Wave Energy Power Take-Off Validation With a Hydraulicly Actuated Rotary Dynamometer and a Bidirectional High-Power DC Supply

Preprint

C. Nichols, S. Lambert, R. Fao, and R. Raye

National Renewable Energy Laboratory

Presented at European Wave and Tidal Energy Conference
Bilbao, Spain
September 3–7, 2023

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Conference Paper
NREL/CP-5700-86178
September 2023

Contract No. DE-AC36-08GO28308

Wave Energy Power Take-Off Validation With a Hydraulicly Actuated Rotary Dynamometer and a Bidirectional High-Power DC Supply

Preprint

C. Nichols, S. Lambert, R. Fao, and R. Raye

National Renewable Energy Laboratory

Suggested Citation

Nichols, C., S. Lambert, R. Fao, and R. Raye. 2023. *Wave Energy Power Take-Off Validation With a Hydraulicly Actuated Rotary Dynamometer and a Bidirectional High-Power DC Supply: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5700-86178. https://www.nrel.gov/docs/fy23osti/86178.pdf.

Conference Paper
NREL/CP-5700-86178
September 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Wave Energy Power Take-Off Validation With a Hydraulicly Actuated Rotary Dynamometer and a Bidirectional High-Power DC Supply

C. Nichols, S. Lambert, R. Fao, and R. Raye

Abstract— **There are many organizations working toward the commercialization of wave energy converter technologies and advancing their designs through the technology readiness levels. A critical step before the field deployment of prototype wave energy converters is the validation of the subsystems and components that are contained in the wave energy converter through laboratory testing and performance characterization. In 2021, the National Renewable Energy Laboratory (NREL) developed and demonstrated a system for testing power take-offs (PTOs) with a low-speed, high-torque dynamometer and a grid-tied high-power DC power source and sink before field deployment. The hydraulic dynamometer allows for the simulation of PTO actuation from wave motion and is capable of a wide range of wave periods and heights, which are represented as various speeds and torques from the dynamometer. The high-power bidirectional power supply allows for hardware-in-the-loop and controller-in-the-loop testing to be conducted on wave energy converter power electronics. This paper describes the methods used by NREL research staff to test all components and subsystems in the PTO of a novel wave energy converter before field deployment.**

Keywords—**Dynamometer, PTO, Testing, Validation, WEC.**

I. INTRODUCTION

WAVE energy is a promising and growing technology to aid in the transition to a clean energy future. The advancement of this technology into higher technical readiness levels (TRLs) is burdened with the high cost associated with field testing due to permitting, ship fees, dock fees, and prototype fabrication, among others. Field testing is an essential part of the development of wave energy converters (WECs), but the high risk associated with this form of testing needs to be addressed and mitigated to allow for WEC developers to succeed in commercialization. It is more cost-effective to validate WEC technology at lower TRLs through laboratory testing, including dynamometer testing and power-hardware-in-the-loop testing. The likelihood that problems will arise in the field is high, and hiring boats and trained personnel to retrieve the device or to complete field modifications is cost-prohibitive.

According to the U.S. Department of Energy's (DOE's) Technical Readiness Assessment Guide [1], TRLs 3–5 require laboratory validation to advance the technology being developed. In wave energy, these levels range from subcomponent testing, such as generator testing, up to full-scale prototype testing, which includes all subsystems—integrated and independently functional. The methodology described in this paper and employed at the National Renewable Energy Laboratory (NREL) seeks to move wave energy devices from TRL 5 to TRL 6 with high confidence in the success of a field deployment.

It is essential to test all components of wave energy converters before deployment, but among the most critical are the components included in the power-take-off (PTO). The performance and reliability of the PTO is the major driver in the effectiveness and efficiency of the wave energy technology. Furthermore, the PTO system is also essential to the survival of the WEC by keeping energy storage banks (e.g., batteries) charged and available to assist with device survival. The WEC industry has not converged on a certain type of PTO or WEC design, so there is no standard dynamometer or other types of PTO testing. The IEC 62600-103 technical specification provides the guidelines for early-stage development of wave energy converters, but due to the high variability in device designs, this standard cannot provide an exact dynamometer design to employ other than what exists in other industries [2].

