Electrical Validation Testing for ORPC MHK Generator, Modification 6: ORPC SBV for MHK Generator System

Cooperative Research and Development Final Report

CRADA Number: CRD-17-00716

NREL Technical Contacts: Calum Kenny, Scott Lambert, Ismael Mendoza, Eduard Muljadi, and Shazreen Meor-Danial

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Technical Report
NREL/TP-5700-97958
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Cooperative Research and Development Final Report

Report Date: October 29, 2025

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Ocean Renewable Power Company (ORPC)

CRADA Number: CRD-17-00716

CRADA Title: Electrical Validation Testing for ORPC MHK Generator, Modification 6: ORPC SBV for MHK Generator System

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Wind Energy Technologies Office, Small Business Vouchers Pilot

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources Government In-Kind
Original Agreement Modifications #1-5	\$300,000.00 \$0.00
TOTALS	\$300,000.00

Executive Summary of CRADA Work:

For the U.S. Department of Energy's (DOE) 2016 Small Business Voucher for Marine and Hydrokinetic (MHK) System, Second Round 2016, ORPC intends to work with the National Renewable Energy Laboratory (NREL) to perform dynamometer testing of the MHK generator systems and its associated controls and inverters. ORPC will provide the generator, variable frequency drives (VFD), controls, and inverter for this testing. NREL will utilize the NREL Energy Systems Integration Facility (ESIF) and dynamometer facilities at the National Wind Technology Center (NWTC) for this work.

Modification 6: Additionally, NREL will conduct a feasibility study for implementing passive DC rectification at the turbine.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assists laboratory in achieving programmatic scope
- Uses the laboratory's core competencies

Summary of Research Results:

Both simulation and parametric modeling work were conducted to ensure good power quality and grid integration of ORPC's tidal generating unit. Alternative electrical topologies involving passive and active rectification offshore were considered to reduce transmission losses and improve overall power output. Key findings include:

- Observation of susceptibility of turbine to oscillation at lower power speeds. Successful development of active power control strategy to reduce mechanical oscillations.
- Investigated relative merits of three approaches to minimize power flicker of the turbine electrical system. This includes:
    - Reactive power compensation.
    - Battery energy storage system (BESS) smoothing.
    - Adaptive (reactive current and grid voltage) control.
- The BESS was found to be the most effective method of reducing short-term flicker. However, due to this system's high cost, the adaptive control method is a favorable option for scenarios where BESS is not an option.
- Passive rectification can reduce transmission losses and improve energy yield by 2.7%. Active rectification and power transmission at 850V and 1200V can further improve energy yield by 6.0% and 8.0% respectively.

Purpose

ORPC has worked to develop water to wire hydrokinetic systems. The turbine generating unit (TGU) was designed, tested and validated the functionality of these systems in full-scale, open-water applications, and in particular the ORPC has proven an approach to connecting MHK turbine/generator sets to grids at the micro and macro level. While this test work has proven the overall system architecture, the testing to date has not fully investigated the interactions between the grid, and the control and inverter electronics and the impact that these interactions may have on electrical and mechanical stressors on the balance of the plant. As an example, in the field testing of the MHK Power System in Igiugig, Alaska, power output from the system is quantitatively and qualitatively determined by the control scheme selected, and depending on that control scheme, may range between completely steady power output to widely variant transient power placed on the grid, in this case, a small isolated grid primarily powered by diesel generation. The effects of these voltage/current transients on the electrical and mechanical integrity of the MHK system are not well understood. Electrical transients may degrade generator stator insulation. Mechanical transients may affect the life expectancy of shafts, bearings, and potentially seals for the generator. Additionally, utilization of the energy from the MHK device by an isolated micro grid with the end goal of reducing diesel fuel consumption requires optimization of control schemes that interface well with the existing power diesel generation equipment and also avoiding technical issues with this equipment caused by electrical transients.

The purpose of this project is to leverage experience and knowledge gained in many years of generator testing and inverter testing in the area of wind power generation and photovoltaic (PV) generation at NREL. And at the same time utilizing the equipment/hardware (e.g. dynamometer, power system simulator, load simulator, etc.) at the NREL laboratories. This effort will assist ORPC to advance the system readiness of Ocean Renewable Power Corporation's Turbine Generator Unit (TGU) in anticipation of commercial units to fulfill the market.

Statement of Work

ORPC seeks to test a representative generator/control/inverter system on a NREL dynamometer and to instrument the system to elucidate and quantify these effects. Information from this testing will be utilized to inform commercial design of the MHK generator to ensure that ORPC provides a high availability system for the commercial installations.

