NREL
Transforming ENERGY

Advanced Permanent Magnet Generator Topologies Using Multimaterial Shape Optimization and 3D Printing

Latha Sethuraman,[1] Andrew Glaws,[1]
Miles Skinner,[1] and Parans Paranthaman[2]

[1] National Renewable Energy Laboratory (NREL)
[2] Oak Ridge National Laboratory (ORNL)

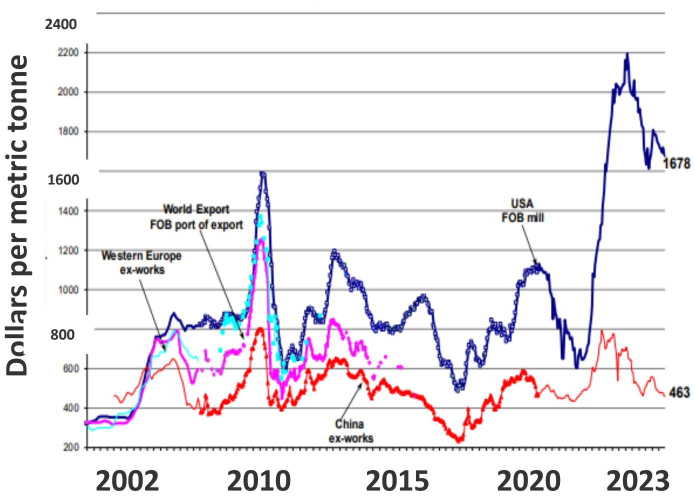
Acknowledgments
Tod Hanley (Bergey Windpower), Mike Bergey (Bergey Windpower)

Background

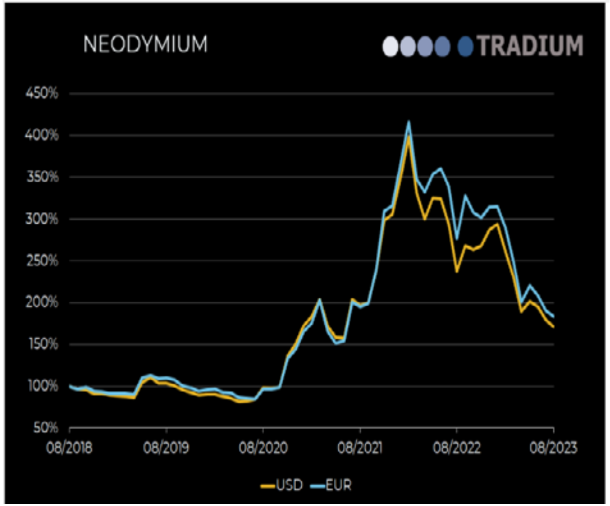
Several small wind OEMs are facing supply chain bottlenecks for key raw materials.

- Rare earth magnets and steel prices have been volatile.
- Manufacturing costs have doubled.

The OEMS are pursuing continuous improvements to their generator designs to lower the cost/kW installed.



Steel price trend. Source: Steel Benchmarker



Neodymium price trend. Source: Tradium

Bergey Excel 15-kW direct drive permanent magnet generator.

Photo credit: Bergey Wind Company

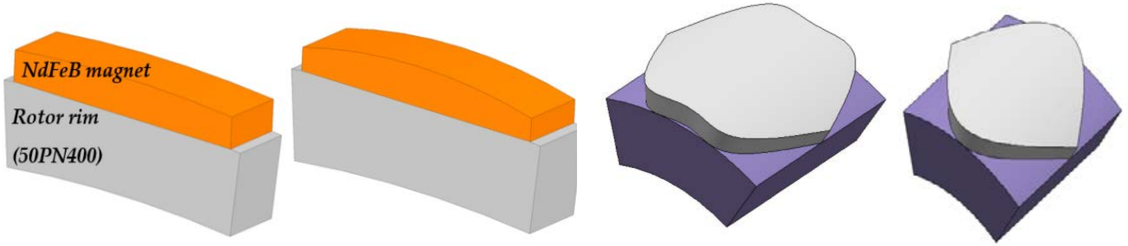
Aeolos 50-kW direct drive permanent magnet generator.

Photo credit: Aeolos Wind Turbine Company, UK

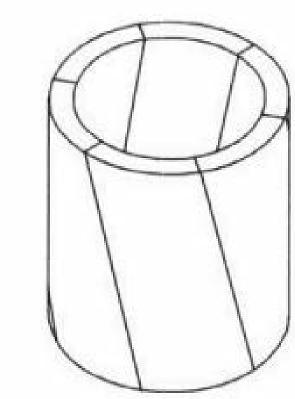
PM mass typically between 5 and 15 kg.