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

All authors are associated with the National Renewable Energy Laboratory, Golden, CO, USA (e-mails: casey.nichols@nrel.gov, scott.lambert@nrel.gov, rebecca.fao@nrel.gov, robert.raye@nrel.gov).

Digital Object Identifier: https://doi.org/10.36688/ewtec-2023-169

Previous work has shown custom dynamometer designs that have been used to validate WEC PTOs. Primarily, the dynamometer designs have been used to absorb energy that is converted by the WEC from incoming waves in a tank. The work described in [3] was successfully used to test a type of WEC called an oscillating wave surge converter in a wave tank. This design focused on characterizing the WEC's response to incoming waves generated in a wave tank while coupled to a force feedback dynamometer, which is capable of supplying and sinking rotational energy to/from the WEC. This dynamometer was capable of 33 N·m, which is representative of a small-scale WEC. The work described in [4] also designed a dynamometer for use in a wave tank that was capable of 59 N·m with a gearbox. The dynamometers designed in [5] and [6] were capable of testing PTOs at a power of 95.6 W but the dynamometers were only useful for linearly displaced PTOs.

To assist WEC developers, NREL has developed a hydraulic dynamometer that is currently capable of testing devices of approximately 2 kW and that meets relevant standards described in IEC 62600-103. This is useful to PTO designs that operate from a rotating or oscillating shaft with high torque and lower speeds—a common trait of point absorbers, oscillating wave surge and wave attenuator WEC designs. The dynamometer design is rotary and is not currently compatible with linearly displaced systems; linear PTO testing can be implemented at facilities like the SWEPT laboratory [6] at Sandia National Laboratories and by using NREL's other dynamometer facilities [5].

The majority of larger-scale WECs convert wave-actuated mechanical motion into electrical energy; therefore, there is a need for electrical PTO testing to advance the TRL. To achieve this, the NREL PTO testing includes a high-power bidirectional power supply to simulate various electrical loads and sources that may be present in the WEC PTO. For example, WEC designs often include power components such as batteries, transformers, inverters, capacitors, resistors, and rectifiers; the bidirectional power supply can simulate real and full-scale operating voltages and currents through these components.

This WEC PTO testing setup is novel because it is rated at 2 kW, rotates at low speed, operates at high-torque, and is coupled with a high-powered DC load. Leveraging a DC load for PTO testing has been designed and/or implemented in prior work [7] [8]; however, this novel setup allows a full-scale device to be validated with realistic input rotation (oscillation and complete rotations) actuated by the hydraulic dynamometer while simulating the output of a WEC PTO, which is often transferred to an external load on shore or at the seafloor. Further, the DC load is bidirectional, and therefore an array or units can be configured to both supply and sink energy from a WEC PTO. This may accelerate testing once the mechanical power transmission has been characterized with the hydraulic dynamometer. Long-duration sea state testing may be completed this way with lower cost than by running the hydraulic dynamometer for many hours. The modular design of this WEC testing platform expands testing capabilities and therefore maximizes the benefits of laboratory testing.

Another critical design aspect of a PTO testing program is to include a capable data acquisition (DAQ) system that can sufficiently acquire sensor data and store it in a reliable, standardized, and efficient format. NREL has developed an IEC standard-compliant and accredited DAQ system that has been leveraged for many years in the field and for laboratory testing of wind turbine PTOs and other validated turbine components. This system can be integrated with the dynamometer infrastructure at NREL but reaches a limit when integrating with a supervisory control and data acquisition (SCADA) system of a device under test. The limitation is overcome by implementing the Modular Ocean Data Acquisition (MODAQ) system, which can operate as a laboratory-grade DAQ and perform certain supervisory control tasks.

