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# Analysis of the Power Extraction Capability for the Wave Energy Converter *BOLT*®

Johannes Bedos Ulvin (johannul@stud.ntnu.no), Marta Molinas (marta.molinas@ntnu.no), Jonas Sjolte (jonas.sjolte@ntnu.no)

*Department of Electrical Power Engineering,*
*Norwegian University of Science and Technology,*
*O.S. Bragstad plass 2E, Trondheim, Norway*

**Abstract**

The goal of this paper is to investigate the power extraction capability for the *Wave Energy Converter* (WEC) concept *BOLT*®. Specifically, the impact of different *control strategies* on the power extraction and their high sensitivity to the incoming waves will be presented. The *BOLT*® concept is based on a flat point absorber designed with a small mass and a *Power Take-Off* (PTO) solely controlling the amplitude of the WEC's motion, *passive loading*. It is reported that the small weight of the device makes passive loading suitable for most sea states. As the device is still on the pilot stage, there is room for exploring the potential improvement of the power extraction for different sea states by determining the optimal control strategy for sinusoidal waves of different amplitudes and frequencies. In addition, when considering realistic designs of PTOs, the constraint on the peak power should be taken into account. The power handled by the electro-mechanical system is limited by the ratings of the electrical components and the mechanical force limits. Imposing a constraint on the peak power will greatly affect the control strategies' impact and thus the average extracted power.



*Keywords:* Wave Energy Converter, control strategies, Power Take Off, passive loading.

## 1. Introduction

Despite having the potential of satisfying a significant fraction of the world's energy needs [1], wave energy has been overshadowed by more mature and profitable renewable technologies like wind and solar.

There are many prototypes with very different concepts being investigated around the world and it is very hard to predict which of the technologies holds the most promise [2]. The *BOLT*® Wave Energy Converter [3], depicted in figure 1, is developed by Fred Olsen Renewables [4]. *BOLT*® is a circular, flat, semi-submerged point absorber and is located near Risør, Norway. Currently, Fred Olsen Renewables are working on a second version which is to be installed at the Wave Hub [5], near Hayle in the United Kingdom.

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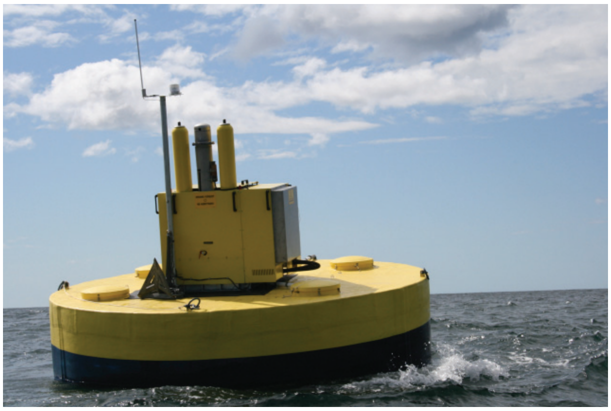

Fig. 1: Fred Olsen's Wave Energy Converter BOLT®, located outside Risør, Norway

To maximize the extractable power, the Power Take Off (PTO) of the device needs to be tuned according to the incoming sea waves. For sinusoidal waves, the theoretical maximum is obtained by controlling the phase and the amplitude of the WEC's motion to be in resonance with the incident wave. However, such control, usually referred to as optimal control, requires costly oversizings of the system's mechanical structure and electrical ratings.

While designing *BOLT*® and as the result of a techno-economical optimization, Fred Olsen decided to apply a simpler control strategy which is more likely to respect the electro-mechanical limitations, only resorting to control the amplitude of the WEC's motion. This is done by only controlling the damping of the device, commonly called passive loading. To make the WEC more suitable for this control strategy, *BOLT*® has a low mass to ensure a saturation on force and power already in low sea states.

The purpose of this paper is to investigate the improvement of the power extraction by including a phase control for these low sea states. With a limitation on the maximum extractable power, passive loading can be beneficial during high amplitude waves whereas optimal control has the ability to extract more power during calmer seas [6], [7].

For this investigation, the WEC and PTO system is modelled as an electrical equivalent. An estimation of the wave excitation force is used as voltage source and the point absorber is modelled as an RLC circuit. The PTO consists of a power extracting element (resistance) and a reactive element (inductance). By performing an electrical analysis of the circuit, the control problem is optimally solved by using an iterative numerical method in MATLAB.

Finally the electrical circuit is simulated in Simulink using the proposed control method.

## 2. Device Presentation

The device under investigation in this study is the *BOLT*® Wave Energy Converter developed by Fred Olsen and is a prototype that has been tested and used in operation outside Risør in Norway since June 2009. The idea was to make a simple, light and cost-effective device.

The point absorber is semi-submerged and shaped as a cylinder tightly moored to the sea bottom. The dimensions of the point absorber can be found in table 1.

