Techno-Economic Implications of Electrical Machine Scaling for Wave Energy Converters

Preprint

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National Renewable Energy Laboratory

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Techno-Economic Implications of Electrical Machine Scaling for Wave Energy Converters

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***Abstract*—The sizing of an electrical machine for a Wave Energy Converter (WEC) can have a substantial impact on the overall sizing, cost, and rating of the device. An electrical generator is typically part of the power take-off system, which is the mechanism by which the energy absorbed by the prime mover is transformed into usable electrical energy. For practically all WECs, the rate of change of actuation is predominantly determined by the wave resource (i.e., the wave height and frequency), and devices will see a sinusoidal varying velocity according to the wave conditions. The same can then be said for both directly and indirectly coupled power take-offs with electrical generators. This techno-economic study investigates electrical machine scaling and associated cost implications through core machine design theory, manufacturer data, supporting literature, and the Reference Model Project sponsored by the U.S. Department of Energy. The Reference Model Project was a partnered effort to develop open-source marine energy point designs as reference models to benchmark marine energy technology performance and costs, methods for design and analysis of marine energy technologies, estimations for capital costs, operational costs, and levelized cost of energy. The results from this study show torque is directly related to (1) the physical size of the machine required to increase the air-gap sheer stresses, (2) the amount of active material, (3) the support structure, (4) bearing size and rating, and (5) offshore cable rating, all of which have a significant effect on overall system costs in terms of both capital and operational expenditures. This paper aims to be a critical benchmark in helping determine an "optimal" nameplate rating for wave energy devices and their associated power take-offs. With an optimized rating and sizing process, WEC costs can be reduced and overall performance can be improved.**

Keywords*—wave energy, PTO, cost, WEC, torque, force, power, rating, capacity factor, cables, scaling, mass, electrical machine, induction, permanent magnet

I. Introduction

As an emerging field with utmost potential for global impact, wave energy faces unique challenges as it strives for technological advancements and transition toward commercialization. The potential to harness energy from wave resources around the U.S. coastline is immense and can provide unique opportunities to different states, regions, and communities. Recent estimates indicate the annual energy that could be produced from waves is approximately 1,400 TWh per year, which is approximately 34% of the nation's total annual electricity consumption and capable of powering about 130 million homes [1].

A wave energy converter (WEC) is a device that harnesses the kinetic and potential energy from the movement of ocean waves and converts it into electrical energy. For a WEC, the power take-off (PTO) serves the fundamental role of converting mechanical energy to useful electrical power. An important component within a PTO is the electrical generator, as it is the primary means by which energy is converted and is the key determinant of the overall system efficiency, reliability, and costs of energy production. The rating of a wave energy device is determined by its electrical power, which, for devices with an electrical generator PTO, is a function of rated velocity, rated torque, rated voltage, and rated current. The challenge with rating WEC PTOs is that they differ from traditional, standard ratings, which typically assume a constant speed and torque [2]. The acting force, or the wave, is in a cyclical, bidirectional motion, causing the device to cyclically experience variation from zero to maximum speed in a highly stochastic environment. Therefore, a constant speed or torque is never achieved. While mechanisms have been suggested to smooth or normalize operation, the systems remain pulse-based and erratic.

An important question in wave energy is how to optimize the rating of a generator and determine and define a proper nameplate rating [2]. When scoping a generator, developers must still choose a generator design rating with a stated rated speed, torque, and corresponding voltage and current. This rating is usually related to optimal performance and the machine components selected for these operating values. Beyond these rating characteristics, there are a wide range of operating points that can affect the instantaneous power, performance, and efficiency of a generator. Currently, there are no defined or standardized practices for determining these design values in wave energy applications. The challenge is further exacerbated by the dramatic variation of a WEC's expected average and maximum velocities, which depend on the local wave conditions at a deployment site. Furthermore, the motion of wave energy devices regularly results in an order of magnitude difference between average and peak loading in a normal wave cycle.

