Novel Control Design for a Wave Energy Generator

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This paper presents the derivation of a novel control method for a permanent magnet linear generator for use in wave energy applications. The control design is an extension of optimal wave energy converter (WEC) control theory. Adaptations have been made to account for a variety of real-world limitations. Dynamic generator loading is used to control the motion of the WEC. The novel control presented maximizes power output while also protecting the WEC system.

Nomenclature

F_e	Hydrodynamic excitation force, N
F_{gen}	Generator force, N
m_b	Buoy mass, kg
A_b	Buoy added mass, kg
c_b	Buoy hydrodynamic damping, Ns/m
k_b	Buoy bouyancy, N/m
z_w	Water vertical position, m
z_b	Buoy vertical position, m
m_{gen}	Apparent generator mass, kg
c_{gen}	Apparent generator hydrodynamic damping, Ns/m
c^*_{gen}	Optimal apparent generator hydrodynamic damping, Ns/m
k_{gen}	Apparent generator bouyancy, N/m

I. Introduction

OSU's direct-drive wave energy buoy research focuses on a simplification of energy conversion processes. This is done by replacing systems employing intermediate hydraulics or pneumatics with direct-drive approaches to allow wave energy generators to respond directly to the movement of the ocean by employing magnetic fields for contact-less mechanical energy transmission, and power electronics for efficient electrical energy extraction. In order to achieve efficiency, a control method must be developed to dictate the behavior of the buoy. It is this controller that makes decisions in real-time that governs the generator loading. Once these decisions are made, control signals are sent to an active power converter. It is this IGBT drive that gives us the ability to dynamically change the loading on the generator in order to affect the motion of the heaving buoy. Figure 1 is a schematic of the entire Wave Energy Converter (WEC) control system.

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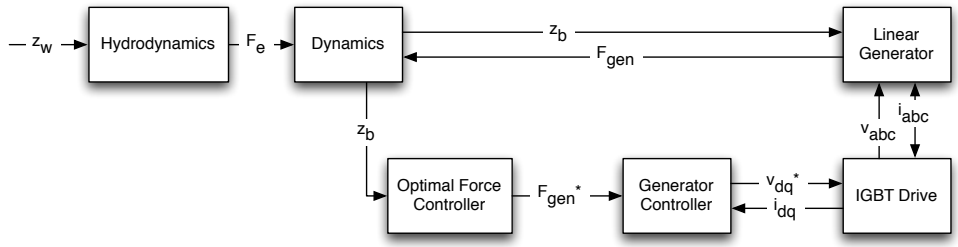

Figure 1. Schematic of WEC controller.

II. Hydrodynamics

II.A. The Morrison Model

One of the most widely accepted linearizations of a heaving body's response to an ocean wave is the Morrison model.[1] The Morrison model utilizes the concept of an excitation force to describe how the wave acts on the body. The excitation force depends on the incident wave and the hydrodynamic characteristics of the floating object:

$$F_e = m_b \ddot{z}_w + c_b \dot{z}_w + k_b z_w \tag{1}$$

where z_w is the vertical position of the water surface at the buoy, m_b is the mass, c_b is the linear damping coefficient, k_b is the waterplane stiffness, and F_e is the excitation force. The second governing equation is the dynamic response of the buoy from the excitation force and any applied generator force.

$$F_e + F_{gen} = (m_b + A_b)\, \ddot{z}_b + c_b \dot{z}_b + k_b z_b \tag{2}$$

where z_b is the vertical position of the buoy and A_b is the added mass. We have theoretically determined the values of the coefficients m_b, A_b, c_b, and k_b based on the dimensions of OSU's 1 kW buoy.

III. Optimal Control of a Single-Axis Buoy

III.A. Reactive Power Requirements

The optimal control of a point absorber buoy that is constrained to motion in a single direction is well treated in literature.[2–4] Optimal control provides the highest possible power output for any single-axis buoy (i.e. point absorber). In order to achieve optimal control the buoy needs to respond in resonance to the incident wave. There are two ways that a buoy can be tuned for resonance. The first is to mechanically design the buoy to have a resonant frequency equal to that of the incident wave. Equation (3) is the mechanical resonance equation:

$$\omega_0 = 2\pi \sqrt{\frac{k_b}{(m_b + A_b)}} \tag{3}$$

where ω_0 is the natural frequency. Designing a WEC by this equation to have a resonant frequency near the ocean wave frequency would likely yield an impractically heavy buoy . The alternative to mechanical optimization is to use active loading of the electromechanical generator to achieve resonance. In this case the generator is used to simulate the presence of additional mass or reduced buoyancy. This method may be referred to as reactive control due to the requirement of outside energy to drive the generator at various points in the wave cycle. This occurs when the generator force is not completely in-phase with the velocity.

