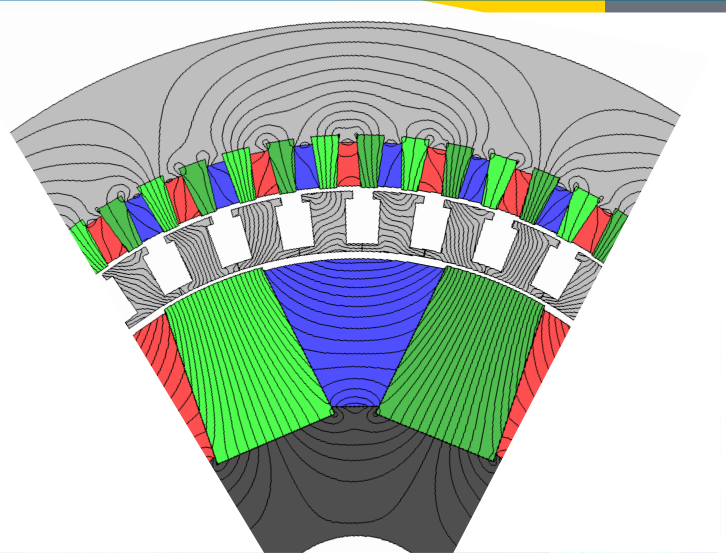

A Hermetically Sealed Magnetically Geared Marine Hydrokinetic Generator

EE0008100

Marine and Hydrokinetics Program

Presentation Date: Thursday, October 10

Jonathan Bird

Portland State University

Project Overview

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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× 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.

Project Information

Project Principal Investigator(s)

Jonathan Bird, PI
Portland State University
Wesley William, co-PI
University of North Carolina at Charlotte

WPTO Lead

Erik Mauer
Steve Dewitt

Project Partners/Subs

Advisory board members:
National Renewable Energy Laboratory–
Ocean Renewable Power Company (ORPC)
Magnecon – Advisory board member
Verdant Power – Advisory board member

Project Duration

- Project Start Date: 09/01/2017
- Project End Date: 08/31/2020

Alignment with the Program

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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

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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

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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.

Project Budget

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Total Project Budget – Award Information		
DOE	Cost-share	Total
$800.0K	$88.9K	$888.9K

FY17	FY18	FY19 (Q1 & Q2 Only)	Total Actual Costs FY17–FY19 Q1 & Q2 (October 2016 – March 2019)
Costed	Costed	Costed	Total
$44.7K	$253.4K	$192.0K	$490.1K

Management and Technical Approach

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- **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

[1] Baninajar H., J. Z. Bird, S. Modaresahmadi, W. Williams, *Electromagnetic Design of a Halbach Rotor Magnetic Gear for a Marine Hydrokinetic Application* presented at Eleventh IEEE Energy Conversion Congress and Expo Conference, Baltimore, MD, Sept. 29-Oct 3. 2019. http://www.ieee-ecce.org/2019/

[2] H. Baninajar, J. Z. Bird, S. Modaresahmadi and W. Williams, "Electromagnetic and Mechanical Design of a Hermetically Sealed Magnetic Gear for a Marine Hydrokinetic Generator," *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, Portland, OR, 2018, pp. 4987-4993. https://doi.org/10.1109/ECCE.2018.8557386

[3] S. Modaresahmadi, A. Hosseinpour and W. B. Williams, "Fatigue Life Prediction of a Coaxial Multi-Stage Magnetic Gear," *2019 IEEE Texas Power and Energy Conference (TPEC)*, College Station, TX, USA, 2019, pp. 1-6. https://doi.org/10.1109/TPEC.2019.8662170

[4] J. Bird, Magnetically Geared Rotary Generators for Marine Hydrokinetic Power Take-Off – A Status Update, *IEEE OCEANS 2019*, June 17-20, Marseille, France.

