Post Access Report

Dynamometer testing of a magnetically geared electrical generator

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EXECUTIVE SUMMARY

Ocean Renewable Power Company's (ORCP) RivGen device is a horizontal crossflow hydrokinetic turbine, featuring a proprietary Turbine Generator Unit (TGU) mounted on a chassis. This system has been proven in real-world conditions in Alaska and is now the longest operating hydrokinetic project in the Americas. By harnessing energy from rivers without dams or impoundments, it strengthens grid performance and contributes to long-term carbon reduction. ORPC systems typically use direct drive permanent magnet (PM) generators which are highly efficient, but large and relatively costly. To reduce cost ORPC has identified several geared PM generators that may be suitable as replacements, however the efficiency of these components has not been evaluated across a range of operating conditions.

A critical aspect of evaluating potential replacement generator's benefit to RivGen is establishing the candidate generators efficiency once assembled. This efficiency is driven not only by the generator's characteristics, but also other system components (e.g., seal losses, bearing friction, etc.) that are dependent on operating state. This can be difficult, if not impossible, to achieve with in situ testing. Thus, similar measurements are generally performed using a laboratory test bed, or dynamometer. Specifically, a prime mover (e.g., a motor) with adequate supporting sensors can provide a known mechanical power to the machine under test. Measurements of torque, speed, and electrical power generated by the machine under test then capture system efficiencies as a function of operating state.

The Applied Physics Laboratory at the University of Washington (APL-UW) has developed a laboratory dynamometer that has been previously used to characterize tidal turbine and wave energy converter power take-offs. Similar analyses were be performed with the candidate generator, an EMF Synchronous Torque Motor (model SQM200-500) with a rating of 18.8 kW. This model is a permanent magnet, direct drive generator with magnetic gearing. A custom submersible enclosure for the generator was designed and assembled by ORPC. After installation, alignment, and coupling of the EMF assembly to the dynamometer prime mover, the dynamometer drove the EMF assembly across the full range of torque and shaft speed setpoints within the capabilities of the dynamometer system (i.e., up to shaft speeds of 120 RPM and input shaft torques of 1750 N-m). Testing was performed in 10 RPM increments of shaft speed and 250 N-m increments of resistive (power generating) torque applied by the generator. Results of the tests were post-processed to evaluate mechanical losses in the system and calculate overall power efficiencies (i.e., electrical power output divided by the mechanical power provided to the driveshaft). The data reveal clear, steady trends in mechanical losses as a function of shaft speed and torque while maximum power efficiencies for the generator, installed in its submersible housing, exceeded 90%. Furthermore, the system was determined to achieve its target power efficiency of 85% over across a broad range of tested setpoints.

1 INTRODUCTION TO THE PROJECT

When operating in situ, ORPC's RivGen units convert power from the ambient inflow into mechanical power. The mechanical power, which is product of the torque generated by the rotor and the shaft speed, transmitted to the driveshaft that is not dissipated by losses inherent to the system is ultimately converted to AC electrical power. Many components associated with a system's driveline, often including a generator itself, lack the full specifications with which to adequately predict performance over the range of operating conditions. To close this gap, ORPC was interested in characterizing a candidate magnetically geared PM generator. Of primary interest was the efficiency of the generator in converting mechanical shaft power into AC electrical power across the range of torque and RPM conditions expected in field operation during a hypothetical deployment of a RivGen unit equipped with the candidate generator and associated mechanical assembly.

Controlled testing of assembled drivetrains or generators can take place on a dynamometer. For the purposes of power take-off as described herein, characterization using a dynamometer requires that the system can accommodate the mechanical loads required to support the critical components, allow for alignment of the systems, and maintain adequate control during testing under a range of speeds and torques. Once installed, a dynamometer's "prime mover" controls the mechanical inputs to a driveshaft, which transmits the power to the "test article" (in this case the full ORCP generator/housing assembly. By properly measuring torques and speeds applied to the input shaft of the test article and measuring variables associated with mechanical and electrical power of the test article, system efficiency can be determined. By testing over a broad range of conditions a general performance map for the test article can be created.

The Applied Physics Laboratory (APL) at the University of Washington developed a dynamometer for testing and characterization of power take-offs to support its ongoing work on tidal turbines (Bassett et al., 2025) and wave energy converters (Rusch et al. 2023). While RivGen, and the candidate generator, can operate at conditions that exceed the capabilities of APL's dynamometer, the dynamometer's operating envelope (i.e., shaft torque, speed, and electrical power limitations), captures critical portions of RivGen's targeted operating envelope.

Once installed on a dynamometer, the measurements required to characterize a system can be relatively straightforward. In this case, the system's prime mover (referred to here as the dyno motor) was attached to a driveshaft equipped with a torque cell and encoder. The dyno motor can be driven by arbitrary signals falling within its capabilities, with a target control state update rate of 4 kHz. Sampling of the torque and speed provided to the driveshaft were used directly to measure mechanical power (P_m) input to the system. By simultaneous sampling of variables from the test article, shaft position (encoder), mechanical speed, voltage, shaft torque, winding current, power factor, electrical power generated (P_e), and efficiency ($\eta=P_e/P_m$) can all be either directly measured or calculated. The objective of this project was simple: the candidate EMF (model SQM200-500) motor, fully assembled in its underwater enclosure, was integrated with APL-UW's dynamometer, and subsequent testing resulted in detailed efficiency estimates of the EMF system in the anticipated torque and RPM ranges.

2 Roles and Responsibilities of Project Participants

2.1 Applicant Responsibilities and Tasks Performed

ORPC worked closely with APL-UW to carry out the project.

- To make APL's dynamometer suitable for integration with ORPC's generator housing, modest mechanical modifications to the testbed were required to support the structural loads and ensure shaft alignment. In addition, prior to performing the work it was necessary to ensure all electrical components were suitable for integration with existing equipment. To facilitate the modifications ORPC provided detailed mechanical and electrical drawings to APL-UW engineers.
- Before testing and integration occurred, ORPC commissioned a stable and shippable generator/housing assembly and prepared ancillary equipment and documentation for system integration.
- ORPC organized the shipment of the assembled system and ancillary electrical equipment (e.g., electrical drive, braking resistor, power cabling, etc.) to and from APL-UW.
- Remote oversight of commissioning and operation of the generator, including provision of controller settings and guidance on generator-side data streaming was supported by ORPC.
- Prior to decommissioning the dynamometer and ORPC assembly after the tests, ORCP reviewed data outputs for acceptability. This included efforts during preliminary testing to verify system configuration.

2.2 Network Facility Responsibilities and Tasks Performed

APL-UW carried out all necessary tasks to ensure that integration, testing, and characterization of the EMF system was performed successfully. This included several preparatory activities, active control of testing, and limited data post-processing and analysis, which is described in greater detail in Sections 6 and 7.

Procurement: APL-UW's dynamometer was initially designed for lower power and lower torque generators than the EMF system. Furthermore, the EMF driveshaft is much larger, at a 100mm diameter, than the 60mm diameter standard across dynamometer driveline hardware. A new shaft coupling was procured to connect the EMF shaft to the dynamometer driveline, and a new motor module was procured to maximize the overlap between the EMF and dynamometer operating ranges.

Dynamometer preparation: The ORPC enclosure was too large to fit on the existing foundation of the dynamometer, both in terms of the shaft centerline height and the mount width. APL-UW engineers developed new mounting plates to allow the EMF assembly to be integrated onto the dynamometer, and installed, aligned, and coupled to the ORPC system to the dynamometer foundation and driveline.

The dynamometer's direct drive PM motor also required a gearbox to apply torque greater than approximately 750 N-m, and the installation, alignment, coupling and removal of this gearbox were also performed by APL-UW.

Operations: APL-UW mechanical and electrical/software engineers carried out testing and data acquisition. Preliminary quality control of data was performed in near-real time, along with more detailed statistical analysis of selected representative sampling windows.

Data processing: APL-UW provided raw and curated data to ORPC for further post-processing (see Sections 6 and 7).

3 Project Objectives

ORPC has built and deployed multiple systems in river and tidal environments. These units have used direct drive permanent magnet generators, rather than smaller geared motors, to avoid the complexity of underwater gearboxes, and to maintain high power generation efficiency. However direct drive PM generators are expensive and heavy. To reduce capital costs, ORPC wished to evaluate a magnetically geared generator system.

The purpose of this work was to assess the efficiency of a commercial off the shelf (COTS) magnetically geared generator, which has been packaged by ORPC for underwater applications. Should testing confirm that the packaged generator has high efficiency across a wide range of operating conditions, it may be adopted in ORPC's river power systems, significantly reducing capital cost of the MHK device. This will also prove the concept of a non-mechanically geared PM generator for use by other technologies.

The major physical characteristics of interest are generator output voltage as a function of shaft speed, generator output current as a function of shaft torque, and the interaction of voltage/speed, current/torque over a range of combined settings.

From these physical characteristics a map of system efficiency as a function in shaft speed and shaft torque was derived. Targeted performance metrics for the system were:

- Shaft speeds of 0 to 120 RPM
- Shaft input torques of 0 to 1,750 N-m.

At testing input shaft speeds and torques net power production, efficiency, and torque losses are derived from measurements made from the prime mover, shaft torque cell and encoder, and the test article. Critical measurements for interpreting power production and system efficiency include input shaft torque and speed and current, voltage, electrical power generation, torque, and speed associated with the generator, which is located within the housing and therefore impacted by the presence of the unit’s housings seals and other lubricants. Because these variables are inherent products of APL’s dynamometer and ORPC’s generator assembly, the relevant metrics are readily determined so long as the data are logged and timestamps corresponding to all instruments are sufficiently aligned.