III.B. Optimal Control

Consider Eq. (2). Taking the Laplace transform and rearranging, the equation can be stated as

$$F_e(s) + F_{gen}(s) = (s\,(m_b + A_b))\,(s z_b(s)) + c_b\,(s z_b(s)) + (k_b/s)\,(s z_b(s))\,. \tag{4}$$

Under this formulation, an analogy to an electrical circuit can be drawn. Force is analogous to voltage, and the buoy velocity $s z_b(s)$ is analogous to current. The mass $m_b + A_b$ is analogous to inductance, the

damping c_b to resistance, and k_b to inverse capacitance. This leads to a definition of analogous hydrodynamic impedance in the phasor domain:

$$\bar{Z}_b = j\omega\left(m_b + A_b\right) + c_b + \frac{k_b}{j\omega}. \tag{5}$$

The control law for the generator force can be defined as simply producing force proportional to buoy acceleration, velocity, and position. In this case, the generator has an analogous apparent hydrodynamic impedance:

$$\bar{Z}_{gen} = j\omega m_{gen} + c_{gen} + \frac{k_{gen}}{j\omega} = -\bar{F}_{gen}/\left(j\omega\bar{z}_b\right). \tag{6}$$

By using this control law, the generator can act to modify the apparent mass, damping, and buoyancy of the buoy.

Equation (4) can now be expressed in the steady state phasor domain as

$$\bar{F}_e = j\omega\bar{z}_b\left(\bar{Z}_b + \bar{Z}_{gen}\right). \tag{7}$$

The optimal control problem now becomes simple impedance matching at any given frequency. Under matched impedances, the maximum power transfer from the wave to the generator is 50% of the raw wave energy at that frequency. However, perfect impedance matching means that the generator reactive terms, m_{gen} and k_{gen}, must be non-zero. This means that the generator must deliver power to the water for parts of the wave cycle. Because of the low frequency of ocean waves, significant energy storage is required, and is impractical for the scale of this project. If the complex parts of the impedances cannot be matched, the next best case is to have:

$$c_{gen} = |\bar{Z}_b| \tag{8}$$

This condition is called c^*_{gen}. It is assumed that under all practical operating conditions, this optimal control condition will be maintained.

$$F_{gen} = -c^*_{gen}\dot{z}_b = -|\bar{Z}_b|\dot{z}_b \tag{9}$$

IV. Operating Limitations

Generally it is ideal to use optimal control techniques whenever possible in order to maximize energy generation. Unfortunately, system design and operation is often constrained by real-world criteria that can prohibit the continual use of an optimal control strategy.

IV.A. Energy Storage Limit

As discussed above, true optimal control requires a significant amount of energy storage, as the generator is required to deliver power to the water for several seconds at a time. This is impractical for the scale of this project. The next best condition is described by Eq. (8). Although no longer the true optimal control, this control law still yields a significant fraction of the power, as the force loss due to the mass and buoyancy terms of Eq. (5) are small in a well-designed WEC.

IV.B. Velocity and Stroke Limit

Normally, high velocities are desired in a WEC system in order to increase the generator voltage. The permanent magnet generator has been designed to have large diameter coils and a large number of turns to increase the voltage. With the generator velocity being directly proportional to the voltage, caution must be taken not to exceed the voltage capability of the windings and the power electronics. Limiting the generator velocity is also the primary method for keeping the overall stroke under control. The system has been design with a maximum stroke of 1 meter. Under optimal control it is expected to see buoy strokes as large as 4 times that of the incident wave. This would mean for a 1.5 meter wave, the buoy could travel as much as 6 meters. In such a case, optimal control, as described by Eq. (9), is no longer practical. The situation is analogous to that of a wind turbine. For medium wind conditions, the turbine maintains an optimal tip-speed ratio to maximize power production. However, as the wind speed increases, the turbine must restrain its speed and feather its blades to spill the excess power.

