A New Maximum Power Point Tracking Algorithm for Ocean Wave Energy Converters

Terry Lettenmaier, Annette von Jouanne, and Ted Brekken

School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR 97331 USA

Abstract

This paper describes a new maximum power point tracking (MPPT) algorithm developed to control a wave energy converter (WEC) in random seas. This algorithm, named the cycling MPPT algorithm, is compared to a perturb and observe algorithm described in numerous literature. Both algorithms were initially tested during 2012 ocean tests of the half-scale prototype Wave Energy Technology – New Zealand (WET-NZ) WEC off the Oregon coast. During these sea trials the perturb and observe algorithm failed to provide effective control of the WET-NZ, while the cycling algorithm was observed to give effective control. More complete investigations were later carried out using MATLAB-Simulink simulations of an autonomous WEC (AWEC) being developed at Oregon State University. The results of the AWEC simulations also showed the cycling algorithm provided better control than the perturb and observe algorithm. The operation of the cycling algorithm was fully characterized during the AWEC simulations and these results are presented.

Keywords - Marine energy, maximum power point tracking (MPPT), ocean wave energy, power control, wave energy converter (WEC).

I. Introduction

Ocean wave energy is an area of increasing interest, with a number of wave energy converter (WEC) prototypes being developed around the world. In order to facilitate the commercialization of marine energy technology, the Northwest National Marine Renewable Energy Center (NNMREC), headquartered at Oregon State University (OSU), is developing ocean test facilities that can be used by WEC developers to test their prototype devices. As part of that effort, NNMREC has developed the Ocean Sentinel instrumentation buoy, a 6-meter buoy that facilitates open-ocean, stand-alone testing of prototype, scale model WECs with average power outputs of up to 100 kW. The Ocean Sentinel is normally deployed at a Pacific Ocean test site that is located three miles offshore, near Newport, OR. When in use, the Ocean Sentinel is connected to the WEC being tested with an umbilical cable. Load banks on board the Ocean Sentinel dissipate power generated by the WEC. The Ocean Sentinel includes generator power conversion and control equipment that can provide an adjustable resistance load to the electrical generator of the WEC being tested using the Ocean Sentinel load banks. This allows testing of WECs that do not have their own generator power converter, so that prototype WECs in early stages of development can be tested. A detailed description of the Ocean Sentinel and its capabilities is included in [1], and a more detailed description of the Ocean Sentinel power conversion and control system is included in [2]. The Ocean Sentinel was deployed for the first time in August 2012 for a six-week period to test the experimental half-scale Wave Energy Technology New Zealand (WET-NZ) WEC.

When the Ocean Sentinel power conversion and control system is used to operate a WEC during an ocean test, WEC control is provided by this equipment, which is operated by NNMREC staff. This has led NNMREC to work on developing WEC control methods that can be easily implemented in the Ocean Sentinel controller, in order to assist developers. One control method that NNMREC has investigated is Maximum Power Point Tracking (MPPT). MPPT has potential as an easily implemented control method that can adjust a control parameter to maximize the output power of a WEC being tested as sea conditions vary. MPPT is a common technique used to adjust the electrical loading applied to solar panels in order to maximize their power output. A survey of literature describing MPPT control of photovoltaic systems is provided in [3], where different MPPT control methods described in 91 reviewed papers are segregated into 11 primary methods. Perturb and observe MPPT methods are most commonly described in the reviewed literature, where the operating voltage of photovoltaic arrays are repeatedly perturbed and changes in array power observed to determine the direction of subsequent voltage adjustments. Different MPPT techniques have also been used to control wind turbines. In [4], the authors provide experimental results for a proposed small wind turbine control system that uses a perturb and observe algorithm to adjust the torque applied to the rotor based on observations of turbine output power. A similar MPPT method for control of rotor torque in utility scale wind turbines is described in [5].

The use of a simple “perturb and observe” MPPT method to control WECs was demonstrated during previous work at OSU. This work is described in [6]. A MPPT algorithm was used to control the electrical load applied by a power converter to the generator of a point absorber WEC. This WEC used a linear electrical generator, with the generator windings installed in a central spar and an outer section of permanent magnets installed in a toroidal float that moves up and down relative to the spar. The MPPT control was tested in a laboratory, where the generator components from the WEC were mounted in a Linear Test Bed at OSU that could move the permanent magnets relative to the fixed windings of the generator per pre-programmed time-based position profiles. The Linear Test Bed was programmed with a 15 minute duration sea surface elevation recording made during an earlier WEC deployment. This allowed laboratory testing of the electrical generator with motions that mimicked ideal wave following motions of the WEC float relative to a fixed spar in the recorded sea conditions. Repeated experimental runs were performed with different settings of the MPPT algorithm. The results showed that 1) effective MPPT control of the generator load was possible, and 2) long MPPT iteration times with small control steps gave the best results. Although these results were promising, this testing was performed with the WEC generator only and did not include the effects of hydrodynamic forces on the WEC. This led to the follow-up work described in this paper being performed during the WET-NZ deployment with the Ocean Sentinel in 2012, and by computer simulations of an Autonomous Wave Energy Converter (AWEC) design that was developed at OSU.

