WEC Array Optimization with Multi-Resonance and Phase Control of Electrical Power Take-Off

Madelyn G. Veurink[1], Wayne W. Weaver[1],David G. Wilson[2], Rush D. Robinett III[1], Ronald C. Matthews[2]

[1]Michigan Technological University, Houghton, Michigan, USA,
[2]Sandia National Labs, Albuquerque, New Mexico, USA

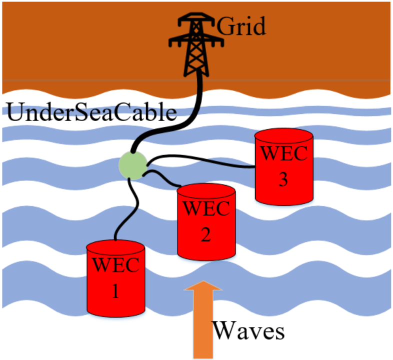
IFAC Symposium on Mechnatronic Systems
September 6-9, 2022

Introduction

- Wave Energy Converters (WECs) can be used to extract energy from the world's oceans.
- The electric machine on each buoy must be controlled with a multi-resonance controller to optimize the power output of each WEC.
- The electrical energy from each of the electric machines oscillates with the wave period
- Shifting the physical placement of the buoys will create a phase shift in the electrical signals

Main Components of a WEC

- Buoys
- Mechanical Drive-trains
- Electric Machines
- Power Electronics
- Energy Storage
- Under-sea Cable
- Grid connection

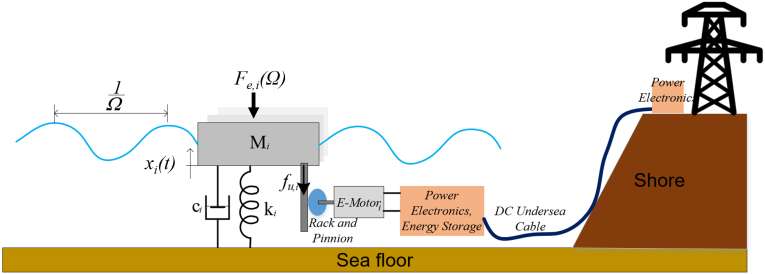


Mechanical Model of the WEC Array

- The mechanical systems of the buoys are modelled as mass-spring-damper systems:

$$m_i\ddot{x}_i + c_i\dot{x}_i + kx_i = f_{e,i} + f_{u,i} \tag{1}$$

- Power Electronics convert mechanical energy from E-Motor to dc
- Transmit dc power to the shore - Shore side inverter couples to local transmission grid



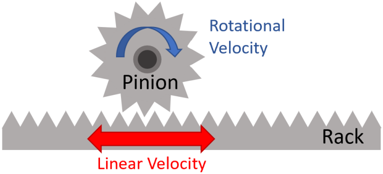
Electrical Drives of a WEC Array

The control force $f_{u,i}$ is replaced with the linear force on a PMDC machine

$$f_{u,i} = \frac{\tau}{r} = \frac{i_{a,i} K_m}{r} \tag{2}$$

The linear motion of the buoys is translated to a rotational motion that turns the electric machines.

$$v_i = \dot{x}_i = r w_{m,i} \tag{3}$$



Electrical Model of the WEC Array

The electric machine on each of the buoys is

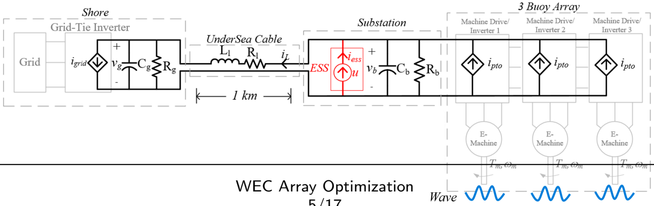
$$\dot{i}_{a,i} = \frac{1}{L_a}\left(v_{a,i} - i_{a,i}R_a - \frac{K_m v_i}{r}\right) \tag{4}$$