Ideally, testing across these conditions would yield a peak efficiency greater than 85%, but efficiencies are ultimately constrained by the performance of the generator are the submersible housing. Thus, the objective of the project was simply to characterize the performance for consideration in future system adoption. Testing was able to achieve and, in the case of shaft input torque, exceed, the stated targets. Note, however, that due to electrical power restrictions it was not possible to simultaneously test at high shaft speeds and torques.

4 Test Facility, Equipment, Software, and Technical Expertise

APL-UW is a research department at the University of Washington that has a broad range of resources that support the organization's field-facing research activities for sponsors including numerous government agencies, philanthropic organizations, and private industry. This includes laboratory spaces and warehouse/storage spaces used for preparation and testing of large equipment. The work proposed here leverages a testbed used for characterizing components of marine energy systems. Facility requirements for operation of the testbed include adequate spaces, basic shop equipment and tools, three-phase power (240 or 480 VAC and transformers), and lifting equipment (e.g., forklifts or cranes). The testbed itself is set up in a large staging area that can be reserved by APL-UW staff for long-term needs that meets all these requirements (including multiple 240 VAC receptables up to 60 A).

APL-UW's test bed (Figure 1) was designed to serve multiple purposes associated with the development and characterization of marine energy converters. The first is to serve as a dynamometer for evaluating torque-speed-efficiency maps of generators or assembled components of power take-offs. The second design objective was to provide the system with sufficient flexibility to allow for broader system characterization, including realistic (i.e., oscillatory) loads, and to support development of controls algorithms. To achieve these goals the testbed (Figure 1) is built around a large steel frame with modular components for mounting motors, gearboxes, and other structures. The prime mover (dyno motor) in the system is a Siemens 1FW3202 torque motor. This motor can provide torques of up to 500 N-m at speeds up to 150 revolutions per minute (RPM) under continuous operations while torques up to 925 N-m, with speeds exceeding 200 RPM can be achieved under duty cycled operation. These speeds and torque can be augmented with the use of gearboxes. Thus, the system can apply continuous mechanical powers up to 7.8 kW (10.9 kW in duty-cycle operation) to a drive shaft coupler and supporting equipment and marine energy converter power take-off subsystems. Siemens Sinamics S120 components are used for power and system management. Peak operating powers in the lab are limited by 60 A breaker on 3-phase 240 VAC lines making the prime mover and associated electronics the limiting components in operations. Experience has shown that the existing equipment and controls reach their setpoints quickly, making duty cycled operations feasible.

The motor is equipped with an absolute encoder (2^{24} counts per revolution). The angular position, voltage and winding currents, winding temperature, and applied torque (calculated from motor specifications) are communicated to system computers over Profinet. When operating the testbed power generated may be either dissipated through air- or water-cooled load dumps or transformed and dumped back to the grid. For the present effort, ORPC shipped a passively air-cooled resistor bank to serve as the load dump for power generated by the EMF motor. The dyno motor acted exclusively in motor mode (requiring input power to drive the system), and therefore a load dump was not required for the prime mover.

Controls and data acquisition are driven by a custom application with a graphical user interface based in Qt (written in C). From this interface the motor can be controlled to apply constant torque, constant speed, or to follow arbitrary speed/current waveforms imported from .csv files (typically exported from Matlab). Under any control strategy the system can be either controlled manually to set dwell times and shift between set points. Shifts between set points are ramped to provide a smooth transition using a function like a Hann window (a raised cosine window whose derivative goes to zero at the end points).

The motor shaft is connected to a 60mm driveshaft equipped with a Himmelstein MCRT® 84004V wireless inline torque cell (torque rating 2260 N-M, speed rating 8500 RPM, sampling rate up to 20 kHz). Between the torque cell generator shaft coupler flexible mounting for gearboxes is provided. A Nidec-Shimpo VRT 285 5:1 ratio planetary reducer was used for setpoints requiring a torque above the capacity of the dyno motor in direct-drive mode. The final coupling to the generator shaft is made using a R+W America LPH disc pack coupling (a suitable coupling will need to be procured to match the shaft size of the ORPC unit).

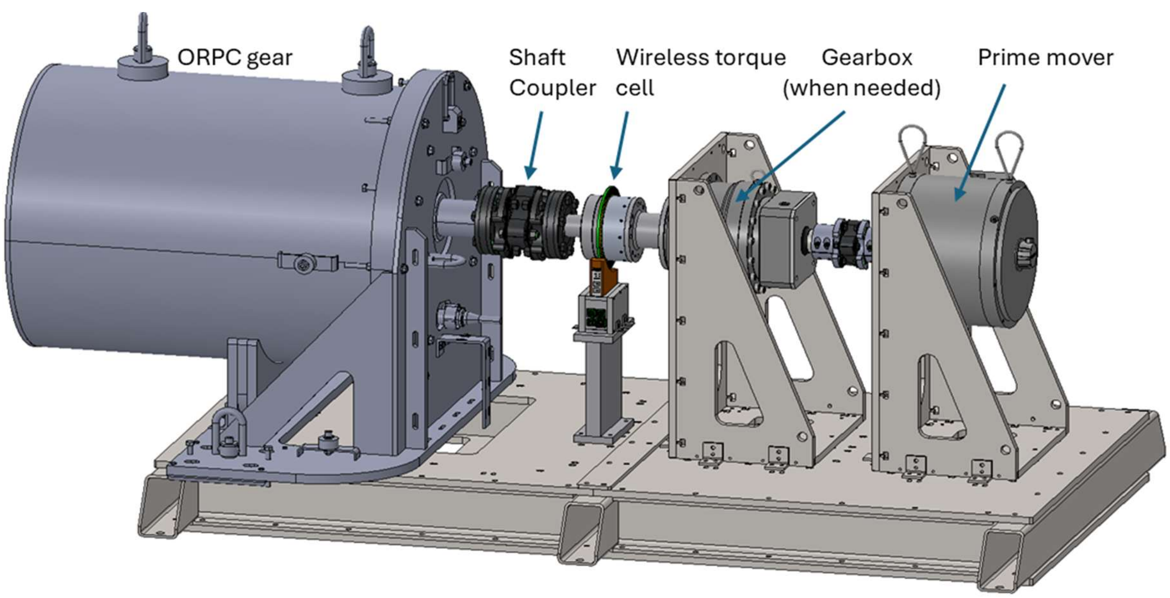

Figure 1. A rendering of APL-UW's dynamometer showing critical components including the dyno motor, gearbox, torque cell, shaft coupler, and ORPC generator/enclosure. Not shown is the 240 to 480 VAC transformer available at APL-UW's warehouse, or any of the control system power electronics.

Data collection requirements for the testbed vary by use case and can be modified. Herein, data were collected from the Siemens equipment and load cell, which is written into auxiliary channels in the Siemens data acquisition script, at 1 kHz. Data are stored in binary (.dat) files that were post-processed using Matlab. Data strings included in these binary files including timestamps (UTC, NTP synchronized), winding voltage, winding current, incremental encoder position, absolute encoder position, motor torque, motor speed, electrical power, winding temperature, and speed/torque setpoints. The data streams were recorded in several formats consisting of between 16 and 32-bits follow system specifications. When triggered to acquire data the system automatically began writing .dat files with date and timestamp in the filename and corresponding to each line of data. During operations, data acquisition with the ORPC systems using a laptop computer to log data from the electrical drive (see Section 6 for details), recorded all standard data streams (voltage, current, power, and power factor). Prior to testing, both data acquisition computers were synchronized (Network Time Protocol) to ensure timestamp alignment. Note that this proved to be an issue, as the Rockwell CCW software did not successfully push time synchronization from the laptop to the drive, as is discussed below.

Four APL staff supported the efforts to carry out system design modifications, integrated ORPC's system, perform the tests, and analyze the data. testing, C. Bassett (APL-UW lead) directed project and generated the initial post-processed data products for further analysis prior to providing the outputs to ORPC. A mechanical engineer (P. Gibbs) procured all necessary supplies, oversaw design modifications and equipment integration, and completed the analysis following the first stage of post-processing. A software/electrical engineer (J. Dosher) operated APL's dynamometer during tests. An electrical engineering (B. Cunningham) carried out all electrical system integration.

5 Test or Analysis Article Description

Ocean Renewable Power Company, Inc. (ORPC) is a global leader in marine renewable energy (MRE) technology and a developer of ecoconscious projects that harness the power of oceans and rivers to generate clean, predictable renewable energy. ORPC has made significant progress towards implementing high reliability hydrokinetic systems with six generations of turbine technology tested through fourteen system deployments since 2004, and has built, operated, and delivered power to the grid from both tidal and river projects.

The RivGen Power System is a commercial offering from ORPC, rated to deliver 40kW of electricity at flow speeds of 2.25 m/s. ORPC is developing a smaller version of the RivGen Power System, called Modular RivGen, to provide a power generation system with specific application in low flow riverine environments. The Turbine Generator Unit (TGU) is the core component of our Power Systems. A TGU consists of an underwater permanent magnet generator mounted between multiple crossflow turbines on a single drive shaft; these components are then mounted on a chassis.

ORPC sought to evaluate a different and novel electrical generator for use on the Modular RivGen Device. The generator is an EMF Motor Synchronous Torque Motor, model SQM200-500 with a rating of 18.8 kW. This model is a permanent magnet, direct drive generator with magnetic gearing. A custom submersible enclosure for the generator was designed and assembled by ORPC. The nacelle is air filled and submerged during operations (Figure 2). Thermal management is handled by internal cooling fans.

The use of magnetically geared generators has been suggested for multiple marine renewable energy technologies, but has not yet been reduced to practice in a device, as far as ORPC is aware. This work will provide qualitative and quantitative data on how well such a generator system could operate under operating conditions typical of a river current energy converter.

Figure 2 Picture of the submersible housing for the EMF generator that was tested on the dynamometer.

6 Work Plan

The project work plan contains three basic phases: preparation, testing, and post processing. Each of these is described independently in Section 6.1.