During ocean testing of the WET-NZ, MPPT control was used to adjust the WET-NZ generator load resistance. The WET-NZ generator load resistance indirectly determines the load on the float through a hydraulic PTO, although unintended PTO power losses in the scaled device being tested made control more challenging. Initially, a perturb and observe algorithm similar to that tested previously at OSU [6] was used. Long MPPT iteration times were used because this had given the best results during the previous OSU tests. Erratic behavior was observed with this algorithm and it did not appear to provide effective control of the WET NZ. This led to the initial development and

testing of a new “cycling” MPPT algorithm. The cycling MPPT algorithm gave better results. Due to the varying sea states that occurred and the limited test time available, however, it was not possible to systematically test the two MPPT algorithms and settings under the same sea conditions during the WEC-NZ deployment.

Following the WET-NZ tests, more thorough testing of both the perturb and observe and the cycling MPPT algorithms was performed using simulations of a small 200 W Autonomous Wave Energy Converter (AWEC) under development at OSU. Simulations of the WET-NZ were not feasible because that design is proprietary. Although the AWEC and the WET-NZ are both point absorber WECs, their geometry and PTO designs are quite different. The AWEC is a much smaller device that has a cylindrical float that slides up and down over a tubular spar to generate power from the heave motion of the waves. It has a direct-drive PTO that provides a direct linkage between the electrical generator and the float. The WET-NZ, by comparison, has a float that rotates with respect to the spar and allows power generation from both wave heave and surge and uses a hydraulic PTO to link the float to an electric generator. For this reason the WET-NZ ocean test and the AWEC simulations can’t be directly compared, but represent separate tests of the algorithms with two different WEC designs. During simulations of the AWEC, a systematic investigation of the two MPPT algorithms was made with different settings. The results of the AWEC simulations showed that the new cycling MPPT algorithm provided better WEC control and was easier to implement than the perturb and observe algorithm.

II. MPPT Algorithms Investigated

Two MPPT algorithms were investigated during this work: 1) a perturb and observe algorithm similar to that demonstrated previously at OSU [6], and 2) a newly developed cycling algorithm. Both algorithms were configured to control the load resistance applied to the electrical generator in the PTO of point absorber WECs. Although these algorithms are described for that use here, both can be adapted for different purposes. During the WET-NZ tests, the Ocean Sentinel power converter was configured to provide passive rectified control of a permanent magnet (PM) ac generator, with the load resistance applied on the dc side of the generator rectifier. The AWEC also has a PM generator, and that device was simulated with the same passive rectified resistive loading. The load resistance that is applied to the dc side of the rectifier and was controlled by the MPPT algorithms is referred to as “ R_{dc} ” throughout this work.

A. Perturb and Observe Algorithm

A block diagram of the perturb and observe MPPT algorithm that was used for this project is shown in Figure 1. This is the same algorithm described in [6]. Regulation of the resistive load R_{dc} applied to a WEC electrical generator is illustrated in Figure 1. 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 k^{th} interval the average WEC output power $P_{avg\ k-1}$ is calculated. Assume that R_{dc} is then increased by a fixed control step $R_{dc\ k}$ to give the resistance $R_{dc\ k}$ used for the k^{th} interval. At the end of the k^{th} 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 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} .

Figure 1 Perturb and observe MPPT algorithm. R_{dc} is increased or decreased by C_{step} at the end of each time interval T_{MPPT} depending whether average power has increased or decreased from the previous interval and whether R_{dc} was increased or decreased at the previous time step.

B. Cycling Algorithm

A block diagram of the cycling MPPT algorithm is shown in Figure 2. This algorithm was developed as part of this work. When using this algorithm to regulate R_{dc} , the value of R_{dc} is modulated about a nominal value $R_{dc\ nom}$ using a modulation waveform M . M can either be a sine wave, as shown in Figure 2, or alternatively a square wave or other waveform. During the WET-NZ ocean tests square wave modulation was used. $R_{dc\ nom}$ is held constant during each MPPT interval T_{MPPT} . At the end of each interval the influence of the modulation in R_{dc} on output power is determined by calculating the covariance of M and output power P over the interval. This quantity is normalized by average output power P_{avg} for the interval and multiplied by a gain to determine the amount to increment or decrement $R_{dc\ nom}$ for the next interval. The modulation period T_{mod} is always an integer multiple of T_{MPPT} , and the amplitude of the deviation in R_{dc} , $R_{dc\ dev}$, is always a fixed percent deviation of $R_{dc\ nom}$. The selection of T_{MPPT} , T_{mod} , the percent deviation, and the gain have significant effect on the operation of the algorithm.

Figure 2 The newly developed "cycling" MPPT algorithm. R_{dc} is modulated by a fixed percentage of its nominal value during each time step T_{MPPT} . At the end of each time step, R_{dc} is changed by the covariance of the modulation waveform and instantaneous power during the previous interval, multiplied by a fixed gain.

III. Results of Experimentation with the Half-Scale WET-NZ WEC

A. *The WET-NZ*

The WET-NZ is a point absorber WEC with a float that rotates up and down in the waves with respect to a spar to generate power. 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 WET-NZ is being introduced to the US market by Northwest Energy Innovations (NWEI), a Portland, OR firm. 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. Characteristics of the device are listed in Table 1. The design of the WET-NZ and the 2012 Pacific Ocean tests are described in further detail in [7]. The Ocean Sentinel power conversion and control equipment was used to operate the WET-NZ throughout that deployment. The Ocean Sentinel control was programmed to provide an adjustable resistance load to the electrical generator of the WET-NZ power take-off (PTO). This caused the device to operate with constant damping, where the force applied to the device float was proportional to the speed of the float through each ocean wave. The damping constant, or ratio of float force to speed, was approximately proportional to the applied generator resistance. The load resistance setting was adjusted manually to characterize the device performance with respect to this setting throughout most of the test. Near the end of the deployment, some test time was also used to experiment with control of the load resistance using different MPPT algorithms.