The current injected into the electrical bus from each of the DC electric machines is

$$i_{pto,i} = \frac{P_{pto,i}}{v_b} = \frac{v_{a,i}i_{a,i}}{v_b} \tag{5}$$

The sum of the currents is

$$i_{ptosum} = \sum_{i=1}^{N} i_{pto,i} \tag{6}$$



Array Connection to the Onshore Grid

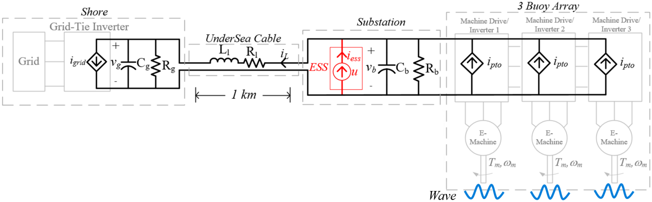
The electrical bus, the line to shore, and the grid can be modelled by the following equations.

$$\dot{v_b} = \frac{1}{C_b}(i_{ptosum} - \frac{v_b}{R_b} - u - i_L) \quad (7)$$

$$\dot{i_L} = \frac{1}{L_L}(v_b - i_L R_L - v_g) \quad (8)$$

$$\dot{v_g} = \frac{1}{C_g}(i_L - i_{grid} - \frac{v_g}{R_g}) \quad (9)$$

u is the current injected to the bus by the ideal energy storage system (ESS).



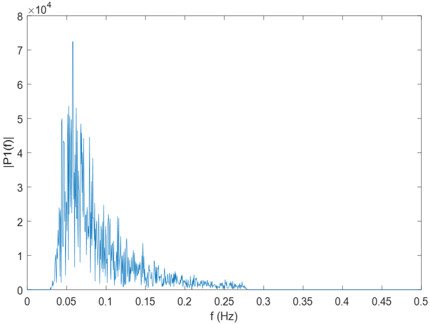
Excitation Force on the WEC Array

- Ocean waves contain many frequencies.
- One model of a sea state is the *Bretschneider Spectrum*.
- The multi-frequency excitation force is the sum of multiple frequency components.

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

- To maximize power output of the Array the buoys must resonate with the peak frequencies of the waves.

The Bretschneider Spectrum



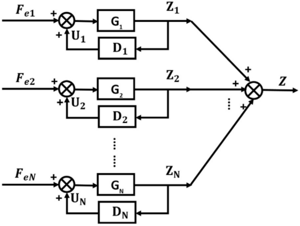
Multi-Resonance Control

- The multi-frequency excitation force can be decomposed into its individual components using a Discrete Fourier Transform.
- PDC3 requires that a PD controller be designed for each of the main frequencies.

$$k_{p,i} = w_i^2 m_i - k. \qquad (11)$$

$$k_{d,i} = c_i. \qquad (12)$$

- The individual channels are then summed to create the full control force.



Buoy Shifting and Electrical phasing

- For a shifted WEC in an array the output power is

$$p_i(t) = \frac{1}{2}(cos(2\omega_n t - 2(i-1)\phi) + 1) \tag{13}$$

- The power from N WECs is

$$P_{array} = \sum_{i=1}^{N} p_i(t) = \frac{1}{2}(csc(\phi)sin(N\phi)cos(2\omega_n t + \phi(1-N))) + N). \tag{14}$$

- The total sum of the power is constant if

$$csc(\phi)sin(N\phi) = 0 \text{ when } \phi \in \left\{\frac{\pi}{N}, \frac{2\pi}{N}\right\}. \tag{15}$$

Example System

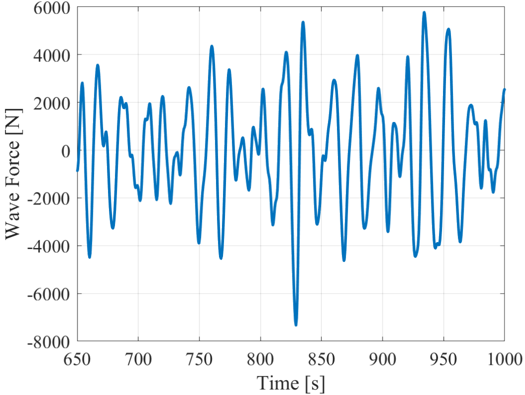
- 3 WECs
- Bretschneider Wave Force
- DC machines on the buoys connect to DC bus

