SAND2024-08530C

UMERC+METS
2024 Conference
7-9 August | Duluth, MN, USA

An Analytical Generator for Wave Energy Converter Optimization Using Co-Design Methods

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Abstract
Employing codesign approaches to WEC optimization relies on the simultaneous and coordinated specification of hydrodynamic, power-take-off, and controller design parameters. In doing so, dynamically significant parameters like inertia, torque constant, and rated torque/speeds of generators are frequently assumed to be independent, when in fact they are non-trivially coupled through device physics. Some arbitrary combinations of these parameters are not realistically attained. However, this is a distinct subset of combinations that are not found in commercially available generators. Power-take-offs specifically developed for wave energy converters that increase power performance while balancing cost may be physically realizable. This study explores the potential design space of generators designed for WECs, comparing LCOE optimal configurations to commercially available off-the-shelf generator options in terms of dynamics and cost. To achieve this, we create and deploy an analytical generator model that defines the generator morphology and restricts it to physically realizable configurations. We then tune this model with existing catalog data and conduct a parametric search that defines the bounds for a feasible set of idealized generators. These results will enable us to perform a cost-informed co-design optimization study to find LCOE optimal generators, identifying potential areas for novel component development.
Keywords: Optimization, Wave Energy Converter, RM3, Co-Design

1 Introduction

In numerical optimization a common approach is to sweep over a continuous parameter space [1]. Within wave energy converter optimization, the Wave Energy Converter Design Toolbox (WecOptTool[1]) employs the same approach to identify trends. WecOptTool is an open-source software that uses co-design methods that couple control design with electro-mechanical design due to the strong dependency of electrical power capture on these closely-coupled sub-systems. WecOptTool always finds the optimal controller for a given Wave Energy Converter (WEC) and Power Take Off (PTO) configuration, so that the user can focus on the

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[1] https://github.com/sandialabs/WecOptTool

design of the hardware components. For example, if the user would want to match a generator to the WEC and PTO they could either optimize using commercial off-the-shelf generators, but be limited to availability of such, or they could abstract the generator to its fundamental dynamics and constraints, specifically its winding resistance and inductance, its torque constant and its maximum torque. WecOptTool has many examples that implement a generator based on those fundamental parameters and an intuitive next step for optimization would be to discretely alter each parameter based on an admissible range. However, the fundamental generator parameters are not independent of each other and if the optimization tool is not aware of this, the optimal solution based on the abstract parameters might not actually a physically viable solution for a generator.

1.1 Motivation

Our previous work in *Preliminary Co-Design and Structured Innovation* from UMERC 2023 [2] identified two high-impact areas for WEC innovation- reactive mechanical components as well as generator selection and cost reduction. Using our knowledge from the latter finding, the determinations between an economically attainable or unattainable design could be addressed through available commercial generator technical specifications and a first-principles generator model bounding physically realizable devices.

Today, generators used in the power-take-off (PTO) systems of wave energy converters (WECs) are commonly purchased off the shelf. The customization of generators for wave energy applications could open up a space where higher moments of inertia, maximum torques, and torque constants could be favorable. In this exploratory study, an analytical generator function is created to couple with WecOptTool. The function provides a comparison on commercially available off the shelf (COTS) generator component options and how an idealized generator compares in terms of motor design parameters and cost is explored to develop a power and cost-effective design for WECs.

2 Methodology

To create a more interdependent and physically realistic model of a WEC-specific generator, the analytical generator function breaks down motor constants into first principles such as generator windings, wire gauge, and material cost. This analytical generator employs a series of calculations considering the motor's physical dimensions, the winding materials' electrical properties, and the WEC system's operational requirements. Through this process, we aim to investigate to what extent existing off-the-shelf generators can enhance the performance of WECs, and to explore the physically realizable design space for which no commercial solutions exist. The following subsections detail the methodology used for each calculation.

2.1 Analytical Generator

The analytical generator is a numerical model of a motor that could be used for WEC applications. It is assumed to be a Permanent Magnet Synchronous Motor (PMSM) with a shaft and a frame. Physically, the analytical generator is assumed to have an orthocylic coil structure, internal permanent magnet, and a solid shaft as seen in Fig. 1. The inputs to the analytical generator are free variables that can be adjusted based on user needs, and will be the design variables in future optimization studies. The input variables are shown in Tables 1 and 2. The wire gauge data is pulled from the table found in [3].