NREL will perform five different tasks in collaboration with the ORPC team to characterize ORPC's MHK Generator and power electronics components. Based on inputs from the project team, NREL will also provide design review and simulation of the generating systems, prepare the set up for the hardware testing interface equipment, performs full system testing and data analysis, grid integration testing at ESIF with the equipment available at NREL laboratories (NWTC and ESIF).

Task Descriptions

Task 1.0 - Design Assessment and Simulation:

NREL led design assessment of entire electrical system from the permanent magnet thee phase synchronous generator (operated in variable speed) connected to the grid through one of two power conversion systems: a power converter which includes a passive AC-DC rectifier, and a DC-AC three phase inverter, or the inverter stage of a VFD used to actively rectify AC-DC, and DC-AC three phase inverter. This dynamic modeling of the generator/power converter will allow us to determine the necessary changes in the control strategy to ensure that the optimization can be achieved on these fronts:

- • Optimization of the power electronic conversion.
- • Ensuring good power quality and grid integration

Additionally, a simulation of the power system can be performed to include the microgrid with a diesel generator and the variable microgrid load to ensure the compatibility of the MHK Power Systems with the rest of the power systems. There is also potential capability for the MHK to provide ancillary services to the grid to support the grid voltage and grid frequency during normal operation or during disturbances, unexpected, extreme events or contingencies. NREL will manage contributions to the project using established project management practices and systems. NREL will update ORPC on project status throughout the life of the project.

NREL Deliverables:

- Report on the assessment of entire electrical system covering both the permanent magnet thee phase synchronous generator (operated in variable speed) the passive rectification circuit, the VFD providing active rectification, and the inverter(s), under normal and abnormal operation.
- Report on the grid integration and control strategies for the TGU connected to the grid within microgrid environment, including the provision to potentially provide ancillary services to the grid.

Task 1 Results:

Initially, simulation and modeling was conducted on mitigating power flicker using active power control. The following conference paper was delivered and presented at HydroVision 2018:

1. Conference paper and poster: "Oscillation Damping with Active Power Control on a River Generator"
    a. Presented at: HydroVision International - June 25-28, 2018
    b. Technical summary: Developed dynamic model of river generator in Power Systems CAD. Observed susceptibility of turbine to oscillation at lower power speeds. Implemented active damping using active power control strategy, demonstrating reduction in mechanical oscillations.

Funding was used to support an Auburn University masters student for approximately 1 academic semester of work. The masters student completed 2 conference papers and a master's thesis on the subject of power quality improvement by flicker mitigation. This student was also jointly supported by Auburn facility start-up funding and James Danaher distinguished professorship funding. The publications include:

2. Conference paper: "Flicker Mitigation for a Grid-Connected Tidal and River Power Generator Using the BESS"
    a. Presented at: 10th International Conference on Power Electronics-ECCE Asia – May 27-30, 2019, Busan, South Korea.
    b. Technical summary: Investigates the use of a battery energy storage system to smooth the power output of a tidal turbine. Uses Power Systems CAD model and a MATLAB/SIMULINK flicker meter. Shows that flicker can be mitigated using the BESS even in a weak grid scenario.
3. Conference paper: "Reactive Power control to Mitigate Flicker in a Tidal and River Power Generation"
    a. Presented at: Power & Energy Society-General Meeting, Aug 4-8, 2019 Atlanta, US.
    b. Technical summary: Models a tidal turbine with a back-to-back converter. Describes mitigation of flicker by reactive power control in the grid side converter. Flicker meter developed in MATLAB/SIMULINK to measure flicker. Shows that reactive power flicker mitigation works in all grid conditions but may struggle in weak grid scenarios due to the large amount of reactive power required.
4. Masters thesis: "Marine Hydrokinetic Power Plant: Software Simulation for Voltage Flicker Mitigation"
    a. Defended July 2020.
    b. Technical summary: Uses Power System CAD digital simulation to model the output of a tidal turbine electrical system using three methods. These methods include: reactive power compensation, battery energy storage system (BESS) control and adaptive (reactive current and grid voltage) control. This thesis measures the short-term flicker intensity P_{st} of the power output of all three techniques and the base scenario, at different turbulence intensities, see results on Figure 1. Showing that a BESS is the most effective method of reducing short-term flicker. However, due to this system's high cost, the adaptive control method is a favorable option for scenarios where BESS is not an option.