Figure 3 The WET-NZ wave energy converter. The float rotates up and down with respect to the hull to generate power. The left photo was taken during the 2012 Oregon deployment of the WET-NZ; OSU's Ocean Sentinel is in the background.

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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

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B. MPPT testing with the WET-NZ

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During the course of the 2012 half-scale WET-NZ WEC deployment with the Ocean Sentinel, which is described in detail in [7], NNMREC experimented with MPPT control of the WET-NZ using both the perturb and observe and the cycling MPPT algorithms. Both algorithms were used to control the WET-NZ generator load resistance R_{dc} . The MPPT testing was performed near the end of the WET-NZ deployment. Prior to MPPT testing, a large set of data was collected with R_{dc} adjusted to a wide range of fixed settings. To collect this data, R_{dc} was cycled repeatedly through a sequence of different fixed settings, with changes in R_{dc} synchronized to the 20 minute measurement period of the TRIAXYS wave buoy used to measure sea state. In this way 20 minute average WET-NZ power data was collected for each R_{dc} setting together with TRIAXYS wave data for the same time period. Over 550 hours of operating data was ultimately collected with R_{dc} settings between 4 Ω and 128 Ω over a wide range of sea states (T_e between 6.5 s and 13 s, and H_{m0} between 0.5 and 3 m). This data was analyzed to characterize the output power P of the WET-NZ with respect to R_{dc} . This analysis is described in [7]. The results showed that P was maximized when R_{dc} was somewhere between about 10 Ω and 50 Ω over a wide range of sea states. The optimum was not well defined within this range, however, due to unintended power losses in the PTO of the half-scale prototype. The results also showed that for all R_{dc} settings the scaled WET-NZ device primarily responded to portions of the wave spectra with periods 7 s or shorter, and produced little power from longer period portions of the spectra.

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Optimum regulation of R_{dc} using the perturb and observe algorithm was not successful for the half-scale WET-NZ. During experimentation with the algorithm using different T_{MPPT} and C_{step} settings, erratic behavior in R_{dc} was observed and the algorithm failed to keep R_{dc} to within the optimum 10 Ω to 50 Ω range. These tests were performed in ocean conditions with T_e between 7 s and 9 s, and H_{m0} between 1 m and 2 m. The T_{MPPT} and C_{step} settings used for experimentation were based on results of the previous work at OSU [6], where MPPT control of a WEC generator using a similar perturb and observe algorithm was successfully demonstrated in the laboratory. That work showed a trend towards better results with longer T_{MPPT} , with the best results at a T_{MPPT} of 2 minutes, the longest tested. C_{step} settings that incremented or decremented R_{dc} from its optimum by 1% to 20% gave similar results at this T_{MPPT} . During the WET-NZ tests, erratic behavior occurred during initial testing with similar T_{MPPT} and C_{step} settings. This led to further testing with longer T_{MPPT} settings, but results were no better. The results of the longest test run are shown in Figure 4, where T_{MPPT} was set to 20 minutes and geometric incrementing and

decrementing by a C_{step} of 1.41 was used. The minimum and maximum limits for R_{dc} were $8\ \Omega$ and $128\ \Omega$, respectively. R_{dc} and output power are shown together in the top plots, and 20 minute H_{m0} and T_e recordings from a nearby wave buoy are shown together in the bottom plots. During this test run R_{dc} ranges between $23\ \Omega$ and $128\ \Omega$. Output power of the WET-NZ is affected by both the wave height and wave period. Output power has a positive correlation with H_{m0} , and, because the scaled WET-NZ responds best to portions of the wave spectra below 7 s period, output power has a negative correlation with T_e for the sea conditions encountered at the test site. The Figure 4 results indicate that R_{dc} has less effect on scaled WET-NZ output power than wave height and period and other conditions; even when R_{dc} swings widely over short time periods corresponding changes in % Power are not noticeable. For example, after time 9:00 R_{dc} decreases from $128\ \Omega$ to $32\ \Omega$ over a 120 minute period, then increases back to $128\ \Omega$ during the following 120 minutes. Output power does not show a consistent trend with respect to R_{dc} during these two 120 minute periods. These difficulties with the perturb and observe algorithm led to the development of the cycling algorithm.

Figure 4 Results for control of the WET-NZ using the perturb and observe MPPT algorithm. The optimum R_{dc} is known to be between $10\ \Omega$ to $50\ \Omega$ for these wave conditions, based on previous testing of the WET-NZ. Although the test run was started with R_{dc} in that range, R_{dc} swung widely and was not maintained within that optimum range throughout the test.

