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

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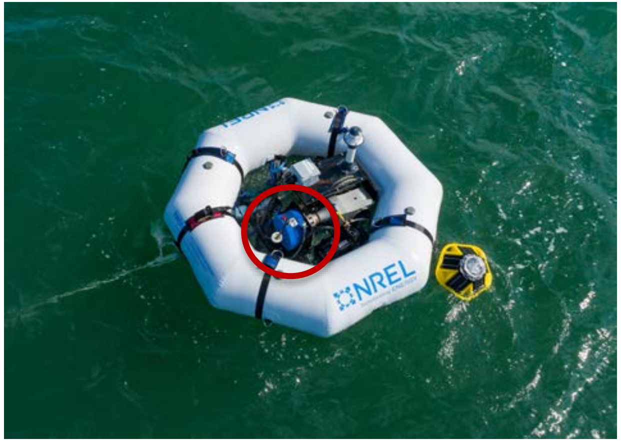
Photo by Dennis Schroeder, NREL 46840

Wave Energy Overview

Background on Wave Energy Converter's

- Wave Energy Converter (WEC)
  - Device that harnesses the kinetic and potential energy from the movement of ocean waves and converts it into electrical energy
- Electrical Power Take-Off (PTO)
  - Serves fundamental role of converting mechanical energy to useful electrical energy
  - Electrical generator is primary means by which energy is converted
    - Key determinant of system efficiency, reliability, and costs of energy production
- Rating of WEC's
  - Function of rated velocity, rated torque, rated voltage, and rated current
  - A constant speed or torque is never achieved - highly stochastic environment.

CAD model of NREL's HERO WEC with electrical generator component (circled in red). *Model from Scott Jenne, NREL.*



In-water deployment of NREL's HERO WEC with electrical generator component (circled in red). *Image by John McCord, CSI.*

Research Overview

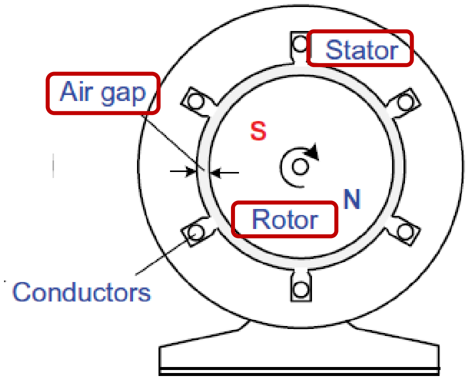
Research Question: How do we optimize the rating of a generator and determine / define a proper nameplate rating for wave energy devices?

- 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
- 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
- Dramatic variation of a WEC's expected average and maximum velocities
  - Depends on the local wave conditions at a deployment site.

Background on Electrical Machines

Electrical Machine Basics

- Electrical Machine
  – Electromechanical conversion device that can convert either mechanical energy to electrical energy or vice versa
    - Converting mechanical energy to electrical energy → **generator**
    - Converting electrical energy to mechanical energy → **motor**
- Two main parts (constructed with an iron core):
  1) Stationary part → **stator**
  2) Rotating part → **rotor**
- There is an air-gap between the rotor and stator to allow rotor to spin.

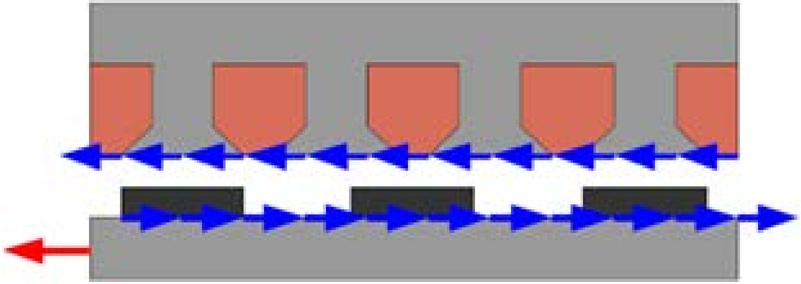


Configuration of AC synchronous machine.
Illustration from Kim (2017).