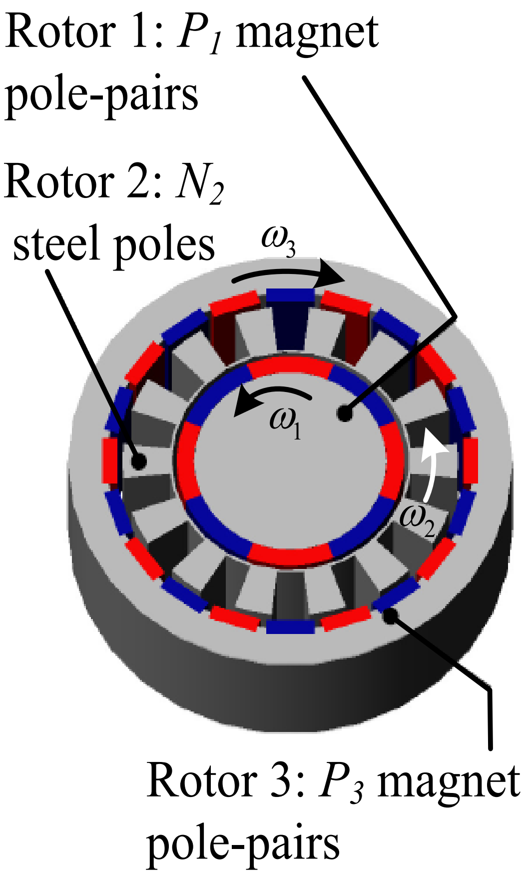
[5] H. Baninajar, J. Z. Bird, Comparing the Torque Density Performance of a Series and a Nested Magnetically Geared Generator, submitted to *IEEE Transactions Energy Conv.*

[6] J. Bird, "A new type of Halbach rotor magnet and modulator typology for use in a magnetic gear or motor", Provisional patent submitted.

Coaxial Magnetic Gearbox

A magnetic gear consists of:

- p_1 pole-pair permanent magnets on an inner ring rotating at ω_1,
- p_3 pole-pair permanent magnets on outer ring rotating at ω_3
- A middle ring with n_2 ferromagnetic steel poles that is rotating at ω_2.



If the relationship between the steel poles is chosen to be $p_1 = |p_3 - n_2|$ (1)

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

$$\omega_1 = \frac{p_3}{p_3 - n_2}\omega_3 + \frac{n_2}{n_2 - p_3}\omega_2 \qquad (2)$$

For the case when the outer rotor ring is stationary, ω_3=0, the speed relationship is just

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

G is the gear ratio

Coaxial Magnetic Gearbox

A magnetic gear consists of:

