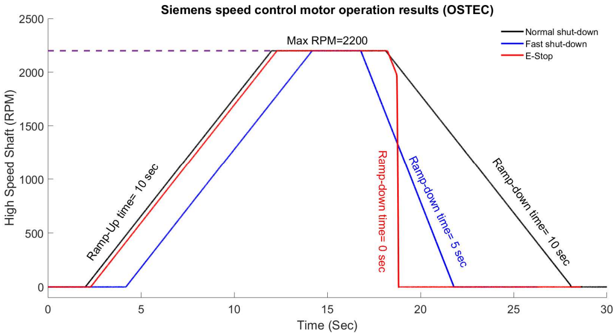

Fig. 8. Siemens servo drive speed control with different safety functions tested in the lab.

In cases where an immediate stop is not necessary, but a rapid deceleration is still required, a fast shutdown sequence is utilized. Unlike the E-Stop, this approach implements a controlled ramp-down process, which slows the turbine within a shorter-than-normal timeframe while avoiding mechanical damage. The ramp-down rate is optimized based on the rated/normal forces the drivetrain and rotor can tolerate, ensuring that all components remain intact. Like the emergency stop function, fast shutdown can be triggered manually or digitally, depending on the specific operational needs.

To validate the performance and reliability of the safety measures, extensive laboratory tests were conducted under no-load conditions. As shown in Fig. 8, the results confirm the drive system's effective response to various shutdown scenarios, demonstrating that the implemented safety protocols successfully reduce operational risks while maintaining system integrity. Similar tests will be carried out under full system inertia and load conditions, which are expected to result in different ramp times.

C. *System balancing*

Precision balancing of turbine rotors enables optimal power conversion efficiency and reduced fatigue on PTO components [29,30]. The weight distribution of the instrumentation payload in the OSTEC rotor hub was designed to achieve a G 16 minimum balance quality grade, like that recommended for wind turbine rotors, to comply with international standards [ISO 2016]. After assembly, any imbalance introduced by redistribution of the sensor-instrumentation payload in the rotor hub must be quantified and mitigated if it exceeds this G 16 minimum balance requirement. Reference [29] defines procedures and tolerances for balancing rigid rotors, specifying permissible residual unbalance, correction planes, and considerations for balancing errors. This standard applies to rotors whose unbalance distribution does not cause significant flexure at any operating speed, ensuring their mass distribution is assessed and adjusted as needed to meet specified unbalance tolerances.

For the OSTEC turbine, system balancing will be conducted during the system integration and dry testing phase, in conjunction with the integrated PTO subsystem. Throughout this process, the turbine's drivetrain will be operated at varying rotational speeds under motorized conditions, with its servo engaged. Load data from a multi-axis load cell, along with rotor speed data from the Siemens control system, will be analysed and compared between drivetrain operation alone and with the hub and rotor installed. Any detected imbalance will be corrected by strategically distributing counterweights inside the rotor hub, following the same methodology used for wheel balancing in automobiles.

VIII. CONCLUSION & FUTURE WORK

This study presented a comprehensive approach to the design, integration, and commissioning of the PTO system in the OSTEC testbed. The research outlined key design considerations, including drivetrain configuration, generator and gearbox selection, cooling strategies, and system integration. By leveraging a structured methodology, the PTO system was successfully configured for use in a highly-sensored research turbine, while maintaining flexibility for future adaptations.

The results from laboratory testing and commissioning demonstrated that the selected PTO configuration aligns well with the operational requirements of the OSTEC turbine, ensuring reliable performance under realistic conditions. The integration of advanced control systems and real-time data acquisition further enhances the adaptability and monitoring capabilities of the system, facilitating its use on turbine research including testing novel blade designs, characterizing loads in response to turbulent inflow, and implementing advanced control schemes for optimizing performance.

Future work will focus on validating the PTO system's performance in real-world deployments, refining torque control strategies, and exploring additional optimizations to improve durability and usability. The insights gained from this work provide a valuable foundation for advancing open-source research in tidal energy conversion, contributing to the broader goal of making marine renewable energy systems more reliable, cost-effective, and scalable.

ACKNOWLEDGEMENT

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This work was authored in part by the Pacific Northwest National Laboratory, operated by Battelle Memorial Institute for the U.S. Department of Energy (DOE) under Contract No. DE-AC05-76RL01830. This abstract describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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