Focus Areas for Small Wind OEMs

1. Improve efficiency
   a) Thinner laminations
2. Minimize cogging torque
   a) Magnet edge shaping (bread-loaf)
   b) Varying magnet width
   c) Skewing stator stack
3. Minimize manufacturing cost.



Methods: Magnet shaping, e.g., use of bread-loaf and tapered bread-loaf magnets (Son and Lee 2023) and butterfly and egg-shaped magnets (Du and Lipo 2019).



Magnet skewing

Stator stack skewing

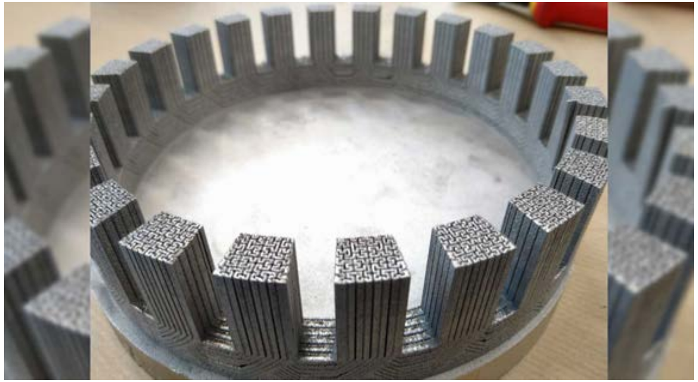
Manufacturing of shaped magnets needs molds, including skewed ones, which increase their cost and wastage.

Skewing makes slot filling difficult and also increases tooling costs.

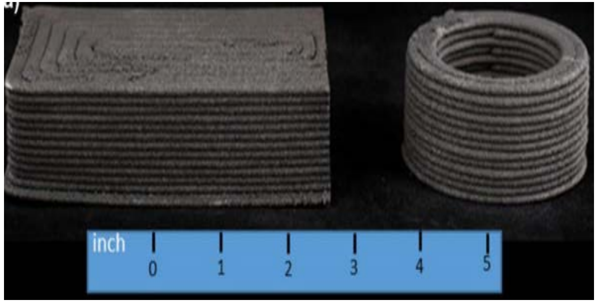
Recent Trends in Manufacturing

- Fe3.0Si and Fe6.5 steels have been fabricated by selective laser melting and binder jetting and have resulted in new high-performing designs.

- NdFeB-bonded magnets fabricated via extrusion process have shown energy product of 20 MGOe demonstrated to date and have promising electrical properties.



New cross-sectional geometries have been shown to reduce the eddy current losses in cores (Goodall et al. 2023).

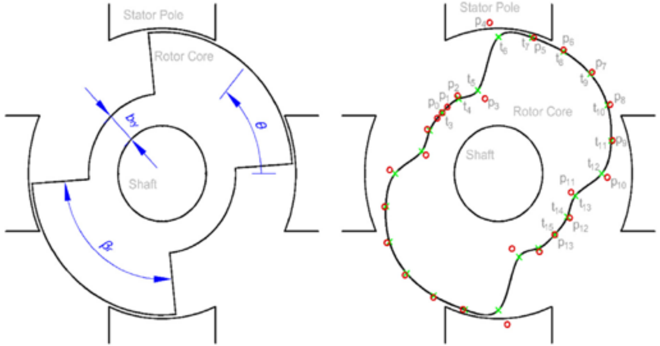


Polymer bonded printed magnets from Gandha et al. (2020).

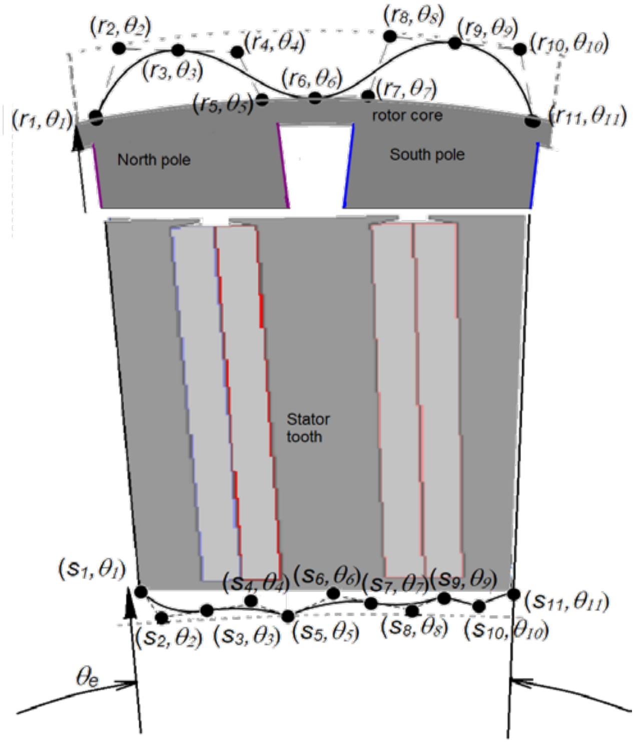
Recent Trends in Design: Shape Optimization

- Boundaries of geometries are parametrized using curves.