- p_1 pole-pair permanent magnets on an inner ring rotating at ω_1,
- p_3 pole-pair permanent magnets on outer ring rotating at ω_3
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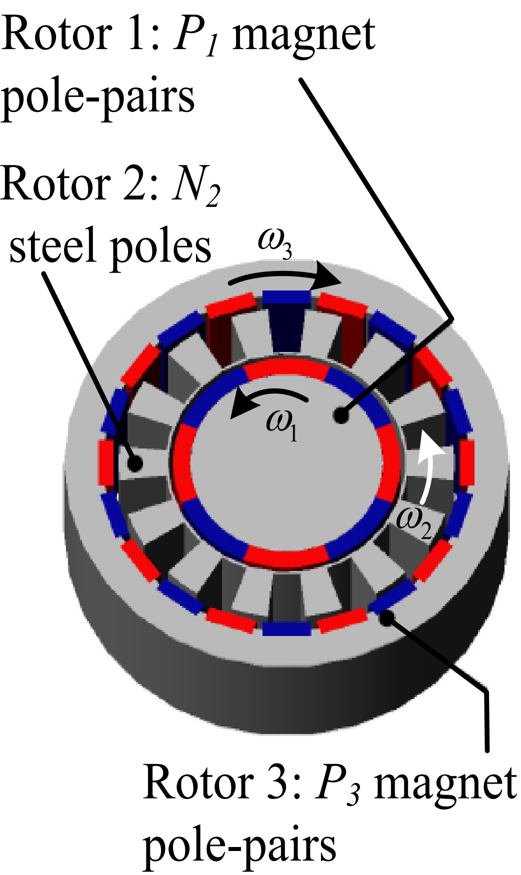
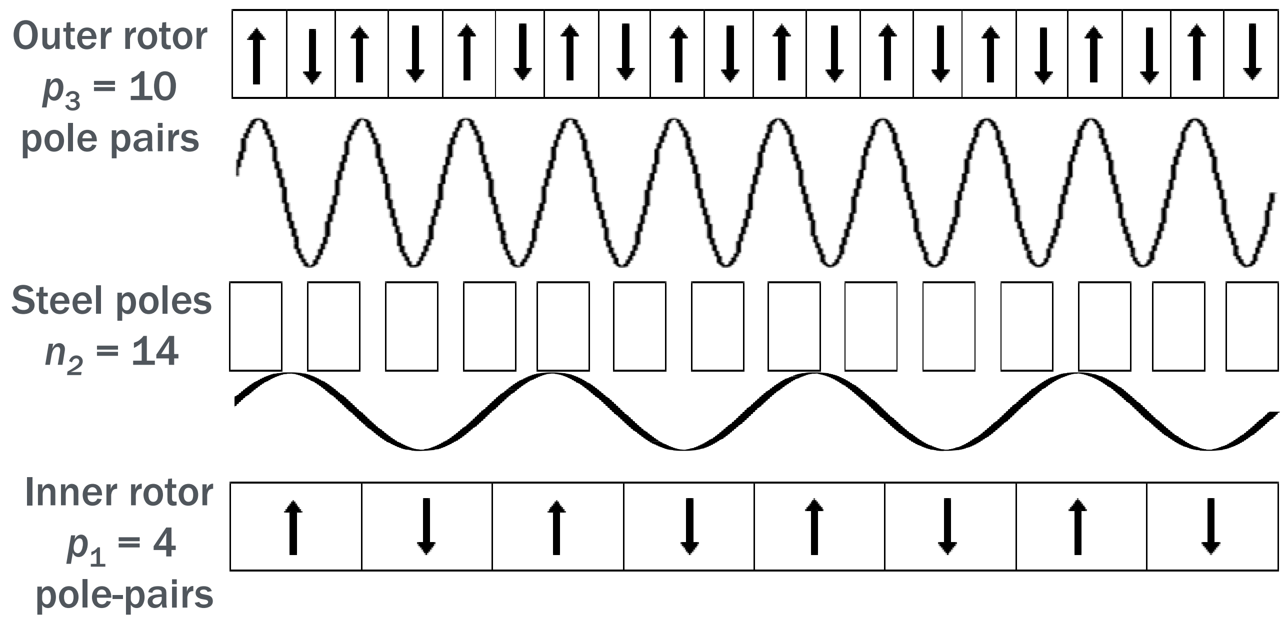
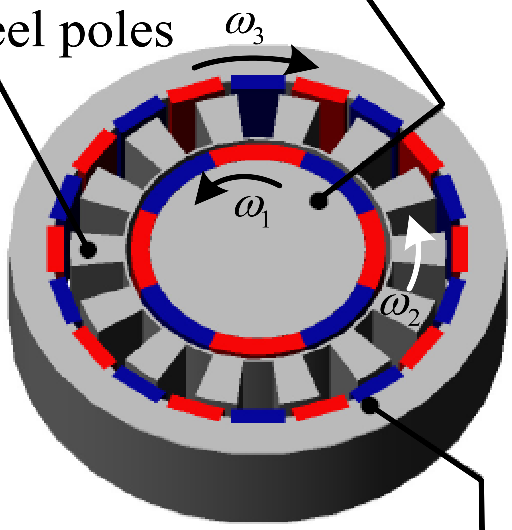




Coaxial Magnetic Gearbox



For the example shown in the figure

- p_1=4 pole-pairs on inner high speed rotor
- n_2=14 steel poles on center rotor
- p_3=10 pole-pairs on outer stationary rotor.