SCR = 6 & X/R Ratio = 2			
Control	P_{st} (%TI = 3.2%) (Moderate)	P_{st} (%TI = 7.2%) (Severe)	P_{st} (%TI = 11.6%) (Very Severe)
Base	0.6027	1.1228	1.9020
VAR	0.4572	0.9931	1.6456
BESS	0.3576	0.5229	0.6894
Adaptive	0.3968	0.6685	1.0196

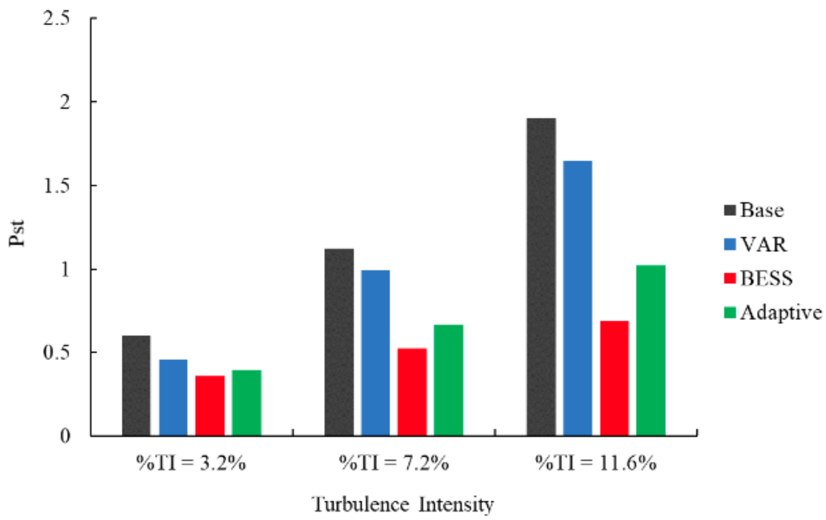

Figure 1. Short-Term Flicker (Pst) at Varying Turbulence Intensities (TI) for Base Scenario and Three Flicker Mitigation Methods.

Due to the Intergrid inverter supply chain issue preventing Tasks 3 and 4 from proceeding, remaining SBV funding was used to assess the ORPC TGU electrical system topology. A parametric mechanical to electrical energy conversion model was built, which covered the tidal turbine, generator, subsea cable, onshore power electronics and transformer in expected tidal flow conditions. This model found considerable losses in power transmission through the subsea cable to shore. As such, alternative electrical topologies were considered, which employed either passive or active rectification offshore. The offshore active rectification topology is shown in Figure 2.

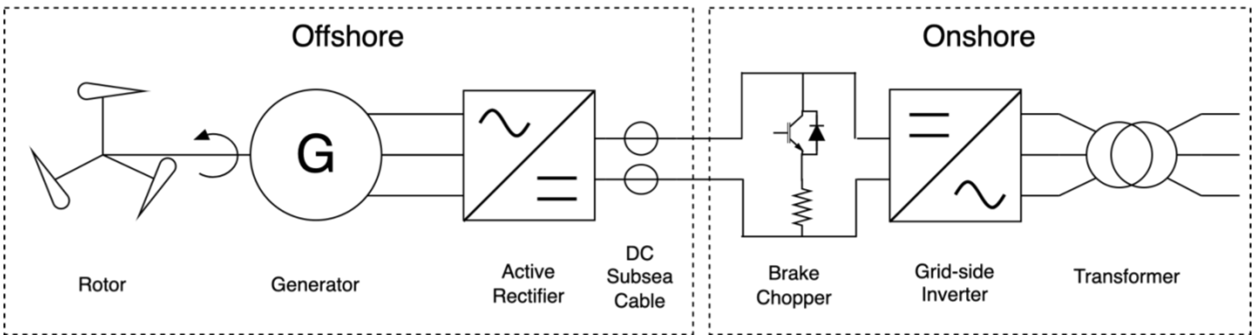

Figure 2 Proposed Alternative Electrical Topology 2: Offshore Active Rectifier.

In the active rectification scenarios, power transmission over the power electronics direct current bus was considered at both 850V DC and 1200V DC. The results of the model are shown in Figure 3 and summarized in Table 1. In the baseline transmission scenario, whereby 'raw' alternating current is transmitted to shore directly from the generator, line losses are shown to reach up to 4.5kW at tidal flow speeds above 2.5m/s. This transmission loss is shown to be reduced by offshore passive rectification, which can increase energy yield by 2.7%. Energy yield can be further increased by offshore active rectification, which can improve energy yield by 6.0% and 8.0% by transmitting power to shore at 850V DC and 1200V DC respectively.