This paper details the design specification of the WEC PTO testing platform that NREL implemented in 2021 to support industry partners developing prototype WECs and advancing the TRL to reach a commercially viable product. Despite the highly variable designs in the WEC industry, NREL hopes to leverage this design in future testing campaigns to continue to support industry partners. Also, to aid the broader WEC testing community, this paper describes lessons learned during the design, implementation, and use of the PTO testing platform, and discusses future work necessary to improve the efficiency and quality of WEC PTO testing.

Note: due to a nondisclosure agreement with the WEC testing setup users, we are unable to share specifics on dynamometer performance while operated with an integrated device under test.

II. DESIGN OF THE HYDRAULIC DYNAMOMETER

The design goals of the dynamometer system were to provide constant speed rotation in both directions, oscillate to reproduce wave motions, and have a reconfigurable architecture to allow for many different types of WECs to be tested and validated. The system actuation utilized a TM30 axial piston hydraulic motor with an integrated 39-to-1 ratio speed-reducing planetary gearbox. The motor has a theoretical maximum speed of 2800 rpm, yielding a system output speed limit of 71.6 rpm. During commissioning it was found that higher speeds were possible, but during testing, speeds were generally kept below 30 rpm. The motor and gearbox assembly were connected to a Himmelstein MCRT 4800 rotary torque transducer rated to 22.6 kN·m by using large, machined hubs that incorporated tapered-shaft locking devices. These types of couplings were selected to reduce backlash in the drive system, which would be undesirable

TABLE I
DYNAMOMETER SYSTEM SPECIFICATIONS

Parameter	Value
Make	Doosan
Model	TM30VD-A-B4
Motor maximum working pressure	34.3 MPa
Motor maximum capacity	175 cm^3/revolution
Motor maximum speed	1909 rpm
Gearbox ratio	39.14
Gearbox maximum output torque at max. working pressure	33.6 kN·m
Gearbox maximum output speed	50 rpm
MTS controller operating pressure	20 MPa
Achievable torque at MTS op. pressure	15 kN·m

for the reversing loads imparted by the oscillating motion. A Siko MSK320 encoder was used to acquire position and speed data from the rotating shaft. To drive-control the motor, an MTS Systems hydraulic power supply and controller were used. This system consisted of a 17 m^3/hr (75 gpm) hydraulic pump operating at 19.3 MPa (2800 psi), a hydraulic service manifold, a series 252 servo-valve, and an MTS Series 793 FlexTest Controller. The system specifications are described below in Table I and the simplified hydraulic schematic is shown in Figure 1.

A variety of sensors were integrated into the hydraulic dynamometer and the full list is described in Table II. In developing the dynamometer, it was determined that there would be use for a velocity and position control algorithm of the dynamometer. To clarify, this is the input set point variable that is received by the MTS system to use in the proportional-integral-derivative (PID) control loop to actuate the dynamometer. The velocity control system receives a set point in rpm and a real-time velocity feedback signal to execute the PID control loop. The primary challenge with this control system was the development of the real-time velocity feedback to the PID loop. The MTS system by default utilizes analog signals to execute its PID. The position measurement from the encoder is inherently a digital transistor–transistor logic (TTL) signal, and therefore was incompatible with the MTS controller. To overcome this, a field-programmable gate array (FPGA) and real-time Linux based absolute encoder processor was developed to achieve a real-time conversion between TTL and the analog voltage needed by the MTS controller. This was done using the National Instruments compactRIO real-time embedded controller with an integrated FPGA. The design consists of a 40 MHz clock, a counter, and a ±10 V analog output card. The most performant way of converting the differential position was to count clock ticks between encoder TTL counts/pulses.