II. Background on Electrical Machines

An electrical machine is a type of electromechanical conversion device that can convert either mechanical energy to electrical energy or vice versa. An electrical machine is referred to as a generator when the device is used to convert mechanical energy to electrical energy, and as a motor when converting from electrical energy to mechanical energy [3]. A typical electrical machine is composed of two main parts: a stationary part referred to as the stator and a rotating part referred to as the rotor, both of which are constructed with an iron core [4]. To allow the rotor to spin, a typical electrical machine has an air-gap between the rotor and stator, with a physical length (l) and a radius (r) [5].

A. Power in an Electrical Machine

Both motors and generators are typically defined by their rated power. This rating is usually defined by the rated torque and rated speed, which constitute the mechanical power, and the rated current and rated voltage, which determine the electrical power. In pure power terms, the mechanical power, P_{mech}, and electrical power, P_{elec}, of a generator are related as follows:

$$P_{mech} = \frac{P_{elec}}{\eta} \tag{1}$$

where η is the efficiency of the machine and is a result of the power lost during the conversion from heat, noise, friction, etc. This equation is further defined as:

$$P_{mech} = \omega \times \tau \tag{2}$$

$$P_{elec} = V \times I \tag{3}$$

where ω is rotational velocity and τ is torque, V is voltage, and I is current. Equation (1) can then be rewritten as:

$$\omega \times \tau = \frac{V \times I}{\eta} \tag{4}$$

B. Forces in an Electrical Machine

An electrical machine works by producing a shear stress $(\bar{\sigma})$ in the air gap, which is the useful force and is mathematically obtained using the peak air gap flux density $(\hat{B})$ and peak linear current density $(\hat{K})$, as shown in (5) [5].

$$\bar{\sigma} = \frac{1}{2}\hat{B}\hat{K} \tag{5}$$

Shear stress in the air gap is directly proportional to the torque generated, which is mathematically obtained by multiplying the shear stress by the air-gap surface area of the rotor $(2\pi rl)$ to obtain a force. Torque is then the product of the force and rotor radius (r), resulting in the relationship depicted in (6) [5]. This relationship implies that torque is proportional to twice the volume (*Vol*) enclosed by the air gap. As illustrated in Fig.1, shear stress is perpendicular to the air gap, implying that it does not impact closure of the air gap.

$$T = 2\pi\bar{\sigma}r^2 l_{gen} = 2\bar{\sigma}Vol \tag{6}$$

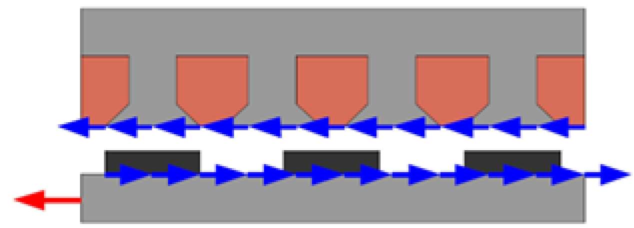

Fig. 1. Shear stress (blue arrows) perpendicular to air gap, between rotor (bottom) and stator (top), and direction of rotor movement (red arrow) [5].

Since the current density $(\hat{K})$ is a function of the current and the cross-sectional area of the conductor (the windings in electrical machines), there exists a directly proportional relationship between the torque acting on an electrical machine and the current produced while generating, and/or the current required to produce a torque while motoring:

$$T \propto \bar{\sigma} \propto \hat{K} \propto I \tag{7}$$

From this, if there is no current being applied to or drawn from an electrical machine, the useful torque, and therefore useful work, will be zero. This is assuming an ideal system, but in actuality there will be some resistive torque from mechanical losses such as bearing friction and windage.