- Recent work using Bézier curves by the authors showed smoother shapes that can be realized and better opportunities for lightweighting generator.



A rotor shaped by B-spline curves and machined by wire-EDM (electro-discharge machining). This technique is too expensive for mass production (Lee et al. 2003).



Bézier parametrization (Sethuraman and Vijayakumar 2022).

Research Gaps

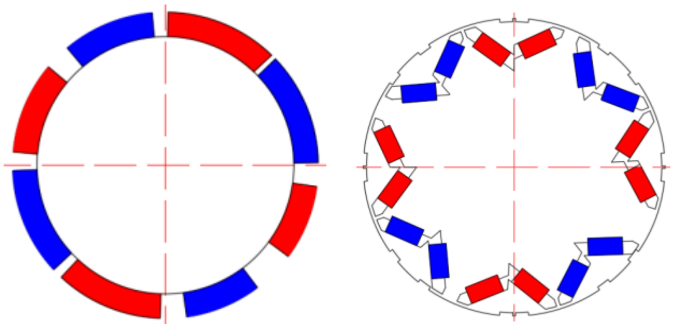
- Optimization techniques focus on **symmetrical design** approach.
  - Assumes that every pole or tooth geometry is identical and symmetric.
  - All electrical characteristics are repeated

More useful if the electric machine rotates in two directions—can result in excessive material use.

- Very little research has been done on ***asymmetrical design*** approaches.
  - Selective shaping of poles allows for a variable air-gap profile and improves back-electromotive force waveform.
  - Can help conserve material and minimize mass.
  - Helps minimize cogging and ripple torques.

More useful if the electric machine rotates in one direction.

High manufacturing cost due to the complexity

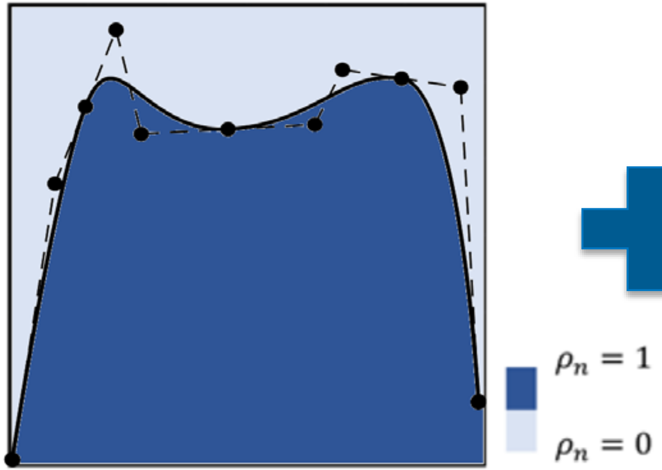


Examples of asymmetric designs (Sun et al. 2019).

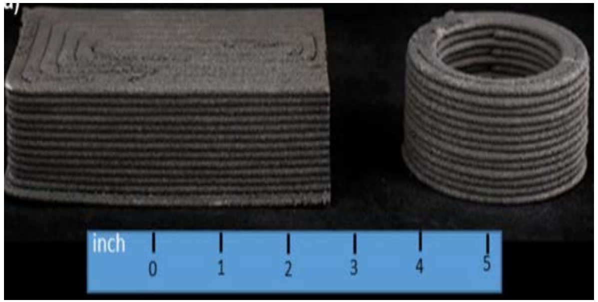
This Work

Explored full design space for a baseline 15-kW wind turbine generator using printed materials (magnets and electrical steel):

- Interpolar shape optimization exploring novel symmetric and asymmetric designs
- Extending the Bézier curve approach for magnets and electrical steel for multimaterial shape optimization.

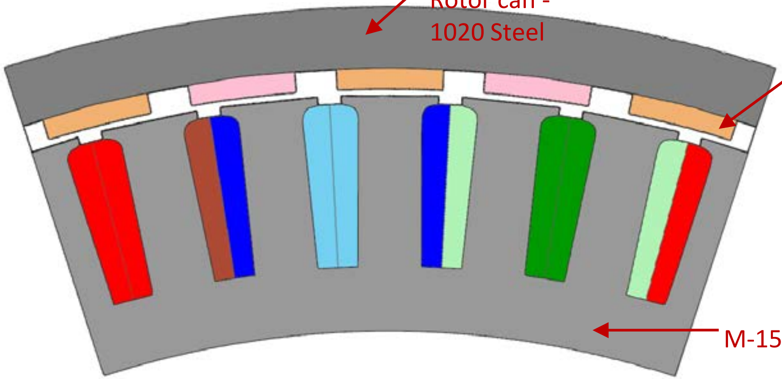


Bézier curve approach



Printed magnet properties inferred from Gandha et al. (2020).