IV.C. Maximum Current and Power Limit

Generator conductor size and power electronics ratings limit the current and therefore generator force. This limit must be considered in the control algorithm.

V. Novel Control Design

The proper design of an effective controller should accomplish two major goals. The first and most important is to protect the generator from any damage that is the result of operating outside of its area of safety. The second is to maximize power production whenever possible.

V.A. Regions of Operation

There are three regions of operation.

1. **Optimal Region.** Low to medium wave conditions.
   The generator is controlled according to optimal control. Power extraction is maximized.

2. **Limiting Region.** High wave conditions.
   The generator continues to operate. However, the raw wave energy available exceeds the capacity of the system. The generator is controlled according to sub-optimal control, and the excess power is spilled.

3. **Survival Region.** Storm conditions.
   The generator is shut down and the system reverts to survival mode.

The Survival Region is dependent on the system. For this project, it is considered that the float is allowed to separate from the spar, relieving the hydrodynamic forces on the system. The Optimal Region corresponds to Eq. (9). The Limiting Region requires a modification of the optimal control law. The Limiting Region is discussed in more detail below.

V.B. Conditional Damping Control

There are two major components to the novel control scheme presented. The first is the boundary definition between the Optimal Region and the Limiting Region. This definition can be based on any number of inputs from wave height, buoy position, buoy velocity, generator current or even generator temperature. For our controller we are most interested in the buoy velocity and position. The second major component is the control law in the Limiting Region.

V.B.1. Single Dimensional Control

Refer to Figure 2. For this system, $c^*_{gen} \approx 0.6$ x 10^4 N/(m/s). The boundary between the Optimal Region and the Limiting Region is defined as $|\dot{z}_b| > 0.5$ m/s. When in the Optimal Region, the system operates under optimal control ($c_{gen} = c^*_{gen}$) and the generator force F_{gen} is controlled to be 0.6 x 10^4 times the buoy velocity. However, when the buoy velocity exceeds 0.5 m/s, the system enters the Limiting Region and the generator force per velocity is increased exponentially ($c_{gen} > c^*_{gen}$) in an attempt to limit the overall stroke.

As a side note, the process of piecewise defining c_{gen} for the Optimal Region and Limiting Region effectively defines c_{gen} to be a function of buoy velocity $\dot{z}_b$.

$$F_{gen} = -\dot{z}_b \, c_{gen}(\dot{z}_b) \tag{10}$$

V.B.2. Multi Dimensional Control

An extension of the single dimensional idea is to define a boundary and control law that depends on both buoy position and velocity, in addition to other limiting factors.

