A Hermetically Sealed Magnetically Geared Marine Hydrokinetic Generator

EE0008100
## Project Summary

This project will design, fabricate, and test a hermetically sealed 50 kilowatt (kW) multistage magnetically geared generator (MGG). At the end of this project we will have:

1. experimentally demonstrated a 59:1 gear ratio multistage MGG with a torque density that has at least $3\times$ higher torque density than prior-art baseline published designs and
2. utilized water tank testing to demonstrate that the efficiency of the hermetically sealed multistage MGG is competitive with existing technology.

## Project Objective & Impact

**Objective:** Design, fabricate, and test a hermetically sealed 50 kilowatt (kW) multistage magnetically geared generator (MGG). In order to reduce risk, a sub-scale 5kW multistage MGG was first built.

**Impact:** This project will benefit MHK device developers by providing an MHK PTO that overcomes the reliability concerns of the mechanical gears and the sizing constraints of the direct-drive generators.
Alignment with the Program

Marine and Hydrokinetics (MHK) Program Strategic Approaches

Data Sharing and Analysis

Foundational and Crosscutting R&D

Technology-Specific Design and Validation

Reducing Barriers to Testing
Alignment with the Program

Marine and Hydrokinetics (MHK) Program Strategic Approaches

Data Sharing and Analysis

Foundational and Crosscutting R&D

Technology-Specific Design and Validation

Reducing Barriers to Testing
Alignment with the MHK Program

Foundational and Crosscutting R&D

- Drive innovation in components, controls, manufacturing, materials and systems with early-stage R&D specific to MHK applications
- Develop, improve, and validate numerical and experimental tools and methodologies needed to improve understanding of important fluid-structure interactions
- Improve MHK resource assessments and characterizations needed to optimize devices and arrays, and understand extreme conditions
- Collaboratively develop and apply quantitative metrics to identify and advance technologies with high ultimate techno-economic potential for their market applications

Drive innovation in component design by developing the magnetic gearing technology to overcome the reliability concerns of mechanical gears and the sizing constraints of direct-drive generators.

After completing testing, a set of magnetic gear testing standards for MHK generators will have been formulated.
## Total Project Budget – Award Information

<table>
<thead>
<tr>
<th>DOE</th>
<th>Cost-share</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$800.0K</td>
<td>$88.9K</td>
<td>$888.9K</td>
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</tbody>
</table>

## Total Actual Costs

<table>
<thead>
<tr>
<th>FY17</th>
<th>FY18</th>
<th>FY19 (Q1 &amp; Q2 Only)</th>
<th>Total Actual Costs FY17–FY19 Q1 &amp; Q2 (October 2016 – March 2019)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costed</td>
<td>Costed</td>
<td>Costed</td>
<td>Total</td>
</tr>
<tr>
<td>$44.7K</td>
<td>$253.4K</td>
<td>$192.0K</td>
<td>$490.1K</td>
</tr>
</tbody>
</table>
Management and Technical Approach

- **Portland State University**
  - Dr. Bird providing the overall project management for the project
  - Responsible for the electromagnetic design and mechanical assembly and testing of the magnetic gears and generator

- **University of North Carolina at Charlotte**
  - Dr. Williams providing the mechanical analysis and design support.

- **Advisory Board**
  Provide feedback on the testing and performance capabilities of the completed magnetic geared generators
  - National Renewable Energy Laboratory (NREL) – Advisory board member
  - Ocean Renewable Power Company (ORPC) – Advisory board member
  - Magnecon – Advisory board member
  - Verdant Power – Advisory board member
End-User Engagement and Dissemination Strategy

• An end-use advisory board:
  – Advisory board assessing final performance capabilities of the magnetic gear generator technology

• Modular magnetic gear being developed to maximize end-user benefit:
  – Series connected stages allows different gear ratios to be created

• Dissemination strategy:
  – Present results at national and international conferences published in conference proceedings and journal publications.

• A start-up company formed:
  – Increase end-user engagement by transitioning technology from university testing environment to company product development environment.
End-User Engagement and Dissemination Strategy

http://www.ieee-ecce.org/2019/

https://doi.org/10.1109/ECCE.2018.8557386

https://doi.org/10.1109/TPEC.2019.8662170


Coaxial Magnetic Gearbox

A magnetic gear consists of:
- \( p_1 \) pole-pair permanent magnets on an inner ring rotating at \( \omega_1 \),
- \( p_3 \) pole-pair permanent magnets on outer ring rotating at \( \omega_3 \),
- A middle ring with \( n_2 \) ferromagnetic steel poles that is rotating at \( \omega_2 \).

If the relationship between the steel poles is chosen to be
\[
p_1 = \left| p_3 - n_2 \right|
\]  
(1)

Then the inner and outer rings that contain PMs interact with the middle steel poles (\( n_2 \)) to create space harmonics.

\[
\omega_1 = \frac{p_3}{p_3 - n_2} \omega_3 + \frac{n_2}{n_2 - p_3} \omega_2
\]
(2)

For the case when the outer rotor ring is stationary, \( \omega_3 = 0 \), the speed relationship is just

\[
\omega_1 = \left( \frac{n_2}{n_2 - p_3} \right) \omega_2 = G \omega_2
\]
(3)

\( G \) is the gear ratio.
A magnetic gear consists of:

- $p_1$ pole-pair permanent magnets on an inner ring rotating at $\omega_1$,
- $p_3$ pole-pair permanent magnets on outer ring rotating at $\omega_3$
- A middle ring with $n_2$ ferromagnetic steel poles that is rotating at $\omega_2$.