Baseline Design Specifications and Targets



Baseline 15-kW permanent magnet synchronous generator modeled around Bergey wind turbine

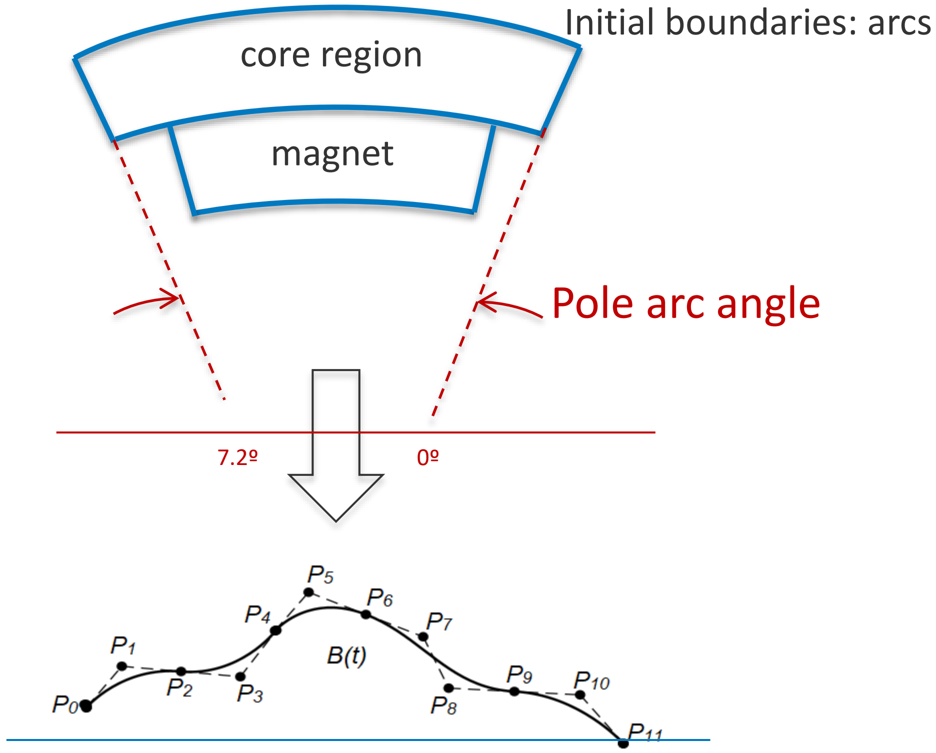
- Fractional-slot concentrated winding
- *Slot-pole combination*
  - 60 slots, 50 poles.

Performance Parameters and Optimization Targets

Parameter	Baseline	Target
Rated voltage	≤ 575 V	≤ 575 V
Efficiency	95%	≥ 95%
Cogging torque	33 Nm	< 25 Nm
Magnet material	Sintered	Printed polymer-bonded (0 % Dy)
Magnet resistivity (Ωm)	1.5×10^{-6}	0.0258
Normal coercivity at 60ºC	1041.7	485.9
Magnet BH_{max} (MGOe)	45	20
Rotor core material	1020 steel	1020 steel/cast iron
Magnet mass	1 p. u.	< 0.9 pu
$B_{rmin\text{-}SC\ and\ stall}$ (T)	0.45	0.3
$T_{winding}$	180ºC	180ºC
T_{mag}	60ºC	60ºC

Method Extending the Bézier Curve Approach

- Rotor and magnet boundaries were simultaneously changed to result in shapes that yielded better performance.
- Circular arcs were converted to **parametrized Bézier curves** with control points defining the radius at each angular position.
- Shapes can be easily manufactured by transferring control points to commercial CAD tools or 3D printers.
- Very popular for designing turbine blades and ship hulls.

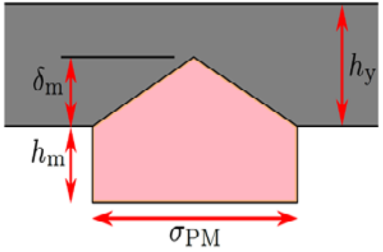


Boundaries redefined using Bézier curves.

Types of Parametrization

Baseline design

- Five different parametrizations were studied.
- Both front and rear side of magnets are shaped.
- The optimized designs with printed magnets were compared against baseline Bergey design with N48H grade.