Forces in Electrical Machines

Shear Stress ($\bar{\sigma}$)

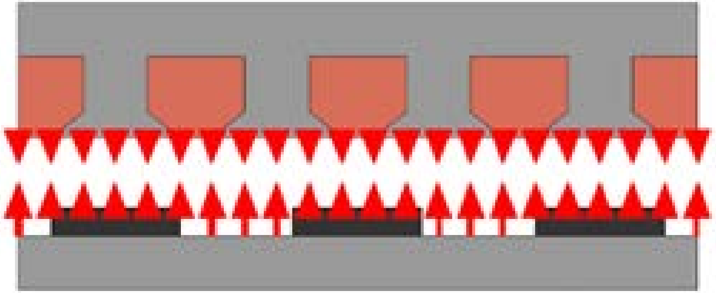
- An electrical machine works by producing a shear stress (useful force) in the air gap
  - Perpendicular to air gap → does not impact closure of the air gap.



Shear stress (blue arrows) perpendicular to air gap, between rotor (bottom) and stator (top), and direction of rotor movement (red arrow). *Image from McDonald et al. (2008)*

Normal Stress (q)

- Results from the magnetic field in the air gap between the rotor and the stator
  - Parallel to air gap → can serve to close air gap.



Normal stress (red arrows) across air gap, between rotor (bottom) and stator (top). *Image from McDonald et al. (2008)*

Cost Implications of Machine Scaling

Machine Scaling Implications

Larger torque is directly related to:

1) The physical size of the machine to increase air-gap shear stresses
2) The amount of active material
3) The support stature
4) Bearing size and rating
5) Offshore cable costs
6) Installation and transportation costs due to increased mass.

Active Material

- Electromagnetically active components include:
  - Permanent magnets (PM)
  - Copper (Cu) windings
  - Back iron (Fe)
- Cost is directly proportional to mass.