The Power Take-Off system is a hybrid PTO, which means that it's a combination of a mechanical/electrical and a hydraulic PTO. The hydraulic system works as some kind of energy storage but will not be further mentioned in this study.

The PTO system uses the mooring rope as production rope. The rope is tied around a winch, which transforms the linear motion from the motion of the point absorber into a rotational motion. The angular velocity is increased through a gear system consisting of belts. The gear system is in place so that an induction machine can be connected.

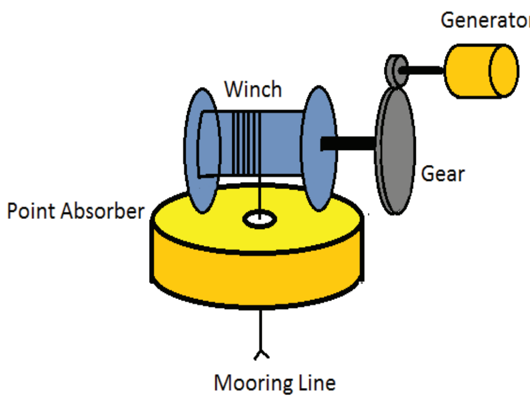


Fig. 2: Principal sketch of the WEC

Table 1. Point absorber dimensions

| | |
|---|---|
| Diameter | 5,15$m$ |
| Height | 1,5$m$ |
| Mass | 5000$kg$ |

$BOLT^{®}$ has not been connected to the grid. However the goal for the next generation $BOLT^{®}$ device, $BOLT2^{®}$, is to build a commercial system in operation at the wave test facility Wave Hub in the UK. It is planned to use a permanent magnet synchronous machine (PMSM) and a suitable back-to-back converter. With this topology the gear system can be made redundant. The reduction in rotational speed can be compensated by a high number of poles in the PMSM. The frequency converter ensures that the frequency at the point of common coupling with the grid is constant.

## 3. Modelling of a point absorber in heave

### *3.1. Hydrodynamic diffraction model*

The hydrodynamic diffraction model is a well known representation of a point absorber in heave. Some basic assumptions are required to make use of this model. The movement of the device is restricted to one degree of freedom (heave) and the waves are propagating in an infinite water depth with small motion. The following equation is then valid:

$$(M + a(\omega))\frac{d^2x(t)}{dt^2} + B(\omega)\frac{dx(t)}{dt} + Kx(t) = F_E(t) - F_L(t) \quad (1)$$

$F_E(t)$, the excitation force, is the force applied by the wave on the device. The point absorber is characterized by its mass, M, its frequency dependent damping, $B(\omega)$ and its stiffness, $K$. In addition, the coefficient $a(\omega)$ represents the added mass from the body of water that takes part in the buoy motion. $F_L(t)$, the Power Take Off force, is the force applied from the device to the shaft of a generator through a gear system. The solution to this second-order linear ordinary differential equation gives the position of the WEC with respect to time, $x(t)$.

*3.1.1. Parameter identification*

In order to perform the analysis of the power extraction capability of $BOLT^{®}$, the parameters of (1) need to be determined. $BOLT^{®}$ is cylindrical with a radius $r = 5,15m$ and a mass $M = 5000kg$. From the radius and the geometry of the device, the stiffness can be derived:

$$K = \pi r^2 \rho g = \pi(\frac{5.15m}{2})^2 \cdot 1027\frac{kg}{m^3} \cdot 9.81\frac{m}{s^2} \simeq 209\frac{kN}{m} \tag{2}$$

In addition, Fred Olsen provided frequency-dependent vectors of 27 points for the added mass, $a(\omega)$, the damping, $B(\omega)$ and the excitation force coefficient, $\widehat{H}_{F\zeta}(\omega)$ .

*3.1.2. Estimation of the excitation force*

The excitation force is dependent of the incoming wave, the geometry and the design of the WEC. An approximation of the excitation force [8] is given by the excitation force coefficient and the incident wave elevation, $\zeta$:

$$\widehat{F_E} = \widehat{H}_{F\zeta}(\omega)\zeta \tag{3}$$

The incident wave elevation will be referred to as the amplitude of an incoming sinusoidal wave, A. The excitation will be modelled as a sinusoidal excitation force. The rms-value will be used for the calculations in this paper by the following formula:

$$F_E(\omega) = \frac{\widehat{H}_{F\zeta}(\omega)A}{\sqrt{2}} \tag{4}$$

*3.2. Electrical Analogue*

The hydrodynamic diffraction model given by (1), is essentially a spring-mass system. It is known that an electrical RLC-circuit can be written on the exact same form as the spring-mass system:

$$L\frac{d^2Q(t)}{dt^2} + R\frac{dQ(t)}{dt} + \frac{1}{C}Q(t) = E(t) - V_L(t) \tag{5}$$

In an electrical circuit, the current $I(t)$ is of more importance than the charge $Q(t)$. Thus, using $I(t) = \frac{dQ(t)}{dt}$ and $\frac{dI(t)}{dt} = \frac{d^2Q(t)}{dt^2}$, and inserting into (5):

$$L\frac{d^2I(t)}{dt^2} + R\frac{dI(t)}{dt} + \frac{1}{C}I(t) = \frac{d}{dt}(E(t) - V_L(t)) \tag{6}$$

The solution $I(t)$ is composed of a transient and a steady-state solution. Theoretically, the transient solution dies out because of the damping as $t \to \infty$, but in practice it will become negligible after a relatively short time. Since we are assuming a sinusoidal input (excitation force) the steady-state response of the current will be sinusoidal with the same frequency as the input including a phase shift. When steady-state is assumed, an analysis in the frequency domain can be performed.

