PAPER

Testing the WET-NZ Wave Energy Converter Using the Ocean Sentinel Instrumentation Buoy

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ABSTRACT

This paper describes ocean testing of the half-scale Wave Energy Technology-New Zealand (WET-NZ) prototype wave energy converter (WEC) using the Ocean Sentinel instrumentation buoy during a 6-week deployment period in August–October 2012. These tests were conducted by the Northwest National Marine Renewable Energy Center (NNMREC) at its Pacific Ocean test site off the coast of Newport, Oregon. The WET-NZ is the product of a research consortium between Callaghan Innovation, a New Zealand Crown Entity, and Power Projects Limited (PPL), a Wellington, New Zealand private company. The Oregon deployment was project managed by Northwest Energy Innovations (NWEI), a Portland, OR firm. NNMREC is a Department of Energy sponsored partnership between Oregon State University (OSU), the University of Washington (UW), and the National Renewable Energy Laboratory (NREL). The Ocean Sentinel instrumentation buoy is a 6-m surface buoy, developed in 2012, that provides a stand-alone electrical load, WEC generator control, and data collection for WECs being tested. The Ocean Sentinel was deployed and operated for the first time during the 2012 WET-NZ tests. During these tests, the operation of the WET-NZ was demonstrated and its performance was characterized, while also proving successful deployment and operation of the Ocean Sentinel.

Keywords: wave power generation, ocean energy, wave energy converter, data acquisition, testing

Introduction

Ocean waves have several distinct advantages over other renewable energy resources such as wind and solar. Ocean waves are usually present, they are predictable, and they have high energy density, with approximately 30 kW/m of wave crest length typical off the West Coast of the United States. A number of private companies in the United States are now developing wave energy converters (WECs) that will take advantage of this resource and convert wave energy to electrical power. Along with the advantages of ocean waves as an energy source, however, come a number of challenges to developing WECs. Due to the high energy density of ocean waves, WECs have severe survival design requirements. WECs also must be designed for a difficult seawater environment, and both deployment and maintenance are difficult at sea. In order to design WECs that can meet these challenges, prototype testing is an important part of the development process. Usually WEC developers follow a testing program that initially includes wave tank testing of small-scale models, and ultimately leads to prototype testing in the open ocean. Until recently, ocean testing has been difficult for WEC developers in the United States because of the costly infrastructure and lengthy permitting process required.

One of the missions of the Northwest National Marine Renewable Energy Center (NNMREC), headquartered at Oregon State University (OSU) is to facilitate the commercialization of marine energy technology. To fulfill this mission, one NNMREC objective is to develop ocean test facilities that can be used by WEC developers to test their prototype devices. NNMREC has prepermitted a Pacific Ocean test site that is located 2.5 miles offshore, near Newport, OR, and has developed the Ocean Sentinel instrumentation buoy for use at that test site. The Ocean Sentinel, built in 2012, is a 6-m buoy that facilitates open-ocean, stand-alone testing of WECs with average power outputs of up to 100 kW.

The Ocean Sentinel was deployed for the first time in August-September 2012 to test an experimental half-scale Wave Energy Technology New Zealand (WET-NZ) WEC. The Ocean Sentinel and WET-NZ were moored at NNMREC's test site for a 6-week period from August 22, 2012 until October 5, 2012 while the testing was performed. The WET-NZ tests had a number of objectives as follows:

1. To deploy in open ocean for the first time in U.S. waters and to demonstrate and characterize the performance of the WET-NZ concept at half scale.
2. To demonstrate operation of the Ocean Sentinel and to gain experience testing a WEC with the Ocean Sentinel.
3. To gain experience deploying both the Ocean Sentinel and a WEC in the ocean.
4. To perform environmental monitoring during ocean testing of a WEC.

The results of the WET-NZ tests are presented here, focusing on the first two objectives. The operation of both the WET-NZ and the Ocean Sentinel were successfully demonstrated during the deployment, and the performance of the half-scale WET-NZ was characterized under a wide range of loading and sea conditions. The Ocean Sentinel was used to control the load applied to the WET-NZ power take-off (PTO) and to collect WEC power and ocean data throughout the deployment period. This allowed experimentation with different adaptive control methods during the deployment. Following the deployment, data collected by the Ocean Sentinel was analyzed in order to characterize WET-NZ performance when operated with the different control methods.

Although the Ocean Sentinel was operated by NNMREC staff throughout the WET-NZ deployment, all WEC data collected on board the Ocean Sentinel during this period is proprietary to the WET-NZ developers. NNMREC has been given permission to publish some of the data collected on board the Ocean Sentinel here. Data were also collected on board the WET-NZ using an independent data acquisition system; that data are not presented here, although reference is made to analysis of this data to support interpretation of the NNMREC results.

Ocean Sentinel Instrumentation Buoy

The Ocean Sentinel is an instrumentation buoy based on the 6-m NOMAD (Navy Oceanographic Meteorological Automatic Device) buoy design that was developed by NNMREC and AXYS Technologies for WEC testing. See the January/February 2013 issue of the *Marine Technology Society Journal* for a paper that gives a detailed description of the Ocean Sentinel (von Jouanne et al., 2013). The Ocean Sentinel facilitates open-ocean, stand-alone testing of WECs without utility grid connection through a cable to shore. As shown in Figure 1, WECs under test are moored approximately 125 m from the instrumentation buoy and are connected by an umbilical cable. Power generated by the WEC is controlled by switch gear and power conversion equipment located on board the instrumentation buoy and dissipated in an on board load bank. Wave data measured by a TRIAXYS wave measuring buoy moored nearby is transmitted to the instrumentation buoy via wireless telemetry.

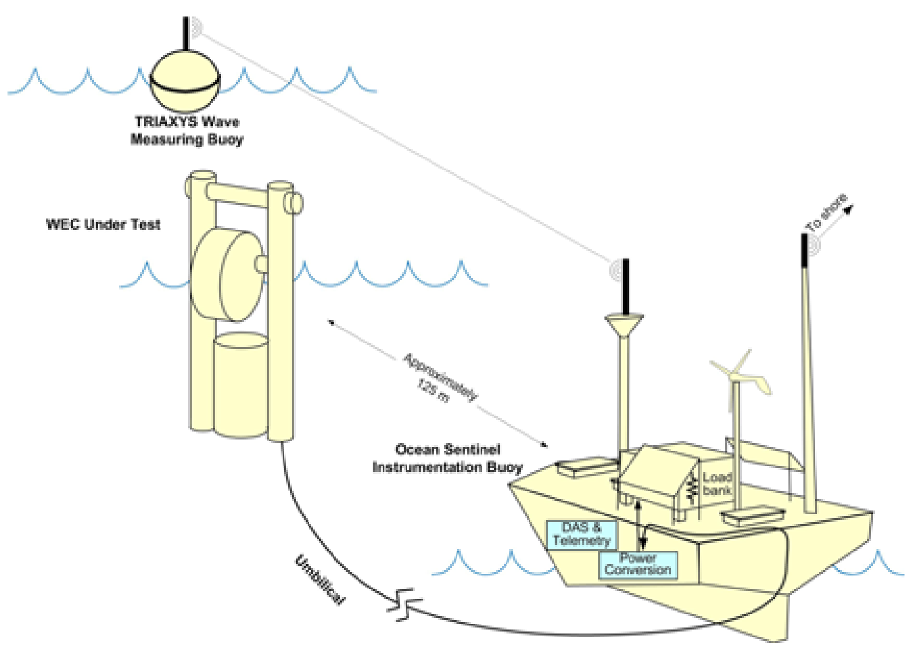
The primary functions of the instrumentation buoy are as follows:

1. provide stand-alone electrical loading and power conversion for the WEC under test;
2. measure and record WEC power output;
3. collect and store data transmitted from a wave measuring instrument moored close by;
4. transmit collected data to a shore station via a wireless telemetry system;
5. conduct environmental monitoring.