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

$$M_{act} = M_{Cu} + M_{Fe} + M_{PM}$$

$$C_{act} = C_{Cu} M_{Cu} + C_{Fe} M_{Fe} + C_{PM} M_{PM}$$

R_{arm} = air − gap radius

M_{PM} = mass of electromagnetic component

l_{gen} = axial length of machine

t_{em} = thickness of electromagnetic component

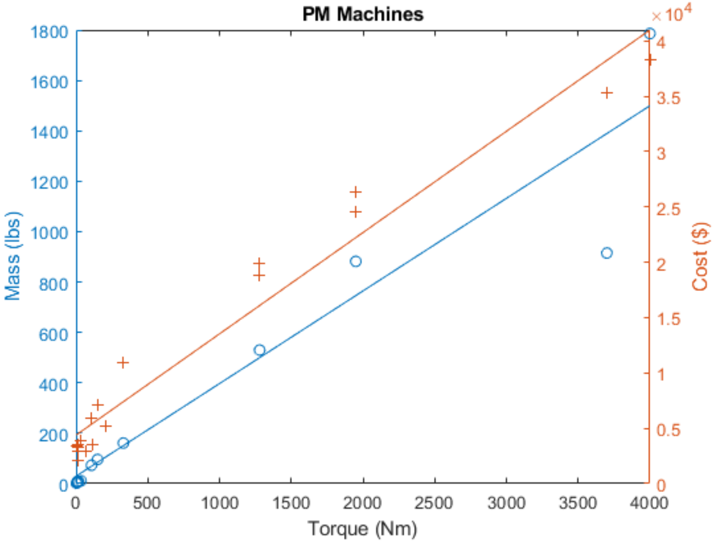
ρ = density of material

M_{cu}, M_{Fe}, M_{PM} = mass of copper, iron, and permanent magnet

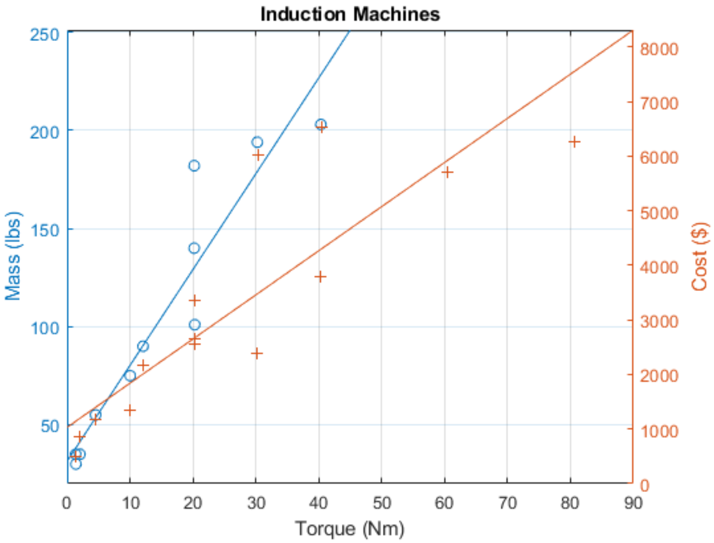
C_{cu}, C_{Fe}, C_{PM} = cost of copper, iron, and permanent magnet

Structural Assembly

- Maintaining clearance between rotor and stator is critical
  - Requires strong structure to ensure air gap does not close due to forces
- More iron structure is required
- Machine mass is directly related to high normal stress



Torque vs. mass and cost for permanent magnet (PM) machines. *Graph from this research.*



Torque vs. mass and cost for induction machines. *Graph from this research.*

Challenges with Electrical Machine Rating for WECs

Machine Rating vs. WEC Performance

- When scoping a generator, developers must select a generator rating (speed, torque, nameplate power)
- Direct implications on a device's performance in four key areas:

1) Underrating speed
   - Generator could see substantially higher speeds than anticipated
   - Could result in higher than anticipated voltages, potentially damaging other electrical components or causing safety issues.
2) Overrating speed
   - Generator will regularly be operating below the rated speed, producing less than expected energy
   - Increased losses, lower efficiency.
3) Underrating torque
   - Generator sub-optimally sized and limited in torque
   - Does not maximize energy potential.
4) Overrating torque
   - Generator oversized and overall system becomes costly.

Peak vs. Rated Torque

- Nameplate ratings for electrical machines include:
  1) Peak torque: maximum torque output for a short period of time
  2) Rated torque: nominal torque output for continuous operation
- Most machines produce significantly more torque than their nameplate ratings
- Ratio between rated vs. peak is usually between 2 and 4 times in PM machines.

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

Proposed Method for WEC Rating

Proposed Generator Optimization Method

Background:

- Ideally, generator design in wave energy can meet all goals, but many trade-offs exist.
- Optimally rating a generator needs to consider many parameters, such as:
  1) Capacity factor
  2) Capture width
  3) Normalized wave power
  4) Annual energy production
  5) Efficiency index.

Proposed Solution:

- A modeling capability that performs sizing and costing metrics for generators
  - Per case analysis to satisfy a user's input or design requirements
- Trade off economics, efficiency, and lightweight design.

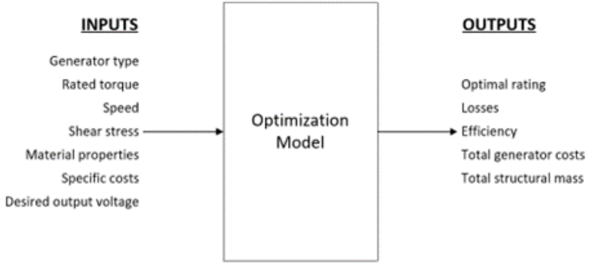


Illustration for proposed optimization model. *Illustration from this research.*

Summary

- Sizing of an electrical machine for a WEC can have a substantial impact on the overall sizing, cost, and rating of the device.
- Larger torque is directly related to:
    1) The physical size of the machine to increase air-gap sheer stresses
    2) The amount of active material
    3) The support stature
    4) Bearing size and rating
    5) Offshore cable costs
    6) Installation and transportation costs due to increased mass.
- Proposed method for developing a standard practice for defining "optimal" nameplate ratings for WECs.

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Thank you

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