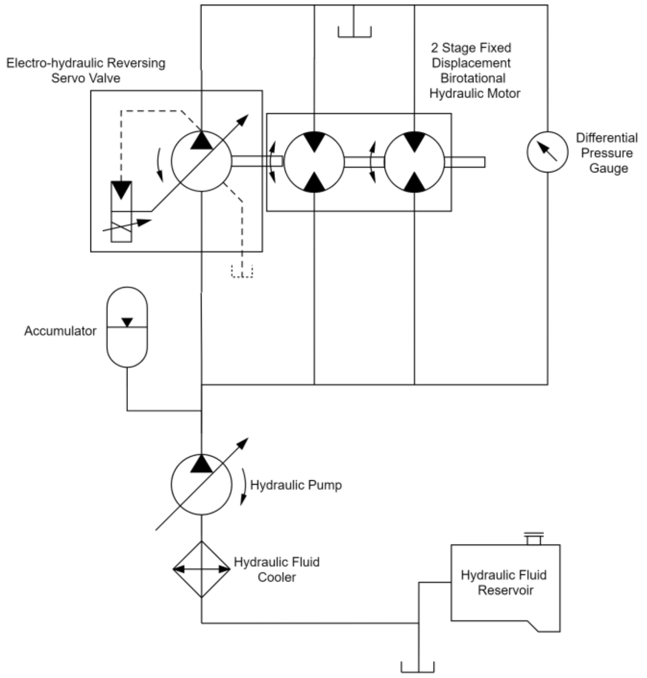

Fig. 1 Simplified hydraulic system schematic.

$$RPM = \frac{\Delta counts}{\Delta ticks} * \frac{ticks}{minute} * \frac{revolution}{counts} \qquad (1)$$

The main principle was to count the clock ticks between each change in encoder count rather than a change in counts with a set change in time. This better leverages the speed and determinism of the FPGA and allows for a quicker and more precise calculation of rpm.

The position control of the dynamometer was a much simpler system; however, it was significantly limited by the lack of a digital position feedback into the MTS controller. There was a limit to the number of rotations allowed by the MTS controller, and with more rotations, there was less resolution available between rotations. For example, if 0 degrees was represented by an input signal of -10 V, and 360 degrees was represented by 10 V, then we are inherently limited to one rotation. The limit of rotations could be increased, but at higher values the inherent noise in the analog signal has the potential to introduce rotational instability into the system.

A torque control loop is possible with this dynamometer system but was not attempted in this work. A noteworthy concern with implementing the torque control system is the high risk of instability caused by torsional resonance in

TABLE II
DYNAMOMETER SENSOR SPECIFICATIONS

Sensor	Location	Working Range
Rotary torque transducer	Low-speed shaft	±100 kN·m
Encoder	Low-speed shaft	14400 ppr
Hydraulic pressure transducer	Hydraulic motor input	34.5 MPa
Output pressure transducer	Hydraulic motor output	34.5 MPa

the dynamometer shaft, which could result in damage to the system without the proper engineering controls in place. Future work would include implementing a torque control system and improving the quality of the position control, allowing for max resolution over many rotations.

III. PERFORMANCE OF THE HYDRAULIC DYNAMOMETER

During the first testing campaign using this WEC testing setup, shown in Figure 2, we were able to achieve the specified speed and torque of the hydraulic dynamometer. Several observations were made, including the difficulty associated with pre-installation analysis of the hydraulic motor. The selected motor was not designed for dynamometer testing, and therefore its pertinent performance characteristics were not well understood. Further, the hydraulic system dynamics were complex, and some operating points were observed to introduce resonance in the rotation of the shaft. However, because the hydraulic system is attached to a WEC PTO that also has complex and highly variable system dynamics, the coupling of these two dynamic systems would alter the system resonance frequencies, which could not be modeled without a significant effort in single-component characterization and subsequent model validation. This would require a very large modeling collaboration between WEC developers and dynamometer designers, which can be cost-prohibitive in a laboratory validation project.

Also, the backlash of the hydraulic motor coupled with the static friction in the system made the zero crossings more unsteady than desired. This can also be attributed to the uncertainty associated with the construction of the hydraulic motor. It is recommended to control speed based on feedback from the high-speed motor shaft rather than from the low-speed shaft.