Furthermore, the induced EMF, or voltage, in an electrical machine can be demonstrated to be directly proportional to the rotor velocity through Faraday's Law of Electromagnetic Induction, which states that the voltages induced in a coil, or machine winding, is determined by the rate of change of the flux (ϕ) passing through the coil and the number of turns (N):

$$V = -N\frac{d\Phi}{dt} \tag{8}$$

In the time domain and with a sinusoidal flux, this can be rewritten as:

$$V = -N\frac{d\Phi}{dt} = \omega N\hat{\Phi}cos(\omega t) \tag{9}$$

where $\hat{\Phi}$ is the peak flux value.

There is also a force resulting from the magnetic field in the air gap between the rotor and the stator, known as normal stress (q), such that the iron surface of the stator is attracted radially inward, and the inner iron surface of the rotor is attracted radially outward. This force is illustrated in Fig. 2 and can serve to close the air gap. The normal stress in a machine is a function of the square of the air-gap flux density over two times the permeability of free space (μ_0), as shown in (10). This has direct implications for the amount of support structure and material that is required in higher-force machines to maintain the air gap.

$$q = \frac{\hat{B}^2}{2\mu_0} \tag{10}$$

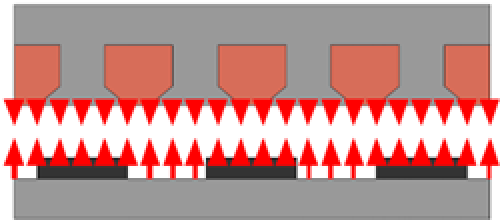

Fig. 2. Normal stress (red arrows) across air gap, between rotor (bottom) and stator (top) [5].

III. Cost Implications of Machine Scaling

An electrical generator is one of the most expensive elements in the PTO and therefore challenges the PTO's upscaling potential. Although high efficiency and adequate system performance of WECs are desired, high reliability, less weight, and low costs are also critical, and trade-offs exist among these variables. In wave energy the speed of the generator is predominantly determined by the wave resource (i.e., the wave height and frequency). A reciprocating force must be applied against the motion of the wave energy device to extract energy. In traditional rotary generators, this is the applied torque, τ, which is directly related to the current drawn by the generator. The rating in wave energy devices differs from traditional ratings because standard ratings assume a constant speed and torque. Without any speed enhancement mechanism in the wave device actuation is relatively low-speed in the scale of 1–10 second wave periods. Additionally, while in wave energy there has not been major technology convergence, generally devices will see a psuedo-sinusoidal varying velocity according to the wave conditions. This means that a wave energy device, in addition to the relatively low maximum actuation speeds, will cyclically be going through zero displacement, speed, and velocity points. There is generally far more available energy in wave than a wave energy device can practically capture. As the power of an electrical machine is related to its speed and applied torque, there are limited options to achieve higher power capture. These solutions can be characterized as either velocity enhancement mechanisms, such as gears or hydraulic pumps, which can increase costs and operations and maintenance issues related to greater system complexity, or a generator with a higher rated torque. Larger torque in electrical machines is directly related to (1) the physical size of the machine to increase the air-gap sheer stresses, (2) the amount of active material (permanent magnets, copper windings, etc.), (3) the support stature, typically made from metals, which maintains the air gap and supports the machine's rotation, (4) bearing size and rating, (5) offshore cable cost, and (6) installation and transportation costs due to increased mass.

A. *Active Material*

Electromagnetically active components include the permanent magnets (PM), copper (Cu) windings, and back iron (Fe). The mass of the permanent magnetic material is a function of the surface area of the machine, as shown in (11), where M_{PM} is the mass of the electromagnetic component, R_{arm} is the air-gap radius of the machine, l_{gen} is the axial length of the machine, t_{em} is the thickness of the electromagnetic part, and ρ is the density of the material [6]. The costs of these materials are directly proportional to their masses. The cost of active material is determined from the total mass, which is calculated using (12), and the total cost of a generator's active material is determined from (13), where C_{Cu}, C_{Fe}, and C_{PM} specify the costs of copper, iron, and permanent magnet, respectively [7].