The Ocean Sentinel includes a 24-V instrumentation power system, developed by AXYS Technologies, that generates power using solar panels, a

FIGURE 1

WEC testing with the Ocean Sentinel instrumentation buoy.



wind turbine, and a backup diesel generator to charge a large bank of storage batteries. This system powers the equipment on board the Ocean Sentinel and also has sufficient capacity to export power via the umbilical to operate equipment on board the WEC being tested. A control and monitoring system, also developed by AXYS, controls the power system, provides safety functions, records data from environmental sensors and cameras on board the Ocean Sentinel, and interfaces with the TRIAXYS wave buoy.

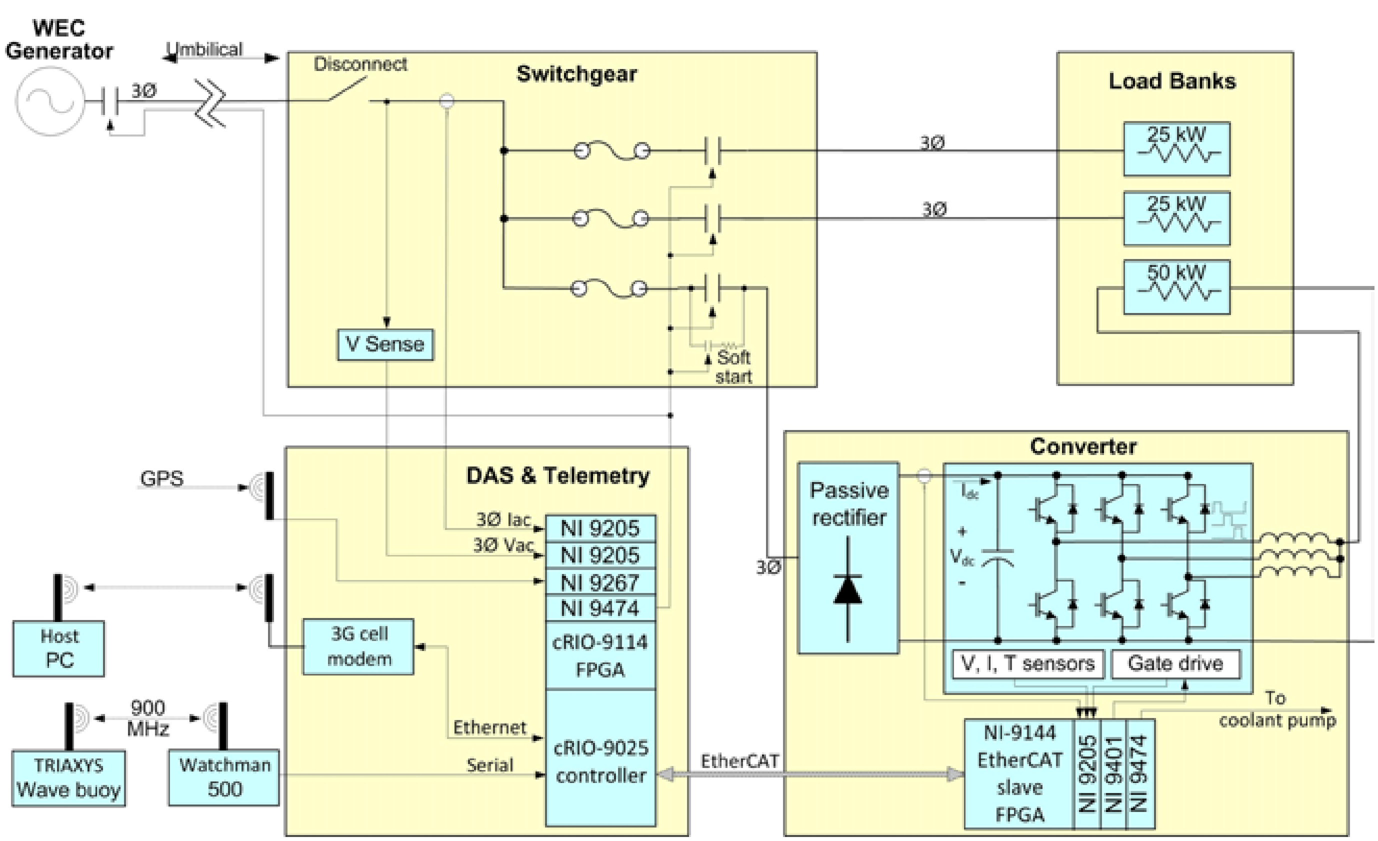
The WEC electrical loading, power conversion, and data acquisition system that is used to test WECs was developed by NNMREC. This system, shown in Figure 2, interfaces WEC electrical generators to the Ocean Sentinel load banks and also records WEC power output and ocean wave data. Generator control is provided for WECs in early stages of development that do not include onboard generator power conversion. This system consists of the following equipment:

1. air-cooled resistive load banks that dissipate the power generated by the WEC being tested;
2. electrical switchgear that includes a disconnect and fuses, contactors for direct switching of the load banks, contactors and soft start circuitry for a power converter, and voltage and current transducers to measure the output power of the WEC being tested;
3. a power electronic converter that can provide a continuously adjustable load to the generator of the WEC being tested;
4. a National Instruments (NI) CompactRIO data acquisition and control system that controls the switchgear contactors and the power electronic converter and records electrical data from the switchgear and converter, the output power of the WEC being tested, and ocean wave and ocean current data.

The CompactRIO data acquisition and control includes a host PC on shore that communicates via wireless telemetry with the Ocean Sentinel and provides the user interface for controlling and monitoring WEC operation during tests. The CompactRIO system is programmed in NI LabVIEW software and is an off-the-shelf system that can be reconfigured for the requirements of different WECs tested with the Ocean Sentinel.

FIGURE 2

The WEC electrical loading, power conversion, and data acquisition system on the Ocean Sentinel.