It was also observed that the speed measurement of the low-speed shaft was susceptible to noise caused by a custom encoder design, which inherently had a magnet spacing issue. The high-speed FPGA speed calculator interpreted this incorrect spacing as a spike in shaft speed. The recommended way to measure rotational velocity is to put the encoder on the high-speed shaft within the two-stage hydraulic motor or to implement a higher precision encoder magnet wheel with much less variance in magnet spacing.

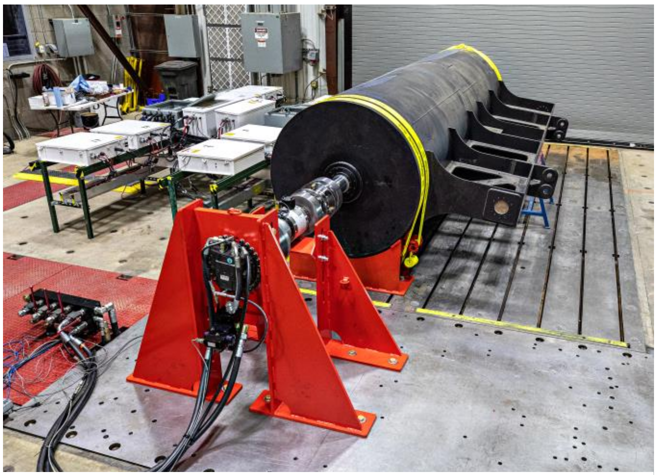

Fig. 3. Hydraulic dynamometer used in C-Power's SeaRAY pre-deployment laboratory validation. (Photo by Werner Slocum, NREL)

These modifications are included in the recommended future work for using the WEC testing system for new device laboratory validation.

IV. BIDIRECTIONAL HIGH-POWER DC SUPPLY

The bidirectional high-power DC supply was instrumental in the advancement of the WEC PTO testing capabilities at the NREL testing platform. As noted, the PTO very often includes advanced power electronics, which are a critical component to the WEC's overall operational effectiveness. Further, it is often impractical to include the microgrid and power delivery devices in dynamometer testing without large scope and budget increases. The inclusion of this power supply allows researchers to simulate the behavior of the microgrid when connected to the WEC for a significantly lower cost, which is indicative of power-hardware-in-the-loop (PHIL) testing.

The system implemented at NREL includes multiple power modules, which provide the opportunity of both supplying power to and sinking power from the WEC. Initially, the unit was configured to sink power from the WEC PTO to simulate a typical load connected to a WEC, such as a battery or grid. This would allow the simulation of wave motion through the mechanical components of the PTO supplied by the hydraulic dynamometer and the output of power from the mechanical-to-electrical energy converter within the PTO sunk by the DC load. The system operating areas, both in source and sink mode, are shown in Figure 3.

Alternatively, the bidirectional DC supply can be configured to be the input to the PTO (skipping the mechanical-to-electrical power converter) and the load. The benefit of supplying power to the WEC in place of the actual generator is to improve testing efficiency and test boundary cases of potential voltages and currents into the

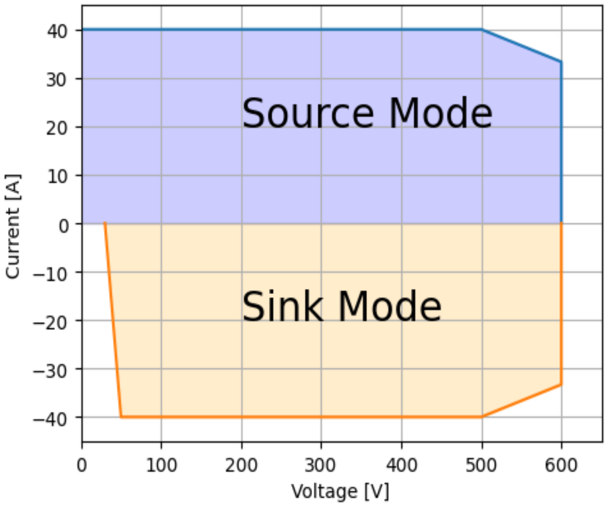

Fig. 2. Regatron TC.GSS. 20. 600.4WR.S, voltage/current operating area [4]

