CONSTRAINED OPTIMAL CONTROL OF A FLAP-TYPE WAVE ENERGY CONVERTER WITH A HYDRAULIC POWER TAKE-OFF AND REALISTIC LOSS MODEL

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INTRODUCTION

In this paper we present a framework for controls optimization of a flap type wave energy converter (WEC) with a hydraulic power take off (PTO). Results are presented for four different PTO topologies classified based on their ability to provide continuous vs discrete control and one-way vs two-way power flow. These four topologies are used to model realistic PTO configurations where a model predictive controls framework (MPC) is used to improve performance over baseline "slow tuning" method. MPC allows us to conveniently introduce constraints imposed by the PTO and evaluate the impact of those PTO-related constraints on average annual power capture, which can directly be used in the economic assessment of these trade-off options as part of the device development process.

The WEC Device and Controller

We consider a WEC with 1 degree of freedom which operates in shallow water wave conditions. The WEC is bottom-mounted hinged flap that drives a hydraulic PTO. The buoyancy provided by the submersed flap provides a restoring stiffness, allowing the system to resonate in pitch. The oscillatory motion of the flap drives a hydraulic PTO. A MPC-based algorithm framework is used to optimally control the PTO force. Figure 1 shows a high level illustration of the control algorithm setup for this WEC.

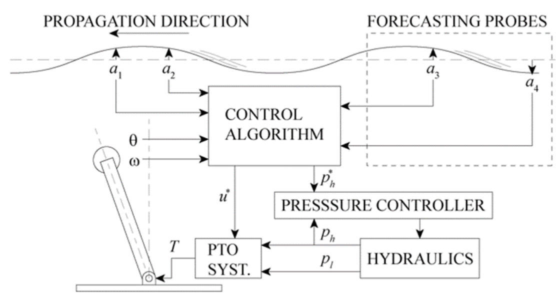

FIGURE 1. BLOCK DIAGRAM OF FEEDFORWARD CONTROL OF A FLAP TYPE WEC.

The Controls Framework

A non-linear MPC controls framework was chosen for this device due to the strong non-linearities present in the viscous losses and the PTO related loss models. While this increases the computational cost of the algorithm, it allows for optimality to be enforced. The optimization objective is to maximize average power capture, while respecting various constraints and considering all wave-to-wire losses of the system. Constraints considered include PTO related capabilities such as maximum torque, velocity, acceleration, power-flow, and device motion amplitudes. The introduction of constraints, allows us to run sensitivity studies on the annual average power capture of different PTO-related constraints imposed on the device. Using techno-economic cost functions for these PTO capabilities, we are able to determine the economically optimal PTO device configuration.

PTO Losses and Constraints

During the conversion from mechanical energy to grid-compliant electrical energy, significant energy is lost. Typical average energy losses are on the order of 10% to 50%, making an appropriate loss model for the PTO an essential integral part of the WEC device to be optimized. In case of a hydraulic PTO, a significant number of electrical, mechanical and hydraulic components need to be considered in determining an adequate loss model. The MPC control objective is suitably modified to maximize the generated power (P_{gen}) which is the difference between the absorbed power (P_{abs}) and the sum total of losses (P_{loss}).

$$P_{gen} = P_{abs} - P_{loss} \quad (1)$$

This modified controls objective is a significant departure from the standard MPC problem where oftentimes an ideal PTO is assumed and losses are treated as negligible. This type of MPC formulation has been proposed by J. Hals et.al in [1]. We have expanded on this idea to incorporate "controls-oriented" loss models for MPC optimization with a hydraulic PTO.

The optimal control inputs which maximize the generated power should also account for physical constraints on the device motion and hardware constraints on the PTO. In our MPC framework we setup the algorithm to handle motion constraints on the flap (position and velocity) and force constraints on the PTO (maximum torque). These constraints are important to keep the cost of the PTO within reasonable limits. Such constraints can be easily accommodated in a non-linear MPC framework as shown in literature (for e.g. see [1 – 4]).

A Matrix of PTO topologies

As mentioned earlier we established a matrix of 4 different PTO configurations, which represent different hydraulic topologies. This allows us to establish fundamental trade-offs between control types (continuous vs discrete) and power flow constraints (one-way vs two way power).