**Rotor 1:** $P_1$ magnet pole-pairs

**Rotor 2:** $N_2$ steel poles

**Rotor 3:** $P_3$ magnet pole-pairs
A magnetic gear offers many advantages over its mechanical counterpart such as contact free torque production, no gear lubrication and inherent overload protection.
Visualization of Magnetic Gearbox Operation

Rotor 3, $p_3 = 12$ pole-pairs

Rotor 2, $n_2 = 16$ ferromagnetic segments

If rotor 1 has $p_1 = 4$ pole-pairs rotors will be coupled
Cut-through view of the complete 63:1 dual stage series connected 5kW multistage magnetically geared generator. The stage 1 magnetic gear consists of a 6.67:1 gear ratio coaxial MG. The stage 2 magnetic gear consists of a 9.5:1 gear ratio coaxial magnetic gear.
Stage 1 Magnetic Gear Rotor Structure (6.67:1)

Quarter view of the stage 1 magnetic gear typology with the flux concentration inner rotor and Halbach outer rotor with ferromagnetic back-iron support structure.

Stage 1 high-torque rotor cage rotor with Garolite inserts.

Inner pole pair, \( p_1 = 6 \)

Outer pole pair, \( p_3 = 40 \)

Modulator segments, \( n_2 = 46 \)

### Torque Density Performance for Final Design

<table>
<thead>
<tr>
<th>Metric</th>
<th>2-D FEA</th>
<th>3-D FEA</th>
<th>Specified</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input torque, ( T_3 )</td>
<td>1815</td>
<td>1391</td>
<td>≥1193</td>
<td>N·m</td>
</tr>
<tr>
<td>Torque density</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volumetric, ( T_d )</td>
<td>399.9</td>
<td>306.4</td>
<td>≥250</td>
<td>N·m/L</td>
</tr>
<tr>
<td>Magnet mass, ( T_m )</td>
<td>113.7</td>
<td>87.1</td>
<td></td>
<td>N·m/kg</td>
</tr>
<tr>
<td>Mass, ( T_m )</td>
<td>74.2</td>
<td>56.2</td>
<td></td>
<td>N·m/kg</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td></td>
<td>≥ 95</td>
<td>%</td>
</tr>
<tr>
<td>Torque ripple</td>
<td></td>
<td>98</td>
<td>≤3</td>
<td>%</td>
</tr>
</tbody>
</table>
Technical Accomplishments (Cont.)

Stage 2 5kW Magnetic Gear Rotor Structure (9.5:1)

![Half-view of the stage 2 magnetic gear typology](image)

- Outer rotor
- Cage rotor
- Inner rotor
- Outer rotor laminations
- Inner rotor back-iron

- Fully assembled stage 2 magnetic gear

Inner pole pair, \( p_1 = 4 \)
Outer pole pair, \( p_3 = 34 \)
Modulator segments, \( n_2 = 38 \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak torque, ( T_5 )</td>
<td>277.9</td>
<td>N·m</td>
</tr>
<tr>
<td>Volumetric torque density</td>
<td>348.9</td>
<td>N·m/L</td>
</tr>
<tr>
<td>Mass torque density</td>
<td>62.1</td>
<td>N·m/kg</td>
</tr>
</tbody>
</table>

Complete assembly for (a) inner rotor (b) the cage rotor
Technical Accomplishments (Cont.)

- Completed construction of the subscale 5kW magnetic gear.
- Completed magnetic design for the 50kW multistage magnetic gear.
- New magnetic rotor structure and endplate design invented that reduces tolerance inaccuracies and improve assembly process.
- One provisional patent has been submitted.
- Start-up company, FluxMagic, Inc. has been created to focus on commercializing the magnetic gear technology. License agreements with Portland State University have been signed.

![Graph showing comparison of different designs](image-url)
Stage 2 50kW Magnetic Gear Rotor Structure (7.66:1)

**Stage 2 Gear Pole and Slot Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner rotor pole-pairs, $p_4$</td>
<td>6</td>
</tr>
<tr>
<td>Cage rotor slots, $n_5$</td>
<td>46</td>
</tr>
<tr>
<td>Outer rotor pole-pairs, $p_6$</td>
<td>40</td>
</tr>
<tr>
<td>Gear ratio, $G_{12} = n_5 / p_4$</td>
<td>7.66</td>
</tr>
<tr>
<td>Input rotor torque, $T_5$</td>
<td>$\geq$1833 N·m</td>
</tr>
<tr>
<td>Output rotor torque, $T_4$</td>
<td>$\geq$239 N·m</td>
</tr>
</tbody>
</table>

**Design Requirements for 50kW Magnetically Geared Generator**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input into Stage 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input angular speed, $\omega_2$</td>
<td>$\leq$ 40</td>
<td>RPM</td>
</tr>
<tr>
<td>Rated power</td>
<td>$\geq$50</td>
<td>kW</td>
</tr>
<tr>
<td>Input torque, $T_2$</td>
<td>$\geq$11.93</td>
<td>kN·m</td>
</tr>
<tr>
<td>Generator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output angular speed, $\omega_4$</td>
<td>2000</td>
<td>RPM</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$\geq$93</td>
<td>%</td>
</tr>
<tr>
<td>Torque ripple at ¼ load</td>
<td>$\leq$3</td>
<td>%</td>
</tr>
<tr>
<td>Input rotor torque, $T_4$</td>
<td>$\geq$239</td>
<td>N·m</td>
</tr>
<tr>
<td>Required gear ratio, $G_{24}$</td>
<td>$\geq$49.92</td>
<td>-</td>
</tr>
</tbody>
</table>
• Complete testing of the multistage subscale magnetic gear (September 2019)

• Use subscale test setup to verify a suitable testing standard with the advisory board. (January 2020)

• Complete construction and testing of the 50kW magnetic gear (August 2020)