6.1 Experimental Setup, Data Acquisition System, and Instrumentation

Preparation

Preparation for the dynamometry work included procurement, fabrication, and setup before the experiments could be carried out. ORPC provided mechanical drawings of the generator enclosure. These drawings were used to finalize the foundation modifications (as shown in Figure 1). A new motor module (to increase the current limit of the system from the pre-existing unit that would have further constrained operational setpoints) and shaft coupler were ordered, along with fasteners and shims. The shaft coupler was required for transmitting mechanical power from the dyno motor to the larger driveshaft on the ORPC system. While not technically demanding, installation and alignment of dynamometer driveline components supported by independent bearings is complicated because they are heavy and challenging to align precisely enough to prevent premature bearing failure. Shaft alignment was carried out with dial indicators and an SKF TKSA11 shaft alignment kit being used to verify adequate alignment, and torque wrenches used to ensure all bolt groups were adequately tightened.

Experiment

The objective of the testing was to map out as much of the potential operation space for the EMF motor as was possible. This was ultimately determined by a combination of the torque and speed limits of the prime mover, with and without the 5:1 gearbox, and power draw limitations. The dyno motor and the EMF assembly were controlled independently. The dynamometer operated in constant speed control. Thus, a target RPM shaft speed was directed by the dynamometer controller, and torque delivered by the dyno motor was varied to maintain this setpoint shaft speed. The dynamometer controller set the target RPM for the shaft of the Siemens direct drive motor. When the 5:1 gearbox was installed, the dynamometer controller RPM setpoints were 5x the shaft speed seen by the ORPC system. All speed setpoints referred to in this document relate to shaft speed experienced by the driveshaft external to the ORPC housing and the torque cell.

The ORPC system operated in torque control mode. The Rockwell Automation Connected Components Workbench (CCW) software package was used to configure the Allen Bradley drive to only allow the EMF motor to absorb power (i.e., to only operator as a generator). CCW torque setpoints were defined as a percentage of the EMF rated torque (2000 N-m). Thus, to achieve a particular torque of, say 250 N-m, the software setpoint value was 250/2000*100% = 12.5%. Because this is torque generated by the EMF windings, the driveline torque measured by the loadcell will always be higher, as it must supply both the winding torque and any torque lost due to seals, bearings, magnetic gearing, windage, eddy currents, and magnetic hysteresis.

The dynamometer driveline was configured as shown in Figure 1 and a simplified system schematic is shown in Figure 3. During operations, a custom supervisory control and data acquisition (SCADA) interface is used to control the prime mover while STARTER, a Siemens software package for commissioning and monitoring equipment, is instantiated and used as an additional interface for real-time monitoring of the equipment. Any time the system is operating, the SCADA logs the prime mover's voltage, torque, speed, electrical power, position (encoder) data, and winding temperature at 1 kHz. These signals are prepared and communicated by Siemens equipment and are written in multiple formats from ranging from 16- to 32-bits. Timestamps are recorded in recorded in UTC with Network Time Protocol used to minimize timing errors. Conversion factors for the various variables provided by the Siemens equipment are explained in the equipment manuals and associated with the prime mover's motor specifications. The shaft torque cell records analog +/- 10 V signals that are converted to torque using manufacturer calibrations and written as floating point values sample at 1 kHz. All the data are written into a single file, whose filename is determined by the time at which the file started, are unpacked in post-processing using a custom MATLAB script. Data from the prime mover were recorded to support the characterization of the ORPC system, but are not necessary for analysis as the torque cell provides the relevant torque data without ambiguity (i.e., no assumptions about losses in the gearbox are necessary).

CCW's Trend tool was used to log data from the Allen Bradley drive at 10 Hz, which was determined by ORPC to be sufficient resolution. The following parameters were included in the log files:

- Velocity [RPM]
- Commanded torque [% of Rated Torque]
- Torque feedback current [Amps]
- Output current [Amps]
- Output voltage [Volts]
- Output power at the AC drive generator terminals [kilowatts]
- Output power factor [-]

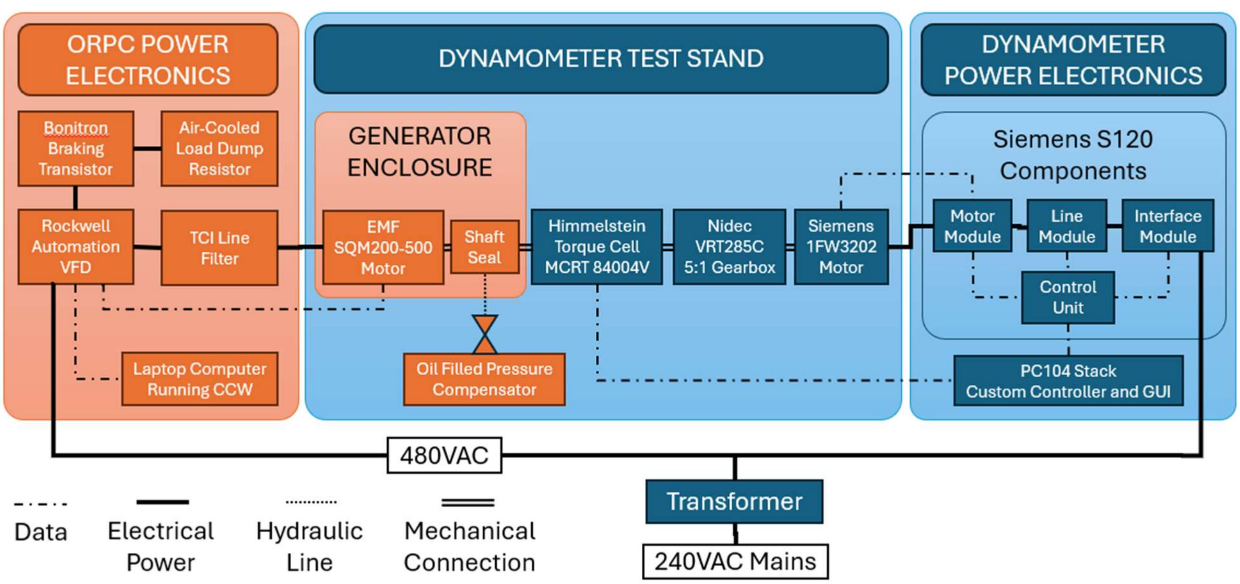

Figure 3 A labeled schematic of the system used for the testing.

The EMF housing assembly came with an oil-filled, pressure compensated shaft seal. This seal was connected to the pressure compensator during testing, with the valve open, allowing pressure to transfer through to the shaft seal. The bell housing on the EMF assembly was removed prior to testing to allow for venting of the shaft seal, and all testing was run with the housing removed, allowing for better cooling of the EMF generator. Note that EMF winding temperature was *not* tracked during testing, and this would be a potential improvement for future tests, as resistive losses in the windings can change significantly due to winding temperature.

A river current turbine is expected to operate over a wide range of operating conditions and be capable of modulating output power from 0 to 100%. For a stall regulated turbine this is achieved by allowing the turbine to spin at a higher speed than is optimal for maximum power generation. Under no load conditions this results in a high tip speed ratio, high generator output voltage, but low shaft torque/generator current. Optimal system efficiency is expected to occur at intermediate shaft speeds and high shaft torque. Accuracy of efficiency measurement in this regime is critical. Understanding higher speed operation, and torque response is also important to assess the ability of this magnetically geared generator to operate over the required range of operational conditions.

6.2 Test and Analysis Matrix and Schedule

Pre-data collection commissioning of the system occurred in several steps.

1. Installation of the dyno motor, gearbox, torque cell, and EMF assembly on the test stand. This involved installing the standoff plates and coarse positioning of the equipment.
2. Fine alignment of the driveline components. The coupling connecting the EMF shaft to the torque cell was installed. At this point, bolt patterns were torqued to specification except for the coupling between the EMF shaft and the torque cell.
3. Wiring up, commissioning, and testing of the ORPC assembly and controller equipment to ensure the motor was behaving according to expectations and that data was being recorded.
4. Commissioning and testing of the prime mover system.
5. The generator-to-torque cell shaft coupling was tightened to specification, and initial runs of the combined system at low torque and increasing RPM took place to validate that the system could be controlled as expected.
6. Independent shutdown safety was tested. The EMF and dyno motor were each shut down independently in the middle of a test to ensure that both system controllers were able to maintain control during a loss-of-counterpart event.

The first tests performed were not required for characterization of the generator. Rather, they were to ensure that high quality data was acquired. Only after these were completed did characterization efforts commence.

Response time test

Prior to beginning efficiency testing, system response timescales were estimated and adequate thermal management was confirmed. In prior testing with the dyno system, it was found that test articles coupled to the dyno motor were able to transition between set points in a second or less. For the current effort, torque and RPM transients between setpoints took slightly longer to dampen out. As demonstrated in Figure 4, roughly 3 seconds were required when the gearbox was installed, and 5 seconds without the gearbox. A minimum of 10 seconds of data was collected for each setpoint when the gearbox was installed, and 15 seconds for setpoints without the gearbox. Note that these short sampling periods are more than adequate to collect suitable data for power generation and efficiency data from the system. As shown in Figure 4, when set points are stable both the prime mover and test article produce near constant data outputs. Thus, simple time of the outputs, corresponding to periods of at least six seconds, from the various system components result in robust estimates of system performance.