The electrical circuit described by (6) is depicted in figure 3 and a summary of the mechanical quantities and their respective electrical quantities are summarized in table 2. It is desirable to develop the electrical equivalent to be able to analyse the power extraction with knowledge from electric circuits theory.

## 4. Control

*4.1. Control Strategies*

The aim is to maximize the power supply to the PTO. By manipulating the PTO damping and the PTO added mass, the power extracted by the PTO can be controlled.

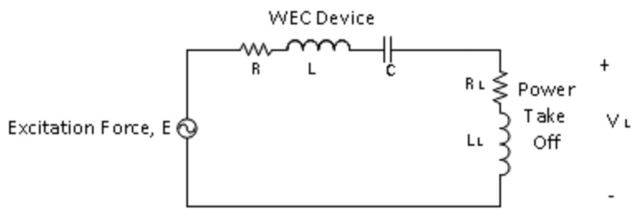


Fig. 3: Electrical equivalent circuit of the hydrodynamical system

Table 2. Relations between the hydrodynamical and electrical model

| **Mechanical system** | **Electrical system** |
|---|---|
| Excitation force, $F_E$ | Voltage source, $E$ |
| Position, $x$ | Charge, $Q$ |
| Speed, $v$ | Current, $I$ |
| Total mass, $M + a(\omega)$ | Inductance, $L$ |
| Damping, $B(\omega)$ | Resistance, $R$ |
| Stiffness, $K$ | Inverse capacitance, $C^{-1}$ |
| PTO force, $F_L$ | Load voltage, $V_L$ |
| PTO damping, $B_L$ | Load resistance, $R_L$ |
| PTO added mass, $M_L$ | Load reactance, $L_L$ |

### *4.1.1. Optimal Control*

The reactive component of the PTO is set as to exactly compensate the reactive components of the physical device. The device will then be in resonance with the incoming wave and the excitation force will be in phase with the speed of the WEC. When the total reactive term is equal to zero, the PTO damping should be tuned to the same value as the device damping to achieve maximum power transfer. Hence, the tuning of the control parameters are given as follows:

$$R_L = R \quad (7)$$

$$X_L = -(wL - \frac{1}{wC}) \quad (8)$$

For this type of control, a bi-directional flow of power is required. Since this is an all-electric PTO, the generator will have to switch between motor and generator operation. Also, the power electronic converter will require bi-directional switches.

### *4.1.2. Passive Loading*

A simpler way of controlling the power extraction is by only having a resistive control of the PTO. The optimal power transfer is then given by:

$$R_L = \sqrt{R^2 + (wL - \frac{1}{wC})^2} \quad (9)$$

In this case, the power flows in one direction since the PTO power factor is unity; i.e. the PTO force is in phase with the WEC speed. This is the type of control that is currently applied to BOLT.

*4.1.3. Control Constraints*

Without any limitations to the system, optimal control would always maximize the average power output. However, wave energy is troubled by extremely high instantaneous peaks of power compared to the average extractable power. High peaks in power requires a huge and costly over-dimensioning of the electromechanical system and reduces the power quality supplied to the grid.

For sinusoidal conditions the peak-to-average ratio, $k$, can be described by the following equation [9]:

$$k = 1 + \frac{1}{cos(\phi_L)} \tag{10}$$

Where the PTO power factor, $cos(\phi_L)$, is given by:

$$cos(\phi_L) = cos(arctan(\frac{X_L}{R_L})) \tag{11}$$

For passive loading, $X_L = 0$ and the power factor will be equal to 1 (unity). $k$ will then always be equal to 2, regardless of the magnitude of $R_L$. Passive loading gives the lowest possible value for $k$.

Evidently, the increase of the reactive load element, while keeping $R_L$ constant, increases the displacement angle $cos(\phi_L)$ and $\frac{1}{\phi_L}$ can quickly become a large number and hence the peak-to-average ratio $k > 2$.

Optimal control requires the largest reactive element to compensate for the reactive elements of the device. The average power extraction can be increased by increasing the reactive power compensation, at the expense of a increasing peak-to-average ratio $k$.

*4.2. Development of a Constrained Optimization Problem*

As mentioned, for an unconstrained problem optimal control will always give the optimal solution. Nevertheless, previous arguments have shown that a trade-off needs to be met between two conflicting aims: maximizing the average power while minimizing investment costs.