The cycling algorithm was successfully used to regulate R_{dc} to the optimum $10\ \Omega$ to $50\ \Omega$ range during the WET-NZ deployment. The T_{MPPT} and percent deviation settings used for test runs were in equivalent ranges to the T_{MPPT} and C_{step} settings used for the perturb and observe algorithm. See Figure 5 for time data recorded during a 45 hour run using this algorithm. In this case, the modulation period T_{mod} was set to 1 minute, T_{MPPT} was initially 20 minutes during the first half of the run then changed to 60 minutes for the second half of the run, the percent deviation was 10% with a square wave modulation, and the gain was set to 3. R_{dc} was set to $128\ \Omega$ at the beginning of the run, and under MPPT control R_{dc} slowly decreased until after 6 hours it was less than $50\ \Omega$. For the next 19 hours R_{dc} generally stayed between $20\ \Omega$ and $40\ \Omega$ while output power varied significantly. At time 10/2 0:00, R_{dc} was perturbed to $8\ \Omega$, and under MPPT control it then slowly increases to around $20\ \Omega$ by the end of the run. The ability of the MPPT algorithm to maintain R_{dc} within the optimum range while output power varied

significantly demonstrated successful regulation. Experimentation during several other, shorter test runs of 5 to 20 hour duration were also performed. During those test runs modulations with percent deviations of 3%, 5%, and 10% were used. The best results were observed during the runs with 10% modulation; during each of those cases R_{dc} was regulated to within the optimum 10 Ω to 50 Ω range. The test runs with 3% and 5% modulation were started with R_{dc} at 128 Ω . R_{dc} slowly decreased during these test runs but was still above 50 Ω at the end of each run. All runs were performed with TMPPT of 10 min to 60 min and modulation period T_{mod} of 1 min to 2 min.

Figure 5 Results for control of the WET-NZ using the new cycling MPPT algorithm. R_{dc} was successfully regulated within the optimum 10 Ω to 50 Ω range after starting the test run with R_{dc} at 128 Ω . R_{dc} was perturbed to 8 Ω at time 10/2 0:00 to further test the algorithm. The plots of $R_{dc, nom}$ do not show the 10% square wave modulation of R_{dc} at 1 min period used by this algorithm.

Due to the varying ocean conditions that existed during the scaled WET NZ tests, it wasn't possible to test the two MPPT algorithms in the same sea states. While all of the cycling MPPT algorithm testing was performed in seas with T_e between 8 s to 12 s and H_{m0} between 1.5 m to 3 m, perturb and observe MPPT algorithm testing was performed in smaller, shorter period seas with T_e between 7 s to 8.5 s and H_{m0} between 1 m to 2 m. The different performance of the two algorithms that was observed was not expected due to the different sea conditions, however, because during earlier WET-NZ testing the relationship between R_{dc} and output power was similar for the full range of sea conditions that existed during MPPT testing with both algorithms. Because relatively long MPPT algorithm test runs are required and sea conditions vary during ocean testing, it is difficult to repeat test runs with the same sea conditions. One advantage of performing tests by computer simulation is that repeated test runs can be performed in identical conditions. A more detailed investigation of the performance of the two algorithms was possible with computer simulations of the AWEC for this reason.

IV. AWEC Simulation Model

A complete hydrodynamic model of the OSU AWEC implemented in MATLAB-Simulink was used to simulate the device using 24 hour long irregular wave sea state records for this work. The MATLAB-

Simulink model was used in conjunction with MATLAB scripts that implemented the MPPT algorithms.

A. The OSU AWEC

The AWEC was developed at OSU in 2012-2013 as part of a concurrent project. A drawing of the AWEC is shown in Figure 6. This device, described in detail in [8], is a point absorber WEC that produces power from the heave motion of the waves using a cylindrical float that slides up and down over a tubular spar. The AWEC was designed for remote power applications, and has a rated average output power of 200 W, spar length of 12 m, and a float diameter of 1.6 m. Both the float and spar have masses of approximately 1700 kg. The device uses a simple PTO system with a lead screw connected to the spar and a roller screw that is assembled with the rotor of a PM generator that is fixed to the float; the relative motion between the spar and float drives the generator.

Figure 6 Drawing of the OSU AWEC.

B. MATLAB – Simulink Hydrodynamic Model

See Figure 7 for a block diagram of the two-body hydrodynamic model of the AWEC that was implemented in MATLAB-Simulink for this work. This model, previously developed at OSU as part of the AWEC project, is described in more detail in [9]. This is a time domain model for the heave equations of motion for the device that estimates output power for a given set of wave excitation force inputs using the equations of motion for the device. The excitation force inputs for the AWEC model were calculated separately in MATLAB using ocean wave records as described in the following section. The AWEC parameters used for the model were generated

using ANSYS Aqwa hydrodynamics modeling software as part of the OSU AWEC project, using the methods described in [11]. A solid model of the AWEC design was used to determine the mass, center of gravity, and dimensional inputs necessary for the Aqwa model. These parameters include the constants listed in Table 2 as well as the frequency domain radiation response shown in Figure 8. The AWEC PTO uses a roller screw mechanism that translates vertical motion of the float to rotational motion of a permanent magnet electrical generator. This work simulated resistive loading of the generator, which provides a PTO force that is proportional to the product of the float speed and the load resistance R_{dc} . A friction force in the PTO that was approximately 10% of the total PTO force was included in the simulations.