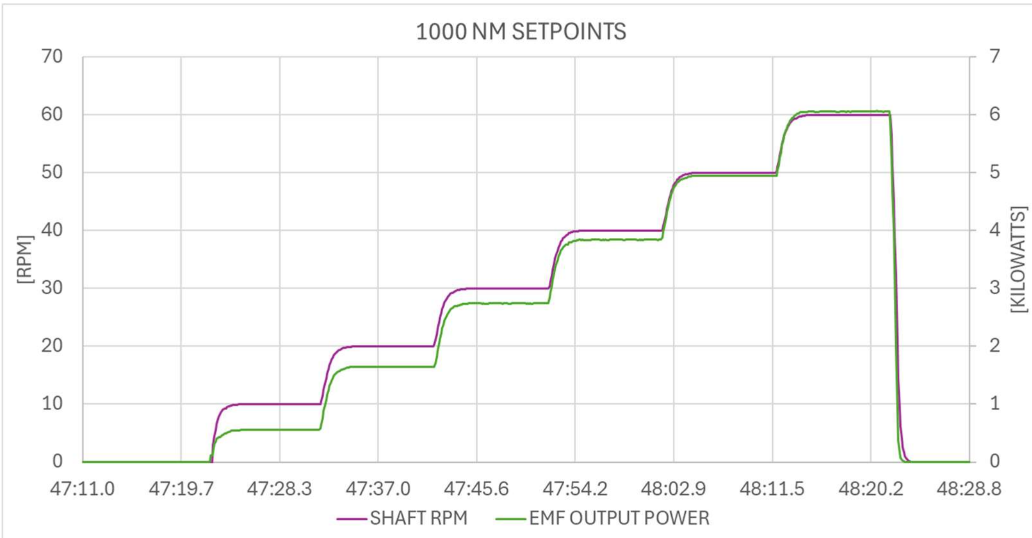

Figure 4 Example of raw data recorded by ORPC system showing ramping and transients between setpoints. The torque setpoint for this test was a constant 1000 N-m, with RPM stepping at 10 RPM steps from 0 to 60 RPM. This setpoint had the 5:1 gearbox installed. Note that both the shaft speed and electrical power generation are stable throughout the sample periods after the system adjust to each setpoint. The x-axis show the time (format min:sec).

Thermal management test

Another issue with the potential to impact testing protocells, the duration of tests, and speed at which they can be completed was thermal management. The dyno motor has a sensor and safety features that will trigger shut down if the system is too warm. Nonetheless, it was necessary to ensure load dumps and other equipment did not overheat, particularly during sustained testing at the higher speeds at torques. Thus, a set of tests was performed early on at high torques and a moderate speed to ensure that the system could accommodate thermal loads to inform subsequent testing protocols. Preliminary testing revealed that when tested with short dwell times at each set point (e.g., < 15 seconds), thermal considerations did not preclude testing at the target set points. Thus, it was not necessary to include additional mechanisms for thermal management of the equipment or to modify the test matrix to allow for additional breaks between target set points.

Torque-speed-efficiency tests

A test matrix was established that defined the scope of planned testing. The matrix of conditions that were sampled is shown in Figure 5. Section 7.2 provides details around the setpoints that were not successfully tested, and those tested outside the original test plan. Setpoints that are blank are those that could not be sampled due to limitations in the dynamometer's capabilities or which are outside the anticipated operating region of the ORPC system.

Testing occurred on three different days:

- Day 1 06/05/25: Shutdown Safety, Response Time, and High Torque Tests.
  - Shutdown safety and response time tests were successfully completed.
  - Electromagnetic interference (EMI) was found to have corrupted data from the high torque tests (setpoints from 0-60 RPM and torque up to 1750 N-m), necessitating the repetition of these setpoints.
- Day 2 07/02/25: Repeat of High Torque Tests
  - EMI was successfully mitigated with a shielded ethernet cable, allowing for collection of all anticipated setpoints except for (60 RPM, 1500 N-m) and (70 RPM, 1250 N-m).
- Day 3 07/29/25: Low Torque Tests
  - 5:1 gearbox was removed from the system.
  - All setpoints were successfully tested except for (70-90 RPM, 1000 N-m)

RPM Setpoints	Torque Setpoints (Nm)							
	0	250	500	750	1000	1250	1500	1750
10	0.00	0.26	0.52	0.79	1.05	1.31	1.57	1.83
20	0.00	0.52	1.05	1.57	2.09	2.62	3.14	3.67
30	0.00	0.79	1.57	2.36	3.14	3.93	4.71	5.50
40	0.00	1.05	2.09	3.14	4.19	5.24	6.28	7.33
50	0.00	1.31	2.62	3.93	5.24	6.54	7.85	9.16
60	0.00	1.57	3.14	4.71	6.28	7.85	9.42	
70	0.00	1.83	3.67	5.50	7.33	9.16		
80	0.00	2.09	4.19	6.28	8.38			
90	0.00	2.36	4.71	7.07	9.42			
100	0.00	2.62	5.24	7.85				
110	0.00	2.88	5.76					
120	0.00	3.14	6.28					

Figure 5. A matrix of the (RPM, Torque) setpoints that were planned for and successfully tested. Planned for setpoints that were successfully tested shown in light green. Planned for setpoints that were not successfully tested shown in red. Set points outside the original test plan successfully tested shown in bright green. Tests at setpoints outlined in purple had minor deviations from the intended setpoints which are detailed in Section 7.2. Values inside the setpoint boxes are the corresponding mechanical power in kilowatts resulting from the speed and torque combination.

Investigation of the corrupted data from the first day of testing revealed that EMI from the prime mover resulted in significant noise on the Ethernet cable used for communications and data acquisition with the EMF generator. To resolve this a new cable with better shielding was purchased and integrated for subsequent testing. This successfully mitigated the noise issue and permitted testing to continue. Despite the corrupted data from the initial test day, all data was collected within the anticipated 3 days originally anticipated to be required.

Table 1 shows the actual schedule of work, which began immediately after budgets were available to support the work. As soon as funds were available in late March, the long lead time parts were ordered and drawings completed. The anticipated total length of time required to go from funding availability to completion of testing was approximately equal to the original schedule.

Table 1. The actual schedule. Note each block represents a two-week period.

	March		April		May		June		July	
Order equipment		■	■							
Drawings to shop			■	■						
Fabrication & Assembly					■	■				
Setup							■	■		
Testing								■	■	■

6.3 Safety

Setup required moving and lifting heavy equipment. This required forklifts and overhead hoists to lift heavy equipment and to align heavy parts on the dynamometer. Only those certified to drive the forklift were permitted to do so and those participating in the assembly of equipment followed standard operating procedures including the use of personnel protective equipment. Checklists were used to ensure mechanical components were properly installed and that bolt groups were torqued to specification. Bolt groups and system driveline alignment were checked periodically throughout testing as well.

Building electrical equipment is wired to code and relevant electrical systems are wired to prohibit access to leads during testing. Rotating components of the dynamometer were protected by an enclosure placed between the motor/generator during testing. Wall disconnects were used to ensure the systems were powered except during testing. During setup, all monitoring systems (e.g., computers) are setup on a rolling table set back approximately 2 m dynamometer. Those participating remained at the table during testing. As noted in the prior section, testing of independent system shutdown safety was performed, and drive parameters ensuring that the EMF system could not operate in motor-mode were checked throughout testing.

6.4 Contingency Plans

No significant modifications to the initial test plan were required to execute the work as described.

6.5 Data Management, Processing, and Analysis

6.5.1 Data Management

Raw data written by the dynamometer controller were logged on local computers and cloud storage (Dropbox). All raw data from the dynamometer are archived as .dat files containing binary data. These data could be accessed in near real-time and were post-processed to produce .mat (MATLAB) files. The .mat files contain a time series of every variable recoded by the dyno (see Section 4) at 1 kHz with corresponding timestamps. Metadata is also written into the raw files and exported into the .mat files by entering testing information in the dyno systems user interface. These data, which were processed and logged on a Desktop computer, were written to a hard drive that are regularly backup up.

Raw times-series data generated by ORPC systems was logged at 10 Hz by a laptop running CCW (see the logged variables listed in Section 6.1) and saved in .csv files. CCW did not have the capability to log at 1 kHz.

Not all tests that created raw data files generated useful data for capturing performance of the EMF system. For any given test, a log was kept of the setpoints for each system during that test, the output file names for both the EMF and dynamometer, the test start time (also defined in the automated naming of the data file produced by the dynamometer), and notes about the test and configuration of the dynamometer. Tests that contained data expected to be useful for characterizing the performance of the ORPC system were flagged for post-post processing. The remaining files were archived, but not fully post-processed.

A summary Excel workbook will be included in the MHKDR submission. This summary file has all the raw time series data for the EMF system, as well as post-processed dynamometer data. The post-processed data from the dynamometer that is included in this workbook is raw data outputs that have simply been truncated to remove data not relevant to tests and the variables have been renamed at the request of the applicant. Thus, the dynamometer data in the summary workbook is sampled from the steady-state parts of each setpoint test, with the sampling method detailed in the Section 6.5.2. Post-processed dynamometer data series are:

- timeHSS: time stamp
- torqueLSS: torque measurement from torque cell [Nm]
- rpmLSS: shaft speed experienced by EMF shaft [RPM]
- powerLSS: mechanical power input to EMF shaft (product of torque LSS and rpmLSS) [kW]

Post processed data contain variables for time, torque, speed, and power, which, in their archived form, are denoted by either a “LSS” or “HSS.” LSS is shorthand for “low speed shaft” and therefore represents the variables measured by the generator driveshaft. Timestamps were aligned using the dynamometer timestamps due to its higher sampling rate, and are thus denoted by HSS (shorthand for high speed shaft).

Table 2. MHKDR files from this project.

File Name	Description	**# of Files**	**Format**
TEAMER_ORPC_Summary_Workbook	All data files from EMF and dyno systems used in this report, as well as summary tables.	1	.xlsx
TEAMER_ORPC_Plotting_Script	Jupyter Notebook containing plotting script for contour plots in Figure 8 and torque loss linear regression model.	1	.ipynb
EMF_DYNO_Primary_Results	Workbook containing data used by plotting script. Tabs contain data copied from tables in the Summary Workbook.	1	.xlsx

6.5.2 Data Processing

Data processing for the proposed dynamometer measurements was relatively straightforward given that the system was operated at a steady state during each setpoint test. After each test day, a custom Matlab script unpacked the raw binary data from the dynamometer. Data was immediately reviewed by APL-UW personnel to ensure that no notable deviation from expected behavior was recorded.