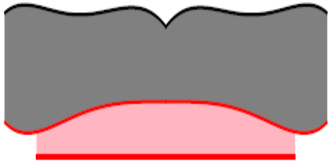


Crown-shape parameter optimization

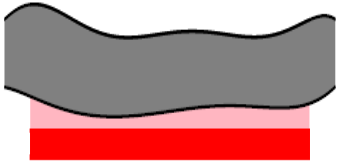
Asymmetric pole: nonconstant air-gap

Asymmetric pole: constant air-gap

Symmetric pole: nonconstant air-gap



Symmetric pole: constant air-gap



Multimagnet asymmetric pole: constant air-gap

Symmetry Parametrization

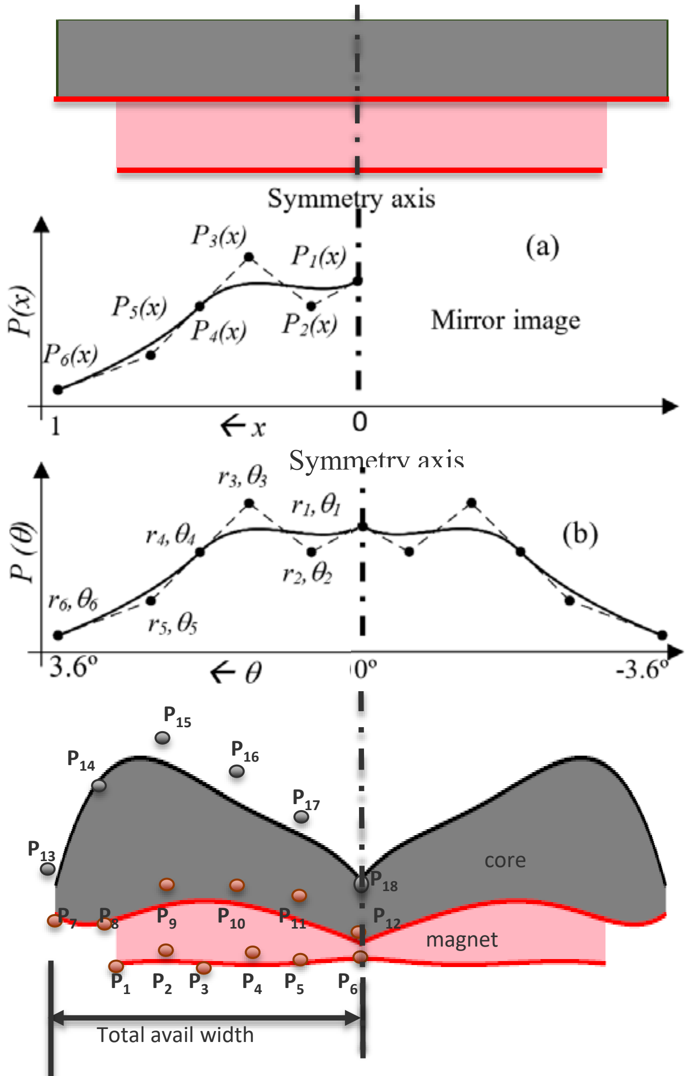
- **Three Bézier curves define the shape of one pole.**
- **Each curve is defined by six points.**
- **Each point in cartesian coordinate → polar coordinate.**
- Shape of right half==mirror symmetry of left.

$$P_i(\theta_i) = r_i, \theta_i$$
$$= P_i(x_i)\cos(i\delta\theta), P_i(x_i)\sin(i\delta\theta), for\ i = 1\ to\ 6$$

Design variables:

18 control points : P1-P18

Ratio $= \dfrac{actual\ width}{total\ available\ width}$



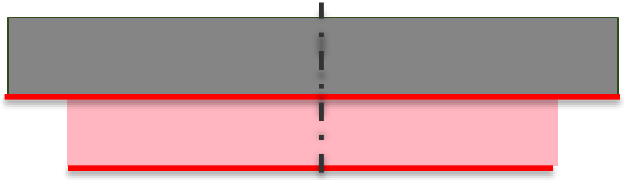
Asymmetry Parametrization Using 33 Control Points

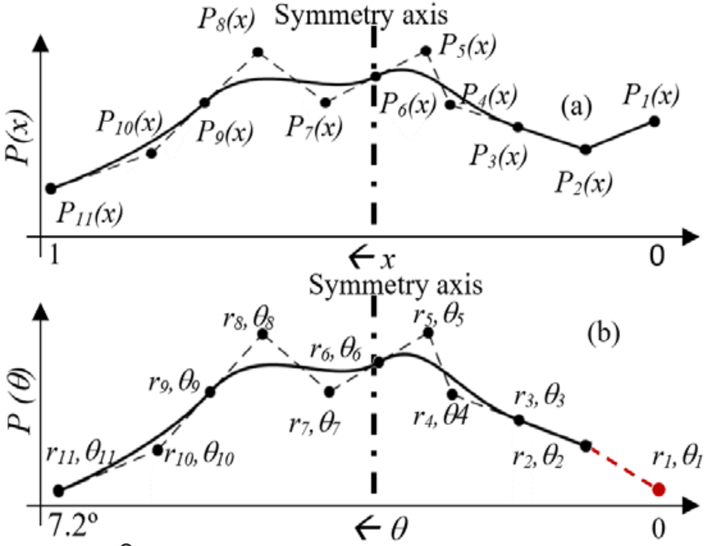
- **Three Bézier curves define the shape of one pole.**
- **Each curve is defined by 11 points.**
- **Each point in cartesian coordinate → polar coordinate.**
- Shape has no symmetry with respect to center line.