For *BOLT*® the problem will be solved with a constraint on the peak power. After being advised by Fred Olsen, the rating of the electrical equipment of *BOLT*® has been set to $P_{max} = 130kW$

When constraining the problem, the most beneficial control strategy and the optimal tuning of the PTO, will change according to the incident wave. It is vital to understand that for each incoming wave of different amplitude or frequency, the electrical circuit will be different and the optimal solution of the circuit will change.

Another important realization is that the optimal solution, might lie in between optimal control and passive loading. For waves where the peak power constraint never is reached, optimal control should be applied. With higher energy waves, the constraint might be reached and hence the peak-to-average power ratio has to be reduced by decreasing the reactive loading. An **intermediate** solution is obtained. Very high energy waves could require to reduce $k$ until passive loading is achieved. To cope with even higher energy waves, and no longer being able to adjust $k$, the peak power can still be kept at the allowed limit by increasing the resistive element of the PTO, at the expense of a reduced average power.

The borderlines between the three control strategies are calculated and a map of the advisable control strategies is illustrated in figure 4. The relevant frequency range has been based on a scatter diagram for the Wave Hub site [10] given in table 3.

Figure 4 suggests that for wave amplitudes below 1.4 $m$, more power can always be extracted by *BOLT*® if some kind of reactive control is included in the control of the PTO. By consulting the scatter diagram for the Wave Hub, *BOLT*® should be operated with some kind of reactive control for at least 4398 hours yearly according to the map.

For the unconstrained case of optimal control, the tuning of the elements are easily calculated, however in the passive loading and the intermediate control area, a mathematical optimization problem needs to be solved. The goal is to maximize the average power extraction by the PTO. A general expression for the average power extracted by the PTO is given by multiplying the square of the current magnitude in the circuit by the resistive PTO element as follows:

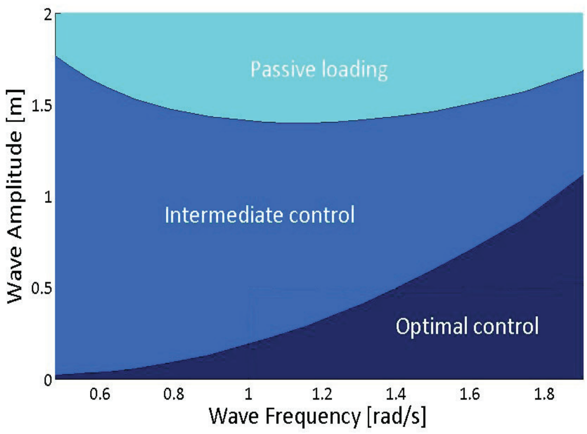


Fig. 4: Map of the optimal control strategies

Table 3. Scatter diagram at Wave Hub, hours per wave state

| Significant wave height [m] | Wave period Tz [sec] 3,5 | 4,5 | 5,5 | 6,5 | 7,5 | 8,5 | 9,5 | 10,5 | 11,5 |
|---|---|---|---|---|---|---|---|---|---|
| 0,25 | 26 | 79 | 44 | 18 | 0 | 0 | 0 | 0 | 0 |
| 0,75 | 499 | 832 | 491 | 140 | 18 | 0 | 0 | 0 | 0 |
| 1,25 | 184 | 1051 | 604 | 307 | 70 | 26 | 9 | 0 | 0 |
| 1,75 | 0 | 587 | 701 | 333 | 149 | 53 | 26 | 0 | 9 |
| 2,25 | 0 | 96 | 534 | 254 | 123 | 44 | 9 | 0 | 0 |
| 2,75 | 0 | 0 | 237 | 228 | 105 | 26 | 9 | 9 | 0 |
| 3,25 | 0 | 0 | 26 | 175 | 123 | 44 | 9 | 0 | 0 |
| 3,75 | 0 | 0 | 0 | 79 | 96 | 35 | 18 | 0 | 0 |
| 4,25 | 0 | 0 | 0 | 9 | 44 | 26 | 9 | 9 | 0 |
| 4,75 | 0 | 0 | 0 | 0 | 26 | 18 | 9 | 0 | 0 |
| 5,25 | 0 | 0 | 0 | 0 | 18 | 26 | 18 | 0 | 0 |
| 5,75 | 0 | 0 | 0 | 0 | 0 | 18 | 9 | 0 | 0 |
| 6,25 | 0 | 0 | 0 | 0 | 0 | 9 | 0 | 0 | 0 |

$$\overline{P} = \frac{E^2 R_L}{(R+R_L)^2 + (wL - \frac{1}{wC} \pm R_L tan(\phi_L))^2} \quad (12)$$

To remove an unknown $X_L$, has been replaced by $\pm R_L tan(\phi_L)$; where the $\pm$ sign depends on the resulting reactance of the WEC device. Since the capacitive element of the WEC is dominant, the sign should be positive.