Figure 7 Two body point observer model used for AWEC simulations

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Table 2 Constants for AVEC simulation model

Float		Spar	
m_1+ma_1	2525 kg	m_2+ma_2	6690 kg
k_{v1}	1000 Ns/m	k_{v2}	1000 Ns/m
k_{hs1}	19600 N/m	k_{hs2}	1000 N/m
		k_m	8000 N/m

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Figure 8 Frequency domain radiation and excitation force response functions for AVEC float and spar, calculated from device geometry using ANSYS Aqwa software. The inverse Fourier transform of these responses are the radiation and excitation force impulse response functions.

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322 C. Generation of irregular wave time series data

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Twenty-four hour long irregular wave elevation time series data were generated from National Data Buoy Center (NDBC) station 42035 spectral records. NDBC Station 42035 is a 3 meter discus buoy that is located 22 miles offshore of Galveston, Texas. The AVEC design was targeted for that environment. The hourly spectral records from station 42035 were first interpolated to create spectra for each four minute time period. Wave elevation time series for each four minute period were then generated from these spectra. These four minute interpolations were done to provide a time series with near continuously varying H_{m0} and T_e rather than only transitioning the underlying spectra each hour.

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Data for each four minute wave elevation time series η was generated from the spectra using the methods described in [13] and [14] as follows. The wave elevation time series η is described by equation (1):

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$$\eta(t) = \sum R_n a_n \sin(2\pi f_n(t) + \phi_n) \quad (1)$$

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where f_n is the frequency of each wave spectra component and a_n are calculated from each component of the wave spectra $S(f_n)$ and its frequency spacing Δf per equation (2):

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$$a_n = \sqrt{2 S(f_n) \Delta f} \quad (2)$$

and the values of R_n and phase ϕ_n for each spectral component were calculated per equations (3), (4), and (5), from Gaussian distributed random numbers r_{1n} and r_{2n} that were generated in MATLAB.

$$R_n = \sqrt{r_{1n}^2 + r_{2n}^2} \quad (2)$$

$$\phi = \tan^{-1} \left(\frac{r_{1n}}{r_{2n}} \right) \quad \text{if } r_{2n} \geq 0 \quad (3)$$

$$\phi = \tan^{-1} \left(\frac{r_{1n}}{r_{2n}} \right) + \pi \quad \text{if } r_{2n} < 0 \quad (4)$$

All of the four minute segments for η were then merged together to make a single, 24 hour long time series. To eliminate discontinuities, a tapered merging method was used. A 270 s time series was generated for each 4 minute (240 s) period using equation (1), then the first and last 30 seconds of each 270 s time series were tapered linearly to zero by multiplying with ramp functions. When concatenating, the adjoining segments were overlapped by 30 seconds and added together in the tapered regions.

Time series data for the spar and float excitation forces, $F_{e1}(t)$ and $F_{e2}(t)$ respectively, were generated from the wave elevation data in MATLAB by convolving the wave surface elevation record with the excitation impulse response of the float and spar per equations (5) and (6):

$$F_{e1}(t) = \int_{-\infty}^t \eta(\tau) f_{e1}(t-\tau) d\tau \quad (5)$$

$$F_{e2}(t) = \int_{-\infty}^t \eta(\tau) f_{e2}(t-\tau) d\tau \quad (6)$$

where the excitation impulse response of the float and spar are the inverse Fourier transforms of the frequency domain excitation responses for the float and spar. The frequency domain excitation responses, shown in Figure 8, were calculated from the device geometry using ANSYS Aqwa software.

D. Implementation of MPPT Algorithms in MATLAB

MATLAB routines with the form shown in Figure 9 were used to simulate AWEC operation for 24 hour long irregular wave ocean data periods while adjusting R_{dc} using either the perturb and observe or the cycling MPPT algorithm. Both MPPT algorithms have loops that iterate once per MPPT time interval T_{MPPT} to update the R_{dc} settings for the following interval. The MATLAB Simulink model described earlier was called by the MATLAB routine once per MPPT iteration. Inputs to the MATLAB-Simulink model for each iteration were vectors of float and spar excitation forces $F_{e1}(t_k)$ and $F_{e2}(t_k)$ for the T_{MPPT} long time period t_k , the nominal resistance $R_{dc, nom}$, the modulation amplitude $R_{dc, dev}$, and the initial positions and velocities for the float and spar. $R_{dc, dev}$ was zero for the perturb and observe algorithm. MATLAB Simulink outputs for each iteration were the output power vector $P(t_k)$ and the final values of position and velocity for the float and spar. $P(t_k)$ data recorded during each iteration were used to calculate the R_{dc} settings

applied to the generator for the next iteration per the MPPT algorithm. The final values of position and velocity were used as the initial values for the next iteration.

Figure 9 MATLAB routine for running MPPT algorithms.

E. Assessment of Optimum R_{dc} for Irregular Wave Data

Two different 24 hour long ocean wave records from NDBC station 42035 were used to assess the performance of the MPPT algorithms. One time period, November 29, 2011, was selected that included some of the faster changing wave heights and periods in the Station 42035 records. The other recording, from August 8, 2011, was selected for relatively slow changing sea conditions. Before simulating the MPPT algorithms, a series of simulations were performed to determine the optimum value of R_{dc} and average power P_{avg} for the AWEC throughout both of these 24 hour data sets. These optimum results are shown in Figures 10 and 11 and were later used as benchmarks for comparison of the different MPPT results. These results were produced by repeatedly simulating each 4 minute segment of both wave records with 17 different R_{dc} values geometrically spaced between 3Ω and 100Ω to find the optimum R_{dc} that gave the highest P_{avg} for each segment. The optimum energy production for these two 24 hour time periods, calculated by integrating P_{avg} over each 24 hour period, is 6.05 kWh and 7.75 kWh for the November 29, 2011 and August 8, 2011 data, respectively.

