SAND2022-1241C

Wave Energy Converter Optimization with Multi-Resonance Controller of the Electrical Power Take-off

Madelyn G. Veurink[1], Wayne W. Weaver[1], Rush D. Robinett III[1], David G. Wilson[2], Ronald C. Matthews[2]
[1]Michigan Technological University, Houghton, MI 49931, USA,
[2]Sandia National Labs, Albuquerque, New Mexico 87123, USA

***Abstract*—The world's oceans hold a tremendous amount of energy and are a promising resource of renewable energy. Wave Energy Converters (WECs) are a technology being developed to extract the energy from the ocean efficiently and economically. The main components of a WEC include a buoy, an electric machine, an energy storage system, and a connection to the onshore grid. Since the absorption of the energy in the ocean's waves is a complex hydrodynamic process a power-take-off (PTO) mechanism must be used to convert the mechanical motion of the buoy into usable electric energy. This conversion can be done by using a rack-and-pinion gear system to transform the linear velocity of the buoy into a rotational velocity that is used to turn the electric machine. To extract the most energy from the ocean waves a controller must be implemented on the electric machine to make the buoy resonate with the frequency of the waves. For irregular wave climates a multi-resonance controller can be utilized to resonate with the wave spectrum and optimize the power output of the WEC.**

***Index Terms*—Wave energy converters, Energy capture, Multi-resonance control, Renewable energy**

I. Introduction

Renewable energies continue to gain attention around the world as the global demand for electricity increases and countries make pledges to reduce carbon emissions. To achieve carbon neutrality a mix of renewable energy sources must be utilized including solar, wind, and wave energy. Solar and wind energy are already economically viable energy sources. To make WECs economical they must maximize the energy conversion from wave to wire [1].

There is an immense amount of energy stored within the world's oceans and the United States alone has 2640 TWh in the water's surrounding it [2]. WECs can be utilized to extract this tremendous amount of energy and convert the force of the waves into usable electricity. The mechanical energy absorbed by the buoy is converted to usable electric energy through a PTO on the buoy.

A rack-and-pinion gear system can be utilized as a PTO on a heaving buoy to convert the vertical linear velocity into a rotational velocity. This rotational velocity can then be used to turn an electric machine on the buoy [3]. In [4] the ac power from the electric machine is converted to dc by an ac to dc inverter before it is stored in a constant dc bus. The dc power is then exported to shore across an undersea cable where it is then injected into the grid. To maximize the power injected to the grid the control system of the WEC must maximize the energy absorbed by the buoy.

Extracting energy from the waves efficiently is made complex by the wave being comprised of varying frequencies across a spectrum. A common wave spectrum is the Bretschneider spectrum that is characterized by the wave energy being more evenly distributed across a bandwidth [5]. The Bretschneider spectrum is representative of the sea state that occurs in a given area.

To be economically viable the controls of the WEC must be optimized to extract energy at multiple frequencies across the wave spectrum [6], [1], [7].

There are many different control strategies developed for WECs operating in a single Degree-of-Freedom (DOF). One of these strategies, Complex Conjugate Control (C3), provides the criteria necessary for maximum energy extraction from the WEC in the frequency domain [8]. The two criteria to be met to implement C3 are resonating the natural frequencies of the system with the wave excitation force and adding damping that is equal in magnitude to the system's damping [9].

In [6], [1], [7] a time domain C3 control was developed by calculating the phase and the magnitudes of the decomposed frequency components of the wave spectrum. This time domain control algorithm can be implemented by creating a proportional derivative feedback loop for each of the decomposed frequencies from the measured signal [6], [1], [7]. The proportional gain of this controller is calculated using each of the decomposed frequencies, and to satisfy the C3 criteria the derivative gain is set equal to the real part of the mechanical impedance [10]. This control is referred to as Proportional Derivative Complex Conjugate Control (PDC3).

This paper will utilize the Bretschneider spectrum to create an excitation wave force for a WEC. The PDC3 will be used to decompose the excitation force into its frequency components and the proportional gain will be tuned to the main frequency and additional frequencies 0.2 Hz apart to cover the full Bretschneider spectrum. This control force will then be used to control the linear force of the electric machine.