The Wave Energy Technology-New Zealand (WET-NZ) Wave Energy Converter

A photo of the half-scale WET-NZ at sea with the Ocean Sentinel in the background is shown in Figure 3, together with a solid model rendering of the device and its power take-off (PTO) system. Characteristics of the device are listed in Table 1. The WET-NZ is the product of a research consortium between Callaghan Innovation, a New Zealand Crown Entity, and Power Projects Limited (PPL), a Wellington, New Zealand private company. The Oregon deployment was project managed by Northwest Energy Innovations (NWEI), a Portland, OR firm. The device tested in 2012 was half-scale by length; output power scaling per the Froude similitude criteria was 1/11 relative to a nominal full-scale device (Holmes, 2009). (A full-scale WET-NZ device is projected to operate across the full wave spectrum present in the open ocean.) The WET-NZ consists of a long submerged hull, with a power pod mounted on top that includes a cylindrical float and the power take-off system. The hull of the half-scale WET-NZ tested with the Ocean Sentinel was fabricated at Oregon Iron Works in Portland, OR, and the Power Pod was fabricated and assembled in New Zealand.

TABLE 1

Half-scale WET-NZ device characteristics.

Length scaling ratio*	1/2
Power scaling ratio (Froude)*	1/11
Peak power	20 kW
Draft	15 m
Spar natural period	15 s
Float natural period	3.5 s

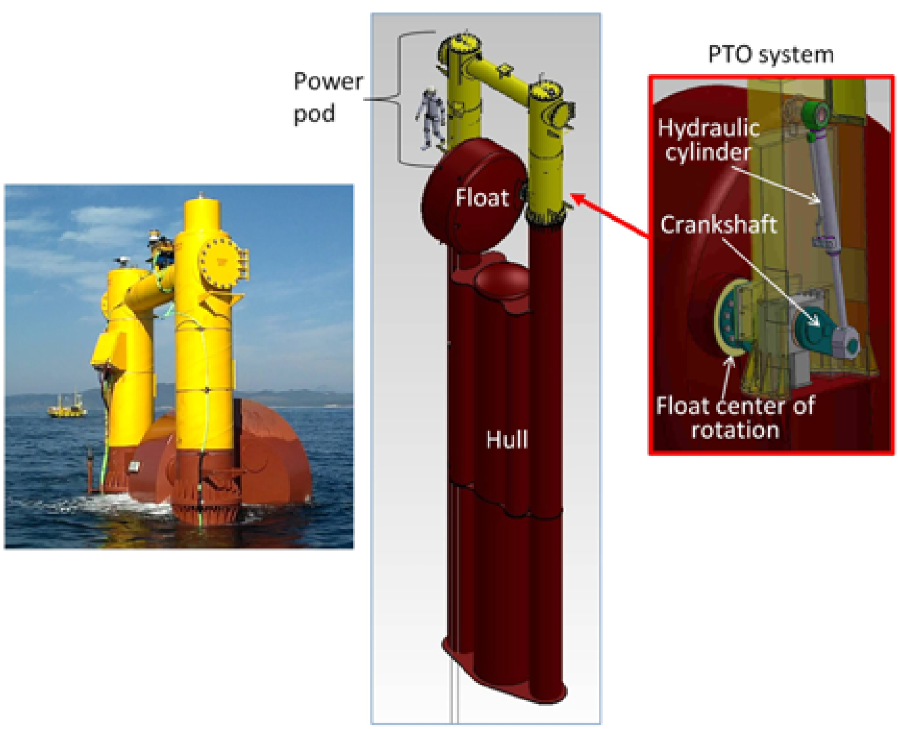
*Relative to full-scale device.

The float of the WET-NZ is coupled through its shaft to the power-takeoff (PTO) system and rotates up and down in the waves to generate power. The WET-NZ is designed to be slack-moored and self-reacting; the hull is flooded with seawater to give it a large inertia for the float to react against (Le-Ngoc et al., 2010). The natural period of the half-scale WET-NZ spar, which consists of the entire device other than the float, is 15 s, and the natural period of the half-scale float is 3.5 s. Due to these natural periods, Callaghan Innovation simulations predicted that the half-scale device would not generate significant power for portions of the wave spectra with periods longer than approximately 9 s. A full-scale device, however, is expected to have longer natural periods and to produce power from longer period waves.

The PTO system for the WET-NZ is shown in Figure 3. A crankshaft that connects to the shaft of the float extends and retracts hydraulic cylinders. The hydraulic cylinders provide pressure to a hydraulic system that includes a hydraulic motor and a small accumulator. The hydraulic motor drives the permanent magnet generator that was controlled by the Ocean Sentinel

FIGURE 3

The WET-NZ wave energy converter.



power converter (see Figure 2) during the test. The hydraulic drive is configured such that the generator only rotates in one direction. An accumulator provides a selected amount of energy storage within the hydraulic system so that the generator speed and torque do not necessarily decrease to zero when the shaft of the float reverses direction twice per ocean wave cycle. This causes a nonlinear relationship between the speed and force of the float with respect to the speed and torque of the generator.

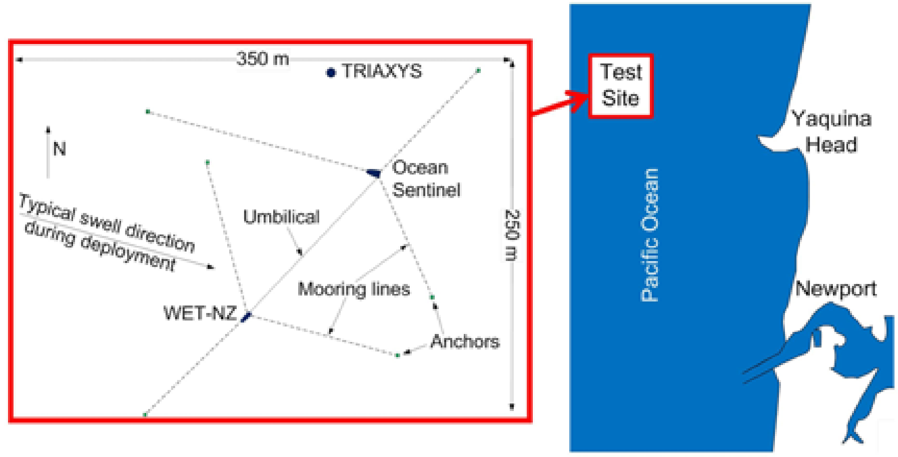
It should be noted that the WET-NZ device contained on-board batteries, generator, load bank and control system as backup in the event that the umbilical connection to the Ocean Sentinel was lost. This charging system created a substantial continuous load on the WEC PTO, irrespective of the power supply provided from the umbilical. The Ocean Sentinel instrumentation was unable to measure this load. The backup systems were not required at any stage during the deployment.

Test Setup

The WET-NZ, the Ocean Sentinel, and the TRIAXYS wave buoy were deployed at the NNMREC test site that is approximately 2.5 nautical miles offshore from Yaquina Head, north of Newport, Oregon (N44°41′, W124°07′). The location of the test site and the layout of the Ocean Sentinel, TRIAXYS wave buoy, and half-scale WET-NZ at the test site during the 2012 deployment are shown in Figure 4. Three-point mooring systems were used for both the WET-NZ and Ocean Sentinel. The TRIAXYS wave buoy was moored to the north side of the test site where it was more protected from pleasure and fishing vessel traffic. The four corners of the 350 m by 250 m test area were marked by corner buoys, per U.S. Coast Guard requirements. Ocean swell is typically from the west-northwest at the test site in August and September, with winds typically from the northwest.