power electronics that may not be possible with the hydraulic dynamometer. The system used in this test setup was a matrix of Regatron GSS Grid Simulators, which are DC sources and loads. The specifications of the Regatron matrix are described in Table III [9] and a schematic of the setup is shown in Figure 4.

The matrix of Regatron units is reconfigurable and allows for serialization and parallelization of the units to increase overall power, voltage, or current, depending on configuration. The Regatron is programmed using the provided TopCon software, which allows the matrix to be configured with multiple units and also provides a user interface for controlling the system and completing troubleshooting of the setup. The safety of the setup and the protection of the device under test can be greatly improved through the configurations of warning and error limits for power, voltage, and current. This is critical for lower-TRL testing, as the behavior of the PTO may not be fully characterized.

The Regatron may also be controlled by using a .NET API on a Windows PC, which allows for the automation of the system set points and the measurement of actual system operating parameters. Previous work at NREL developed a system for utilizing the .NET API to automate the Regatron with the popular Python programming language. This was leveraged for the PTO testing work that was completed for WECs at NREL. The API has the capabilities of reading the measured values from the different voltage and current sensors within the Regatron, performing some control determination and modifying the set points within the Regatron, which enables PHIL testing and experimentation.

The Python-based control of the Regatron is able to simulate many system behaviors, including the long-duration sea state simulation, which can have a wave climate as an input and the modeled voltage or current as output, whichever is necessary for the PHIL test. In parallel, the software can also drive the other Regatron unit(s) to simulate a realistic type of load such as a microgrid or a battery. The extent of complexity with the PHIL model is up to the WEC developer, and past work has primarily included models developed by industrial partners.

TABLE III
REGATRON SYSTEM SPECIFICATIONS

Parameter	Value
Make	Regatron
Model	TC.GSS.20.600.4WR.S
Quantity	4
Max. Module Voltage	600 V
Max. Module Current	± 40 A

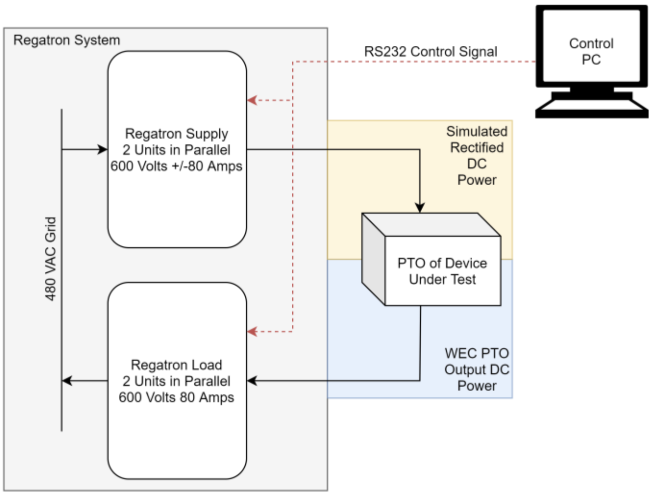

Fig. 4 System diagram of PHIL testing with the Regatron system

V. PERFORMANCE OF THE BIDIRECTIONAL DC SUPPLY

The bidirectional DC supply proved to be very useful in laboratory testing of WEC PTOs. The use of this system allowed users to simulate the typical loads of their PTOs, which in the first case was a seafloor battery. Leveraging this system allowed the WEC developer to validate their technology without being burdened by the large increase in scope and cost necessary for implementing a large battery storage testing platform in a laboratory—especially a battery designed for underwater use. Further, when the full testing campaign using the hydraulic dynamometer was completed, this equipment allowed for the long testing of the WEC without the expense of running a hydraulic power supply, which requires more power and more skilled operators. The PHIL setup greatly improved the efficiency and effectiveness of the WEC PTO testing setup. The Regatron configuration as setup in the laboratory is shown in Figure 5.