II. Electrical and Mechanical Model of WEC

The WEC model is made up of a buoy, an electric machine, an energy storage system, a line to shore, and the electric grid

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

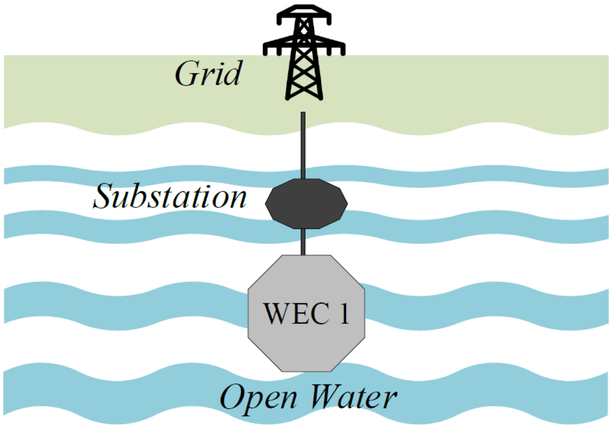

Fig. 1. Position of the WEC with Respect to the Shore

integration. The positioning of the buoy relative to the on shore electric grid is shown in Figure 1.

The electrical PTO of the WEC is shown in Figure 2, where i_{pto} represents the power that is absorbed by the mechanical system and injected into the bus by the electrical system of the buoy. The electrical PTO for the WEC is based off of previous work done in [3].

The interaction of the wave with the electric machine on the WEC is shown in Figure 2. The mechanical system of the buoy is modeled by the following differential equation of a mass-spring-damper (MSD)

$$m\ddot{x_1} + c_1\dot{x_1} + kx_1 = f_{e1} + f_{u1} \tag{1}$$

where the control force term f_{u1} is replaced by the linear force of a permanent magnet dc machine with rack-and-pinion gear such that

$$f_{u1} = \frac{\tau}{r} = \frac{i_a K_m}{r} \tag{2}$$

where K_m is the machine torque constant and r is the radius of the rack-and-pinion gear.

The linear motion of the wave is translated to rotational motion through the rack-and-pinion gear system. The linear velocity is converted to rotational velocity by the gear radius as

$$v = \dot{x} = rw_m \tag{3}$$

where v is the linear velocity that is converted to the rotational velocity, w_m, through the gear radius r. The rotational velocity then turns an electric machine on each of the buoys.

The electrical system on each of the buoys can be modelled by

$$\dot{i_a} = \frac{1}{L_a}(v_a - i_a R_a - \frac{K_m v}{r}). \tag{4}$$

The power injected into the electrical bus from each of the DC electric machines can be calculated as

$$i_{pto} = \frac{P_{pto}}{v_b} = \frac{v_a i_a}{v_b}. \tag{5}$$

The electric PTO is connected to an electric bus which is modelled in the circuit as a parallel RC circuit and ideal energy storage system (ESS). The electrical bus is connected to shore by a 1 km cable modelled by a series resistor and inductance. The grid connection is modelled by an RC circuit in parallel with a current source that represents the power delivered to the grid by the WEC. The electrical bus, line to shore, and grid can be modelled by the following

$$\dot{v_b} = \frac{1}{C_b}(i_{pto} - \frac{v_b}{R_b} - u - i_L) \tag{6}$$

$$\dot{i_L} = \frac{1}{L_L}(v_b - i_L R_L - v_g) \tag{7}$$

$$\dot{v_g} = \frac{1}{C_g}(i_L - i_{grid} - \frac{v_g}{R_g}) \tag{8}$$

where u is the ideal current from the ESS. The ideal current from the ESS can be calculated as

$$u = \frac{v_{sc} - v_b}{ESR}. \tag{9}$$

The variables for the mechanical system, the electric machine, and the electrical system can be found in Tables I, II, and III respectively.