FIGURE 4

The NNMREC test site location and layout used for the 2012 WET-NZ tests.



The umbilical between the WET-NZ and Ocean Sentinel provided the following electrical connections during the test:

1. the three phase WET-NZ generator output to the Ocean Sentinel switchgear;
2. system grounds of the WET-NZ and Ocean Sentinel;
3. 120 V ac Ocean Sentinel power to instrumentation on board the WET-NZ;
4. the coils of WET-NZ generator output contactors (see Figure 2) to the Ocean Sentinel safety system.

This umbilical did not provide communications between the WET-NZ and Ocean Sentinel, so data systems located on board the WET-NZ recorded data independently of the Ocean Sentinel and used their own independent telemetry system. All data systems were time synchronized by GPS.

The WET-NZ generator was controlled by the Ocean Sentinel power conversion equipment and the CompactRIO data acquisition and control system shown in Figure 2 throughout the test. The specific configuration used for the WET-NZ tests were as follows:

- The Ocean Sentinel power converter was used alone to provide the WET-NZ generator load; direct contactor load bank control was not used.
- The load for the Ocean Sentinel power converter was provided by the 50 kW load bank, with the individual elements within the load bank connected for a resistance of 4.2 Ω.

Test Sequence

The following tests were performed during the WET-NZ deployment:

1. Constant resistance load characterization
2. Maximum Power Point Tracking (MPPT) using two algorithms:
   - Perturb and observe
   - Cycling
3. Latching, declutching, and other control tests
4. Survivability tests with no load applied

Most of the deployment period was spent collecting constant resistance load data. This was the default operating condition when other tests were not being conducted. Much smaller portions of the deployment period were dedicated to the MPPT tests, survivability tests, and other control tests. During constant resistance load characterization tests, different constant resistive loads were applied to the WET-NZ generator for fixed time periods over a wide range of sea conditions, while WEC output power was measured. During MPPT tests, adaptive control algorithms were used to vary the constant load resistance in order to track maximize output power as sea conditions changed. In addition to the constant load resistance and MPPT tests, some control tests were performed where different constant load resistances were applied above and below a generator voltage threshold within each wave cycle to provide what is often referred to as latching and declutching control. No-load survivability tests were performed during the highest sea conditions that occurred during the deployment. The WET-NZ generator was operated open circuit for three separate 1-h periods during these tests.

The results of the constant load resistance characterization and MPPT tests are presented here. All data presented here was collected on board the Ocean Sentinel. Results are not included for the other control tests or the no-load survivability tests. The latching and declutching control gave minor improvements WET-NZ output power under very limited sea conditions, but insufficient data were collected to fully characterize performance. No issues were observed during the no-load survivability tests.

Constant Resistance Load Tests

During these tests, the WET-NZ generator was loaded by the Ocean Sentinel power converter so that generator output current was proportional to generator output voltage to give a constant resistance load. This method provides an approximation to constant damping control of the WEC float where the force applied to the float is kept proportional to the speed of the float, assuming that float force is proportional to generator torque and float speed is proportional to generator speed. Generator torque is proportional to current, and generator speed is proportional to voltage. In the case of the WET-NZ, however, the PTO hydraulics and the rotating float create nonlinearities between float and generator speed and also between the float force and generator torque, so that fixed resistance control only approximates constant damping control. Testing was performed with constant resistance control because it was simple to implement. Although PTO nonlinearities and losses were expected to have some effect, results were still expected to be consistent with analysis of the WEC that assumed constant damping.

The constant resistance control of the Ocean Sentinel power converter was implemented in the CompactRIO slave control (see Figure 2). The dc bus current in the converter was controlled to be proportional to the dc bus voltage, rather than directly regulating the ac output of the generator. To avoid confusion, all results and analysis are presented in terms of the control quantity R_{dc}, which is the commanded resistance at the converter dc bus, and R_{dc} is referred to as the "load resistance." Due to the three phase rectification, the effective three phase wye resistance applied to the generator is lower than R_{dc} by a factor of approximately 0.55 at high load. The relationship is nonlinear, however, due to higher relative losses in the converter at low load (high resistance).

Test Method

During initial testing, a load cycling method was developed where the Ocean Sentinel CompactRIO host was programmed to cycle repeatedly through a sequence of different R_{dc} settings every 20 min in order to collect data with different fixed loads applied under similar sea conditions. The 20-min period for each load step was synchronized with the 20-min measurement period of the TRIAXYS wave buoy. This load cycling method was used for the remainder of the test and is illustrated in Figure 5, which shows plots of time series data recorded during a short segment of the test. In this example, the R_{dc} sequence 8-16-32-64-128 Ω was used. The upper plots show the average power recorded for each 20-min interval together with the R_{dc} setting for that interval. The lower plots show the significant wave height (H_{m0}) and energy periods (T_e) for each 20-min period. H_{m0} and T_e are calculated from zero and first negative moments m_0 and m_{-1} of the wave spectra recorded by the TRIAXYS wave buoy, per equations (1) and (2).

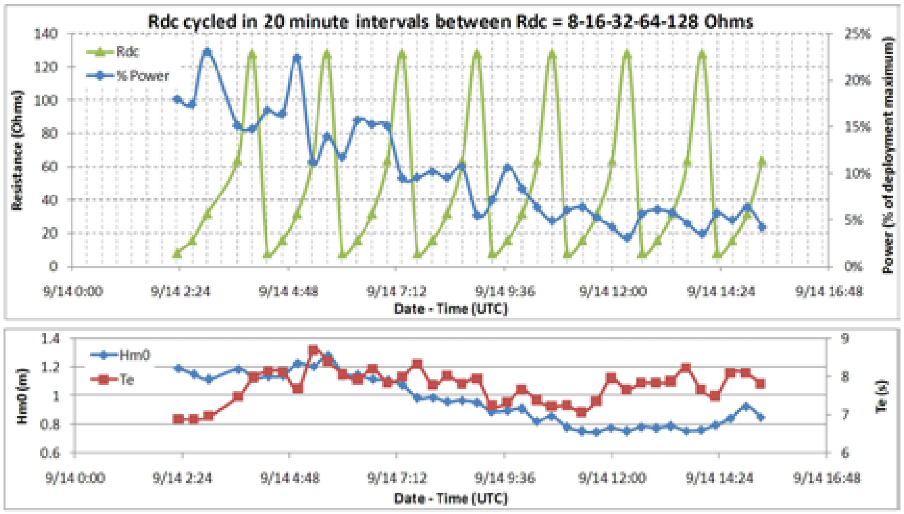
$$H_{m0} = 4\sqrt{m_0} \tag{1}$$

$$T_e = \frac{m_{-1}}{m_0} \tag{2}$$

Similar data plots were used to assess performance during the course of the test. In this example, output power is usually higher at the intermediate R_{dc} values than at 8 Ω or 128 Ω. Most testing was performed with the R_{dc} sequence 8-16-32-64-128 Ω although

FIGURE 5

Sample time series data for constant load resistance tests.



during some periods a 4 Ω step was added.