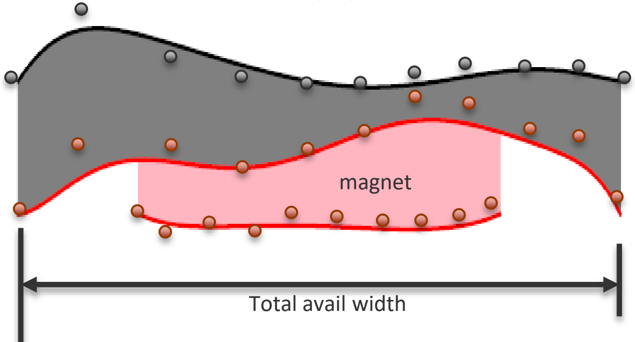
Design variables:

33 control points : P1-P33

$$\text{Ratio} = \frac{\textit{actual width}}{\textit{total available width}}$$

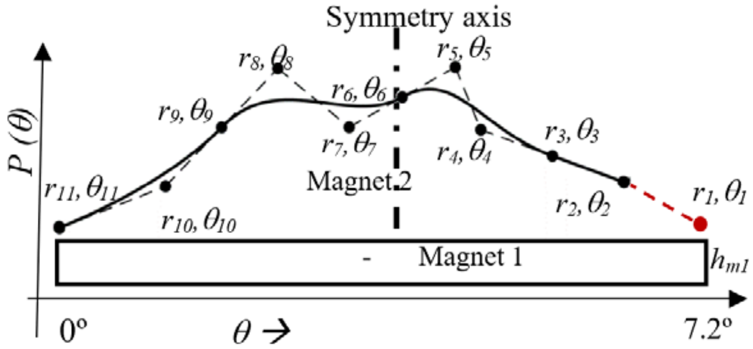






Multimaterial Parametrization

- **Two Bézier curves define the shape of one pole.**
- **Design controlled by 11 control points on each curve.**
- **Sintered magnet closest to air gap.**
- **Sintered magnet is assumed to have a flat base.**

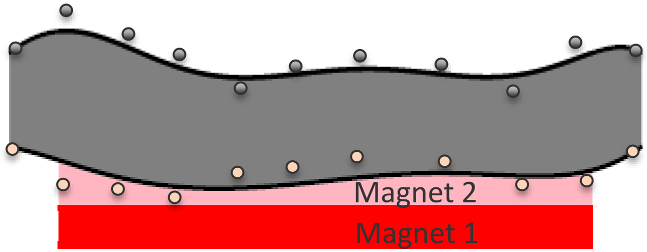


Design variables:

12 control points : P1-P22

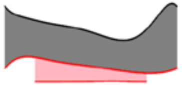
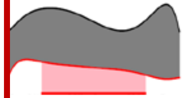
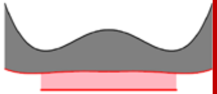
Ratio $= \dfrac{actual\ width}{total\ available\ width}$

Thickness of sintered magnet

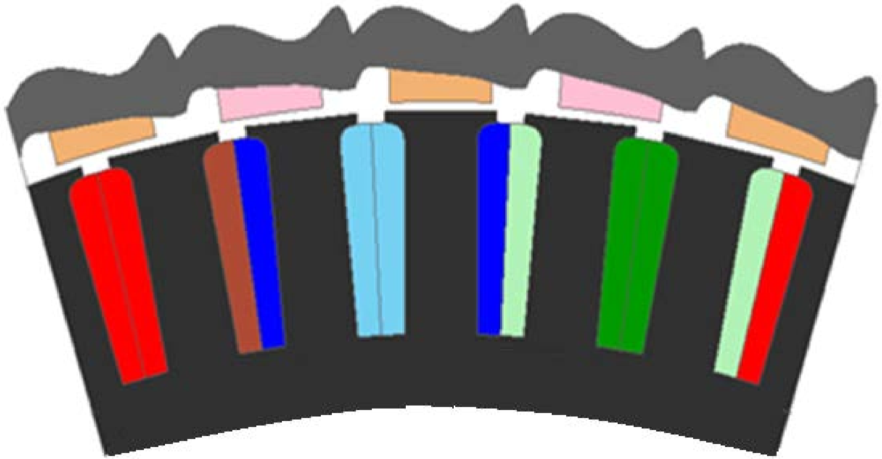


Results

Asymmetric designs were lighter by up to 27% and 35% respectively.