The wave that is interacting with the WEC is modelled as the excitation force and for an irregular water wave comprised

TABLE I
MECHANICAL SYSTEM PARAMETERS

Parameter	Description	Units
m	Buoy Mass	kg
c	Damper Coefficient	$N/\frac{m}{s}$
k	Spring Coefficient	$\frac{N}{m}$
f_e	Wave Excitation Force	N
r	Rack and Pinion Gear Radius	m

TABLE II
ELECTRIC MACHINE PARAMETERS

Parameter	Description	Units
v_a	Armature Voltage	V
i_a	Armature Current	A
K_m	Torque Constant	$\frac{Nm}{A}$
L_a	Armature Inductance	H
R_a	Armature Resistance	Ω

TABLE III
SYSTEM PARAMETERS

Parameter	Description	Units
v_b	PTO Collection Bus Voltage	V
i_l	Line Current	A
v_g	Grid Voltage	V
v_{sc}	ESS Voltage	V
i_{pto}	Current from Electric Machine	A
i_{grid}	Current into Grid Inverter	A
u	Current from ESS	A
C_b	Bus Capacitance	F
R_b	Bus Parasitic Resistance	Ω
C_g	Grid Inverter Resistance	A
R_g	Grid Inverter Resistance	Ω
ESR	Equivalent Series Resistance of C_b	Ω

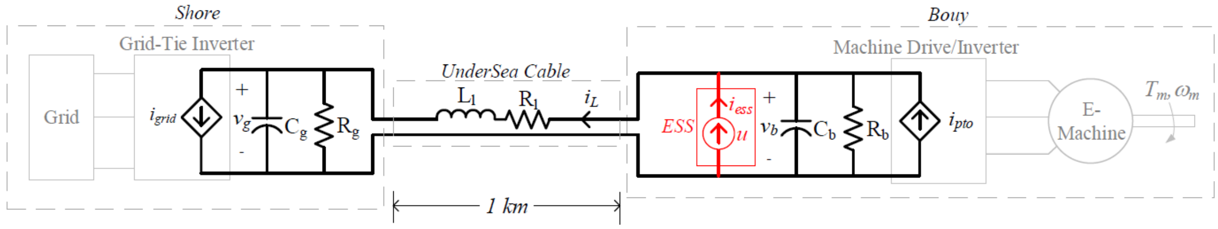

Fig. 2. Circuit Model of the WEC Connected to the Grid [3]

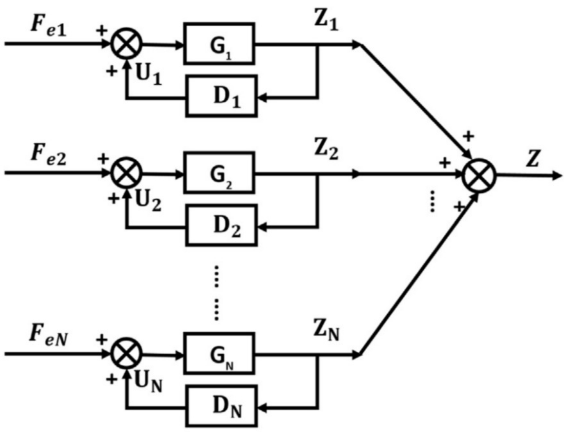

Fig. 3. Block Diagram of the Decomposed Excitation Force and PDC3 [6], [1], [7]

of multiple frequencies the excitation force is the sum of the multiple frequency components

$$f_e = \sum_{n=1}^{N} A_n sin(w_n t + \phi_n). \quad (10)$$

When this multiple frequency excitation force interacts with the WEC the system reacts differently to each one of the multiple input frequencies. To extract the most energy from the WEC the excitation force must be broken into its individual frequencies, and a controller must be designed for each frequency.

The excitation force can be broken into its sub-components using a Discrete Fourier Transform (DFT) as

$$f_e(t) = a_0 + \sum_{n=1}^{N} [a_n cos(n\omega t) + b_n sin(n\omega t)] \quad (11)$$

where a_0 is the average of $f_e(t)$, and a_n and b_n are the amplitudes of the sine and cosine components of one frequency in the decomposed signal. Each of these components can be controlled using a Proportional Derivative Complex Conjugate Control (PDC3) described in [6], [1], [7]. PDC3 requires that the excitation force be decomposed into its individual frequencies and a PD controller be designed for each frequency. These individual control channels will then be summed up to create the control input for the complete excitation force. This process is shown in Figure 3.