Sea Conditions

By the end of the deployment period, a large set of 20-min data samples had been collected on board the Ocean Sentinel for constant resistance operation under a variety of sea conditions. A histogram of the 20-min sample counts for each one-half-meter wide H_{m0} and one-second wide T_e bin is shown in Figure 6.

The half-scale WET-NZ device was not expected to produce significant power from portions of the wave spectra with periods greater than approximately 9 s. More test time was therefore desired in conditions with lower T_e, especially in the 6- to 8-s range, than occurred during the deployment. Much of the testing was carried out in longer period seas, where the WET-NZ responded more to the shorter wind waves in the spectra than to the ocean swell.

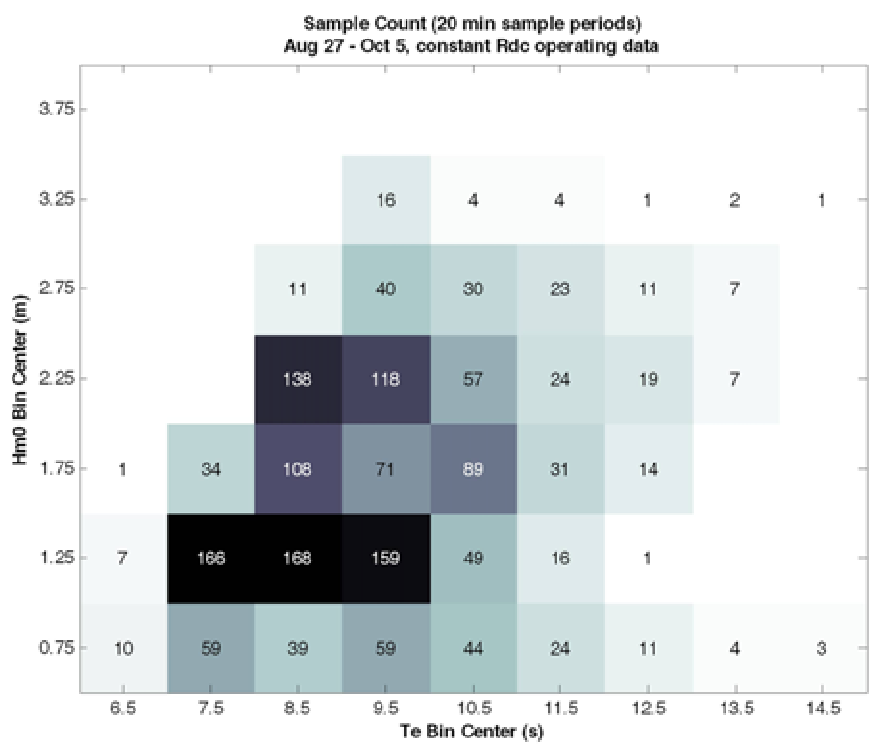
Data Analysis

After the deployment period, data collected by the Ocean Sentinel was analyzed using MATLAB to plot characterization curves showing the power output of the device with respect to the R_{dc} settings under different sea conditions. Data included average power, R_{dc}, and both ocean wave statistics and spectra for each 20-min sample period.

The simplest method of presenting power output with respect to R_{dc} under different sea conditions is to bin data by both H_{m0} and T_e and then plot output power versus R_{dc} for each data bin. When this method was used for the half-scale WET-NZ data, however, the plots did not show distinct trends in output power with respect to R_{dc}. This is partly due to the large variation in wave spectra that occurred within the each H_{m0}-T_e bin and the large variation in WEC output power that resulted. In many cases different 20-min data samples that were collected with very similar H_{m0} and T_e measurements had quite different spectral shapes with different concentrations of energy above and below 0.11 Hz (9 s wave period). Because the half-scale WET-NZ was not expected to produce significant power for

FIGURE 6

Histogram of sample counts for fixed load resistance data.



portions of the wave spectra with periods greater than 9 s, in these cases output power was influenced more by spectral shape than by the R_{dc} settings used.

To remove the effect of spectral variation from the WEC output power versus R_{dc} curves, it was necessary to normalize WEC output power data with respect to the expected device power based on the average response of the device to the energy flux spectra. The average response of the WET-NZ was estimated from the output power and spectral data using equation (3) below and a least squares method:

$$\begin{bmatrix} P_1 \\ P_2 \\ \\ P_n \end{bmatrix} = \begin{bmatrix} J_1(f_1) & J_1(f_2) \dots J_1(f_m) \\ J_2(f_1) & J_2(f_2) \dots J_2(f_m) \\ \\ J_n(f_1) & J_n(f_2) \dots J_n(f_m) \end{bmatrix} * \begin{bmatrix} 1(f_1) \\ 1(f_1) \\ \\ 1(f_m) \end{bmatrix} \tag{3}$$

where $[P_1\ P_2\ \dots\ P_n]^T$ is a vector made up of all 20-min average power measurements in watts made while a constant resistance load (all R_{dc} values) was applied to the WET-NZ; $J_n(f_1)\ J_n(f_2)\ \dots\ J_n(f_m)$ are the frequency components of energy flux spectra in watts per meter associated with the nth power measurement P_n, and $[l(f_1)\ l(f_2)\ \dots\ l(f_m)]^T$ is the average response of the WET-NZ device to the energy flux spectra in meters that was solved for. The average response represents the frequency distribution of what is commonly referred to as the capture length of a WEC (IEC 2012). The spectral components for energy flux or power per meter crest length of the waves were calculated from the wave spectra using equation (4):

$$J(f_i) = \rho g\, C_g(f_i) S(f_i) \tag{4}$$

where $J(f_i)$ denotes the energy flux at frequency f_i, ρ is seawater density (1025 kg/m^2), g is the acceleration of gravity (9.8 m/s^2), $C_g(f_i)$ is the group velocity at frequency f_i, and $S(f_i)$ is the wave spectral component at frequency f_i measured by the TRIAXYS wave buoy. The group velocity at frequency f_i, was calculated using equation (5):

$$C_g(f_i) = \frac{1}{2}\sqrt{\frac{g}{k_i}\tanh(k_i h)}\left(1 + \frac{2k_i h}{\sinh(2k_i h)}\right) \tag{5}$$

where k_i is the wavenumber at spectral frequency f_i and h is the depth (48 m at the test site). The wavenumber was calculated using the dispersion relationship, equation (6), which requires a recursive solution:

$$(2\pi f_i)^2 = g\, k_i \tanh(k_i\, h) \tag{6}$$

Note that equation (5) for the group velocity is often simplified by a deep water approximation when the depth is greater than half the wavelength (kh greater than π); however, at 48 m depth this approximation is only valid for wave periods less than 8 s and was not used for this analysis.