V. Results of AWEC Simulations

Simulations of the AWEC were used to evaluate the two MPPT algorithms by repeatedly simulating the device with the same two 24 hour long wave records. Performance of the two algorithms was assessed by comparing the AWEC energy capture during each run to the energy captures with the optimum adjustment of R_{dc} , shown in Figures 10 and 11 for the two sets of wave data. All MPPT runs were started with the same initial off-optimum R_{dc} value of 50Ω , while the optimum R_{dc} setting

was closer to 20 Ω per Figures 10 and 11. This was done to avoid favoring controls that simply held R_{dc} nearly constant throughout the runs.

Figure 10 Optimum R_{dc} and P_{avg} for 11-29-2011 data. These results were produced by repeatedly simulating each 4 minute segment with 17 different R_{dc} values geometrically spaced between 3 Ω and 100 Ω .

Figure 11 Optimum R_{dc} and P_{avg} for 8-11-2011 data. These results were produced by repeatedly simulating each 4 minute segment with 17 different R_{dc} values geometrically spaced between 3 Ω and 100 Ω .

A. Results for Perturb & Observe Algorithm

Numerous simulation runs of the perturb and observe algorithm were done with different values of the two parameters T_{MPPT} and C_{step} . C_{step} was used to increment or decrement R_{dc} arithmetically during these simulations. Runs were performed with both 24 hour ocean wave records for each T_{MPPT} and C_{step} setting. The results are shown in Figure 12, with six separate plots for T_{MPPT} between 1 min and 20 min. Each plot shows the energy production as a fraction of the optimum energy production for the wave record on the vertical axis, and C_{step}/T_{MPPT} on the horizontal axis. The results generally trend with C_{step}/T_{MPPT} , which represents the maximum rate of change in R_{dc} allowed by the algorithm. The optimum energy for each wave record is 6.05 kWh for Nov. 29 and 7.75 kWh for Aug. 8, as shown in Figures 10 and 11.

The results for the same parameter settings, shown in Figure 12, were generally not consistent between runs made with the two sets of wave data. Performance was usually better with the August 8, 2011 data set that has slowly changing sea conditions than with the November 29, 2011 data set that has more rapidly changing seas. The settings that gave the best results were

a T_{MPPT} of 10 minutes and a C_{step} of 6.6Ω ($C_{step}/T_{MPPT} = 0.66 \Omega/\text{min}$). Plots of R_{dc} versus time for these settings are shown in Figure 13, together with the optimum R_{dc} values from Figures 10 and 11. These plots show that, even with these settings, R_{dc} sometimes deviated far from the optimum.

Figure 12 Perturb and observe MPPT results. The results were not consistent between runs made with two different data sets. A T_{MPPT} of 10 min and C_{step}/T_{MPPT} of $0.66 \Omega/\text{min}$ gave the best results for the two runs.

B. Results for Cycling Algorithm

The cycling algorithm, which has more parameters to set than the perturb and observe algorithm, was assessed by initially experimenting with a variety of settings to find those that gave the best performance. Each parameter was then systematically adjusted while leaving other parameters at the best settings to characterize performance of the algorithm. The parameters listed in Table 3 consistently gave the highest energy capture for simulation runs performed with both ocean wave data sets. Sine wave modulation gave better results than square wave modulation.

Table 3 Cycling MPPT Algorithm Parameters for Best Performance. These values were determined experimentally by simulation.

T_{MPPT}	10 min
T_{mod}	5 min
Percent deviation	25%
Gain	3
Modulation	Sine wave

R_{dc} high limit	100 Ω
R_{dc} low limit	5 Ω

Time plots of $R_{dc\ nom}$ are shown in Figure 13 for cycling MPPT simulation runs using the parameters listed in Table 3. The perturb and observe results are shown in the same plots. The optimum R_{dc} values from Figures 10 and 11 are also plotted in Figure 13. Five point smoothing was applied to the optimum R_{dc} data to better define these plots (see Figures 10 and 11 for unsmoothed data). The energy capture during both of these 24 hour runs with the cycling algorithm is 97% of the optimum energy capture for both sets of wave data relative to the Figure 10 and 11 optimums.

Figure 13 Time plots of R_{dc} for both MPPT algorithms with best parameters, together with the optimum R_{dc} plots from Figures 10 and 11. Cycling algorithm plots show $R_{dc\ nom}$; 25% sinusoidal modulation at 5 min period is not shown. When the cycling algorithm is used, R_{dc} follows the optimum more closely than when the perturb and observe algorithm is used.

Using the cycling MPPT parameters listed in Table 3 as a baseline, multiple simulation runs were then done, changing one parameter at a time. These results are presented in the following subsections.