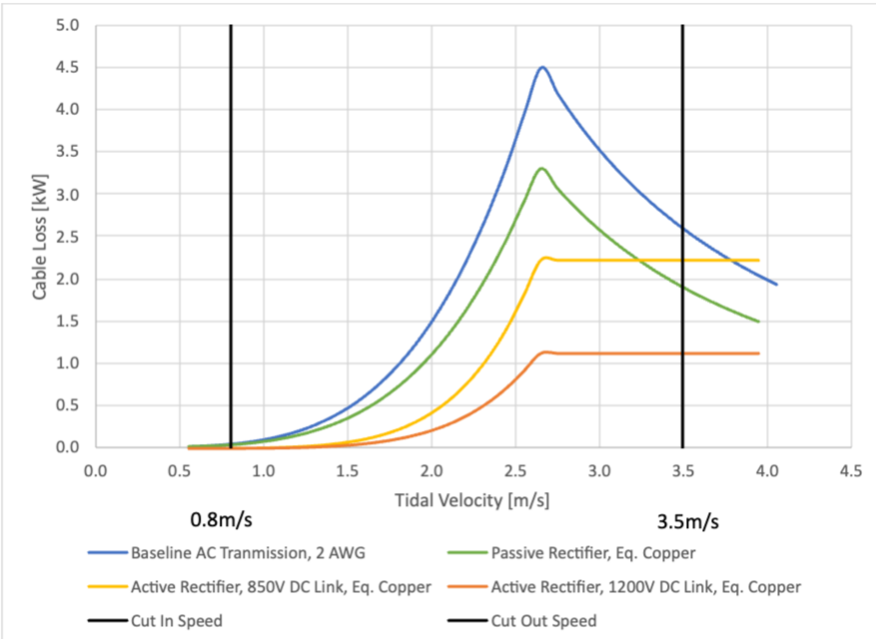

Figure 3. Cable Losses of Baseline AC Transmission, Passive Rectifier, Active Rectifier with 850V and 1200V DC Link.

Table 1. Energy Yield and Power Output of TidGen with Different Transmission Topologies.

Scenario	Energy Yield	Change in Energy Yield	Max Loss	Change in Max Loss
	[MWh/year]	[%]	[kW]	[%]
Baseline AC Transmission, 2 AWG	99.7	0.0%	4.5	0.0%
Passive Rectifier, Eq. Copper	102.4	2.7%	3.3	-26.9%
Active Rectifier, 850V, Eq. Copper	105.7	6.0%	2.2	-51.0%
Active Rectifier, 1200V, Eq. Copper	107.6	8.0%	1.1	-75.4%

Task 2.0 - Instrumentation of System

NREL and ORPC engineers will plan the instrumentation of system to accommodate the requirements to perform the MHK generator tests. The MHK generator will be disassembled at ORPC to install instrumentation related to electrical and mechanical measurements within the generator body itself. Additional instrumentation will be installed at NREL as necessary.

NREL Deliverables:

- Work with ORPC on the instrumentation, monitoring, and data acquisition
- Instrumentation, monitoring, and data acquisition plan

Task 2 Results:

Between October and November 2017, NREL corresponded with ORPC on the instrumentation of the RivGen generator, variable frequency drive (VFD) and Intergrid Inverter. Instrumentation requirements were discussed, including:

- Speed and torque of generator shaft.
- Voltage and current measurement at the output terminals of the generator, VFD and inverter.
- Power quality including real and reactive power, harmonics and transient behavior at the output of the inverter.
- Temperature at the generator shaft seal, VFD heat sink and inverter heat sink.

Task 3.0 - Small Dynamometer Testing (NWTC)

Interface Equipment: For connection of test article to dynamometer test stand and drive motor. Greater fidelity known once modeling is complete. Estimated Completion Date: 12/30/2017

Full System Testing- Small Dynamometer: The small dynamometer is capable to test up to 225 hp. Several gearboxes are available to match the MHK operating speed range. Under each specific condition, AC & DC output data to be collected at ≥ 1 kHz. A range of speed set points will be tested for between 20 and 80 RPM; at each of these speeds data will be collected for a range of loads to enable ORPC to fully characterize the generators output.

a) Testing the generator alone to find the parameters of the equivalent circuit of the permanent magnet synchronous generator (stator resistance, synchronous inductance, open circuit characteristics, and short circuit characteristics).