$$c_{gen} = (z_b, \dot{z}_b, \ddot{z}_b, i_{abc}, \ldots) \, . \tag{11}$$

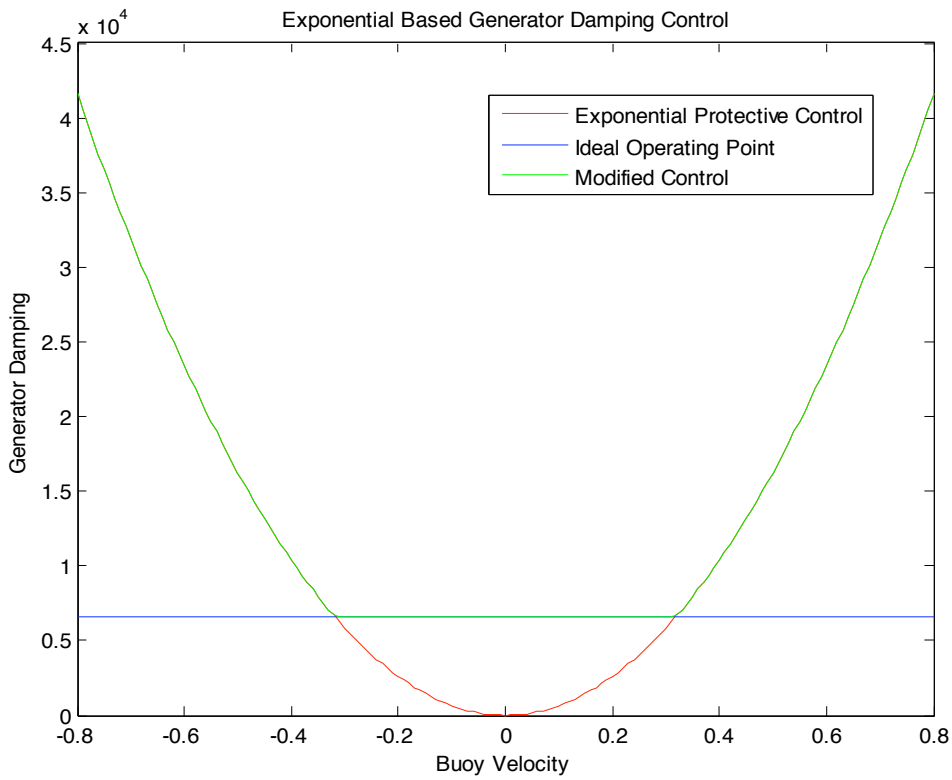

Figure 2. Single variable c_{gen} control.

This may provide a more sophisticated system response. For example, the single dimensional control algorithm above makes no distinction between a large velocity in the center of the stroke, where there may yet be plenty of time to contain the stroke, and a high velocity at the top of the stroke where immediate, severe corrective action is required.

A state space can be created by placing the states buoy position z_b and buoy velocity $\dot{z}_b$ on the x and y axis. Sinusoidal buoy motion will trace an ellipse in this space. Small motions will trace an ellipse of small radius and large motions will trace an ellipse of large radius. Large amplitudes extend the ellipse along the z_b axis and large frequencies extend the ellipse along the $\dot{z}_b$ axis.

Refer to Fig. 3. The generator hydrodynamic damping c_{gen} is on the z-axis, and buoy position z_b and velocity $\dot{z}_b$ are on the x and y axis. The optimal control region, the Optimal Region, is the center of the surface. As both the velocity and position become large, indicating a large speed near the limits of the stroke, c_{gen} is increased above c^*_{gen} to increase the generator hydrodynamic damping to limit the stroke. The boundary between the Optimal Region and Limiting Region is defined by

$$\left(\frac{|z_b|}{z_{b,limit}}\right)^2 + \left(\frac{|\dot{z}_b|}{\dot{z}_{b,limit}}\right)^2 = 1. \tag{12}$$

Equation (12) defines an ellipse on the velocity-position plane.

Region	Region Boundary Condition	Control Law
Optimal Region	$\left(\frac{\lvert z_b\rvert}{z_{b,limit}}\right)^2 + \left(\frac{\lvert \dot{z}_b\rvert}{\dot{z}_{b,limit}}\right)^2 \leq 1$	$c_{gen} = c^*_{gen}$
Limiting Region	$\left(\frac{\lvert z_b\rvert}{z_{b,limit}}\right)^2 + \left(\frac{\lvert \dot{z}_b\rvert}{\dot{z}_{b,limit}}\right)^2 > 1$	$c_{gen} = c^*_{gen}\left(\left(\frac{\lvert z_b\rvert}{z_{b,limit}}\right)^2 + \left(\frac{\lvert \dot{z}_b\rvert}{\dot{z}_{b,limit}}\right)^2\right)$

Table 1. Multi variable control.