VI. FUTURE WORK IN PHIL

Other work at NREL and Sandia has developed an open-source WEC modeling software package called WECSim [10], which has modeling capability that may be necessary to implement a PHIL test with a WEC PTO. Work is in progress for developing a way to integrate this open-source package with physical test systems, including the dynamometer and the PHIL. One major limit of this system is the lack of determinism in controlling the Regatron, primarily due to the nondeterministic execution of the Python system and the lack of real-time preemption in the Windows operating system. Future work will connect WECSim modeling capabilities to a real-time controller to allow for higher-speed, deterministic testing with the Regatron system.

It has also been identified that system performance could be improved with the implementation of a real-time operating system controlling the Regatron units. This would be a necessity for tests where a higher update rate

Fig. 5 Configuration of four Regatron GSS units as seen from the rear panel. (Photo by Werner Slocum, NREL)

is called for. Because this .NET API is only compatible with Windows operating systems, which are inherently not real time, a new solution would be necessary using low-level direct serial communications between a real-time controller/PC a controller/PC and the Regatron units. This is being explored for future projects that utilize the PHIL Regatron setup.

VII. DATA ACQUISITION METHODS

In laboratory testing and validation, quality data acquisition is critical to testing success and validity. This includes the design and plan for what sensors are included and where they are placed throughout the system. The value added by additional sensors when troubleshooting and validating outweighs the initial cost of implementing the sensor. It is also crucial that the system collecting data from the sensors is reliable, repeatable and in many cases accredited. Testing at NREL has addressed this in the past when the EtherCAT Data Acquisition System (EDAS) was developed, tested, and used in many accredited tests to IEC standards for the wind turbine industry. Although this system is useful for sensors in a laboratory setting, there is difficulty associated with integrating system sensors internal to a WEC PTO or other internal systems within a WEC. This in-device sensor system is more indicative of a SCADA system.

As an option for meeting the needs for device integrated measurements, the MODAQ system (shown in Figure 6) was developed to be integrated into deployed WEC devices for laboratory and field validation. This system includes the capabilities of EDAS but also more complex modules that are vital for remotely deployed devices, such as GPS and INS motion tracking with a watch circle, 4G remote connectivity, data upload to cloud storage, email alerting of warnings and faults, and basic device control such as sea state PTO performance optimization. The functionality of the SCADA system is critical to the WEC device's survival in the field, and therefore it is a critical component to be validated in the laboratory before deployment. Because the dynamometer and bidirectional power supply can accurately simulate the real-world operational characteristics of a deployment, it is possible to validate the functionality of the SCADA system in parallel. This yields a more dependable system upon deployment because it better aligns the laboratory validation to an actual deployment.

Fig. 6 Enclosure layout of a MODAQ field enclosure (Photo by Robert Raye, NREL)

The test setup described in previous sections was employed to validate the NREL-developed MODAQ SCADA system. Through this testing, control logic and system communications were tweaked prior to the MODAQ being deployed in a real ocean environment. Furthermore, the combination of the EDAS system for dynamometer controls and data with the MODAQ for in-system measurements enabled greater learning about and characterization of both the test setup and the test article itself. This is indicative of controller-hardware-in-the-loop testing.

To enable this integrated testing and data analysis, the accurate timestamping of the EDAS and MODAQ data was essential for correlating laboratory measurements and device operational measurements. The method used for correlation was asynchronous data acquisition with GPS timekeeping. The systems were running independently, but the timestamp used in each system was based on GPS timekeeping, which can have an accuracy below 500 ns [10]. This allowed the MODAQ and EDAS data to be very closely correlated in data analysis. This implementation of GPS synchronization is an industry standard and is compatible with many SCADA system designs.