b) Entire system test (generator + active and passive rectification + inverter): In this test the ORPC MHK Power System will be connected to the Xcel grid. This test will be performed to:

1. Test and measure the electrical generator to input to the Task 1.0

2. Test the operating range of the MHK generator within the envelope range specified by the ORPC.

3. Test the MHK Generator and power conversion systems using a prototype Intergrid inverter to replace the inverter supplied by ORPC. This inverter is being developed under the NREL Distributed Wind CIP program, subcontract NFC-5-52012-03. The Intergrid inverter is designed for small wind turbines rated up to 40 kW single and three-phase. As such, it is a good match for MHK Power Systems. Intergrid has been involved in MHK testing in the past and will supply an inverter and support for this task at their own cost.

NREL will install modified MHK generator and ORPC Controls on dynamometer test stand and connect ORPC Controls to the variable frequency drive. NREL and ORPC will discuss supply of generator inverter for testing. If an inverter is not provided/unable to be provided by ORPC, the components will be uninstalled by NREL and ORPC components will be returned to ORPC per the terms of Annex C of this Agreement.

NREL Deliverables:

- Report on the characteristics and performance of the MHK generator and power conversion system for the specified range of operation, identify any peculiar characteristics if any, and recommend possible solutions
- Report on the substitution of the lntergrid inverter into the power conversion system

Task 3 Results:

The ORPC tidal generator unit (TGU) and power electronics was delivered to NREL facility on 5th April 2018. This unit was subsequently assembled and installed in the ESIF, in the configuration shown on Figure 4. Unfortunately, the Intergrid Inverter was not supplied by Intergrid within this timeframe. Due to the unknown lead time of the inverter and demand for ESIF facility space and use of the 225kW dynamometer, the ORPC TGU was disassembled and shipped to Flatirons campus for storage.