The average response of the WET-NZ to the energy flux spectra, estimated using equation (3), is shown at the top of Figure 7. The vertical axis scale is not included to protect WET-NZ proprietary data. One thousand six hundred seventy-five 20-min data samples were used in the calculation; data with all values of R_{dc} were included. To improve the fit to the data, the solution was held constant within frequency intervals corresponding to integral wave periods. As expected, the response of the WET-NZ device was negligible for frequencies less than 0.11 Hz (9-s period or greater). The response was greatest for frequencies between 0.17 Hz and 0.2 Hz (5-s to 6-s periods). The results for frequencies higher than about 0.2 Hz are less accurate because the spectral energy was usually low above that frequency. The average response can be used to calculate the expected output power of the WET-NZ based on the measured wave spectra using equation (7):

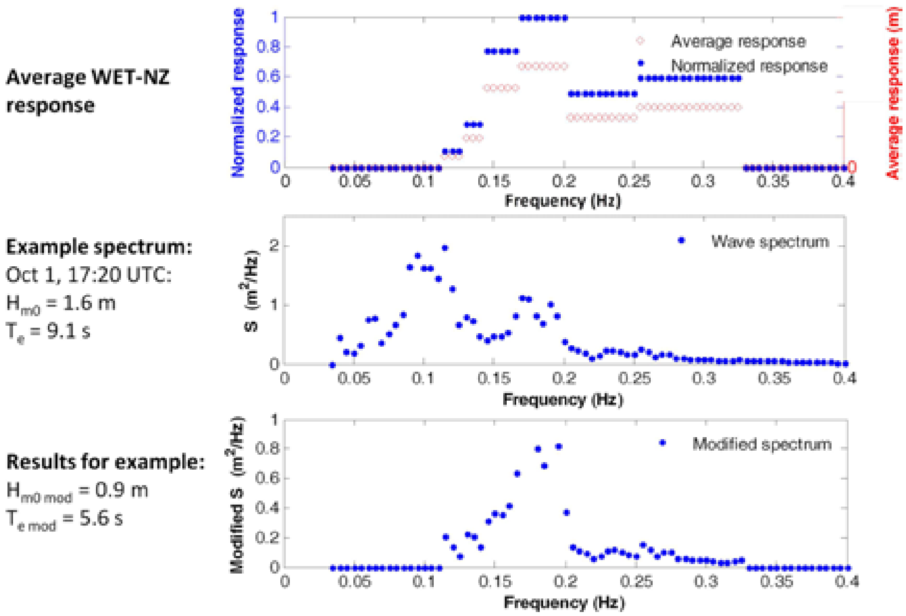
$$P_{expected} = [J(f_1)\ J(f_2)\dots J(f_m)] * [1(f_1)\ 1(f_2)\dots 1(f_m)]^T \tag{7}$$

where $J(f_i)$ are the energy flux components at frequency f_i calculated per equation (4) and $l(f_i)$ are the average response components at frequency f_i shown at the top of Figure 7.

To best present the power versus R_{dc} characterization data, it was desirable to bin the data using a method that better segregates it per the expected response of the WET-NZ than simply binning per T_e and H_{m0}. This was done by calculating modified versions of H_{m0} and T_e that take into account the response of the WET-NZ. This method is shown by example in Figure 7. In the top plot of Figure 7, a normalized version of the half-scale WET-NZ response is plotted that has a maximum of one, along with the average response that was calculated using

FIGURE 7

Data analysis example.



equation (3). A sample wave spectrum is shown in the center plot. A modified version of this spectrum is shown at the bottom of Figure 7 that takes the response of the WET-NZ into account. The modified spectrum is the product of the normalized response in the top plot and the spectrum in the center plot and is the portion of spectrum that the WET-NZ responded to. The modified significant wave height $H_{m0\ mod}$ and modified energy period $T_{e\ mod}$ were calculated from moments of the modified spectrum using equations (1) and (2) and were used for data binning.

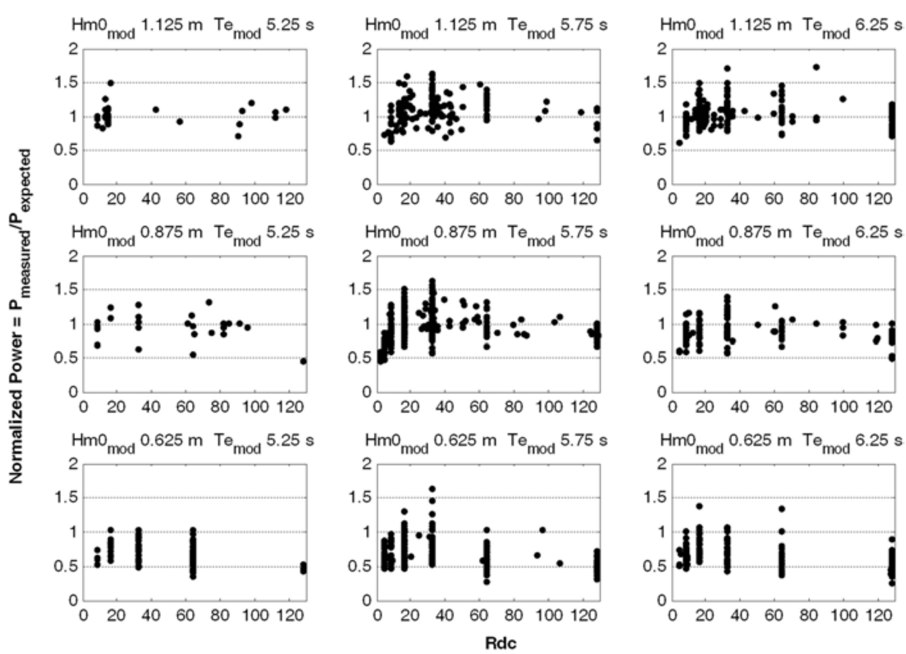
Results

Characterization curves for WET-NZ output power versus R_{dc} are shown in Figure 8; this data were all collected on board the Ocean Sentinel. The analysis methods described above are used to normalize and bin the data. Separate plots are shown in each data bin, where the binning is done by $H_{m0\ mod}$ and $T_{e\ mod}$. Power is normalized to the expected WET-NZ output power based on the average response of the device to the wave spectra; expected power is calculated per equation (7). While significant scatter still exists in these plots, clear trends in the data can be seen for the data bins with larger $H_{m0\ mod}$ and $T_{e\ mod}$, with a maximum in output power occurring somewhere in the range of 10 Ω to 50 Ω.

WET-NZ consortium simulations of the half-scale device predicted a more pronounced optimum power at a lower value of R_{dc} than is seen in Figure 8. The WET-NZ consortium has subsequently analyzed PTO data collected on board the WEC and has shown that significant power losses and other inefficiencies existed within the half-scale implementation of the PTO throughout the test period. Causes included the continuous load from the charger system and overly conservative settings on the hydraulic overload protection systems. These results are proprietary to the WET-NZ consortium and are not presented here. The effect was additional loading on the WET-NZ float throughout the deployment, so that the device was not operating at an optimum load regardless of the resistance applied to the generator.