TABLE IV
BRETSCHNEIDER SPECTRUM VARIABLES

Parameter	Description	Value
H_w	Significant Wave Height	$2.2\ m$
T_s	Peak Period	$9.2\ s$

In PDC3 the proportional gain is designed so each channel of the controller will resonate with an individual frequency component of the decomposed excitation force and can be calculated as

$$k_{p1} = w_1^2 m_1 - k. \quad (12)$$

The derivative gain, k_d is chosen so that the real portion of the control impedance is equal to the real part of the mechanical impedance. The derivative gain is chosen as this in order to maximize the power out and to satisfy the complex conjugate control requirement

$$k_{d1} = c_1. \quad (13)$$

The control signal from the PDC3 in this study is used to control the actuator of the WEC. The Bretschneider spectrum used to create the multiple frequency excitation force was generated for one sea state. The wave height and period were used in addition with the WAFO toolbox to generate the Bretschneider spectrum [11]. The spectrum was generated using the `Bretschneider` function from the WAFO toolbox and was then converted to the time domain using the `spec2dat` function. The generated mean water level data was then scaled to resemble an excitation force acting upon the WEC. This force is shown in Figure 5. This sea state was created using significant wave heights and periods collected from the National Data Buoy Center, buoy number 46073, located in the Bering Sea [12]. The values for the significant wave height and peak period are shown in Table IV.

III. SIMULATION RESULTS

The multi-frequency excitation force used in the MATLAB/Simulink model was modelled after the Bretschneider spectrum. The Bretschneider spectrum was used to create a wave force as is described in Section 2. The Bretschneider wave force was then decomposed into its frequency components using the built in Fast Fourier Transform (FFT) function in MATLAB. The Fourier Transform of the Bretschneider wave force is shown in Figure 6. The highest amplitude of the

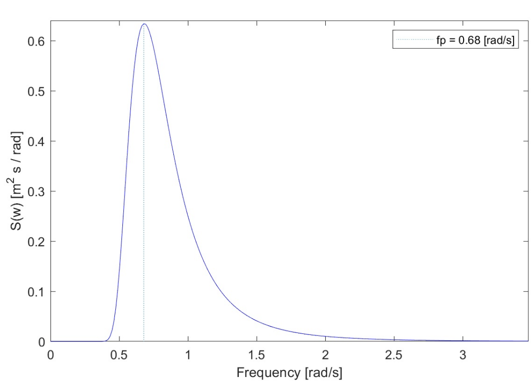

Fig. 4. Bretschneider Spectrum

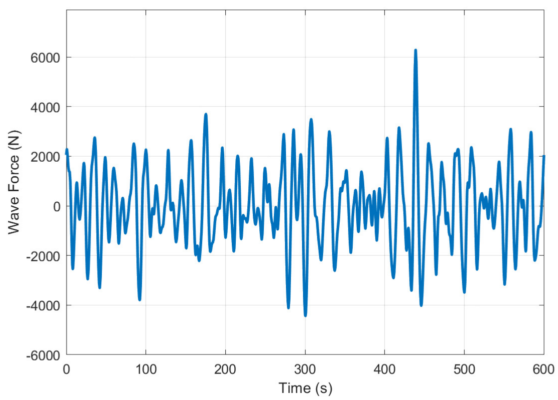

Fig. 5. Excitation Force of Bretschneider Wave

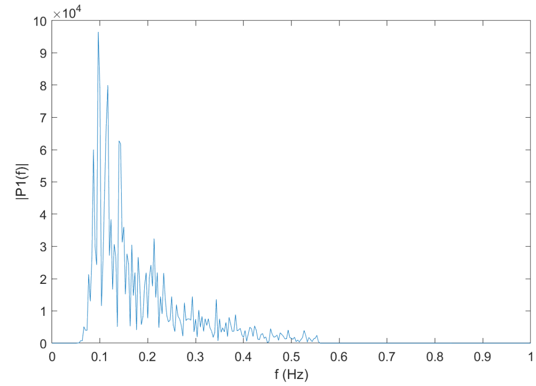

Fig. 6. Single Sided Amplitude Spectrum of the Bretschneider Wave Excitation Force