1) Effects of T_{MPPT}

The effect that MPPT period T_{MPPT} had on AWEC energy capture is shown in Figure 14 for simulations performed with both the November 29, 2011 and August 8, 2011 wave data. Other MPPT parameters were set to the values listed in Table 3, except that for T_{MPPT} less than 5 minutes the modulation period T_{mod} was set equal to T_{MPPT} so that T_{mod} was always an integral multiple of T_{MPPT} . Also, as T_{MPPT} was adjusted the gain parameter was adjusted in proportion because the effect of gain on the algorithm operation is relative to T_{MPPT} , with higher gains necessary at longer T_{MPPT} to give optimum results.

The results show that T_{MPPT} between about 5 minutes and 20 minutes gave the best results. Performance quickly degraded when T_{MPPT} was adjusted to less than 2.5 minutes, and slowly degraded as T_{MPPT} was increased to 30 minutes and 60 minutes.

Figure 14 Energy capture versus MPPT interval T_{MPPT} . Gain was adjusted in proportion to T_{MPPT} because this is necessary to give optimum results at each T_{MPPT} .

2) Effects of T_{mod}

The effect that modulation period T_{mod} had on AWE energy capture is shown in Figure 15. The other MPPT parameters were all left set to the values listed in Table 3. The T_{mod} values in Figure 15 are all integral divisions of the fixed 10 min T_{MPPT} . The T_{mod} setting of 5 minutes gave the best results for both sets of wave data. Performance was especially poor with T_{mod} at one minute, the smallest value tested.

Figure 15 Energy capture versus modulation period T_{mod} ; each value tested is an integral division of the 10 min modulation interval T_{MPPT} .

3) Effects of Modulation Amplitude

The effect that modulation amplitude (or percent deviation) had on AWEC energy capture is shown in Figure 16. The other MPPT parameters were all left set to the values listed in Table 3. The results show a very clear trend with an optimum at 25% to 30% for both sets of wave data. While regulation of the nominal $R_{dc\ nom}$ improves as the deviation about $R_{dc\ nom}$ is increased, the larger deviations cause wider swings in R_{dc} that can degrade performance relative to the ideal R_{dc} settings shown in Figures 10 and 11. The optimum at 25% to 30% deviation for the AWEC simulations is a compromise between these two effects. The optimum percent deviation setting will likely be different for different WECs due to different effects of R_{dc} on output power.

Figure 16 Energy capture versus percent deviation or modulation amplitude.

4) Effects of Modulation Waveform

To compare results for sinusoidal and square wave modulation, the energy capture versus percent deviation curves for both sinusoidal and square wave modulation are compared in Figure 17. The sinusoidal modulation gives higher energy capture, especially for the November 29 wave data, which has more rapidly changing sea conditions. The square wave modulation was simulated with the modulation waveform "M" in Figure 2 replaced by a square wave with a peak of one. The optimum value of percent deviation is lower for the square wave modulation than the sine wave modulation because the square wave has a higher root mean square value than the sine wave. In addition to the improvement in energy capture, sine wave modulation is expected to be better because it minimizes rapid transitions in R_{dc} that might introduce undesirable torque spikes in the WEC.

Figure 17 Energy capture versus percent deviation for sine and square wave modulation.

5) Effects of MPPT Controller Gain

The effect that gain had on AWEC energy capture is shown in Figure 18. The other MPPT parameters were all left set to the values listed in Table 3. The results show a very clear trend with an optimum of about 3 for both sets of wave data.

Figure 18 Energy capture versus gain.

VI. Observations and Discussion

In general, MPPT control is difficult for WECs because large, random fluctuations of output power occur in random seas. To regulate a control parameter such as R_{dc} by assessing its effect on output power, large enough adjustments in R_{dc} are needed to allow measurement of the resulting changes in output power in the presence of the random fluctuations. In the case of the perturb and observe algorithm, this can require a relatively large C_{step} . However, a large C_{step} introduces other problems because it can quickly adjust R_{dc} far from optimum in a few MPPT intervals when adjusted in the wrong direction. This can be observed in the time plots of R_{dc} for the perturb and observe algorithm in Figure 13; these plots, for the algorithm parameters giving the best performance, have a relatively large C_{step} setting that sometimes causes the R_{dc} value to deviate widely from the optimum.

The cycling MPPT control allows a decoupling between large deviations or modulations in the R_{dc} value made during each MPPT interval and the size of the step made in R_{dc} at the end of each

interval. By using a large modulation of R_{dc} and relatively low gain settings that cause relatively small adjustments in R_{dc} at the end of each interval, the cycling algorithm is able to regulate the nominal R_{dc} close to the optimum. Although large modulations of R_{dc} about the optimum are otherwise undesirable, the AWEC simulation results show that total energy capture was improved using this method. This is believed to be the reason that this algorithm was able to successfully regulate R_{dc} during the WET-NZ tests where the optimum in R_{dc} was poorly defined while the perturb and observe algorithm did not. Based on later AWEC simulation results, it is believed that even larger modulation amplitudes might have improved performance of the cycling algorithm during the WET-NZ tests (modulation amplitudes above 15% were not used during those tests).

When the R_{dc} setting is rapidly increased or decreased while a WEC is operating, the force on the float changes so that the speed of the float rapidly increases or decreases. This causes a short term decrease or increase in the output power following the change in R_{dc} that can influence the effectiveness of the MPPT algorithms. This is most likely the reason that the perturb and observe algorithm performed poorly with small T_{MPPT} , and the cycling algorithm performed poorly with small T_{MPPT} or modulation period T_{mod} . This is also believed to be the reason that the cycling algorithm performs better with sine wave rather than square wave modulation; with sine wave modulation, increases or decreases in device output power that occur shortly after the beginning of a new MPPT interval have little effect on the algorithm because the modulation is near zero.