Designs	Baseline Design	I Re-Optimized Baseline	II Crown Design	III Asymmetric Pole: Nonconstant Air Gap	IV Asymmetric Pole: Constant Air Gap	V Symmetric Pole: Nonconstant Air Gap	VI Symmetric Pole: Constant Air Gap	VII Multimaterial Asymmetric Pole: Constant Air Gap
Magnet material	Sintered higher grade with zero dysprosium	N48H sintered magnet with zero dysprosium	55.5% weaker printed polymer-bonded magnet with zero dysprosium					
Magnet mass (pu)	1.0	0.59	0.84	0.75	0.73	0.845	0.82	0.65
Efficiency (%)	96.1	96.9	97.1	96.9	96.88	97.05	96.99	97.05
B_{rmin} (T)	0.453	0.456	0.3	0.31	0.31	0.299	0.302	0.50
T_{cog} (Nm)	25.33	24.8	24	24.21	23.18	27.5	24.78	24.105
Ratio	proprietary	69	65.8	64.62	60.23	65.95	60.64	68.97
Optimized design								
% magnet weight change	-	-41	-16.0	-25	-26.5	-15.45	-18	-35

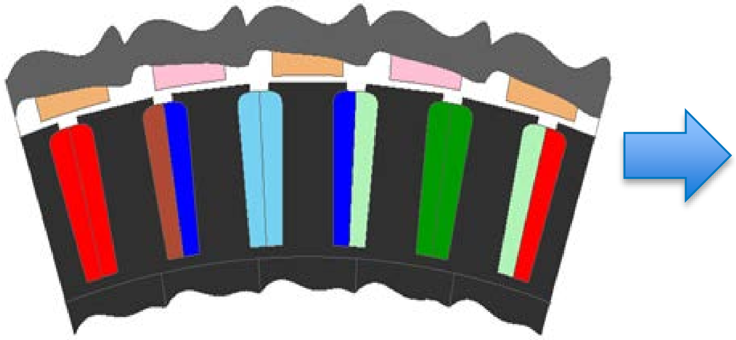
Results From Magneto-Thermal Evaluation

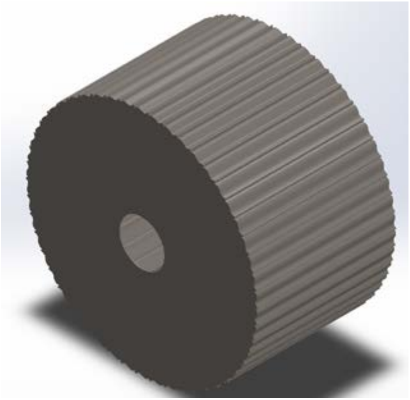


Notice the material bias for a counterclockwise direction.

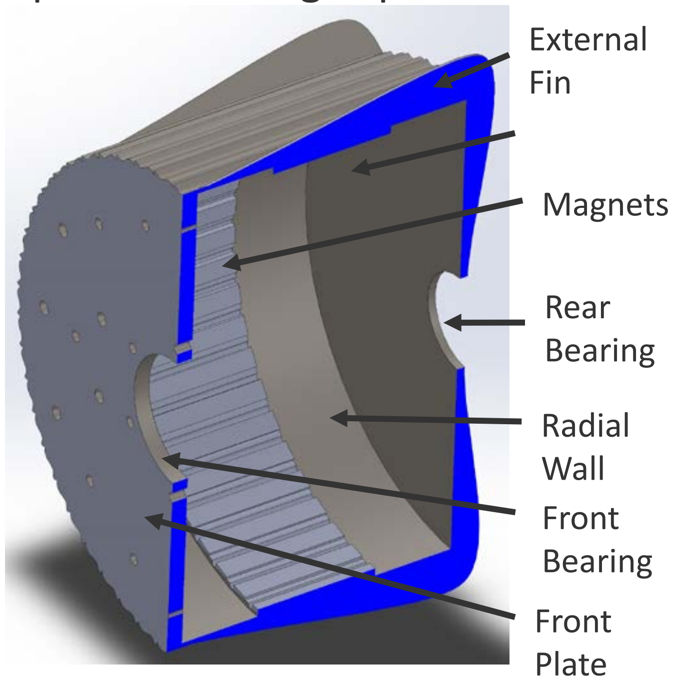
- Asymmetric pole designs are lighter than symmetric pole designs → overuse of materials for unidirectional application, especially wind turbine generators.
- Magnet profiling near the air gap (nonconstant air gap designs) can minimize cogging torque; however, it results in heavier designs.
- The combination of sintered and printed magnets in a layered approach is cost-competitive and results in lightest designs.