Space modulation requirement met:

$$p_1 = |p_3 - n_2| = |10 - 14| = 4$$

This gives a gear ratio

$$\omega_1 = G\omega_2 = \left(\frac{n_2}{n_2 - p_3}\right)\omega_2$$

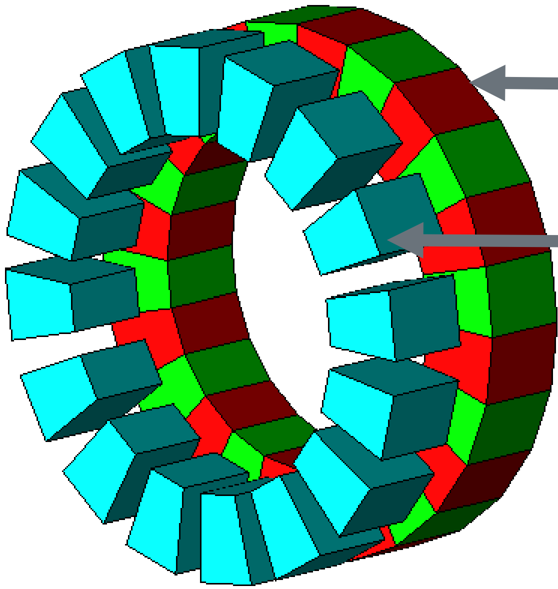
$$= \left(\frac{14}{14-10}\right)\omega_2$$

$$= 3.5\omega_2$$

A magnetic gear offers many advantages over its mechanical counterpart such as contact free torque production, no gear lubrication and inherent overload protection.