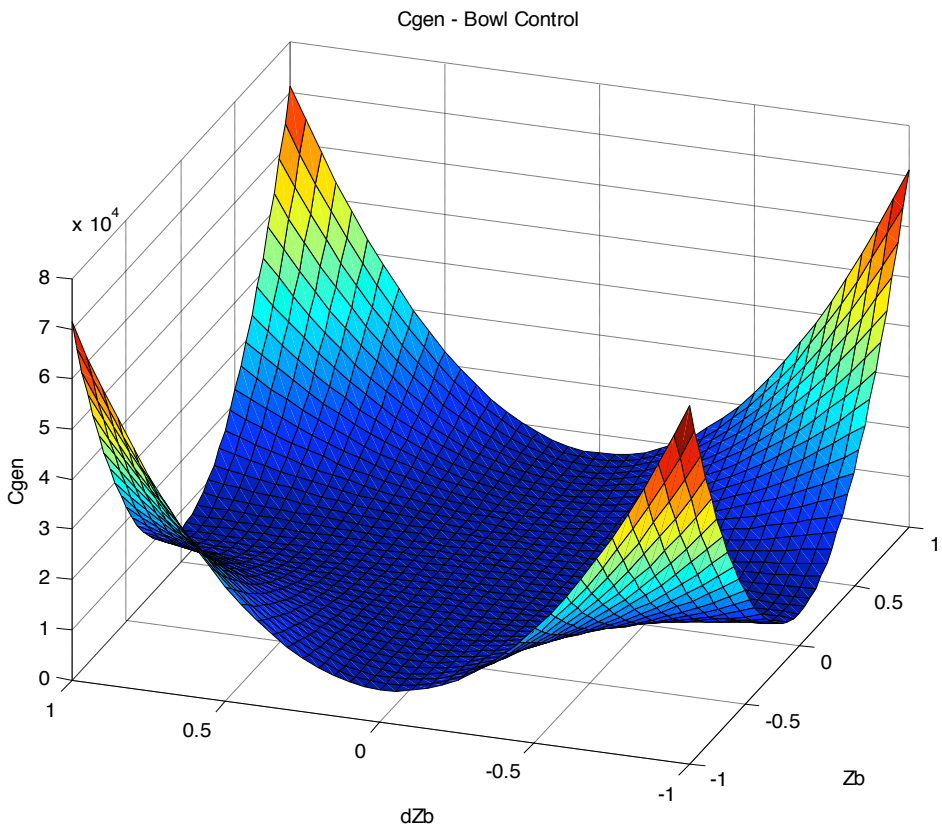

Figure 3. Multi variable c_{gen} control.

VI. Simulations

In order to prove effectiveness of any control design we need generate a realistic wave profile which is representative of actual ocean waves. Much more can be learned from a completely stochastic sea then from any number of individual tests with a monochromatic wave profile. To do this we need to include incident wave frequencies from the entire ocean wave spectra. The first step is to obtain wave spectral density data. This can be done by generating it from one of several wave spectrum calculations. Pierson-Moskowitz (1964) is one of the best known.

Pierson-Moskowitz calculated the wave spectra for various wind speeds, and they found that the spectra were of the form:

$$S(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left(-\beta \left(\frac{\omega_0}{\omega}\right)^4\right) \tag{13}$$

where $\omega = 2\pi f$, f is the wave frequency in Hertz, $\alpha = 8.1$ x 10^{-3}, $\beta = 0.74$, $\omega_0 = g/u$, and u is the wind speed.

Generating the wave spectra gives us the amplitudes and frequencies for all of the component waves in the ocean. Figure 4 is an ocean wave spectra generated from Pierson-Moskowitz calculation using a significant wave height ($H_{1/3}$) of 1.5 meters, representing summer conditions.

Once we have the wave spectra we can determine the relative wave amplitude for each wave frequency. To do this we take an interval length of the frequency spectrum and integrate over it. This gives us the variance over that interval. The variance $< \zeta^2 >$ is related to the significant wave height by

$$H_{1/3} = 4\sqrt{< \zeta^2 >}. \tag{14}$$

Now that we have the wave height information we can generate a wave surface profile by adding all of the component frequencies at their relative magnitudes together in superposition. Using a random offset for