These four different options are illustrated below.

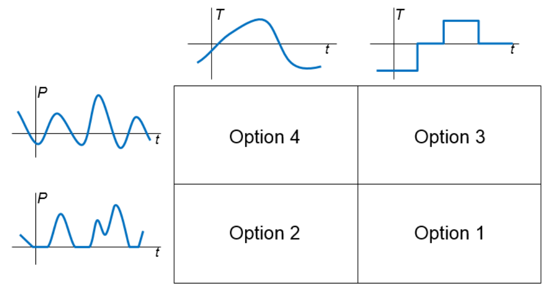

FIGURE 2. PTO OPTIONS PURSUED.

Option 1 (Two quadrant, fixed magnitude control): The PTO system allows one-way power flow and discrete three level control $(-U_{max}, 0, U_{max})$. This strategy uses a slow-varying Coulomb-type damping torque/force where the primary objective is to optimize the switching time to maximize performance.

Option 2 (Two quadrant, continuously variable control): The PTO system allows continuous torque control but is constrained to one-way power flow allowing smooth variation of torque. This control method represents a time varying damping force applied to maximize power absorption with no reactive power returned to the ocean.

Option 3 (Four quadrant, fixed magnitude control): Similar to Option 1, torque is limited to discrete three level control $(-U_{max}, 0, U_{max})$ but with the capability of two-way power flow.

Option 4 (Four quadrant, continuously variable control): Torque is smoothly-varying, with the only constraints being saturation bounds on magnitude and rate. This enables the controller to implement the theoretically-optimal power extraction torque, as dictated by impedance matching theory in smaller waves.

Option 4 requires the most complex hydraulic topology, resulting in a costly hardware solution. From a controls perspective it is the easiest to implement, because it is largely an unconstrained problem. Option 1 on the other hand has fewer demands on the hydraulic hardware required, but is more difficult to solve for optimality. Each one of these specific topology options can be refined using specific constraints that correspond to the sizing of hydraulic PTO component options chosen.

Modelling Nonlinearities

Optimization of WECs also requires proper modelling of the nonlinearities in the system. For example, nonlinearity in the form of viscous drag may have a significant impact on the absorbed power and cannot be neglected or linearized. MPC will try to maximize device motion amplitudes, which tends to force the device into a hydrodynamic regime that is outside of its normal (passive) response. It becomes important to develop a hydrodynamic model that accurately captures losses in these extended hydrodynamic regimes. MPC needs to account for such non-linear phenomena in computing the optimal control action. The MPC framework presented in this paper implements a nonlinear programming algorithm which accounts for such non-linear dynamics, non-linear power flow constraints and nonlinear loss functions.

Performance Benchmarking for Competing Control Options

Once the numerical model of the flap, controls-oriented model of the PTO and the MPC algorithm framework are in place, we establish a performance metric to evaluate the relative worth of competing control options. In our case the annual energy captured for a chosen DOE reference site in Humboldt County, California serves a good choice to benchmark performance of each control option. We also select a suitable “slow tuning” method as our baseline for evaluating the relative improvement using advance controls. The annual energy captured for each control option can be used directly in an LCOE analysis to ultimately down select the optimal control method and related PTO configuration. As expected Option 4 and Option 2 which support continuous torque control perform better than their discrete control counterparts. Performance comparison of all control options is shown in the table below. Note that if cost is a significant driver for the PTO design then discrete control options can also provide significant improvement over slow tuning methods.

TABLE 1. PERFORMANCE COMPARISON OF CONTROL OPTIONS.

Control option	Normalized Annual Energy
Slow tuning	100%
Option 4	188%
Option 3	161%
Option 2	177%
Option 1	157%

CONCLUSION

WEC controls development historically has largely focused on forcing resonant conditions. However, most studies to date neglect the PTO related constraints and losses that are typical in realistic WEC device configurations. In this study, we address this issue through a comprehensive controls design process that enforces optimality under these conditions and enables a systematic device optimization process that can be driven by techno-economic processes.

ACKNOWLEDGEMENTS

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