Errors in testing were generally easy to identify as dynamometer operations are relatively simple. Most errors were avoided by reviewing system data in real-time. The only significant error that was not caught during testing in real-time (although suspicions were raised) was the loss of data from EMI disrupting the ethernet connection between the laptop running CCW and the EMF electrical drive. This was a result of a lack of familiarity with CCW, as well as the intermittent behavior of the packet loss. Figure 6 shows an example of the loss of data packets. CCW, instead of showing packets were lost by leaving data entries empty, would replicate the most recent good data point until the next good data point successfully arrived. While the data shown in Figure 6 *might* still be useful, the packet loss issue immediately became excessive at torque setpoints above 0 N-m.

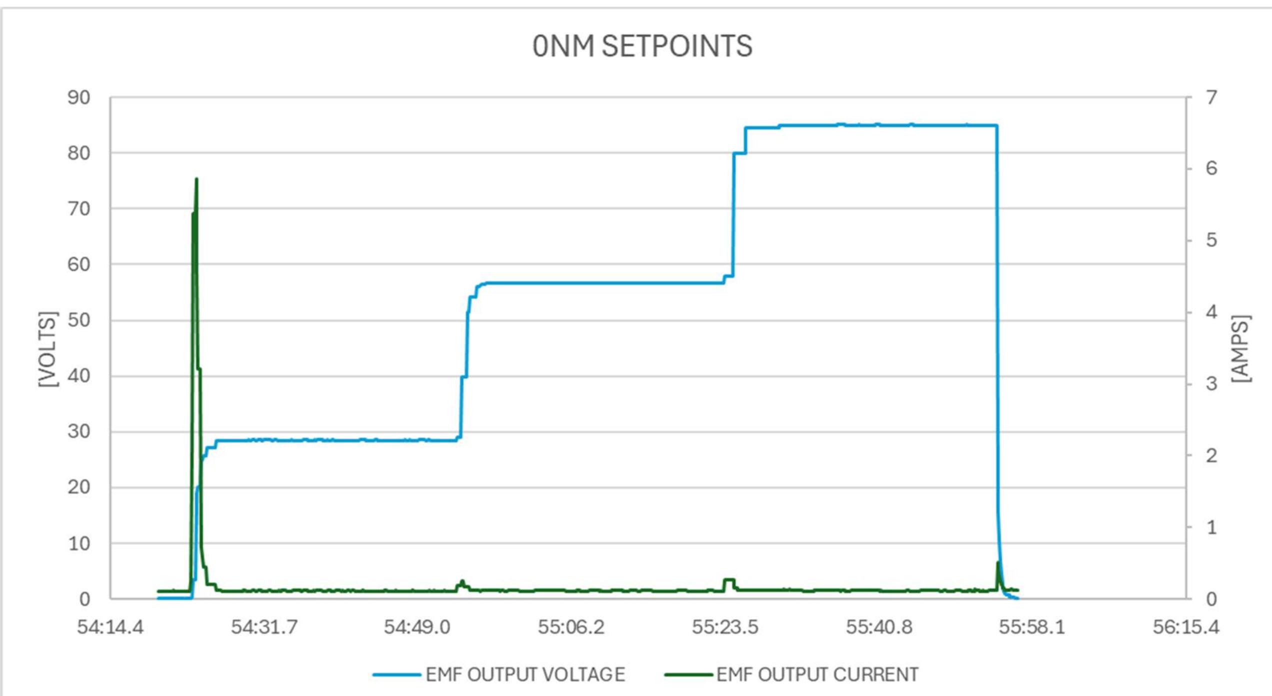

Figure 6. Example of data loss from 0 N-m setpoint run prior to use of shielded ethernet cable between the laptop CCW and the drive controlling the EMF generator. Voltage and current are directly proportional to shaft speed and torque, respectively. Note the choppy, step-wise shape of the voltage curve, particularly during current spikes. The x-axis shows time (min:seconds).

Next, for each test, data was manually reviewed to determined periods when both the prime mover and generating were operating in a steady state for a given setpoint. Timestamps corresponding to these periods were isolated and used to extract all relevant data for that setpoint. Specifically, timestamps associated with the steady state operation of both systems were isolated. Then the dynamometer timestamps were used to identify all data points acquired by the ORPC system in the same timeframe. Despite requesting through CCW that the EMF drive synchronize its clock to UTC, timestamps between the EMF data and dynamometer data were variably asynchronous up to ~2 seconds. Therefore, to synchronize time between the dynamometer and EMF datasets, the time difference for each dataset was measured and applied to the dynamometer time stamps. The time difference was measured by manually identifying the transition from one RPM setpoint to the next in both the EMF and dynamometer data files. Although somewhat imprecise, this manual process does not have significant implications for calculations given that the signals of interest (torque, speed, current, voltage, etc) were stable once the system reached steady state. Once the timestamps were aligned the first three seconds of data at each setpoint were removed to isolate transient signals associated with the shift between setpoints. The subsequent six seconds of data with the systems at steady state were then isolated and used to calculate time averages of all relevant variables as described below. These temporally aligned data are documented in the Excel summary spreadsheet file contains the processed dynamometer data with timestamps synchronized to the corresponding EMF data file.

With the timestamps synchronized, a simple statistical test was applied to the data sets to determine whether average values of each variable within a particular setpoint were sufficient for analysis (i.e., they exhibited sufficiently low noise), or if performance characteristics needed to be calculated for each timestep and then compared. The sample coefficient of variation (CV), defined as the absolute value of the sample standard deviation (s) divided by sample mean ($\bar{x}$) was used to determine whether the variable was approximately constant throughout the timestep:

$$CV \stackrel{\text{def}}{=} \left|\frac{s}{\bar{x}}\right| \qquad \textit{Equation 1}$$

Setpoints with variables that had CV values > 0.02 were individually inspected for data quality. Most situations with high CV values were from setpoint tests where the mean of the variable in question was at or near 0. For example, the EMF torque feedback current from the 0 N-m torque setpoint tests had CV's greater than 1.0 for *all* RPM setpoints, but this is not surprising. Mean current values for these setpoints were all <5 mA, and the standard deviations <10 mA, which, when multiplied by the motor torque constant of 45.45 N-m/Amp, implies the EMF controller was maintaining an average torque of <0.25 N-m with a standard deviation < 0.5 N-m, an excellent result considering the target setpoint was 0 N-m and that the rated torque of the system is 2000 N-m. Other setpoints where CV values > 0.02 occurred were:

- Dynamometer torque measurements at (0 N-m, 10-110 RPM) for the same reason given above.
- At high power and RPM setpoints the dyno controller struggled to reach and maintain the setpoint. Figure 7 show an example setpoint for which the mean RPM deviated significantly from the target setpoint ($\bar{x}$ = 76 RPM, vs 80 RPM target), and indicated that, for an as-yet-unknown reason, the Siemens software was sampling the encoder at 250 Hz, rather than 1 kHz. Actual-vs-target setpoint deviations occurred for several of the highest power setpoints, and were an result of testing on the boundary of the dynamometer's capabilities. See Section 7.2 for

additional comments on these issues. Setpoints where these deviations were observed were ultimately included in our analysis but have been flagged to highlight the greater degree of uncertainty associated with the measurements.

- 80 RPM setpoints generally had dyno speed CV's between 0.02 and 0.05 due to the presence of a speed harmonic around 110 Hz that was consistent throughout the sample period. The cause of the harmonic is unknown.
- In general, any time a speed, torque, voltage, or current variable had a CV over 0.02, the associated power variable (either mechanical power in or electrical power out) had a correspondingly high CV.

All data used to produce the efficiency analysis results from this project either had CV values < 0.02 or otherwise demonstrated through individual inspection as detailed above that sample means were appropriate for calculating power loss, torque loss, and efficiency at each setpoint. Setpoint deviations are further detailed in Section 7.2.

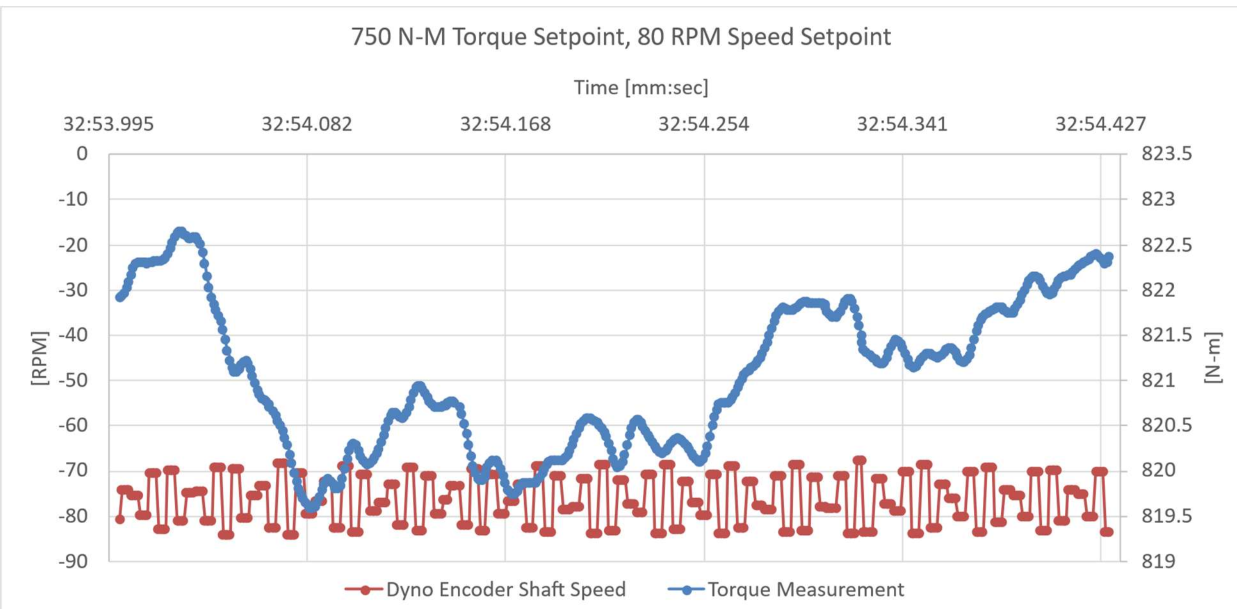

Figure 7 Example of high RPM, high power setpoint where the dyno motor struggled to maintain its setpoint. Also a demonstration of encoder under-sampling. Note that although the torque signal is seen to fluctuate in an unpredictable way, when converted to mechanical power the total deviation in mechanical power provided by the prime mover over the shown time periods is less than 0.5%.