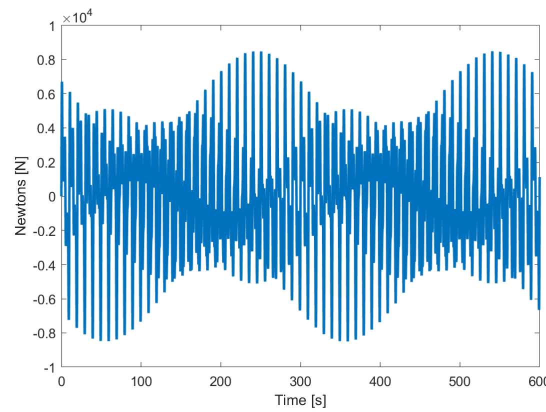

Fig. 7. Simplified Excitation Force

Bretschneider excitation force was determined to be 0.09667 Hz.

The main frequency component from the spectrum as well as additional frequencies with lesser magnitudes were summed together to create a simplified excitation force that resembles the frequencies in the Bretschneider excitation force. The excitation force used in this model is shown in Figure 7. The frequencies and amplitudes of the single frequency components summed together to create the simplified excitation force are shown in Table V. The main frequency component as well as two additional frequency components in the simplified excitation force were chosen to tune the proportional gain in each of the three PDC3 channels. The chosen control frequencies are shown in Table VI. These three frequencies go through the estimator described in Section 2 of this paper in order to estimate the amplitude of each chosen frequency component in the simplified excitation force.

The WEC model was simulated with three PDC3 channels operating. The proportional gain of the channels were tuned to the chosen frequencies of the simplified excitation force. As additional channels are added to the controller the buoy resonates more with the excitation frequency. With each additional channel the power extraction of the buoy increases and thus the power exported to the grid increases. The power that is extracted from the water by the WEC is exported to the grid across the undersea cable. The increase in the PTO power of the buoy by adding additional channels to the PDC3

TABLE V
SIMPLIFIED EXCITATION FORCE COMPONENT PARAMETERS

Parameter	Value
A_1	3000 N
A_2	2100 N
A_3	2500 N
A_4	1000 N
A_5	1600 N
f_1	0.09667 Hz
f_2	0.20 Hz
f_3	0.30 Hz
f_4	0.40 Hz
f_5	0.50 Hz

TABLE VI
CHOSEN CONTROLLER FREQUENCIES FOR THE THREE PDC3 CHANNELS

Parameter	Value
$f_{Channel1}$	0.09667 Hz
$f_{Channel2}$	0.30 Hz
$f_{Channel3}$	0.50 Hz

TABLE VII
AVERAGE PTO POWER FOR DIFFERENT CHANNELS ENABLED

Numbe of Channels	**Value**
1 Channel	$-269\ W$
2 Channels	$-929\ W$
3 Channels	$-1784\ W$

TABLE VIII
AVERAGE GRID POWER FOR DIFFERENT CHANNELS ENABLED

Numbe of Channels	**Value**
1 Channel	$60\ W$
2 Channels	$704\ W$
3 Channels	$1506\ W$

is summarized in Table VII. The PTO power for the WEC is negative due to the fact that it is exporting power. This increase in the PTO power for each added channel is also reflected in the grid power of the system. The increase in the grid power for each added channel is summarized in Table VIII. The grid power in this system is positive because it is being consumed. The power extracted with only one channel enabled is very small due to the fact that the frequency for the enabled control channel was set to 0.5 Hz. The majority of the energy in the wave is concentrated at frequencies lower than 0.5 Hz so the buoy does not resonate well with the excitation force when only this channel is enabled. The armature voltage and current of the electric machine on the buoy with all three PDC3 controller channels enabled are shown in Figure 8.