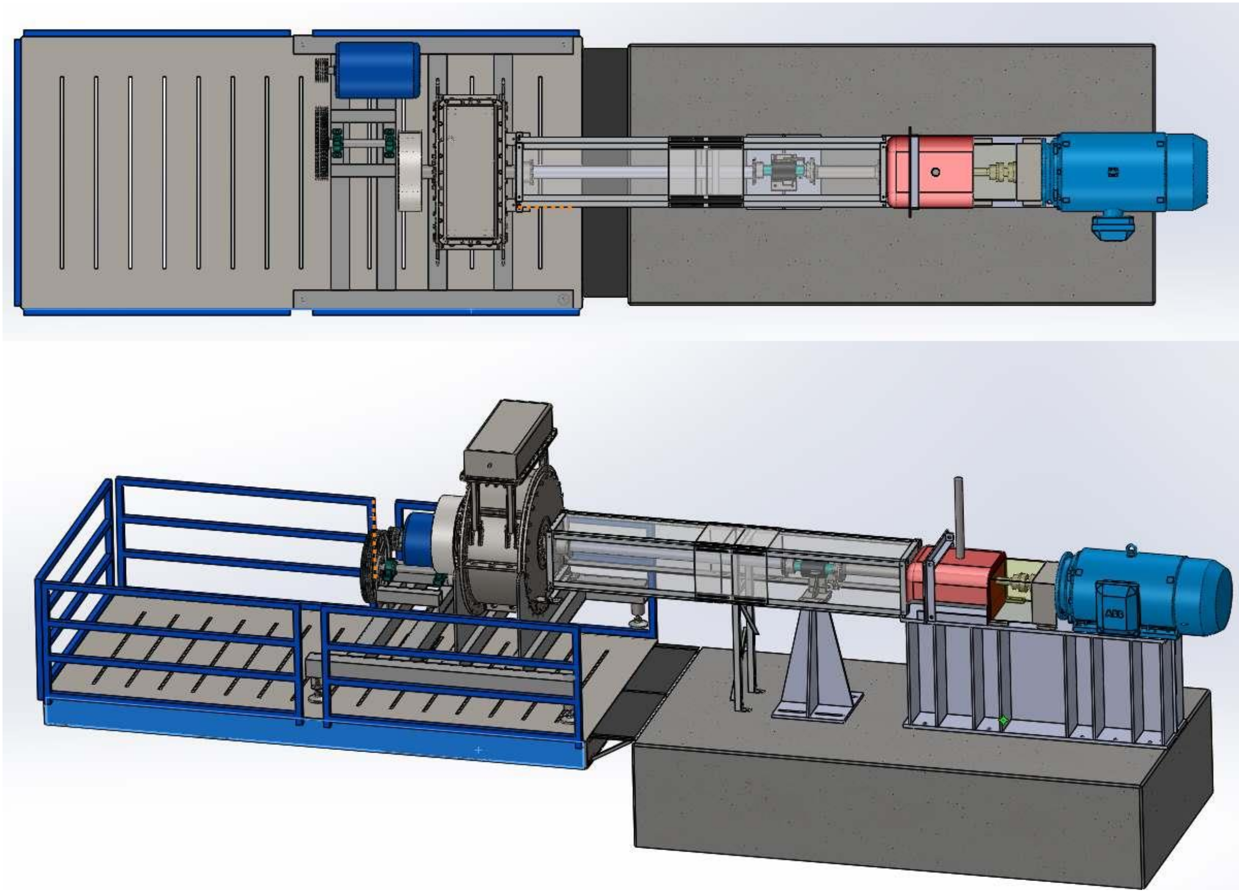

Figure 4. Solidworks CAD Assembly of ORPC Generator skid integrated with NREL Dynamometer.

No subsequent dynamometer testing attempts were made under this CRADA (CRD-17-00716). A related project, FIA-21-21947, completed dynamometer testing for ORPC using a different generator. At the conclusion of FIA-21-21947, all ORPC equipment under CRD-17-00716 and FIA-21-21947 were returned to ORPC on October 17th 2024.

Task 4.0 - Inverter Testing for Grid Interface (NWTC)

The objective of this test is to determine the power quality into the grid, does the inverter meet all requirements (as specified in IEEE 1547 and UL 1741) for power quality in feeding the grid.

This test will focus on the inverter testing connected to the grid. Two inverters will be tested:

1) ORPC supplied inverter
2) Prototype inverter from Intergrid

ESIF has a Power System Simulator that can function similar to CGI at power level up to 1 MW. To test the grid integration aspects of MHK, the inverter and the DC Power Supply can be tested at ESIF without the need to bring the MHK to ESIF. The testing at ESIF will cover:

a) Voltage range of operation as specified on the nameplate of the power converter.

b) Frequency range of operation as specified on the name plate of the power converter

c) Real power and reactive power range (check the name plate)

d) Islanding system protection

e) Power quality generated by the power converter

f) Low Voltage Ride Through if specified by the inverter manufacturer.

NREL Deliverables:

- Grid integration report for the ORPC supplied inverter
- Grid integration report for the lntergrid inverter

Modificaton 6:

Task 4.0 - DC Rectification Feasibility Study

ORPC will provide NREL with documentation related to ORPC's generator, inverter and subsea cable. NREL will conduct a feasibility study for implementing passive DC rectification at the turbine. The objective of the study is to determine the feasibility of implementing a practical control strategy for the offshore generator using an onshore inverter with variable DC input voltage. NREL will engage ORPC inverter suppliers as necessary. NREL engineers will make use of their experience with distributed wind systems and tidal turbine electrical topologies to assess how to implement DC rectification and transmission.

NREL Deliverables:

- DC Rectification Feasibility Report

Task 4 Results:

By November 2017, it was agreed upon by ORPC, NREL and Intergrid that ORPC would not supply an inverter unit, and instead Intergrid would supply a sole Intergrid inverter unit for dynamometer testing. Due to supply chain constraints, Intergrid were not able to supply the inverter, and as such NREL was not able to conduct grid-connected inverter testing.

Additional funding was used to supplement Task 1.0 simulation and modeling activities.

This report serves to meet the requirement for the CRADA Final Report with preparation and submission in accordance with the agreement's Article X

References:

Muljadi, E., Gevorgian, V., Marnagh, C., McEntee, J., 2018. Oscillation Damping with Active Power Control on a River Generator. Presented at the HydroVision International.

Sangwon, S., 2020. Marine Hydrokinetic Power Plant: Software Simulation for Voltage Flicker Mitigation.

Seo, S., Kim, J., Muljadi, E., Meor-Danial, S., Worthington, M., Wills, R., 2019a. Flicker Mitigation for a Grid-Connected Tidal and River Power Generator Using the BESS, in: 2019 10th International Conference on Power Electronics and ECCE Asia (ICPE 2019 - ECCE Asia). Presented at the 2019 10th International Conference on Power Electronics and ECCE Asia (ICPE 2019 - ECCE Asia), pp. 2917–2922. https://doi.org/10.23919/ICPE2019-ECCEAsia42246.2019.8796919

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Subject Inventions Listing:

None.

ROI #:

None.