$$M_{PM} = 2\pi R_{arm} l_{gen} t_{em} \rho \tag{11}$$

$$M_{act} = M_{Cu} + M_{Fe} + M_{PM} \tag{12}$$

$$C_{act} = C_{Cu} M_{Cu} + C_{Fe} M_{Fe} + C_{PM} M_{PM} \tag{13}$$

B. *Structural Assembly*

For an electrical machine, maintaining the clearance between the rotor and stator is critical and requires a particularly strong structure to ensure the air gap does not close due to forces such as normal stress, gravity, thermal stresses, or others [5]. As previously mentioned, because shear stress is perpendicular to the air gap, it is not considered among the forces that affect the spacing in the air gap [5]. For traditional permanent magnet (PM) machines, the normal stress is the largest force and is generally an order of magnitude greater than the torque-producing shear stress. With that said, more iron structure is required to maintain the air gap, and, as a result, most of the machine mass in a PM machine is directly related to its high normal stress [5]. Illustrated in Fig. 3 and Fig. 4 are linear relationships between torque, mass, and cost for PM and induction machines, implying that a machine with higher power requires a greater structural mass, which is a greater portion of the total mass, and therefore cost, of the machine. These relationships are represented as linear functions in (14) through (17). All the trends presented in this section are developed utilizing data collected for PM and induction (subscript ind) machines from industry and literature to support this study [8] [9] [10]. Because this study had a fairly limited data set with a narrow torque range (up to 4 kNm for PM machines) it is possible that the trends become more closely aligned with a second order or logarithmic fit with more data. Assuming a linear relationship between cost and torque, there is no clear cost-value advantage to larger electrical machines if the energy produced also increases at a similar rate. If a logarithmic relationship exists, this would imply that there could be significant advantages if the annual energy produced increases at a faster rate. However, in either case it can be said that, generally, increasing the torque of a machine increases the cost and size required for the machine.

$$M_{PM} = 0.3675 \times \tau + 29.62 \tag{14}$$

$$C_{PM} = 9.151 \times \tau + 4386 \tag{15}$$

$$M_{ind} = 4.883 \times \tau + 31.43 \tag{16}$$

$$C_{ind} = 80.86 \times \tau + 1032 \tag{17}$$

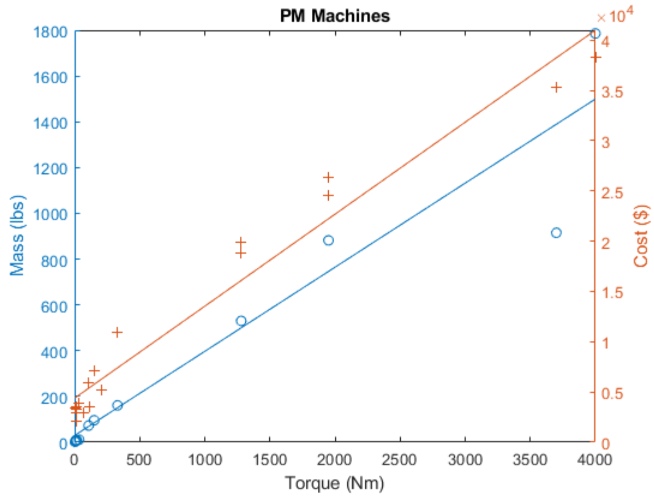

Fig. 3. Torque vs. mass and cost for permanent magnet (PM) machines.