Coaxial Magnetic Gearbox

Visualization of Magnetic Gearbox Operation

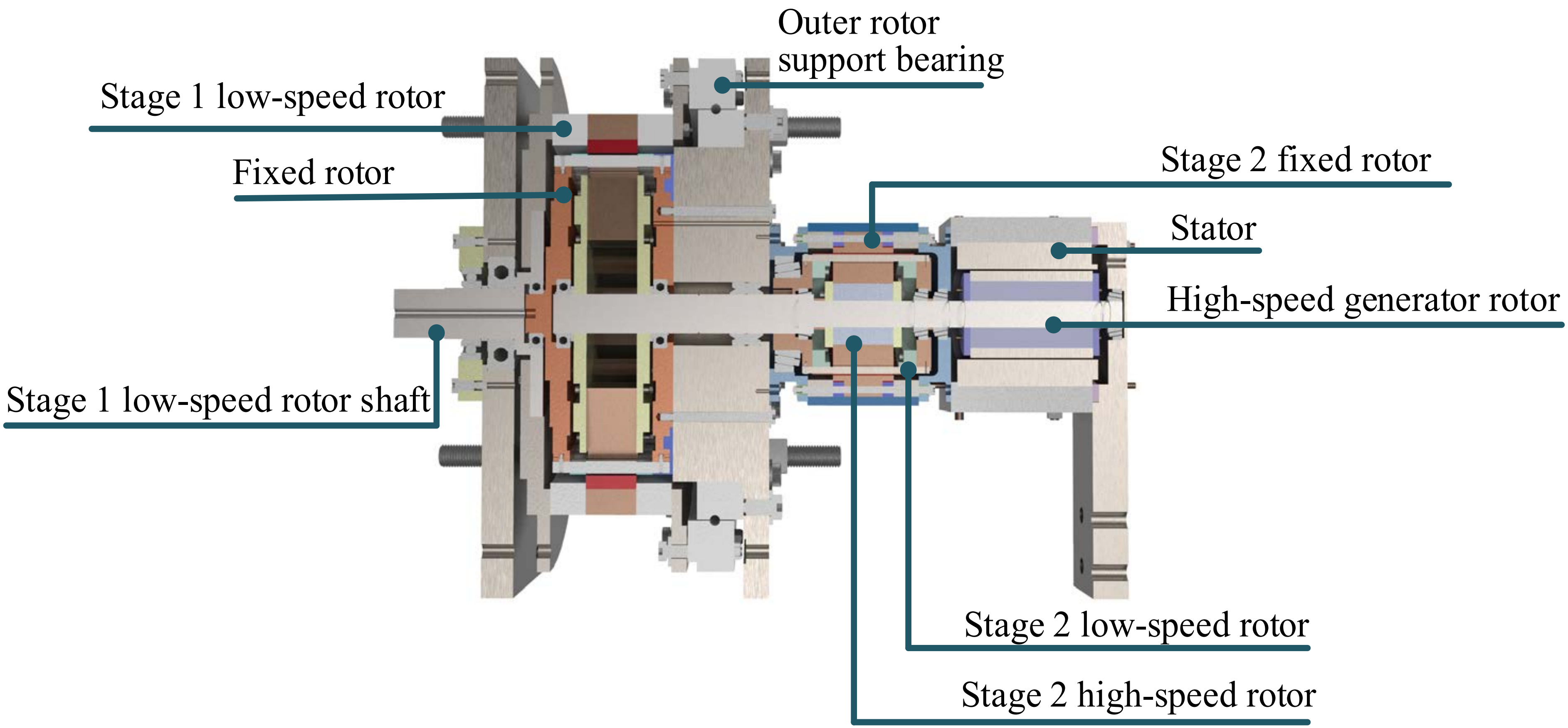


Rotor 3, p_3 =12 pole-pairs

Rotor 2, n_2 = 16 ferromagnetic segments

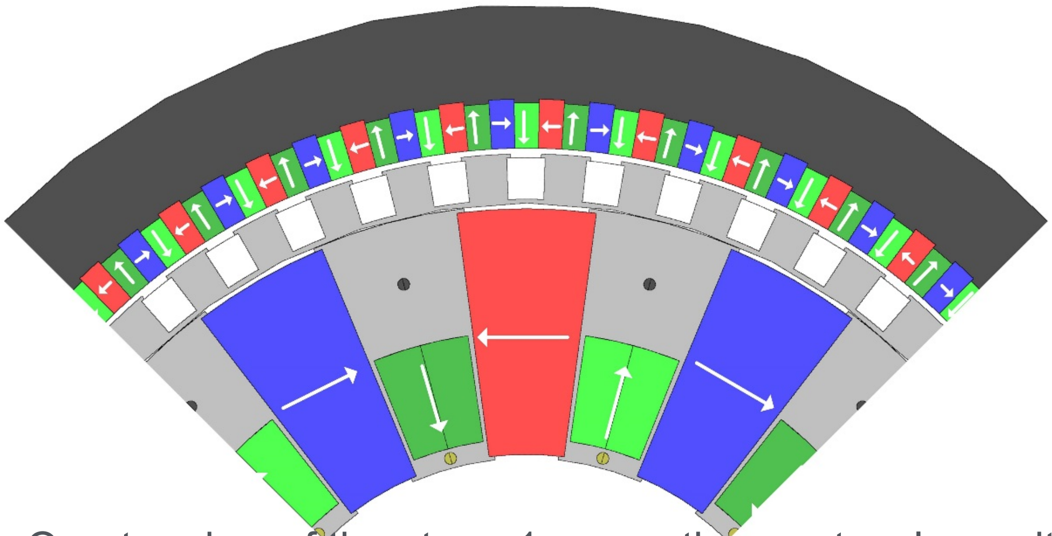
If rotor 1 has p_1 = 4 pole-pairs rotors will be coupled