VII. Conclusions

NNMREC has investigated MPPT control algorithms that can be easily implemented in the power converter controller on board the Ocean Sentinel instrumentation buoy. This equipment is used to operate prototype WECs that do not have their own generator control. These algorithms can be used to adjust control parameters such as the generator load resistance for WECs being tested, in order to maximize WEC power output as sea conditions change. Investigation of MPPT algorithms began during the first deployment of the Ocean Sentinel in 2012 to test the half-scale WET-NZ prototype in 2012. Two algorithms were implemented during the ocean tests to adjust the WET-NZ generator load resistance R_{dc} to within an optimum range. A perturb and observe algorithm described in the literature was used initially, but it did not provide effective control. A new cycling algorithm was then developed and was tested experimentally. The cycling algorithm modulates the control setting that is being regulated above and below a nominal value to test its effect on WEC power output. This algorithm was able to provide effective control of the WET-NZ during limited ocean trials.

Further investigations of both the perturb and observe and the cycling MPPT algorithms were later carried out using MATLAB-Simulink simulations of the OSU AWEC to extend the work that began during the WET-NZ tests. The results of the AWEC simulations were consistent with the WET-NZ results; the cycling algorithm provided better control than the perturb and observe algorithm. While perturb and observe MPPT control of the AWEC was possible, in general regulation was not very good and the performance was often inconsistent between runs that were made with the same algorithm settings and different sea records, indicating chaotic behavior. The cycling algorithm, on the other hand, provided effective control as long as the load resistance was modulated with relatively large deviations above and below the nominal settings. Modulation of about 25% of the nominal resistance gave the best control. These large modulations of the control value were necessary to measure the effect that changes in the control input had on output power, which had large fluctuations due to the random seas, and to determine the best adjustment for the next control interval.

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References

[1] A. von Jouanne, T. Lettenmaier, E. Amon, T. Brekken, and R. Phillips, "A Novel Ocean Sentinel Instrumentation Buoy for Wave Energy Testing," *Mar. Technol. Soc. J.*, vol. 47, no. 1, pp. 47–54, Jan. 2013.

- [2] T. Lettenmaier, E. Amon, and A. von Jouanne, "Power converter and control system developed in the Ocean Sentinel instrumentation buoy for testing wave energy converters," in 2013 IEEE Energy Conversion Congress and Exposition (ECCE), 2013, pp. 344–351.
- [3] T. Esum and P. L. Chapman, "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques," IEEE Trans. Energy Convers., vol. 22, no. 2, pp. 439–449, Jun. 2007.
- [4] E. Koutroulis and K. Kalaitzakis, "Design of a maximum power tracking system for wind-energy-conversion applications," IEEE Trans. Ind. Electron., vol. 53, no. 2, pp. 486–494, 2006.
- [5] B. Shen, B. Mwinyiwiwa, Y. Zhang, and B.-T. Ooi, "Sensorless Maximum Power Point Tracking of Wind by DFIG Using Rotor Position Phase Lock Loop (PLL)," IEEE Trans. Power Electron., vol. 24, no. 4, pp. 942–951, 2009.
- [6] E. A. Amon, T. K. A. Brekken, and A. A. Schacher, "Maximum Power Point Tracking for Ocean Wave Energy Conversion," IEEE Trans. Ind. Appl., vol. 48, no. 3, pp. 1079–1086, Jun. 2012.
- [7] T. Lettenmaier, A. von Jouanne, E. Amon, S. Moran, and A. Gardiner, "Testing the WET-NZ Wave Energy Converter Using the Ocean Sentinel Instrumentation Buoy," Mar. Technol. Soc. J., vol. 47, no. 4, pp. 164–176, Jul. 2013.
- [8] T. M. Lewis, "A remotely operated, autonomous wave energy converter system," Ph.D. Thesis, Oregon State University, 2014.
- [9] B. Bosma, T. K. A. Brekken, H. T. Ozkan-Haller, and S. C. Yim, "Wave energy converter modeling in the time domain: A design guide," in 2013 1st IEEE Conference on Technologies for Sustainability (SusTech), 2013, pp. 103–108.
- [10] T. M. Lewis, A. von Jouanne, and T. K. A. Brekken, "Modeling and control of a slack-moored two-body wave energy converter with finite element analysis," in 2012 IEEE Energy Conversion Congress and Exposition (ECCE), 2012, pp. 938–945.
- [11] B. Bosma, Z. Zhang, T. K. A. Brekken, H. T. Ozkan-Haller, C. McNatt, and S. C. Yim, "Wave energy converter modeling in the frequency domain: A design guide," in 2012 IEEE Energy Conversion Congress and Exposition (ECCE), 2012, pp. 2099–2106.
- [12] S. Elgar, R. T. Guza, and R. J. Seymour, "Wave group statistics from numerical simulations of a random sea," Appl. Ocean Res., vol. 7, no. 2, pp. 93–96, Apr. 1985.
- [13] J. Fréchet, "Realistic simulation of ocean surface using wave spectra," JVRB - J. Virtual Real. Broadcast., vol. 4(2007), no. 11, Nov. 2007.