Variable Name	Definition
Selected Wire Gauge Data	From [3]
Generator Radius	See Fig. 1
Generator Length	See Fig. 1

Table 1: Required Inputs

Variable Name	Definition
Magnetic Flux Density	0.5 N/Am
Three Phase	True
Frameless	False
Number of Windings	200

Table 2: Optional Inputs

The torque constant (K_t) is determined by:

$$K_t = 2NB_{\text{max}}l_{\text{g}}r_{\text{rotor}} \tag{1}$$

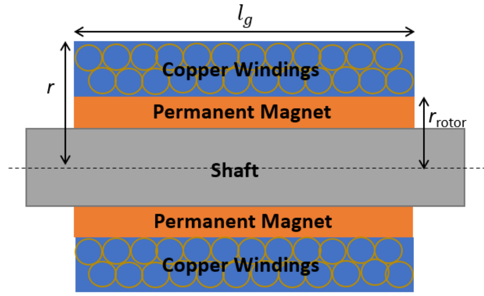


Figure 1: Analytical Generator Physical Outline

where N is the number of windings, B_{max} is the maximum flux density, r_{rotor} is the rotor radius, and l_{g} is the generator length.
Next, we find the maximum torque (T_{max}) deliverable by the system using the relationship:

$$T_{\text{max}} = K_t I_{\text{wire max}} \tag{2}$$

where $I_{\text{wire max}}$ is the maximum allowable current through the copper wire. To calculate winding resistance, we must first calculate the wire length. The wire length of the selected wire is assumed to complete N wraps around the radius r of the rotor, assuming a negligible air gap. The winding resistance (R_{wire})is then calculated using the wire length (l_{wire}):

$$l_{\text{wire}} = N 2\pi r_{\text{rotor}} \tag{3}$$

$$R_{\text{wire}} = \frac{R_{\text{km}} l_{\text{wire}}}{1000} \tag{4}$$

where R_{km} is the resistance per kilometer of copper wire The winding inductance (L_{winding}) was estimated considering the physical coil configuration and material properties:

$$L_{\text{winding}} = \frac{\mu_{\text{Cu}} N^2 A_{\text{coil}}}{l_{\text{g}}} \tag{5}$$

Here, μ_{Cu} is the relative permeability of copper, assumed to be 0.5 N/A^2 and A_{coil} is approximated as surface area occupied by the coil ($A_{\text{coil}} = 2\pi l_{\text{g}} r_{\text{rotor}}$).

The generator mass considers only the mass of copper from the coil and permanent magnet. The permanent magnet mass is assumed to be a function of torque constant [4, 2]. The shaft dimensions are based off the ratio of the average shaft length to generator length and the ratio of shaft radius to generator radius from the Siemens catalog [5]:

$$m_{\text{Cu}} = l_{\text{wire}} A_{\text{wire}} \rho_{\text{Cu}} \tag{6}$$

where the density of copper (ρ_{Cu}) is assumed to be 8960 kg/m^3.

If the optional input for 'frameless' (as seen in Table 2) is true, the generator is considered to be shaftless as well. Therefore, the mass of copper and the permanent magnet are only included in a frameless case. These material mass estimates provide us the means to estimate generator costs based on current material cost rates.

The moment of inertia is determined using the assumed hollow cylinder geometries for the copper windings and permanent magnet, as shown in Fig. 1, and the shaft as a solid cylinder. The calculations assume the shaft is steel with a density of 7930 kg/m^3 and the permanent magnet is neodymium with a density of 7007 kg/m^3.

2.2 Parametric Study

Before coupling the analytical generator with WecOptTool, we conduct a parametric search to understand and bound the search space. In optimization, bounding helps ensure that the results are physically feasible.

For the parametric study, we first tune the constant parameters for the analytical generator function in Table 2 to provide comparable characteristics to industry when using similar generator sizes.

After tuning, we can apply constraints to the space to understand the physically feasible generators. For this process, we create generators across every permutation of generator radius, length, and wire gauge from the values in Table 3. We base both the generator length and radius on the Siemens 1FW3 motor catalog [5] and for the potential integration with a smaller Reference Model 3 (RM3) device [6]. We also assume a maximum coil distance from the edge of the magnet selected to be one inch. While this is somewhat arbitrary, the rapidly weakening magnetic field with radius implies it should be minimized. When calling the analytical generator function, we apply an inequality constraint to check if the wire coil will fit in the generator:

$$l_{\text{wire}} \frac{d_{\text{wire}}^2}{4} \geq l_{\text{g}} \left((r_{\text{rotor}} + 0.0254)^2 - r_{\text{rotor}}^2 \right) \tag{7}$$

If this inequality is true, then the wire cannot fit in the dimensions of the generator, and the combination of input parameters is invalid. In conjunction with the first-principles formulations of generator properties, this will ensure that future co-design optimization studies have a feasible search space that only contains physically possible generators.