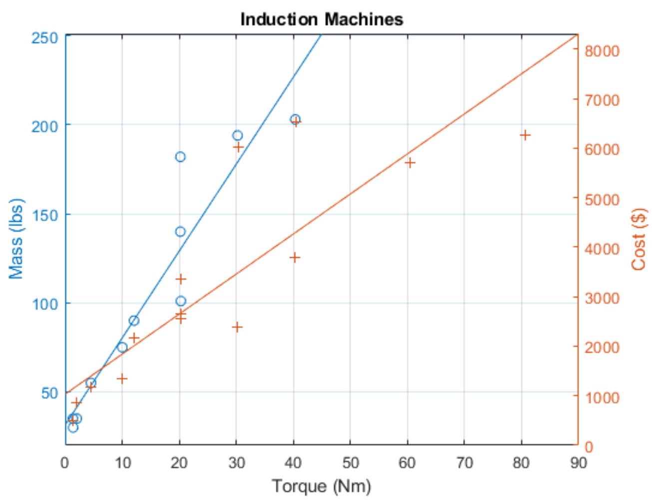

Fig. 4. Torque vs. mass and cost for induction machines.

Bearings, which are considered as part of the structural assembly of a machine, are used to permit a rotary motion and to transmit the power between machine parts. Assuming the bearing mass is the same as the mass of the bearing housing, the total mass of the bearing system can be expressed as a function of the rated power of the machine. This relationship is shown in (18), where M_B is the mass of the bearings and P_{rated} is the rated power of the machine in megawatts [8].

$$M_B = 0.26 \times P_{rated}^{1.75} \tag{18}$$

C. Power Take-Off Sizing

As previously mentioned, an electrical generator on a wave energy device is typically a part of the PTO system, which is the mechanism at which the absorbed energy by the primary converter is transformed into usable electrical energy [11]. This is also true for hydraulic systems, which are an intermediary step in the conversions process. Hydraulic PTOs operate by using the wave energy action to pump pressurized fluid through a hydraulic motor, which is coupled with an electrical generator. While hydraulic systems can increase the machine's rotational velocity at the generator stage allowing for a smaller machine, for greater energy capture and, higher average and peak power ratings, a larger machine and scale will be required with the same challenges as discussed for electrical PTOs. The Reference Model Project, sponsored by the U.S. Department of Energy (DOE), was a partnered effort with the National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), the Applied Research Laboratory of Pennsylvania State University, and Re Vision Consulting to develop open-source marine energy point designs as reference models (RMs) to benchmark marine energy technology performance and costs, methods for design and analysis of marine energy technologies, and estimations for capital costs, operational costs, and levelized cost of energy [12]. The relationships shown in (19) and (20) are open-source hydraulic PTO cost curves implemented in NREL's System Advisor Model, or SAM, for RM3 (a wave point absorber) and RM5 (an oscillating surge wave energy converter). Using the assumptions that are built into SAM, there is a near linear relationship between the PTO power rating and cost, which further highlights the cost implications with a larger scale PTO.

$$C_{RM3} = 2,081,129 \times P_{MW}^{0.91} \tag{19}$$

$$C_{RM5} = 1,600,927 \times P_{MW}^{0.91} \tag{20}$$

D. Offshore Cables

Within the offshore array, subsea cables facilitate the transfer of power from the wave energy device to the onshore load or grid and are classified into two categories: static cables and dynamic cables [13]. This classification is defined by the expected movement of the cable, where static cables are typically buried within the seabed and dynamic cables will operate in the water column, with lots of expected movement [13]. For a floating wave energy device requiring higher torque and power ratings, the electrical generator will require larger dynamic offshore cables with higher power ratings to transfer the power generated by the device to the wave farm's collection point. In turn, larger static cables are required to collect the power generated by the wave farm and export the generated power from the collection point to the shore.

IV. Challenges with Machine Rating

As discussed, electrical machines will have a nameplate, or design, rating with a defined rated speed and torque, and corresponding voltage and current. These ratings are typically set with a constant mode of operation in mind (e.g., 200 Nm at 2,000 rpm) and are related to optimal performance and the machine components selected for these operating values. Beyond this rating characteristic, there is a wide range of operating points that can affect the instantaneous power, performance, and efficiency of a generator. For example, a generator with a 19.8-kW nameplate rating operating at constant 1,800 rpm and applying 105 Nm torque is still a 19.8-kW nameplate rated machine if it is operating at 900 rpm and only producing 9.9 kW. Alternatively, the same machine operating at 3,600 rpm would be producing 39.6 kW.