6.5.3 Data Analysis

Primary results of interest are the torque and power efficiency. The total torque loss (τ_{loss}) in the EMF assembly due to seals, bearings, the magnetic gearing, windage, eddy currents, and magnetic hysteresis is calculated by subtracting the torque experienced by the EMF system (τ_{EMF}) from the torque measured by the load cell ($\tau_{load\ cell}$), as described by:

$$\tau_{loss} = \tau_{load\ cell} - \tau_{EMF}. \quad \text{Equation 2}$$

However, the torque experienced by the EMF system (τ_{EMF}) is not measured explicitly. Instead, the torque feedback current ($I_{torque\ feedback}$), one of the logged variables, must be multiplied by the motor torque constant K_M = 45.45 N-m/A to calculate τ_{EMF}:

$$\tau_{EMF} = K_M * I_{torque\ feedback}. \quad \text{Equation 3}$$

Torque efficiency is defined in Equation 4:

$$\eta_\tau = \frac{\tau_{EMF}}{\tau_{load\ cell}} = \frac{K_M * I_{torque\ feedback}}{\tau_{load\ cell}}. \quad \text{Equation 4}$$

Power loss is calculated by comparing the mechanical input power as measured by the product of the load cell torque and shaft speed (ω_{shaft})against the output power reported by the EMF controller.

$$P_{loss} = P_{input} - P_{EMF\ output} = \tau_{load\ cell} * \omega_{shaft} - P_{EMF\ output} \quad \text{Equation 5}$$

Power efficiency is defined in Equation 6:

$$\eta_{Power} = \frac{P_{EMF\ output}}{P_{input}} = \frac{P_{EMF\ output}}{\tau_{load\ cell} * \omega_{shaft}} \quad \text{Equation 6}$$

Power losses result from a combination of electrical inefficiencies, resistive losses in the motor windings, and torque losses. This project is interested in the total system efficiency, and therefore a breakdown of the individual sources of power loss was not performed.

In general, for a time series the ratio of two averages is not equal to the average of the ratio. In terms of calculating efficiency this is described by:

$$\eta_{Power} = \frac{\langle P_{EMF\ output}(t)\rangle}{\langle P_{input}(t)\rangle} \neq \langle \frac{P_{EMF\ output}(t)}{P_{input}(t)} \rangle, \quad \text{Equation 7}$$

where ⟨⟩ represents the average and the expression on the right is the proper time-averaged efficiency. However, in situations where both the numerator and denominator are stable (i.e., variability due to noise or performance changes is small) over the sampled time period either approach yields the same result. Given that the sampling from ORPC system and APL's dynamometer had different sampling rates and uncertainties in timestamp alignment, additional steps with uncertainty would have been required to perform the "correct" calculation of efficiency. However, because most tests resulted in low variability while stable at each set point, the average efficiency is well represented by the ratio of the averages (left-hand side) of Equation 7. This approach to calculating the average was adopted to avoid the aforementioned uncertainties. This represents how the system can be expected to perform if adopted for integration in an ORPC deployment. However, by isolating the inferred torque losses and accounting for them, the inferred generator efficiency is directly calculated. This allows for comparisons to other off-the-shelf generator units.

7 Project Outcomes

7.1 Results

This section summarizes the results of the characterization of the ORPC's generator/housing assembly, which are mapped onto grids based on the torque and shaft speed setpoint requested by ORPC in advance of testing. Thus, the horizontal dimension is setpoint torque (tested in 250 N-m intervals) and the vertical dimension is shaft speed (10 RPM intervals). Table 3 summarizes the input torques measured by the load cell. The first column of data, where the generator maintains a setpoint of 0 N-m, represents a "freewheel" condition, and can therefore be extrapolated to infer mechanical losses of the full generator/housing assembly. From 10 to 120 RPM, input torque values measured at the load cell varied from approximately 24 to 43 N-m. These set a baseline for mechanical losses in the system. For example, consider the results for a resistive torque of 0 N-m at 50 RPM. By converting the shaft speed to angular velocity (1 RPM = 0.1047 radians per second) and multiplying the measured torque (33.7 N-m) the total power dissipated by the assembly is approximately 176 W. Note that as the shaft speed increases the net input torque provided to the system increases, demonstrating an RPM-dependent torque loss. This is consistent with losses in drivetrain assemblies wherein components often exhibit losses terms depending both on speed and torque. In this case, in addition to viscous losses from bearing lubrication, the generator driveshaft passes through an oil-lubricated shaft seal (see Figure 3) which is expected to exhibit viscous behavior that results in torque drag on the shaft that is a function of the shaft speed. In addition to representing calculated system losses when operated in freewheel, these calculations at all resistive torque setpoints represent the power input to the ORCP generator/housing assembly by the prime mover, which is shown for all the setpoints in Table 4.

Table 3. Average torque measured by load cell. ($\tau_{load\ cell}$).

Input Torque [N -m]									
		EMF Torque Setpoint [N-m]							
		0	250	500	750	1000	1250	1500	1750
Dyno Motor Speed Setpoint [RPM]	10	24.0	285.5	547.5	809.2	1069.9	1332.0	1593.2	1855.4
	20	27.1	288.4	551.7	812.3	1073.7	1335.4	1597.6	1857.1
	30	31.0	292.5	553.2	815.6	1075.6	1337.3	1599.8	1861.0
	40	32.9	293.4	556.9	817.3	1078.5	1340.9	1602.4	1862.9
	50	33.7	296.8	557.7	819.8	1079.9	1341.8	1603.4	1865.0
	60	35.5	297.9	560.6	820.5	1081.7	1344.2		
	70	37.4	299.5	561.5	822.1				
	80	38.3	300.8	562.6	821.8				
	90	38.7	301.2	563.1	822.7				
	100	40.5	301.9	563.6	813.5				
	110	41.9	303.0	564.7					
	120	43.1	323.8	614.4					

Table 4 Average mechanical power provided by the prime move to the ORPC generator assembly. ($P_{input} = \tau_{load\ cell} * \omega_{shaft}$)

Mechanical Input Power [kW]								
	EMF Torque Setpoint [N-m]							
Dyno Motor Speed Setpoint [RPM]	0	250	500	750	1000	1250	1500	1750
10	0.03	0.30	0.57	0.85	1.12	1.39	1.67	1.94
20	0.06	0.60	1.16	1.70	2.25	2.80	3.35	3.89
30	0.10	0.92	1.74	2.56	3.38	4.20	5.02	5.84
40	0.14	1.23	2.33	3.42	4.52	5.62	6.71	7.80
50	0.18	1.55	2.92	4.29	5.65	7.02	8.39	9.76
60	0.22	1.87	3.52	5.15	6.79	8.44		
70	0.27	2.19	4.11	6.02				
80	0.32	2.52	4.71	6.56				
90	0.36	2.84	5.31	7.63				
100	0.42	3.16	5.90	8.52				
110	0.48	3.49	6.50					
120	0.54	4.07	7.71					

The results in Table 3, which highlight the total torque input provided to the generator driveshaft by the prime mover, are not readily interpreted as torque loss in the system. By subtracting the control torque provided by the generator (Table 5) from the input torque values (Table 3), the total torque loss is calculated as shown in Table 6. Measured torque losses increased by approximately a factor of 2 between 10 RPM and 120 RPM. Where measurements were available across the full range of resistive torques (0 to 1750 N-m) the torque losses were observed to be approximately 81 N-m higher at 1750 N-m than in freewheel. Across torque setpoints, the trend of increasing torque losses at a given RPM is approximately linear, with losses increasing by approximately 11.6 N-m per 250 N-m increment. Similarly, the mean torque losses at a given torque increase, on average, by approximately 1.7 N-m/10 RPM. We hypothesize this is due to increased kinetic friction at low speeds. As will be shown in Figure 8, the gradient of the torque loss surface is consistent across the tested setpoints. A simple mathematical model that assumes torque loss is linearly dependent on both setpoint RPM and torque results in Equation 8, with an $R^2 = 0.9962$.

$$\tau_{loss,model} = 0.167 \frac{[N-m]}{[RPM]} * \omega_{setpoint} + 0.0463 \frac{[N-m]}{[N-m]} * \tau_{setpoint} + 24.69[N-m] \quad \text{Equation 8}$$

Table 7 Average difference in mechanical power into EMF generator assembly and output power logged by CCW. (P_{loss}) includes the average power losses at each state, calculated by subtracting the electrical power produced by the system from the mechanical power input. Over the full range of sampled setpoints these values range from as little as 0.25 kW to as high as 1.35 kW following the patterns driven by the inferred torque losses in the system presented in Table 6.

Table 5 Actual average EMF winding torque from each setpoint test ($\tau_{EMF} = K_M * I_{torque\ feedback}$).