Input Parameter	Range	Step Size
Wire Gauge	0000-47	1
Generator Radius	0.1-0.5	0.05
Generator Length	0.05-2	0.05

Table 3: Parametric Study Design Variable Ranges

3 Results

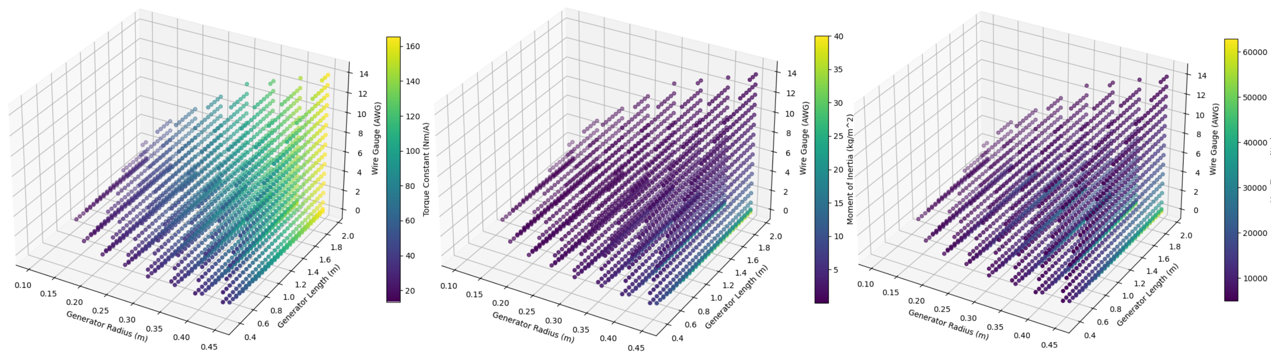
The constraints in Section 2.2 provide us with a physically feasible set of generators to be used in our future co-design optimization study. We also applied a filter, eliminating generators with a max torque less than 5000 Nm - the midpoint of max torque in the Siemens catalog. The finalized range from the parametric study uses generators between 0.4 m and 2.0 m long, a generator radius between 0.10 and 0.45 m, and wire gauges between 0 and 14 AWG. The blank spaces in the graphs below are representative of the invalid data points that resulted from the parametric study.

The torque constant output range is between 20 Nm/A and 160 Nm/A. This is a reasonable range for wave energy applications and expands beyond the maximum torque constant represented in the Siemens catalog [5]. The moment of inertia ranges between 5 kg/m^2 and 40 kg/m^2. And the maximum torque ranges between 10,000 Nm and 60,000 Nm. The generator length and radius seem to have more of an impact on torque constant than the wire gauge in the upper end of the generator length and radius ranges. For example, a generator 2.0 m long with a radius of 0.45 m observed a torque constant of 160 Nm/A across the wire gauge range. For moment of inertia and maximum torque, to reach their maxima a wire gauge of 0 (largest wire diameter on the selected AWG) is needed.

It is important to note that these generators have motor characteristics outside of what is available within the Siemens catalog [5]. Although this parameter sweep does not guarantee better co-design optimization results, it opens up the possibility to explore these generator morphologies.

4 Future Work

The results of the parametric study play a crucial role in shaping the co-design optimization study of the RM3 [6]. By identifying the feasible space for design variables, this study sets up a comprehensive exploration of how generator morphologies influence the dynamics, power performance, and cost of a given WEC archetype.



(a) (b) (c)

Figure 2: Generator Characteristics from Parametric Search with the values for: (a)Torque Constant (b) Moment of Inertia, and (c) Max Torque.

The findings will guide our outer loop of the bi-level optimization, which will proceed as follows:

$$\begin{aligned} \underset{\vec{l}_{\mathrm{g}}, \vec{r}_{\mathrm{rotor}}, A\vec{W}G}{\text{minimize}} \quad & -P_{\$} = -P_{\mathrm{e}}^{\mathrm{an}}/C_{\mathrm{total}} \\ \text{subject to} \quad & \vec{l}_{\mathrm{g}} \in [0.5, 1.95]\,\mathrm{m} \\ & \vec{r}_{\mathrm{rotor}} \in [0.1, 0.45]\,\mathrm{m} \\ & A\vec{W}G \in [0, 14] \end{aligned}$$

where $P_{\$}$ is the power to cost ratio, $P_{\mathrm{e}}^{\mathrm{an}}$ is annual average power, C_{total} is the total cost. This study will apply a penalty function on points outside the feasible space in Section 3. The results of this optimization will suggest LCOE optimal generator configurations that we will contrast against optimal COTS configurations. This comparison will highlight the benefits and trade-offs that an idealized generator can provide.

Acknowledgements

This research was supported by the U.S. Department of Energy's Water Power Technologies Office. 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.

This work was also authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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