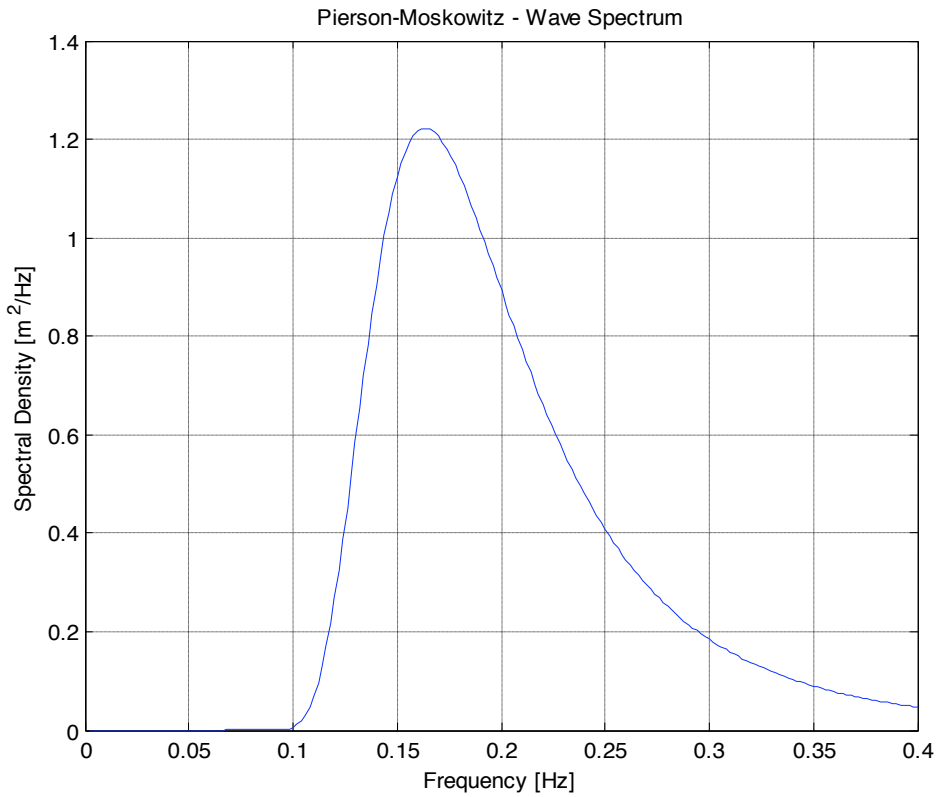

Figure 4. Pierson-Moskowitz Frequency Spectra

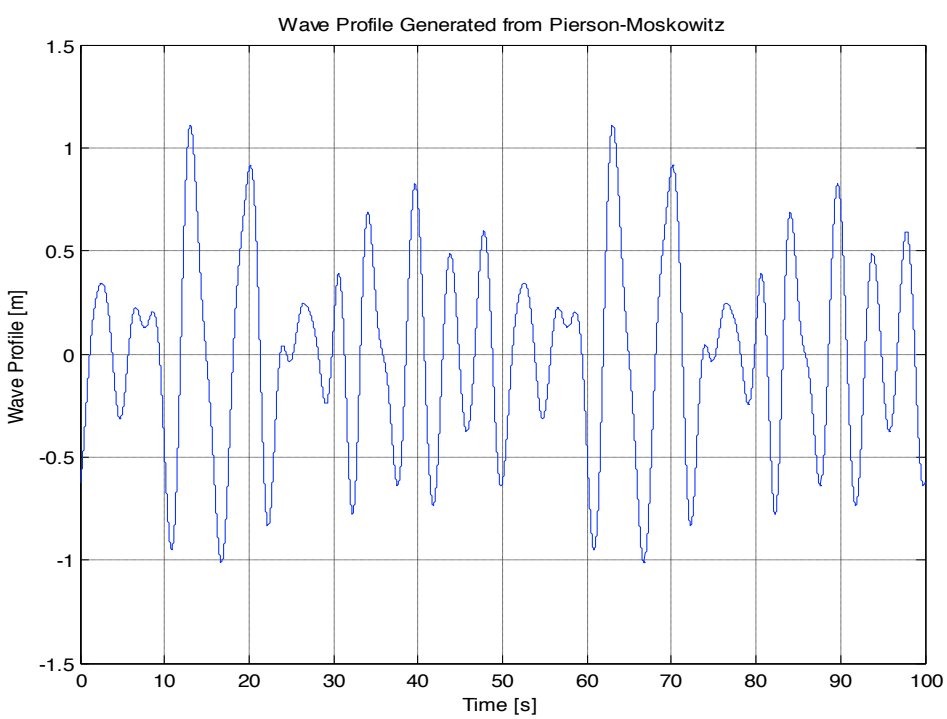

Figure 5. Stochastic Wave Profile.

each frequency component we can represent a truly random sea state that behaves just like that of an actual wave climate. Figure 5 is a sample wave profile with $H_{1/3} = 1.5$

Feeding this random wave profile into our control simulations we can see how well the WEC will respond to a stochastic wave environment. Figure 6 shows the response using exponential control methods. The results show that the amplitude of the buoy stroke is well-limited by the control, while keeping the buoy velocity in phase with the excitation force, maximizing power. Figure 7 shows the control realization in Simulink.