The optimization problem can be expressed:

$$max \ \overline{P} \quad (13)$$

$$while \ \widehat{P} = \overline{P}(1 + \frac{1}{cos(\phi_L)}) < 130kW \quad (14)$$

This problem can be solved analytically with Lagrange multipliers. However, they give very complex equations; hence, a simpler iterative numerical approach is chosen [6]. By implementation in MATLAB,

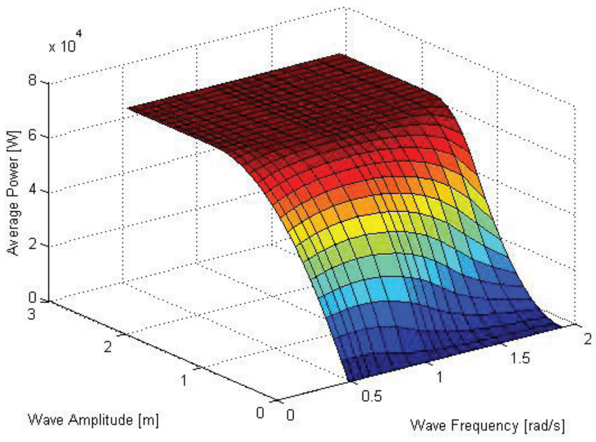


Fig. 5: Surface plot of the average power extraction with the proposed control method for different wave amplitudes and frequencies

the problem could be solved for a similar selection of wave amplitudes and wave frequencies as for figure 4. The average power extraction is plotted in figure 5.

The plot shows the average power according to the incident wave which is characterized by its frequency and amplitude. The average power increases with the amplitude of the wave until it enters the passive loading area where the average power is constant irrespective of wave frequency or amplitude. The extra energy from higher energy waves is oppressed by a higher PTO damping.

To make a comparison of the power extraction with the purely passive control method applied by *BOLT*® and the proposed control method, a 2D-plot of the average power extraction for both methods is given in figure 6. A single frequency is chosen on the basis of the scatter diagram for the Wave Hub. By calculating the average of the most frequent wave frequencies during a year at the Wave Hub location, an average frequency of 1.13 $\frac{rad}{s}$ is obtained. Hence, from the data points provided by Fred Olsen a frequency

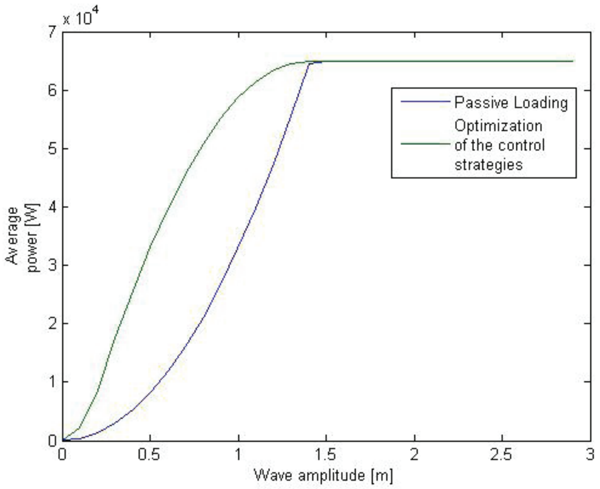


Fig. 6: Comparison of the performance of the two control methods

of 1.1021 is chosen.

Figure 6 clearly confirms that more power is extracted for low amplitude waves with the optimized control method.

### *4.3. Energy Calculations*

With the use of the number of hours a wave state occurs during a year given by table 3, the expected yearly energy output from the WEC can be calculated. Since the wave periods given in table 3 do not exactly correspond to the 27 wave periods provided by Fred Olsen, the closest ones are chosen. The device PTO is optimally tuned according to the wave states and the average extracted power is calculated. By multiplying with the number of hours a given wave state occur per year, the total extracted energy can be determined.

Table 4. Expected yearly energy output with an optimization of the control strategies, MWH per wave state

| Significant wave height [m] | Wave period [sec] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 3,5 | 4,5 | 5,5 | 6,5 | 7,5 | 8,5 | 9,5 | 10,5 | 11,5 |
| 0,25 | 0,08 | 0,45 | 0,44 | 0,24 | 0 | 0 | 0 | 0 | 0 |
| 0,75 | 13,35 | 35,34 | 23,22 | 6,76 | 0,87 | 0 | 0 | 0 | 0 |
| 1,25 | 10,85 | 66,59 | 38,69 | 19,69 | 4,44 | 1,65 | 0,56 | 0 | 0 |
| 1,75 | 0 | 38,16 | 45,57 | 21,65 | 9,69 | 3,45 | 1,69 | 0 | 0,59 |
| 2,25 | 0 | 6,24 | 34,17 | 16,51 | 8,00 | 2,86 | 0,59 | 0 | 0 |
| 2,75 | 0 | 0 | 15,41 | 14,82 | 6,83 | 1,69 | 0,59 | 0,59 | 0 |
| 3,25 | 0 | 0 | 1,69 | 11,38 | 8,00 | 2,86 | 0,59 | 0 | 0 |
| 3,75 | 0 | 0 | 0 | 5,14 | 6,24 | 2,28 | 1,17 | 0 | 0 |
| 4,25 | 0 | 0 | 0 | 0,59 | 2,86 | 1,69 | 0,59 | 0,59 | 0 |
| 4,75 | 0 | 0 | 0 | 0 | 1,69 | 1,17 | 0,59 | 0 | 0 |
| 5,25 | 0 | 0 | 0 | 0 | 1,17 | 1,69 | 1,17 | 0 | 0 |
| 5,75 | 0 | 0 | 0 | 0 | 0 | 1,17 | 0,59 | 0 | 0 |
| 6,25 | 0 | 0 | 0 | 0 | 0 | 0,59 | 0 | 0 | 0 |