FIGURE 8

Normalized power versus R_{dc} binned by $H_{m0\ mod}$ and $T_{e\ mod}$.



Accordingly, only a small portion of the power that was extracted from the waves during the tests reached the WEC electrical generator for measurement by the Ocean Sentinel. These effects broadened the power response of the device so that R_{dc} only had a modest influence on output power during the tests, and are consistent with the results shown in Figure 8. The WET-NZ consortium has been able to identify and quantify the different PTO loss paths, further analyze device operation during the test, and determine improvements to the scaled PTO design that will correct these problems for future deployments.

MPPT Testing

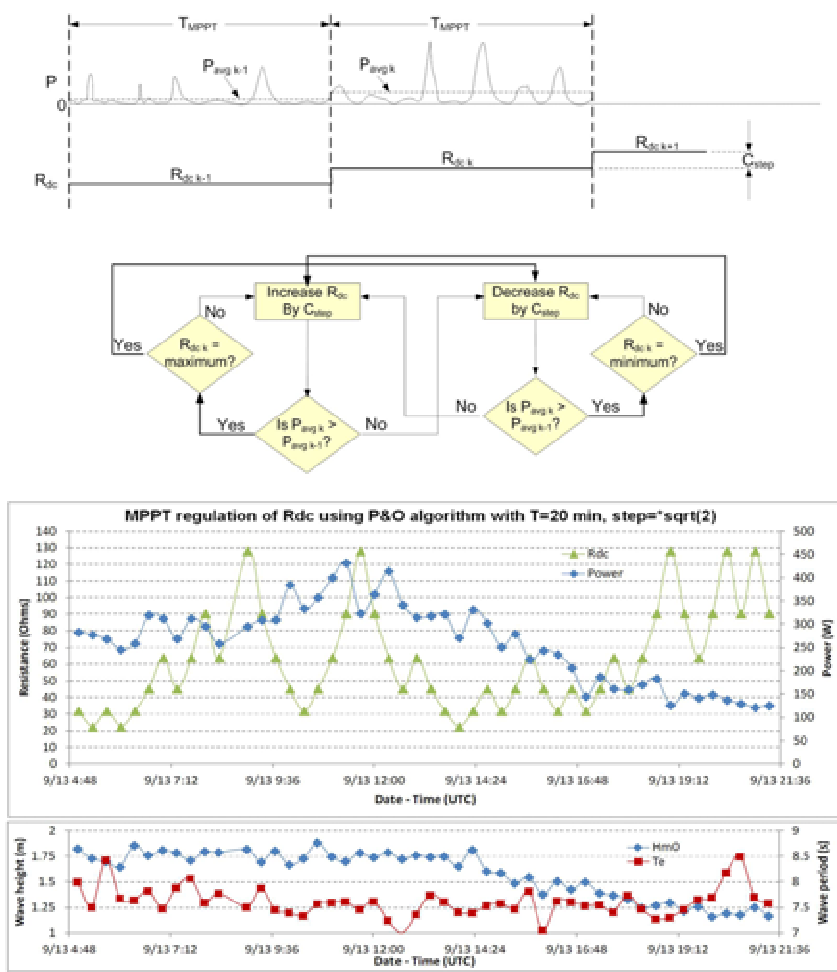
MPPT is a control technique that samples the output power of a device and adjusts a control parameter to obtain maximum power for any given operating condition. The technique is most commonly used to regulate the load applied to solar panels; however, previous work at OSU (Amon et al., 2012) has shown that this technique can also be used for WEC control. During the course of the WET-NZ deployment, NNMREC experimented with MPPT control of the WET-NZ using two different MPPT algorithms that were implemented in the CompactRIO host during the course of the deployment: (1) a perturb and observe algorithm and (2) a cycling algorithm. The MPPT algorithms were used to control R_{dc}. Optimum control of R_{dc} was not achieved with the perturb and observe algorithm, but optimum control of R_{dc} was achieved using the cycling algorithm even though, as shown in Figure 8, the optimum R_{dc} was not well pronounced in the case of the half-scale WET-NZ due to high PTO losses.

Perturb and Observe MPPT Algorithm

A block diagram of the perturb and observe MPPT algorithm that was implemented in the CompactRIO host to regulate R_{dc} is shown at the top of Figure 9. This algorithm is commonly used to control solar panels (Esram & Chapman, 2007). Starting with some load resistance setting $R_{dc\ k-1}$ for the k – 1 interval, the WEC is controlled with this resistance value for a fixed MPPT time period T_{MPPT}, and at the end of the interval the average power $P_{avg\ k-1}$is calculated. Assume that R_{dc} is then increased by a fixed control step C_{step} to give the resistance $R_{dc\ k}$ used for the kth interval. At the end of the kth interval, if the average power $P_{avg\ k}$ is greater than $P_{avg\ k-1}$, R_{dc} is again changed in the same direction by C_{step} and $R_{dc\ k+1}$ is higher than $R_{dc\ k}$, but if power decreases R_{dc} is changed in the opposite direction. The algorithm continues to search for an optimum R_{dc} setting in this manner, incrementing or decrementing R_{dc} by C_{step} indefinitely depending on whether power increases or decreases from one interval to the next. R_{dc} is never increased beyond a maximum setting or decreased below a minimum setting; the algorithm steps R_{dc} in the opposite direction if necessary to avoid

FIGURE 9

Perturb and observe MPPT algorithm (top) and results (bottom).



this. The selection of the two parameters T_{MPPT} and C_{step} have a significant effect on the operation of the algorithm. It is possible to implement the algorithm so that R_{dc} is stepped either arithmetically or geometrically; in one case C_{step} is either added to or subtracted from the previous value, while in the other case the previous value is either multiplied or divided by C_{step}.