5kW Multistage Magnetically Geared Generator

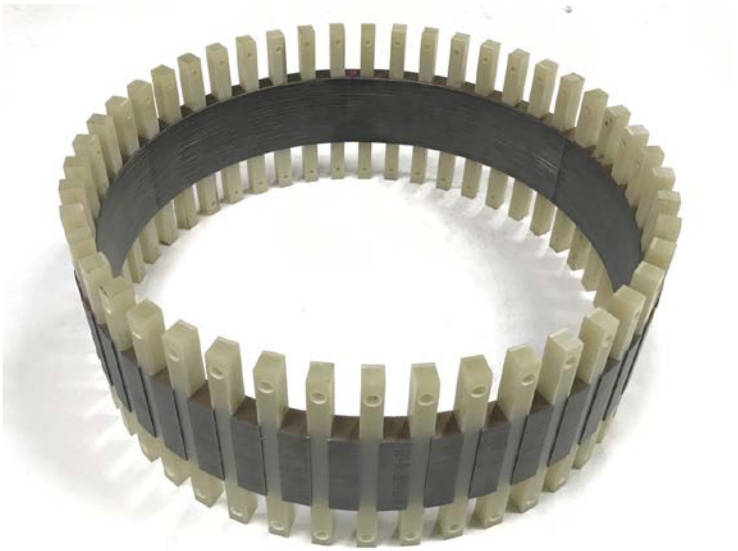


Cut-through view of the complete 63:1 dual stage series connected 5kW multistage magnetically geared generator. The stage 1 magnetic gear consists of a 6.67:1 gear ratio coaxial MG. The stage 2 magnetic gear consists of a 9.5:1 gear ratio coaxial magnetic gear.

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



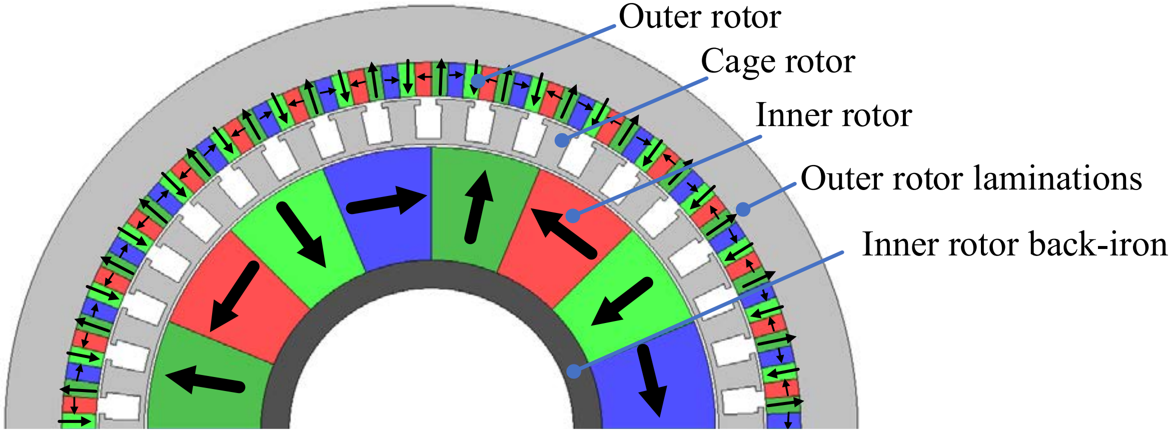
Stage 1 high-torque rotor cage rotor with Garolite inserts.

Inner pole pair, $p_1 = 6$
Outer pole pair, $p_3 = 40$
Modulator segments, $n_2 = 46$

TORQUE DENSITY PERFORMANCE FOR FINAL DESIGN

Metric		2-D FEA	3-D FEA	Specified	Units
Input torque, T_3		1815	1391	≥1193	N·m
Torque density	Volumetric, T_d	399.9	306.4	≥250	N·m/L
	Magnet mass, T_m	113.7	87.1		N·m/kg
	Mass, T_m	74.2	56.2		N·m/kg
Efficiency		-	98	≥ 95	%
Torque ripple		-	1	≤3	%