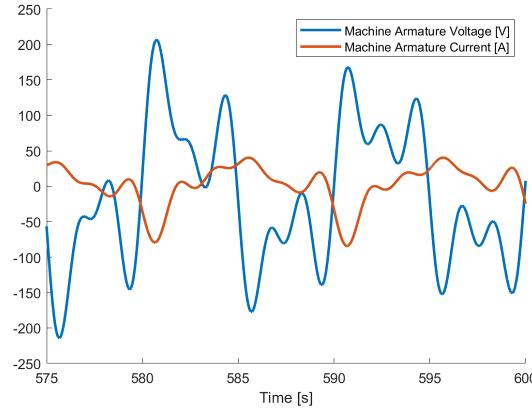

Fig. 8. Electric Machine PTO Armature Voltage and Current

IV. CONCLUSION

This paper shows the implementation of a PDC3 controller on a WEC and it's ability to increase the energy absorption of the WEC through the electrical PTO for multiple frequency excitation forces. The PDC3 was investigated in this paper given its ability to maximize the energy absorption of the buoy without the need for wave predictions.

The wave climate for the simulation was modelled after a Bretschneider spectrum. The PDC3 controller was tested on the simplified Bretschneider spectrum sea state by adding in additional channels that were tuned to frequencies across the spectrum. It was shown that the addition of frequency channels to the PDC3 caused the WEC to resonate more with the excitation force leading to increased energy absorption for each added channel.

V. ACKNOWLEDGMENT

This study was funded by the Laboratory Directed Research & Development (LDRD) program at Sandia National Laboratories. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. Special thanks to Dr. Ray Byrne at Sandia, for his technical review and programmatic leadership for this LDRD project.

REFERENCES

[1] J. Song, O. Abdelkhalik, R. Robinett, G. Bacelli, D. Wilson, and U. Korde, "Multi-resonant feedback control of heave wave energy converters," *Ocean Engineering*, vol. 127, pp. 269–278, 2016.

[2] P. T. Jacobson, G. Hagerman, and G. Scott, "Mapping and assessment of the united states ocean wave energy resource," Electric Power Research Institute, Tech. Rep., 2011.

[3] W. W. Weaver, D. G. Wilson, A. Hagmuller, M. Ginsburg, G. Bacelli, R. D. Robinett, R. Coe, and B. Gunawan, "Super capacitor energy storage system design for wave energy converter demonstration," in *IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, 2020, pp. 564–570.

[4] D. G. Wilson, W. W. Weaver, G. Bacelli, and R. D. Robinett, "Wec array electro-mechanical drivetrain networked microgrid control design and energy storage system analysis," in *2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*. IEEE, 2018, pp. 1278–1285.

[5] J. Prendergast, M. Li, and W. Sheng, "A study on the effects of wave spectra on wave energy conversions," *IEEE Journal of Oceanic Engineering*, vol. 45, no. 1, pp. 271–283, 2018.

[6] D. G. Wilson, G. Bacelli, R. D. Robinett, U. A. Korde, O. Abdelkhalik, and S. F. Glover, "Order of magnitude power increase from multi-resonance wave energy converters," in *OCEANS 2017-Anchorage*. IEEE, 2017, pp. 1–7.

[7] O. Abdelkhalik, S. Zou, R. D. Robinett, G. Bacelli, D. G. Wilson, R. Coe, and U. Korde, "Multiresonant feedback control of a three-degree-of-freedom wave energy converter," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 4, pp. 1518–1527, 2017.

[8] F. Fusco and J. V. Ringwood, "A simple and effective real-time controller for wave energy converters," *IEEE Transactions on sustainable energy*, vol. 4, no. 1, pp. 21–30, 2012.

[9] J. Falnes and A. Kurniawan, *Ocean waves and oscillating systems: linear interactions including wave-energy extraction*. Cambridge university press, 2020, vol. 8.

[10] G. Bacelli, *Optimal control of wave energy converters*. National University of Ireland, Maynooth (Ireland), 2014.

[11] T. Perez and T. I. Fossen, "A MATLAB toolbox for parametric identification of radiation-force models of ships and offshore structures," 2009.

[12] "Southeast bering sea - 205 NM WNW of Dutch Harbor, AK," https://www.ndbc.noaa.gov/station$_{page.php?station} = 46073$, $Accessed: 2021-11-06$.