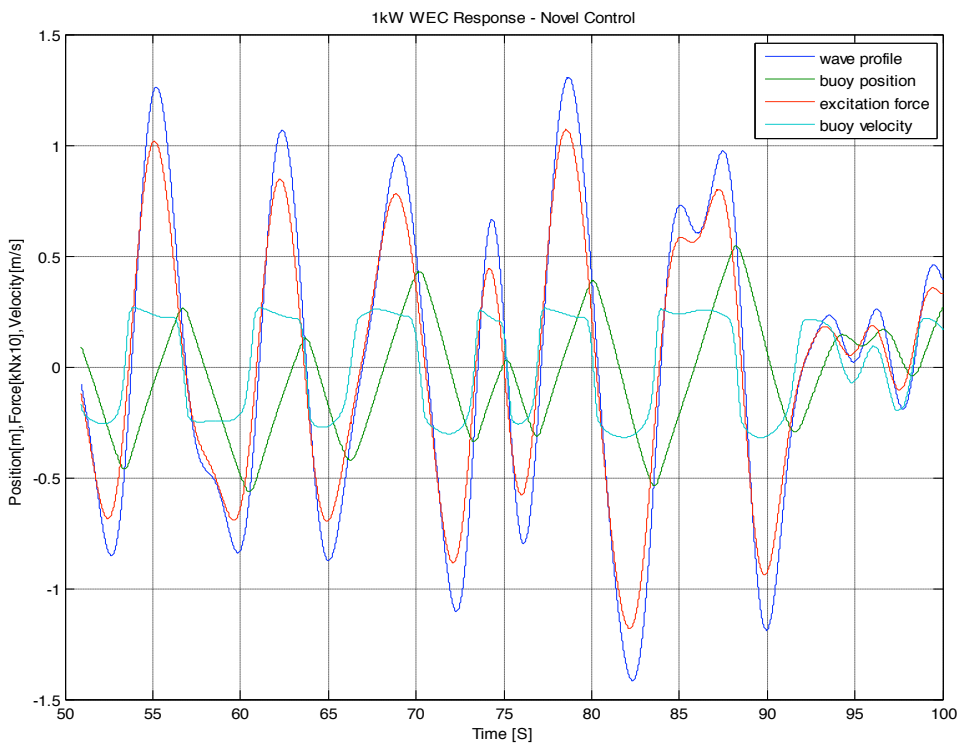

Figure 6. 1kW WEC response with optimal limiting control

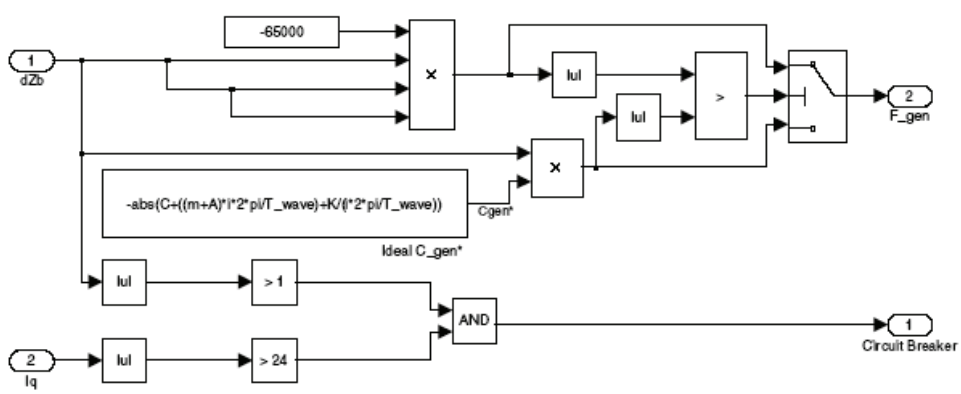

Figure 7. Simulink realization of optimal limiting control

VII. Future Work

A 1kW wave energy buoy will be tested in Oregon State University's Linear Test Bed in January, 2008. The control algorithm presented in this paper will be tested at that time in the laboratory environment. In the summer of 2008, a 1kW wave energy buoy will be tested in the ocean 2 miles off the coast of Newport,

Oregon. The control algorithm will then be tested in the ocean.

Acknowledgments

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