Table 5. Expected yearly energy output with passive loading, MWH per wave state

| Significant wave height [m] | Wave period [sec] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 3,5 | 4,5 | 5,5 | 6,5 | 7,5 | 8,5 | 9,5 | 10,5 | 11,5 |
| 0,25 | 0,04 | 0,16 | 0,09 | 0,04 | 0 | 0 | 0 | 0 | 0 |
| 0,75 | 7,42 | 14,78 | 9,15 | 2,59 | 0,30 | 0 | 0 | 0 | 0 |
| 1,25 | 7,60 | 51,85 | 31,25 | 15,79 | 3,25 | 1,21 | 0,40 | 0 | 0 |
| 1,75 | 0 | 38,16 | 45,57 | 21,65 | 9,69 | 3,45 | 1,69 | 0 | 0,59 |
| 2,25 | 0 | 6,24 | 34,17 | 16,51 | 8,00 | 2,86 | 0,59 | 0 | 0 |
| 2,75 | 0 | 0 | 15,41 | 14,82 | 6,83 | 1,69 | 0,59 | 0,59 | 0 |
| 3,25 | 0 | 0 | 1,69 | 11,38 | 8,00 | 2,86 | 0,59 | 0 | 0 |
| 3,75 | 0 | 0 | 0 | 5,14 | 6,24 | 2,28 | 1,17 | 0 | 0 |
| 4,25 | 0 | 0 | 0 | 0,59 | 2,86 | 1,69 | 0,59 | 0,59 | 0 |
| 4,75 | 0 | 0 | 0 | 0 | 1,69 | 1,17 | 0,59 | 0 | 0 |
| 5,25 | 0 | 0 | 0 | 0 | 1,17 | 1,69 | 1,17 | 0 | 0 |
| 5,75 | 0 | 0 | 0 | 0 | 0 | 1,17 | 0,59 | 0 | 0 |
| 6,25 | 0 | 0 | 0 | 0 | 0 | 0,59 | 0 | 0 | 0 |

The amount of energy extracted over a year with only passive loading as control strategy is also calculated. The results are given in table 4 and 5.

With the proposed optimization method, the total amount of energy that can be produced during a year is $507,63\frac{MWh}{year}$. By only using passive loading as control strategy the expected amount of energy is calculated to be $430,35\frac{MWh}{year}$. This represents an energy increase of $77,28\frac{MWh}{year}$ or $17,96\%$. Assuming that the cost of the electricity produced is similar to Wavestar [12], which has been announced to be around $1\frac{€}{kWh}$ [2], the increase in income by applying the optimized control method would be $77280\frac{€}{year}$. This is without considering any extra investment costs from implementing more advanced control.

### 4.4. Mechanical Considerations

A weakness in the map from figure 4 was pointed out by Fred Olsen. Before entering the electrical domain, i.e. before the generator windings, the power is composed by two components, speed/angular speed and force/torque. The speed is often below the allowed limit for all WEC components [11]. Therefore the PTO force is the main design property and a constraint on force should be included, which translates as a limit on the voltage over the PTO in the electrical equivalent. The resulting map is depicted in figure 7.

With the force constraint included, both the intermediate control area and the optimal control area are significantly reduced. These reductions favours the application of a purely passive control strategy. However, the scatter diagram shows that even with this reduction, the WEC should still operate with intermediate or optimal control for at least 666 hours yearly. 666 hours is found by adding the hours from the scatter diagram for a wave height of 0.25 m and adding the hours for a wave height of 0.75m and a period of 3.5 seconds, which clearly are in a reactive control area. The question is if the extra amount of power extracted for these low energy waves is enough to justify the extra investment from more advanced control.

## 5. Simulations

Time simulations were made in MATLAB/Simulink. In order to show the response from operating in the three different control areas, three different excitation forces were generated. On an interval of 200s each, excitation forces were generated with wave amplitudes of 0.1m, 0.6m, 1.4m. To simplify the simulations, a constant frequency was chosen. The incoming wave frequency was set to 1.1 $\frac{rad}{s}$, as previously. This gives constant values for the RLC-branch describing the device. With the selected frequency L = 42376 $H$, R = 14159 Ω and C = $\frac{1}{209000}$ = 4.7847e-6 $F$. It can be worth noting that the device inductance L is dominated by the value of the added mass as the device itself only weighs 5 tons.