VIII. CONCLUSION

This paper described the design of a new WEC testing setup that utilized a hydraulic dynamometer to simulate the rotational actuator of a WEC PTO and a bidirectional DC supply, which could simulate the typical loads connected to a WEC PTO and also simulate the output of the mechanical-to-electrical converter.

This system was developed to meet an industry need for a full-scale testing system for devices in the scale of approximately 2 kW and that operate with high-torque, low-speed rotational input. Lessons learned with the different aspects of the testing system were described, and actions for improving the system were included.

IX. ACKNOWLEDGEMENTS

The authors would like to thank some of the many contributors to this project, including Ismael Mendoza, Ben McGilton, Ramanathan Thiagarajan, Christa Nixon, Tessa Greco, Mark Murphy, Andrew Simms, Josh O'Dell, Rob Goldhor and Adam Pisoni. Furthermore, the authors would like to thank C-Power, the developer of the SeaRAY WEC, for their early adoption of this new WEC PTO testing system and their continued collaboration with NREL.

X. REFERENCES

[1] M. Frank, "Technology Readiness Assessment Guide — DOE Directives, Guidance, and Delegations." https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-04-admchg1 (accessed Mar. 29, 2023).

[2] "Marine energy – Wave, tidal and other water current converters Part 103: Guidelines for the early stage development of wave energy converters Best practices and recommended procedures for the testing of pre-prototype devices." International Electrotechnical Commission (IEC), 2018. [Online]. Available: https://webstore.iec.ch/publication/32966

[3] D. Banks, J. van 't Hoff, and K. Doherty, "The Development of an Experimental Force Feedback Dynamometer to Investigate the Real Time Control of an Oscillating Wave Surge Converter," in *Volume 8: Ocean Renewable Energy*, Nantes, France: American Society of Mechanical Engineers, Jun. 2013, p. V008T09A048. doi: 10.1115/OMAE2013-10766.

[4] A. Simmons, T. K. A. Brekken, P. Lomonaco, and C. Michelen, "Creating a dynamometer for experimental validation of power take-off forces on a wave energy converter," in *2015 IEEE Conference on Technologies for Sustainability (SusTech)*, Jul. 2015, pp. 148–153. doi: 10.1109/SusTech.2015.7314338.

[5] X. Li *et al.*, "Dynamic characterization and performance evaluation of a 10-kW power take-off with mechanical motion rectifier for wave energy conversion," *Ocean Eng.*, vol. 250, p. 110983, Apr. 2022, doi: 10.1016/j.oceaneng.2022.110983.

[6] G. Bacelli, S. J. Spencer, D. C. Patterson, and R. G. Coe, "Wave tank and bench-top control testing of a wave energy converter," *Appl. Ocean Res.*, vol. 86, pp. 351–366, May 2019, doi: 10.1016/j.apor.2018.09.009.

[7] H. A. Said and J. V. Ringwood, "Intelligent control of a DC microgrid consisting of Wave Energy Converter (WEC) and Hybrid Energy Storage System (HESS)".

[8] X. Li *et al.*, "A compact mechanical power take-off for wave energy converters: Design, analysis, and test verification," *Appl. Energy*, vol. 278, p. 115459, Nov. 2020, doi: 10.1016/j.apenergy.2020.115459.

[9] "TC.GSS.20.600.4WR.S Programmable Bidirectional DC Power Supply - Datasheet." Regatron Inc., Jan. 03, 2023. Accessed: Apr. 17, 2023. [Online]. Available: https://www.regatron.com/programmable-power-supplies/en/

[10] National Instruments, "FPGA Timekeeper and the NI 9467 GPS Module - NI," *National Instruments*, Mar. 30, 2023. https://knowledge.ni.com/KnowledgeArticleDetails?id=kA00Z000000P70iSAC&l=en-US (accessed Apr. 26, 2023).