Average EMF Winding Torque [N-m]									
		EMF Torque Setpoint [N-m]							
		0	250	500	750	1000	1250	1500	1750
Dyno Motor Speed Setpoint [RPM]	10	0.0	249.9	500.1	749.9	1000.1	1250.0	1499.8	1750.1
	20	0.1	250.1	500.2	749.8	1000.0	1250.1	1500.0	1750.0
	30	0.1	250.1	499.9	749.8	999.8	1250.1	1499.8	1750.0
	40	0.1	249.9	500.2	749.9	1000.0	1250.0	1499.9	1750.1
	50	0.2	249.9	500.1	750.0	999.9	1250.1	1500.1	1750.1
	60	0.0	249.9	499.8	750.0	1000.0	1250.0		
	70	0.1	250.0	499.9	749.9				
	80	-0.1	250.0	499.8	750.0				
	90	0.2	250.1	500.1	749.8				
	100	0.1	250.0	500.1	740.2				
	110	-0.1	250.0	500.0					
	120	0.3	268.9	546.8					

Table 6 Average torque lost between torque cell and generator windings. ($\tau_{loss} = \tau_{load\ cell} - \tau_{EMF}$)

Average Torque Loss [N -m]									
		EMF Torque Setpoint [N-m]							
		0	250	500	750	1000	1250	1500	1750
Dyno Motor Speed Setpoint [RPM]	10	24.0	35.7	47.4	59.3	69.8	82.0	93.4	105.3
	20	27.0	38.3	51.5	62.5	73.7	85.3	97.6	107.0
	30	30.8	42.3	53.3	65.8	75.8	87.2	99.9	111.0
	40	32.8	43.5	56.8	67.4	78.5	90.9	102.5	112.8
	50	33.5	46.9	57.6	69.8	80.1	91.7	103.3	114.9
	60	35.5	48.0	60.8	70.4	81.6	94.3		
	70	37.3	49.5	61.6	72.2				
	80	38.4	50.8	62.8	71.7				
	90	38.5	51.1	63.0	73.0				
	100	40.4	52.0	63.5	73.3				
	110	42.0	53.0	64.8					
	120	42.8	54.9	67.6					

Table 7 Average difference in mechanical power into EMF generator assembly and output power logged by CCW. (P_{loss})

Average Power Loss [kW]									
		EMF Torque Setpoint [N-m]							
		0	250	500	750	1000	1250	1500	1750
Dyno Motor Speed Setpoint [RPM]	10	0.03	0.06	0.16	0.29	0.56	0.78	1.03	1.03
	20	0.05	0.10	0.27	0.42	0.60	0.82	1.07	1.34
	30	0.09	0.15	0.30	0.46	0.64	0.86	1.10	1.36
	40	0.13	0.18	0.35	0.50	0.68	0.89	1.12	1.37
	50	0.16	0.24	0.39	0.55	0.71	0.90	1.12	1.35
	60	0.20	0.28	0.46	0.58	0.74	0.92		
	70	0.25	0.34	0.50	0.62				
	80	0.29	0.39	0.54	0.63				
	90	0.33	0.43	0.58	0.67				
	100	0.38	0.48	0.62	0.69				
	110	0.43	0.54	0.67					
	120	0.49	0.60	0.72					

Since the tests were performed in speed control, the driveshaft speed was roughly constant throughout the tests. Therefore, the average efficiency with which torque was transmitted through the system represents the mechanical losses in the system (Table 8). The minimum observed torque efficiencies were approximately 83% and were observed at low torques and high shaft speeds. This behavior is common for mechanical assembles wherein fixed mechanical losses consume a greater proportion of mechanical power input. For resistive torque values exceeding 750 N-m, torque efficiencies exceeding 91% were measured at all setpoints with peak values of approximately 94% at low to moderate shaft speeds and high torques.

Table 8 Average torque efficiency. (η_τ)

Average Torque Efficiency									
		EMF Torque Setpoint [N-m]							
		0	250	500	750	1000	1250	1500	1750
Dyno Motor Speed Setpoint [RPM]	10		87.5%	91.3%	92.7%	93.5%	93.8%	94.1%	94.3%
	20		86.7%	90.7%	92.3%	93.1%	93.6%	93.9%	94.2%
	30		85.5%	90.4%	91.9%	93.0%	93.5%	93.8%	94.0%
	40		85.2%	89.8%	91.8%	92.7%	93.2%	93.6%	93.9%
	50		84.2%	89.7%	91.5%	92.6%	93.2%	93.6%	93.8%
	60		83.9%	89.1%	91.4%	92.5%	93.0%		
	70		83.5%	89.0%	91.2%				
	80		83.1%	88.8%	91.3%				
	90		83.0%	88.8%	91.1%				
	100		82.8%	88.7%	91.0%				
	110		82.5%	88.5%					
	120		83.0%	89.0%					

Average power efficiency, or the ratio of the electrical power measured by the motor drive to the mechanical power input, is shown in Table 9. At a shaft speed of 0 RPM, or a shaft torque of 0 N-m, these values are, in practice, zero. Unsurprisingly, average power efficiency relationships are more complicated than torque efficiency because they include otherwise unquantified electrical losses. At 10 RPM, the peak power efficiency occurs at low speeds. Because of the low speed, relatively low overall mechanical powers from which electrical power is generated are reduced from 80.3% at 250 N-m to 46.9% at 1750 N-m. While this is attributed partially to mechanical losses, large winding currents drive higher resistive losses in the system. For shaft speeds of 40+ RPM power efficiencies exceeding 82.5% percent are observed across the range of setpoints.

Table 9 Average power efficiency. (η_P)

Average Power Efficiency									
		EMF Torque Setpoint [N-m]							
		0	250	500	750	1000	1250	1500	1750
Dyno Motor Speed Setpoint [RPM]	10		80.3%	71.5%	66.1%	50.0%	44.2%	38.6%	46.9%
	20		83.3%	77.0%	75.3%	73.2%	70.7%	68.1%	65.6%
	30		84.2%	82.5%	82.0%	81.0%	79.6%	78.2%	76.7%
	40		85.0%	84.9%	85.3%	85.0%	84.2%	83.4%	82.5%
	50		84.7%	86.5%	87.2%	87.4%	87.1%	86.6%	86.1%
	60		84.9%	87.1%	88.7%	89.2%	89.1%		
	70		84.7%	87.9%	89.6%				
	80		84.7%	88.5%	90.3%				
	90		84.8%	89.1%	91.2%				
	100		84.7%	89.5%	91.9%				
	110		84.6%	89.8%					
	120		85.2%	90.7%					

Figure 8 provides an overview (summary) of the results derived from Tables 3-9. These results reveal trends typically encountered in generators, which is that moderate to high shaft speeds and moderate torques result in the highest operating efficiencies. Values in the 85-92% range suggest the magnetic geared generator pair is quite efficient. For example, 2 to 3 stage mechanical gearboxes typically have efficiencies in the 80-90% range while peak efficiencies for generators are typically in the 90% range. In practice, the efficiency of the combined components is expressed by the product of the individual efficiencies such that $\eta_{tot} = \eta_{gearbox}\,\eta_{gen}$, where the subscripts refer to the total efficiency, gearbox efficiency, and generator efficiency, respectively. Thus, in a scenario where $\eta_{gearbox} = 0.85$ and $\eta_{gen} = 0.9$, $\eta_{tot} = 0.765$, or 76.%. Noting that the power efficiency numbers in Table 7 and Figure 9 include mechanical losses for the assembly, this suggest that the overall efficiency of the system, including the EMF generator and the submersible housing, is quite high. The question of whether it should be adopted for use in a current energy turbine, however, is more complicated than indicated by the performance of the generator alone given that the rotor with which the system is integrated must also efficiently operate at conditions where the assembly's efficiency is high to maximize power production.