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

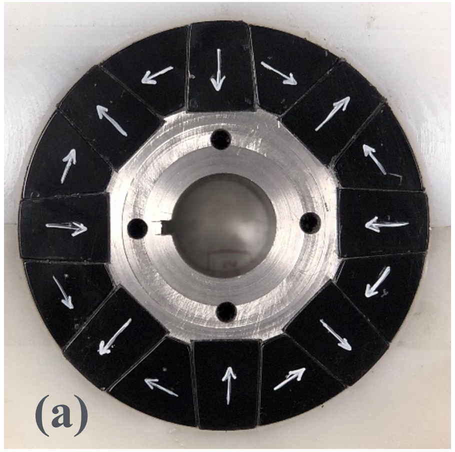


Half-view of the stage 2 magnetic gear typology

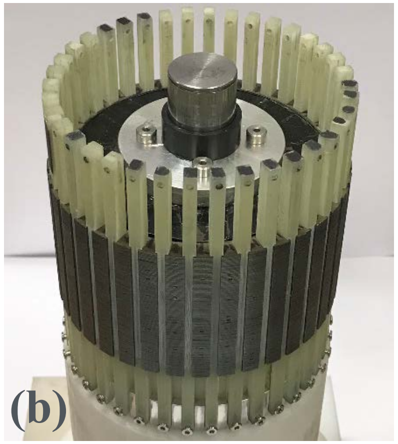
Fully assembled stage 2 magnetic gear

Inner pole pair, $p_1 = 4$
Outer pole pair, $p_3 = 34$
Modulator segments, $n_2 = 38$

Parameter	Value	Unit
Peak torque, T_5	277.9	N·m
Volumetric torque density	348.9	N·m/L
Mass torque density	62.1	N·m/kg



(a)



(b)

Complete assembly for (a) inner rotor (b) the cage rotor

Technical Accomplishments (Cont.)