Increasing the power by increasing the speed of the generator is the easiest way to increase energy production, though this is limited in wave energy due to the relatively low speed actuation. Therefore, the machine constants approach applies poorly to wave energy because the acting force, or the wave, is in a cyclical bidirectional motion, meaning that the device is repeatedly going from 0 to peak speed and a constant speed and torque is likely never achieved. When scoping a generator, developers must still choose a generator rating (speed, torque, nameplate power). This has direct implications on a device's performance in four key areas:

Underrating speed: In this scenario, the generator could see substantially higher speeds than anticipated given the rated speed. Unless correct control and protective measures are taken, this could result in higher than anticipated voltages, potentially damaging other electrical components or causing safety issues.

Overrating speed: In this scenario the generator will regularly be operating below the rated speed, meaning that the device will be producing less than expected energy, reducing the overall viability of the WEC. Additionally, operating at below-rated speeds while attempting to generate the same power will result in higher currents, causing increased losses in the windings, and an overall lower efficiency.

Underrating torque: The generator has been suboptimally sized and is producing less energy than it could if optimized due to being limited in the torque it can apply in higher-energy sea states.

Overrating torque: The generator has been oversized with all of the cost implications discussed. Currently, there are no established practices or standards for determining these design values. The challenge is further exacerbated as, depending on the local wave conditions of a deployment site, the expected maximum and average velocities of a WEC can vary dramatically.

A. *Peak vs. Rated Torque*

An aspect of electrical machines that could be exploited for optimal machine sizing is the ability of practically all electrical machines to produce significantly more torque than their nameplate ratings. Peak torque is the generator's maximum torque it can output for a short period of time, whereas rated, or nominal, torque is the value at which the generator can run continuously without overheating. As previously stated, while the torque is more a function of the machine's physical size and will be limited by the magnetic field in the air gap, by increasing the current drawn by an electrical machine above its rated current, the torque, or force, can be increased, often by multiples of the torque rating. The value between rated and peak torque is usually between 2 and 4 times in PM machines but can be greater than 5 times depending on the model, as shown in Table I. Sizing WEC PTO generators on a range basis rather than constant values could present an optimal solution whereby the PTO operates efficiently at the time-averaged torque and speeds, but also captures more energy at the peaks.

Beyond the limitations of the magnetic field and shear stress, the machine can also have mechanical design limits, and increasing the current draw can substantially drop the efficiency of an electrical machine. These variations can be easily accounted for in unidirectional renewable energy devices, as target speed and torque ratings can be set, a generator sized, and variations accounted for in the control strategy (such as taking gusts as noise [14]). For most wave energy devices, however, the variation and bidirectionality is a fundamental part of operation. Devices will cyclically experience variation for zero to max speed in a highly stochastic environment. There exists yet unanswered questions as to how to set the generator rating of a WEC and how to provide a nameplate rating.

TABLE I. TORQUE RATIOS FOR PM MACHINES.

Machine	Rated Torque (Nm)	Peak Torque (Nm)	Ratio
1	2.6	10.5	4
2	4.7	18	4
3	0.6	3.4	6
4	7.3	35	5
5	420	1280	3
6	1091	4000	4
7	592	1950	3
8	595	1950	3
9	335	1280	4
10	14	108	8
11	26	150	6
12	2000	3700	2
13	125	330	3
		Average	4

B. *Capacity Factor*

To quantify the economic efficiency of a power system, capacity factor (CF) is generally used as an indicator of how much energy a particular technology generates in a particular area or deployment site. CF is determined using the formula shown in (21), where E_{actual} is the total electrical energy generated over a period of time and $E_{potential}$ is the nominal electrical energy that could be produced at continuous full power operation during the same period of time.

$$CF = \frac{E_{actual}}{E_{potential}} \tag{21}$$

According to the Offshore Wind Outlook 2019, published by the International Energy Agency, offshore wind projects have capacity factors of 40%–50%, which is about double the capacity factors of solar photovoltaics. In comparison to tidal energy, capacity factors generally range lower, between 20% and 35% [16].