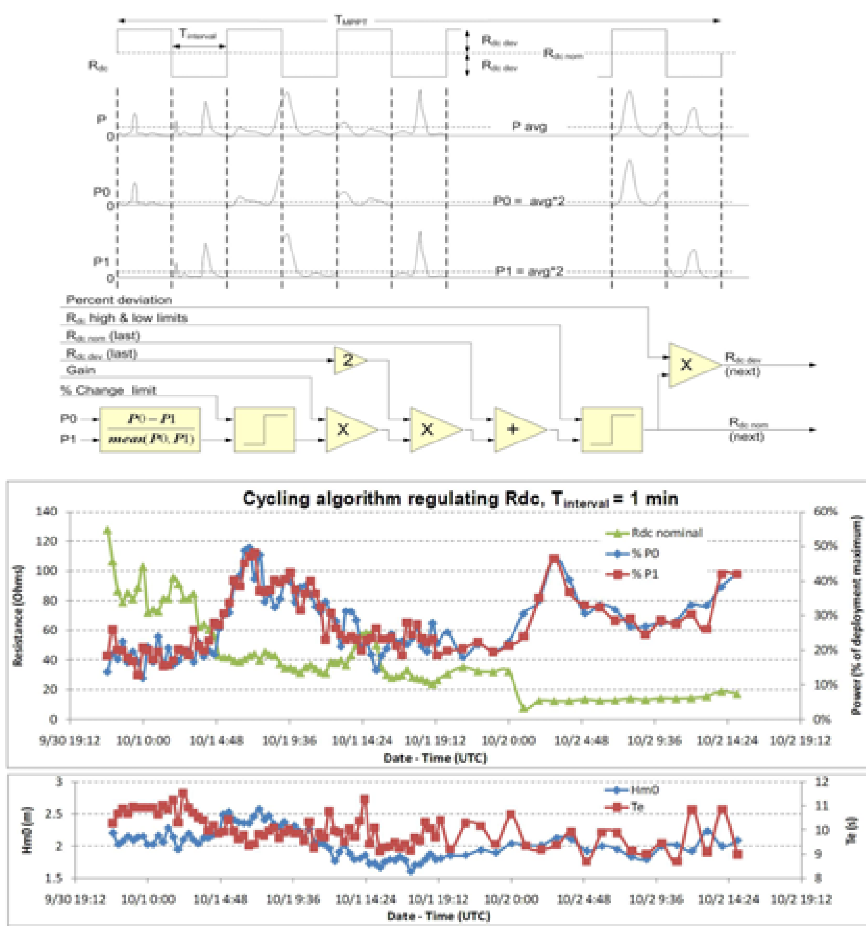
Optimum regulation of R_{dc} using the perturb and observe algorithm was not successful for the half-scale WET-NZ, because output power changed more from one MPPT interval to the next due to variations in sea conditions than due to changes in the R_{dc} setting. This can be seen in the results shown at the bottom of Figure 9 for a trial run using this algorithm with T_{MPPT} set to 20 min, geometric incrementing and decrementing by a C_{step} of 1.41, and minimum and maximum R_{dc} limits of 8 Ω and 128 Ω, respectively. R_{dc} and output power are shown together in the top plots, and H_{m0} and T_e are shown together in the bottom plots. Based on the results shown in Figure 4 11, under optimum regulation R_{dc} should range between about 10 Ω and 50 Ω, but during this trial run R_{dc} ranges between 23 Ω and 128 Ω. Output power is affected by both H_{m0} and T_e, having a positive correlation with H_{m0} and a negative correlation with T_e. R_{dc} has less effect on output power than either H_{m0} or T_e. When power increases due to changing H_{m0} or T_e, R_{dc} swings widely, and when power decreases due to changing H_{m0} or T_e R_{dc} cycles back and forth without regulating to the optimum range. While it might have been possible to correct these problems by using a shorter interval T_{MPPT} and the same C_{step}, this was expected to cause a large amount of dithering in the control.

Cycling MPPT Algorithm

A block diagram of the cycling MPPT algorithm that was implemented in the CompactRIO host is shown in Figure 10. This algorithm was developed during the course of the WET-NZ tests to overcome the difficulties encountered with the perturb and observe algorithm. When using this algorithm to regulate R_{dc}, it is cycled alternately between a nominal value $R_{dc\ nom}$ plus and minus a deviation $R_{dc\ dev}$ throughout each MPPT period T_{MPPT}. At the end of each period the difference between the average power calculated for the portions of time that the WEC was operating at the high and low R_{dc} settings, P0 and P1 respectively, is used to calculate $R_{dc\ nom}$ for the next MPPT period. The R_{dc} cycling time $T_{interval}$ was typically set to 1 min during the WET-NZ tests and the time period T_{MPPT} was typically set to 20 or 60 min. $R_{dc\ dev}$ is always a fixed percentage of $R_{dc\ nom}$, and $R_{dc\ nom}$ is changed in proportion to the difference P0-P1 each period based on a gain parameter. By cycling repeatedly between alternate R_{dc} settings each MPPT interval, the effect that R_{dc} has on WEC output power can be measured even if output power changes substantially over the MPPT period due to changes in sea state. The selection of $T_{interval}$, T_{MPPT}, the percent deviation, and the gain have a significant effect on the operation of the algorithm.

FIGURE 10

Cycling MPPT algorithm (top) and results (bottom).



The cycling algorithm was successfully used to regulate R_{dc} to an optimum range during the WET-NZ deployment. See the bottom of Figure 10 for time data recorded during a 45-h run using this algorithm. In this case, $T_{interval}$ was set to 1 min, T_{MPPT} was initially 20 min during the first half of the run then changed to 60 min for the second half of the run, the percent deviation was 10%, and the gain was set to 3. Based on the results shown in Figure 8, WET-NZ power output was optimized with R_{dc} between approximately 10 Ω and 50 Ω. R_{dc} was set to 128 Ω at the beginning of the run, and under MPPT control R_{dc} slowly decreased until after 6 h it was less than 50 Ω. For the next 19 h R_{dc} generally stayed between 20 Ω and 40 Ω while output power varied significantly. At time 10/2 0:00, R_{dc} was perturbed to 8 Ω, and under MPPT control it then slowly increased to around 20 Ω by the end of the run. The ability of the MPPT algorithm to maintain R_{dc} within the optimum 10 Ω to 50 Ω range while output power varied significantly demonstrated successful regulation. Experimentation during several other, shorter test runs also indicted successful regulation. Only limited time was available during the WET-NZ tests to experiment with this algorithm, and further work is needed to determine the configuration settings that will optimize performance.

Conclusions

The Ocean Sentinel performed well throughout its first deployment, and the ability of the power converter together with the CompactRIO control and data acquisition to control the WET-NZ generator load and collect data proved to be effective for evaluating WEC performance. The method of using the CompactRIO host to cycle between alternate control settings in synchronism with the TRIAXYS measurement period that was developed early in the test was particularly useful for collecting the half-scale WET-NZ characterization data.

Due to Froude scaling, open ocean seas generally had longer periods than desired for half-scale model testing. In addition, the device performance was affected by a number of loss mechanisms in the half-scale PTO that caused additional loading on the float and caused the device to operate off-optimum during the deployment. These loss mechanisms have since been identified and quantified by the WET-NZ consortium. Although the nonideal sea conditions and PTO characteristics made data difficult to interpret, several conclusions were made concerning the half-scale WET-NZ WEC:

- Controlled external resistance loading via the Ocean Sentinel allowed essential on-board data to be collected and the PTO operation characterized in detail under a wide range of real sea conditions.
- The low response of the WEC to wave periods greater than 9 s that was predicted by Callaghan Innovation design analysis was verified.
- An optimum in the device output with respect to the constant resistance load applied to the generator was observed and characterized.
- While not reported in this paper, internal PTO characteristics which prevented optimum resistive loading conditions to be achieved during this deployment have been identified and addressed.

A perturb and observe MPPT algorithm was not able to regulate generator load resistance R_{dc} while output power fluctuated due to changing sea conditions. A new cycling MPPT algorithm that was developed during the deployment did successfully regulate R_{dc} under similar conditions. Further work is necessary to evaluate performance of this algorithm, and to determine the most effective configuration settings.

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