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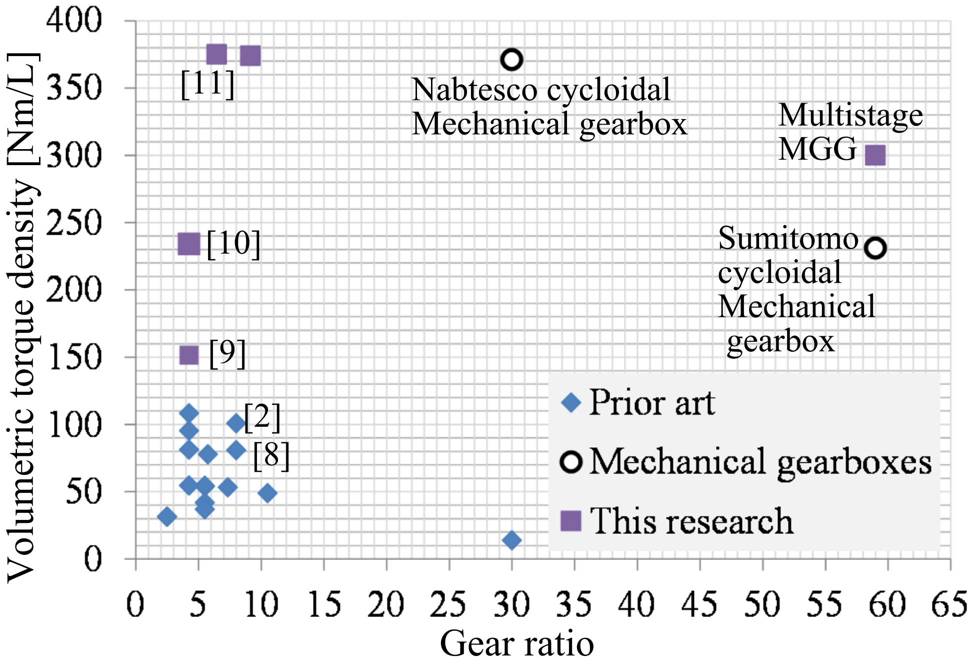
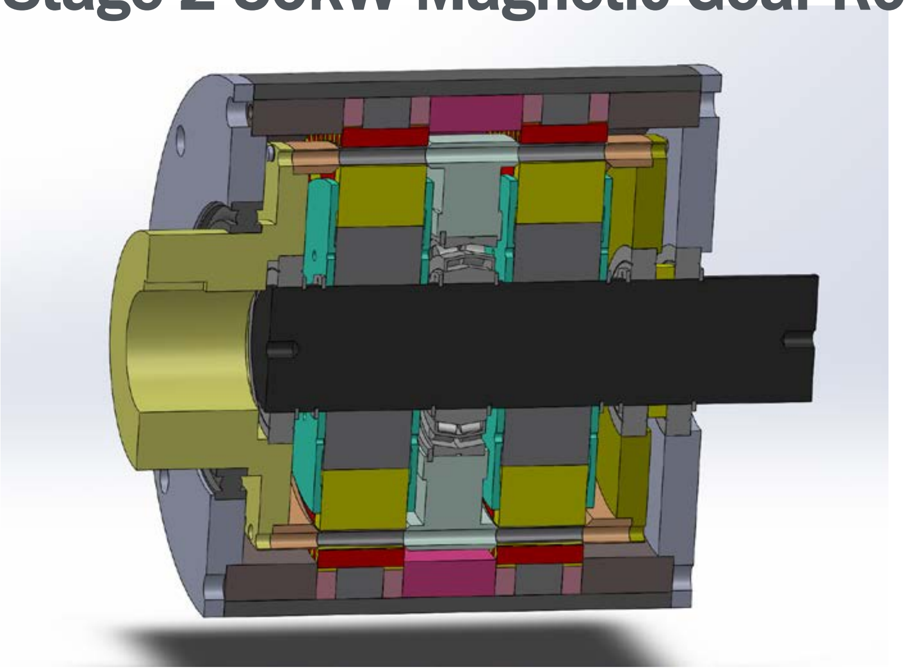
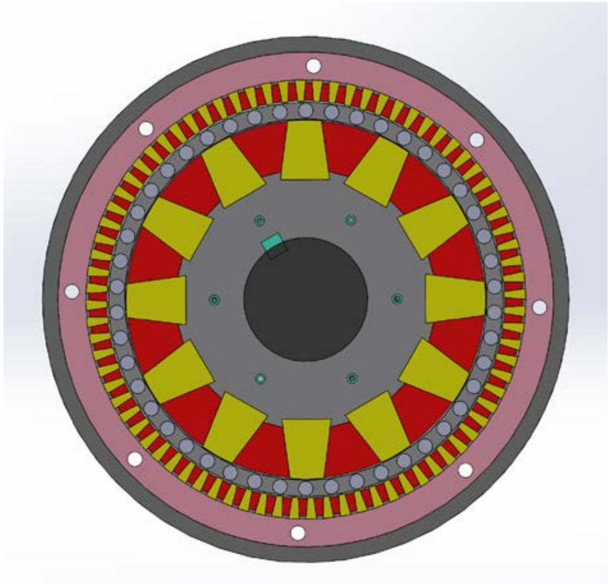
- Completed construction of the subscale 5kW magnetic gear.
- Completed magnetic design for the 50kW multistage magnetic gear
- New magnetic rotor structure and endplate design invented that reduces tolerance inaccuracies and improve assembly process.
- One provisional patent has been submitted.
- Start-up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



Progress Since Project Summary Submittal

Stage 2 50kW Magnetic Gear Rotor Structure (7.66:1)





DESIGN REQUIREMENTS FOR 50KW MAGNETICALLY GEARED GENERATOR

Requirement		Value	Unit
Input into Stage 1	Input angular speed, ω_2	≤ 40	RPM
	Rated power	≥ 50	kW
	Input torque, T_2	≥ 11.93	kN·m
Generator	Output angular speed, ω_4	2000	RPM
	Efficiency	≥ 93	%
	Torque ripple at ¼ load	≤ 3	%
	Input rotor torque, T_4	≥ 239	N·m
Required gear ratio, G_{24}		≥ 49.92	-

STAGE 2 GEAR POLE AND SLOT PARAMETERS

Parameter	Value
Inner rotor pole-pairs, p_4	6
Cage rotor slots, n_5	46
Outer rotor pole-pairs, p_6	40
Gear ratio, $G_{12} = n_5/ p_4$	7.66
Input rotor torque, T_5	≥ 1833 N·m
Output rotor torque, T_4	≥ 239 N·m

Future Work

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- 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)