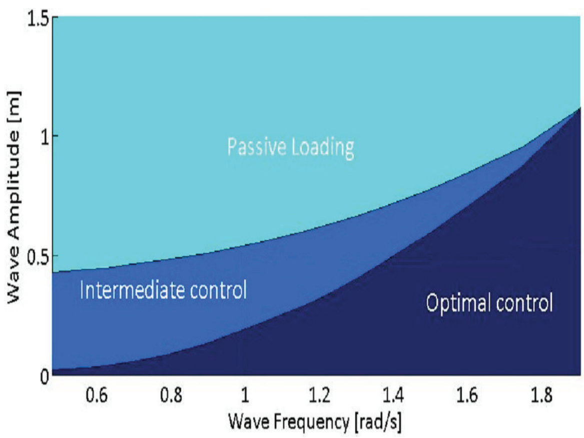


Fig. 7: Map of the optimal control strategies with constraints on force and power

Table 6. Simulation results

| | **Optmization of Control Strategies** | | **Passive Loading** | |
|---|---|---|---|---|
| Wave Amplitude | Peak Power | Average Power | Peak Power | Average Power |
| $0.1m$ | $20560W$ | $1850W$ | $662W$ | $331W$ |
| $0.6m$ | $130000W$ | $38620W$ | $23844W$ | $11922W$ |
| $1.4m$ | $130000W$ | $65000W$ | $129820W$ | $64910W$ |

When A = 0.1m, according to optimal control, the control parameters should be set to $R_L = 14160\Omega$ and $L_L = 128510H$. This gives a peak power of $20560W$ and an average power of $1850W$. For A = 0.6m the control strategy is tuned to an intermediate control, $R_L = 66040\Omega$ and $L_L = 128510H$. As previously explained, the peak power limit is then reached and the average extracted power is $38620W$. At A = 1.4m the control is just about to enter the purely passive domain. The control settings are given by $R_L = 144470\Omega$

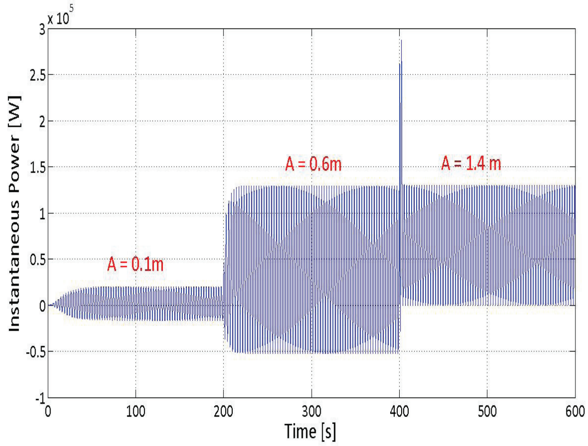


Fig. 8: Instantaneous power for step changes in wave amplitudes with optimal control strategies

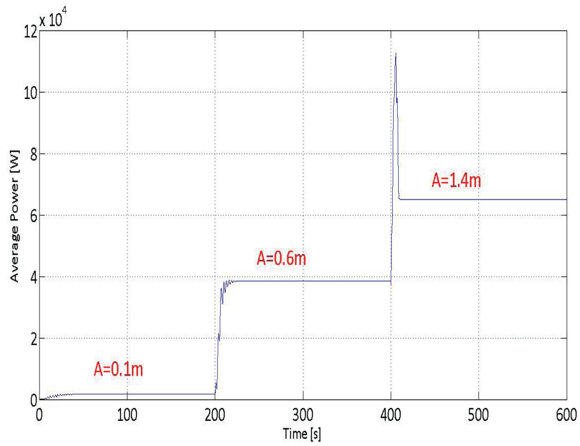


Fig. 9: Average power for step changes in wave amplitudes with optimal control strategies

and $L_L = 200H$. Obviously, the peak and average power is then $130000W$ and $65000W$. These results can be confirmed and viewed in figure 8 and 9 and are summarized in table 6. Figure 8, which shows the instantaneous, power clearly shows that with reactive control, the power flow has to be bi-directional. The unexpected transient peaks are due to switching in the Simulink circuit.

To get an impression of the improved power extraction capability when including reactive control in the control strategy, the same simulations are done for a purely passive control strategy. For simplicity, the frequency is still kept constant throughout the simulation. The tuning of the resistive element is then also constant throughout the analysis: $R_L = 143630\Omega$. The results are given in the table 6 and plots in figure 10 and 11.

From this analysis, at A = 0.1m, the average power can be improved by a factor of 5.6. For A = 0.6m the average power can be improved by a factor of 3.24.