Model Parameters

Parameter	Description	Value
m	Buoy Masses	$268\ kg$
c	Damper Coefficients	$1226\ N/\frac{m}{s}$
k	Spring Coefficients	$1194\ \frac{N}{m}$
r	Rack and Pinion Gear Radii	$0.025\ m$
K_m	Torque Constants	$2\ \frac{Nm}{A}$
L_a	Armature Inductances	$1e^{-3}\ H$
R_a	Armature Resistances	$1e^{-3}\ \Omega$
C_b	Bus Capacitance	$2e^{-6}\ F$
R_b	Bus Parasitic Resistance	$80e^{-9}\ \Omega$
R_L	Undersea Cable Resistance	$2.5\ \Omega$
L_L	Undersea Cable Inductance	$95.6e^{-6}\ L$
R_g	Grid Inverter Resistance	$1000\ \Omega$
C_g	Grid Inverter Capacitance	$2e^{-6}\ F$

Applied Wave Force

- Developed from a Bretschneider Spectrum



Chosen Controller Frequencies for the Three PDC3 Channels

Parameter	Value
$f_{Channel1}$	$0.053\ Hz$
$f_{Channel2}$	$0.0505\ Hz$
$f_{Channel3}$	$0.0655\ Hz$
$f_{Channel4}$	$0.0485\ Hz$

Force Shifting on the WECs

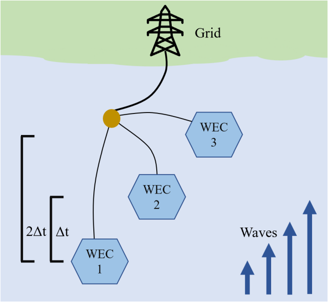
- The WECs are shifted spatially in the water.
- This spatial shift is represented by a time shift in the excitation forces.

$$f_{e,1}(t) = \hat{f}_e(t) \quad (16)$$

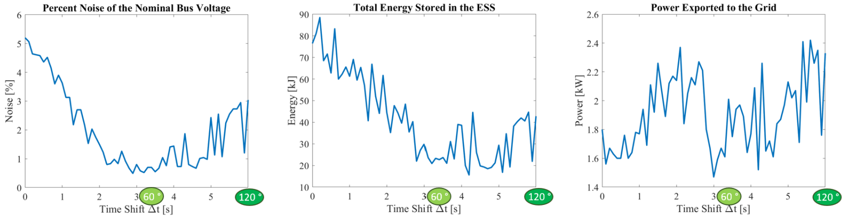
$$f_{e,2}(t) = \hat{f}_e(t - \Delta t) \quad (17)$$

$$f_{e,3}(t) = \hat{f}_e(t - 2\Delta t) \quad (18)$$

- Δt is a design parameter used to determine the optimal spacing of the WECs.



Optimizing the Time Shift



Time Shifting Results

Table: Results Varying Time Shifts on the 3 WECs

Δt [s]	Pk-Pk Voltage Noise [%]	ESS Energy [kJ]	Grid Power [kW]
0	5.20	76.5	1.8
1	3.63	61.3	1.77
2	1.50	44.5	2.14
60 ° 3	0.80	29.8	1.47
4	1.44	38.6	1.77
5	2.43	29.4	2.13
120 ° 6	3.04	42.8	2.33

Best Cases

Conclusions

- Changing the physical spacing of the buoys creates an electrical phase shift.
- Phase shifting the electrical signals reduces bus voltage ripple, ESS size, and maximiez the grid power.
- For three buoys the optimal phase shift occurs at 60^o or 120^o.
- Due to additional frequency components in the wave spectrum the optimal time shift is slightly less than 3 seconds or 60^o.

Acknowledgments

- 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.

Thank You for Your Attention!

Questions?