Structural Evaluation of Asymmetric Rotor Can



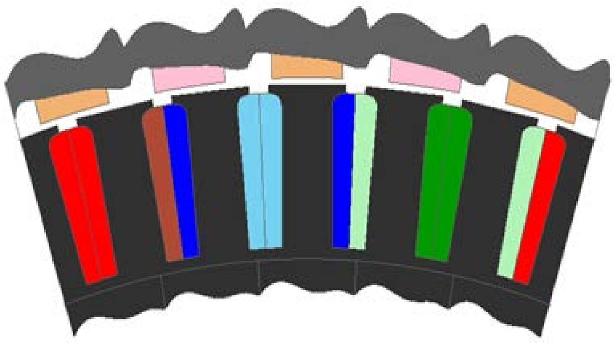


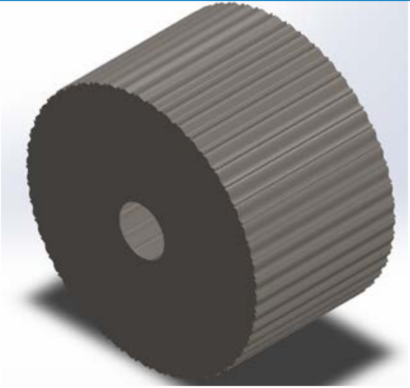
Six parameters were varied to further explore the design space.



- 2D model extruded to 3D.
- Goals: Verify structural integrity by static structural analysis.
- New features: Stiffening fins visible on the back side of the rotor can.
- Parametrize the can and optimize the dimensions

Results From Structural Evaluation





Parameter	Baseline	Optimized
Radial wall thickness (mm)	10.312	3.175
Front plate thickness (mm)	19.05	12.7
Back plate thickness (mm)	9.525	3.175
Number of fins (mm)	0	0
Total structural mass (kg)	108.83	95.16
Radial stiffness/weight	2,027.8	1,063.5

- Wave-shaped profile on the rotor cylinder adds stiffness to radial deformation.
- It can also help improve aerodynamic efficiency.
- Optimal solution within the design space, which reduced overall mass by approximately 13 kg.

Bibliography

- Du, Z., and T. Lipo. 2019. "High Torque Density and Low Torque Ripple Shaped-Magnet Machines Using Sinusoidal Plus Third Harmonic Shaped Magnets." IEEE Transactions on Industry Applications 55 (3).
- Gandha, K., et al. 2020. "Additive manufacturing of highly dense anisotropic Nd–Fe–B bonded magnets." *Scripta Materialia* 183. https://doi.org/10.1016/j.scriptamat.2020.03.012.
- Goodall A. D., et al. 2023. "Loss performance of an additively manufactured axial flux machine stator with an eddy-current limiting structure." *Materials Today Communications* 35. https://doi.org/10.1016/j.mtcomm.2023.105978.
- Lee J. H., et al. 2003. "Minimization of Higher Back-EMF Harmonics in Permanent Magnet Motor Using Shape Design Sensitivity With B-Spline Parameterization." *IEEE Transactions on Magnetics* 39.
- Sethuraman, L., and G. Vijayakumar. 2022. "A New Shape Optimization Approach for Lightweighting Electric Machines Inspired by Additive Manufacturing." Preprint. https://doi.org/10.1109/INTERMAG39746.2022.9827714.
- Sethuraman, L., et al. 2021. "MADE3D: Enabling the Next-Generation High-Torque-Density Wind Generators by Additive Design and 3D Printing." *Forschung im Ingenieurwesen* 85: 287–311. https://link.springer.com/journal/10010.
- Son, R. W., and J. Lee. 2023. "Alternative Surface-Mounted Permanent Magnet Topology for Reducing Voltage and Torque Harmonics in Shaft Generators." *Energies* 2023, 16 (12): 4649. https://doi.org/10.3390/en16124649.
- Sun, G., et al. 2019. "Asymmetrical Design in Electrical Machines." 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA: 3786–3792. https://doi.org/10.1109/ECCE.2019.8913231.
- Voxeljet. "Patent-pending manufacturing process for electric motor housings offers new opportunities." https://www.voxeljet.com/additive-manufacturing/case-studies/automotive/3d-printing-for-optimized-electric-motors/.

Thank You

www.nrel.gov

NREL/PR-5000-87649

This work was 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. Research at NREL and ORNL were funded by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. 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.

Photo from iStock-627281636