For wave energy, because there is not yet a standard method for defining proper nameplate ratings for WECs, it is challenging to utilize CF as a useful metric. In addition, this approach presents complexity for several reasons: (1) there is large variation in wave conditions between deployment sites, (2) the available energy in a wave that can be converted is a dynamic product of the wave height and frequency and the hydrodynamic attributes of the wave energy converter, whereas in wind energy it is mostly wind speed and swept area, (3) there is a lack of technology convergence, which makes it challenging to compare WECs of different types, and (4) the application of a wave energy device can vary.

V. PROPOSED METHOD FOR WEC RATING

As this research has emphasized, generator design in wave energy inherently has multiple objectives, meaning that there are many goals for the design that we would like to simultaneously meet, but trade-offs exist among them. In other words, optimally rating a generator needs to consider many parameters, such as: (1) capacity factor, (2) capture width ratio, (3) normalized wave power, (4) annual energy production per unit of rated power, and (5) efficiency index. Different deployment types and applications will have different sets of requirements depending on the purpose and intended function of the deployment. To address the challenges that exist in machine rating for WECs, a holistic approach to optimizing variable-speed WEC generators based on particular design requirements and goals for a deployment case. As illustrated in the flowchart in Fig. 5, this can best be done by developing a modeling capability that performs sizing and costing metrics intended for optimizing variable-speed generators per case to satisfy a user's input or design requirements. This method can provide the users or developers with the opportunity to trade off certain design dimensions such as economics, efficiency, and lightweight design. Key inputs to the model could include the specific unit costs (i.e., cost per kg of material), power rating, torque, rated speed, shear stress, and material properties, such as material density, magnetic field strength, resistivity, etc. Efforts are currently underway at NREL to develop this as a defined methodology, and to develop a tool capable of applying the to support WEC developers and wave energy researchers.

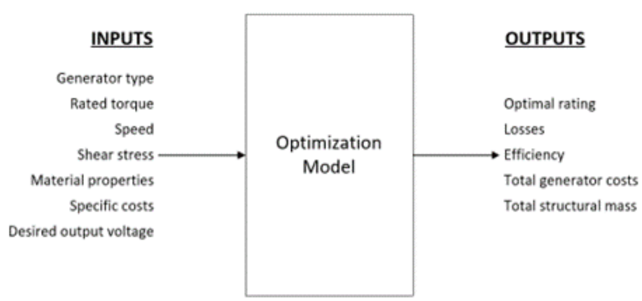

Fig. 5. Proposed generator optimization method.

VI. Conclusion

This research highlighted that the sizing of an electrical machine for a WEC can have a substantial impact on the overall sizing, cost, and rating of the device. Utilizing machine design theory, manufacturer data, and supporting literature, the cost implications associated with electrical generator scaling were highlighted and the importance of careful consideration of generator rating in the design of a WEC's PTO was discussed. The results from this study show torque is directly related to (1) the physical size of the machine required to increase the air-gap sheer stresses, (2) the amount of active material, (3) the support structure, (4) bearing size and rating, and (5) offshore cable rating, all of which have a significant effect on overall system costs in terms of both capital and operational expenditures. In efforts to minimize costs and maximize overall performance, a method for developing a standard practice for defining "optimal" nameplate ratings for wave energy devices was proposed in this study. This research aims to be a critical benchmark in helping determine optimal WEC PTO ratings, and these research efforts will be continued to develop the necessary tools for industry and developers in the design and development of wave energy devices.

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