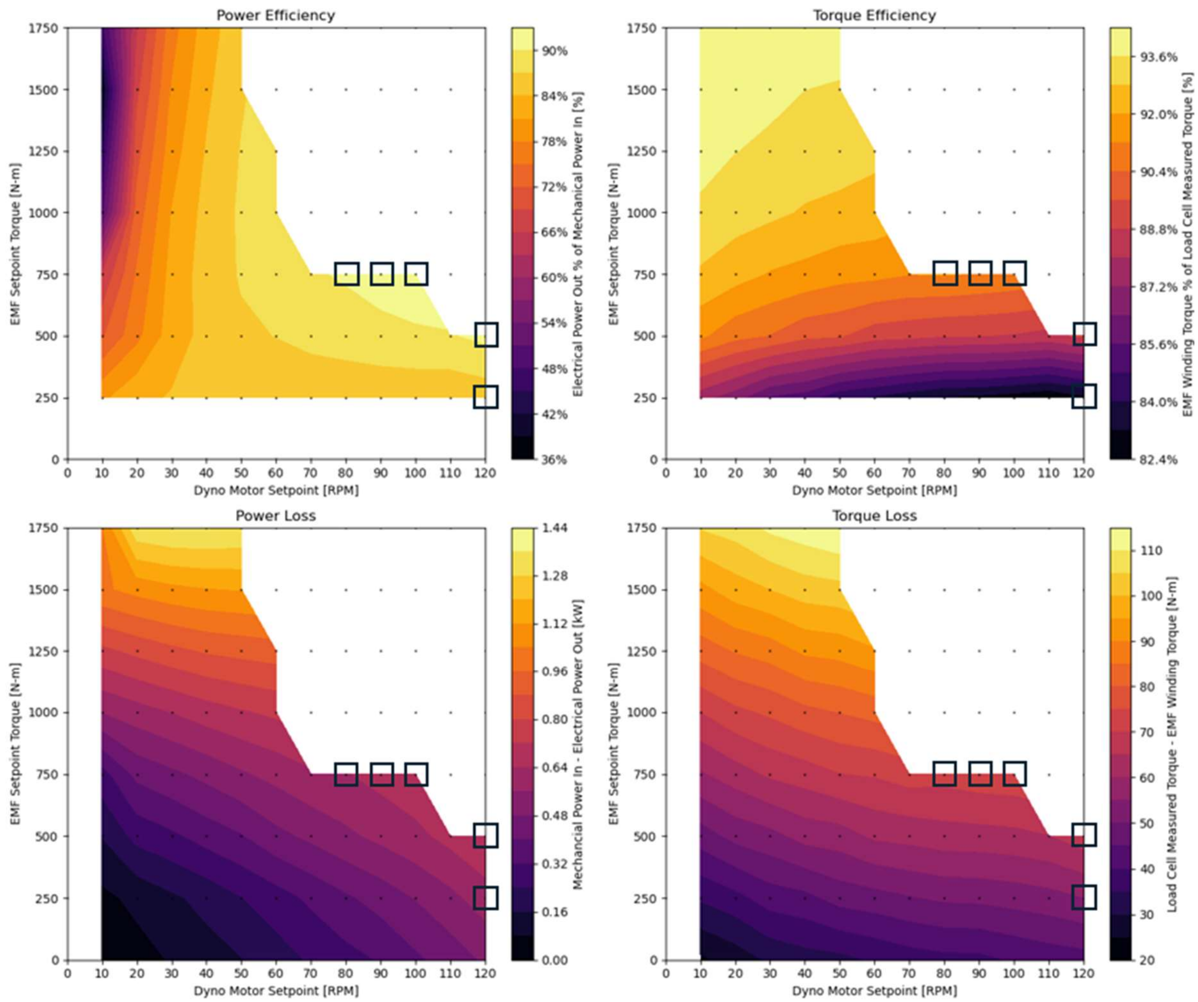

Figure 8 Summary of the power and torque results for the range of [RPM,Torque] setpoints tested. Target setpoints exist on a grid with 10 RPM and 250N-m spacing (grey dots). Setpoints in white region were not tested during this project. Black boxes indicate setpoints where test conditions deviated as detailed in Section 7.2.

7.2 Lessons Learned and Test Plan Deviation

Several deviations from the original test plan occurred, albeit with little impact on the quality of the results. Below is a list of the notable deviations:

- The EMF system architecture resulted in all generated power from the EMF system getting dissipated through heating of a resistor bank load dump, instead of going back into the same supply circuit the dynamometer motor was pulling power from. This meant that, unlike prior efforts involving the APL-UW dyno, the 240VAC circuit supplying power to the test equipment had to pull full electrical power from the grid, as opposed to only the net losses in the system. This resulted in the 12kVA circuit limiting the power states the dyno motor could explore, as the complete system, once inefficiencies in the Siemens power electronics and motor were considered, at times operated at or near this limit.

- Torque setpoints were spaced at 250 N-m to correspond with the requested setpoint map. Preliminary data analysis indicated that the gradients in the efficiency maps were smooth enough to avoid needing smaller torque steps to adequately characterize the system. If we were to repeat this work, we would recommend adding additional, low torque setpoints to achieve more performance data where the gradients get large as the efficiency of the system (and any power take-off) trend towards zero.
- Setpoints were originally intended to be run at a constant RPM, with torque stepping up between setpoints. In practice, the dynamometer software was already set up to step through RPMs, and for most of the test matrix, that functionality was used. For the (60-100 RPM, 750 N-m) setpoints, the torque transients between setpoints were high enough to trip the dynamometer controller into shutdown. To achieve these setpoints, both torque and RPM were slowly ramped up, and the dyno motor windings heated up enough during this sequence that cooling periods had to be added between each setpoint, leading to each setpoint having its own data file. While this has practical impacts on post-processing, it did not significantly impact analysis as all post-processed data were eventually consolidated into a single file.
- The five setpoints shown in Table 10 had the actual average setpoint during testing deviate from the intended value. The dynamometer system was at its performance boundary for the 750 N-m setpoints at shaft speeds greater than 70 RPM and therefore struggled to hit the target values. The EMF controller exhibited an as-yet-unexplained increase in torque above the target setpoint only for the 120 RPM setpoints. All other setpoints had average target torque and RPM met with better than 0.1% accuracy.

Table 10. A summary of target setpoint deviation.

Target Speed [RPM]	**Target Torque [N-m]**	**Actual Speed [RPM]**	**Actual Torque [N-m]**	**Cause of Deviation**
80	750	76.2 (-4.7% diff.)	750.0	Dynamometer capabilities
90	750	88.5 (-1.7% diff.)	749.8	Dynamometer capabilities
100	750	99.99	740.2 (-1.3% diff.)	Dynamometer capabilities
120	250	120.0	268.9 (+7.5% diff)	EMF controller behavior
120	500	120.0	546.8 (+9.4% diff)	EMF controller behavior

- Setpoint data at low RPM was collected for less than the originally planned for 10 cycles. This was shown to be sufficient based on steady state performance of the system at low RPM. The higher CV values for dyno motor RPM data in the 10 RPM high torque tests were a result of harmonics and would not have been reduced with additional sampling. Furthermore, extending the test periods unnecessarily would have caused the equipment to heat up more, requiring addition time to dissipate heat in between tests.
- Thermal management tests were not conducted explicitly because the EMF system was run with the bell housing removed, thereby significantly reducing its thermal risks, as determined by ORPC's experience operating the system. The EMF bell housing was removed to allow access to the shaft seal vent port, as the oil-filled, pressure compensated shaft seal needed to be bled to ensure the seal interface was fully lubricated. Once removed, the housing was left off until all tests were completed, and the unit was prepped for return shipping to ORPC. The dyno motor

winding temperature was actively monitored, and between the high torque tests (>300 N-m on the dyno motor shaft) the motor rested for periods of up to 5 minutes.

- Setpoints (70-90 RPM, 1000 N-m), (70 RPM, 1250 N-m) and (60 RPM, 1500 N-m) were not reached due to system limitations. A 2:1 or 3:1 gearbox would have been needed to reach these setpoints, and even then the 240V/60A circuit may not have been able to supply sufficient power, given the other limitations on the system. While suboptimal from a testing perspective, the trends in the data make clear that these setpoints would have achieved high efficiencies (near 90%).
- A shielded ethernet cable was used to protect communication between the laptop computer logging data using CCW and the drive running the EMF generator. Running multiple RPM setpoints for each test would also have made the packet loss problem obvious on the first day of testing, but since this was initially only done for the 0 N-m setpoint, where the packet loss issue was very intermittent, the packet loss issue remained hidden.
- Dynamometer encoder data was inadvertently sampled at 250 Hz rather than 1 kHz. This is still much higher than the EMF data sampling frequency but reveals there are still some improvements to be made for the dynamometer custom software interface with the Siemens power electronics. Interestingly, the torque cell was sampled at the expected 1 kHz.

The following are lessons learned from this project:

1) Initial system tests should include variations in RPM with a non-zero torque setpoint. This will reveal whether EMI is compromising data logging.
2) Shielded ethernet cables should be used to transmit data over long runs.
3) Winding temperature of the generator would be useful to log during testing if a more detailed breakdown of power losses was required. Given that dissipative losses increase with winding temperature due to changes in resistance, this temperature could help identify any contributions that dissipative losses may play in overall generator efficiency in prolonged testing as winding heat up.

8 Conclusions and Recommendations

The primary goal of this project; to map the performance of ORPC's EMF generator assembly, was successfully accomplished. Of the 58 setpoints originally expected to be characterized, 53 were successfully tested. An additional 15 setpoints that were tested that were not part of the original plan but still provide useful data. The results provide clear trends regarding the role of mechanical losses as a function of operating state and provide ORPC will valuable information regarding assembly efficiencies over much of the generator's operating envelope. Coupled with rotor performance information, this can be used to determine whether the magnetically geared generator is a good fit future their existing systems. The single largest takeaway from this effort is that the EMF generator assembly exceeds ORPC's desired power efficiency of 85% over a wide range of torque and RPM as shown in **Error! Reference source not found.**.

Table 11 Power efficiency data highlighting setpoints exceeding the ORPC's target efficiency threshold of 85%. Setpoints showing as 85.0% that are not highlighted were rounded to 85.0% but are below the threshold.

Average Power Efficiency									
		EMF Torque Setpoint [N-m]							
		0	250	500	750	1000	1250	1500	1750
Dyno Motor Speed Setpoint [RPM]	10		80.3%	71.5%	66.1%	50.0%	44.2%	38.6%	46.9%
	20		83.3%	77.0%	75.3%	73.2%	70.7%	68.1%	65.6%
	30		84.2%	82.5%	82.0%	81.0%	79.6%	78.2%	76.7%
	40		85.0%	84.9%	85.3%	85.0%	84.2%	83.4%	82.5%
	50		84.7%	86.5%	87.2%	87.4%	87.1%	86.6%	86.1%
	60		84.9%	87.1%	88.7%	89.2%	89.1%		
	70		84.7%	87.9%	89.6%				
	80		84.7%	88.5%	90.3%				
	90		84.8%	89.1%	91.2%				
	100		84.7%	89.5%	91.9%				
	110		84.6%	89.8%					
	120		85.2%	90.7%					

9 REFERENCES

Bassett, C., P. Gibbs, H. Wood. *et al. (2025).* Lessons learned from the design and operation of a small-scale cross-flow tidal turbine. *J. Ocean Eng. Mar. Energy* (2025). https://doi.org/10.1007/s40722-025-00411-y

Rusch, C., C. Crisp, E. Hammagren, J. Prudell, and J. Thomson (2023). Wave energy converter power take-off characterization: comparing dynamometer and field data, *Proc. EWTEC*, vol. 15. doi: 10.36688/ewtec-2023-293.

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