Another observation is that the instantaneous power passes zero twice for every wave when applying a reactive control, and that it touches zero for every wave when applying a purely passive loading. Therefore an important feature of wave energy projects is a flexible energy storage to deal with the fluctuating power output and improve the power quality at the grid connection point.

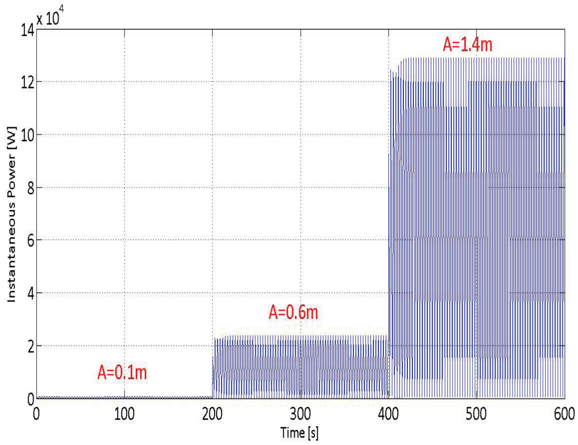


Fig. 10: Instantaneous power for step changes in wave amplitudes with purely passive loading

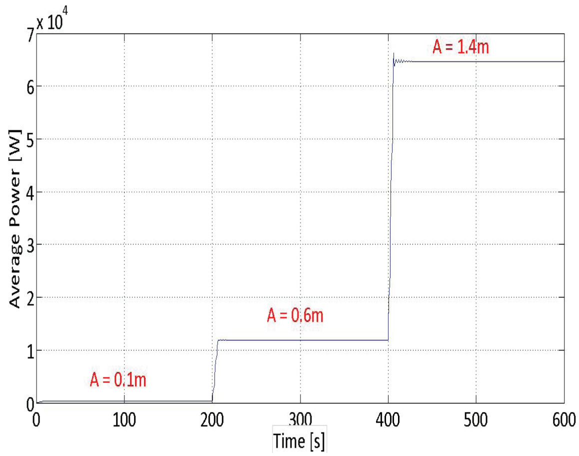


Fig. 11: Instantaneous power for step changes in wave amplitudes with purely passive loading

## 6. Discussion on WEC design

This study has shown how it is possible to optimize the power extraction of the *BOLT*® WEC with an effective tuning of the control parameters. However, the design of *BOLT*® is not optimized with respect to power production and the potential for improving the power extraction would be higher if *BOLT*® had a different design. WEC designers should therefore include control considerations already from the first stages of the product development and design.

### *6.1. Effect of a low mass on WEC design:*

*BOLT*® was designed with a low mass. The effect of this can be viewed by inspecting the electrical equivalent in figure 3. The WEC device has two reactive terms describing it, the inductance L and the capacitance C. Since L is small because of the low mass of the WEC, the capacitance C would be more dominant than for WECs with larger masses: *BOLT*® is a stiff system. The stiffer the system, a larger reactive element is needed in the PTO to compensate.

From this reasoning, a light stiff system would be less susceptible to reactive control than a heavier and less stiff system. Building systems that can easily achieve resonance should therefore be a priority for WEC designers.

### *6.2. Effect of the force constraint on WEC design:*

By introducing the force constraint into the problem the power extraction is effectively reduced. By building a more robust PTO, the force constraint would loosen or even become redundant. The power extraction capability would then move from the map in figure 7 to figure 4.

Greater attention should therefore be paid to increasing the robustness of the PTO. Possible solutions would be to use the strongest production rope available, using two ropes and/or two winches to divide the tension, losing the gear system,...

## 7. Conclusion and further work

This paper explains how an effective tuning of the control parameters can maximize the average power extraction for the Wave Energy Converter *BOLT*®, under sinusoidal conditions. The method utilized took into account a constraint in the peak power to avoid breaching the electrical limits of the system. It is shown how a more elaborate tuning of the all-electric PTO will increase the average power extraction for low amplitude waves. Section 4.3 concludes with a possible energy increase of $77,28\frac{MWh}{year}$ or $17,96\%$ when applying the proposed control method.

However, if an additional constraint on force is included, the benefit from applying the proposed control strategy is significantly reduced. This double constrained maximization problem was not optimally solved and further work should be done to quantify the possible energy improvement.

The next step should be the development of a hydrodynamical model in time domain based on irregular waves which are more closely related to real sea waves. It is known that real sea waves give higher power peaks than for the ideal case studied in this report (even for passive loading $k > 2$) [13]. It is therefore important to build a more accurate model of the sea to view the effect it has on the advisable control strategies.

Finally, a complete wave-to-wire model of the system should be made. This means that a complete model of the electrical system, from the generator to the grid connection point, will have to be implemented. The modelling and control of the power electronics converter will be an essential task. The hydrodynamical time domain model and the accordingly selected tuning of the PTO elements would serve as input to the control of the rectifier circuit to ensure that the desired PTO force is obtained.

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