Bearingless Motor/Generator Opportunities in sCO2 Power Cycles

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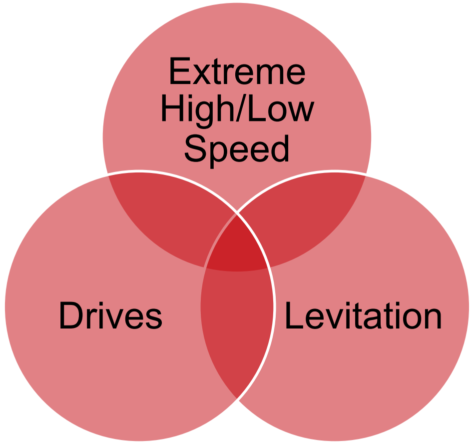
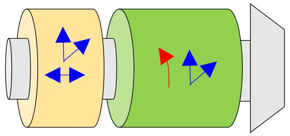
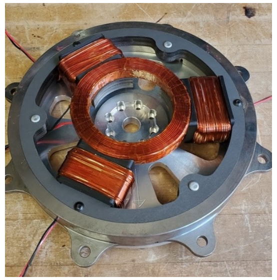
Our Electric Machines Research



Levitation



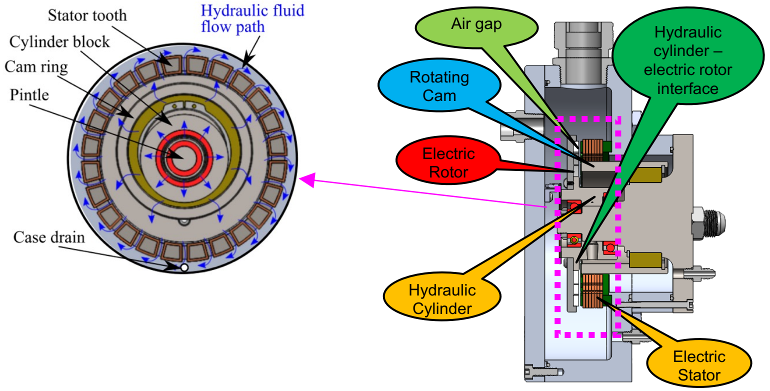


Active Magnetic Bearing

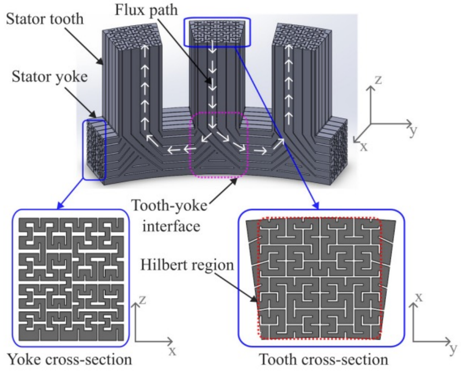
Bearingless IM Rotor

Bearingless PM Motor

Enhance Torque



Additive Manufacturing

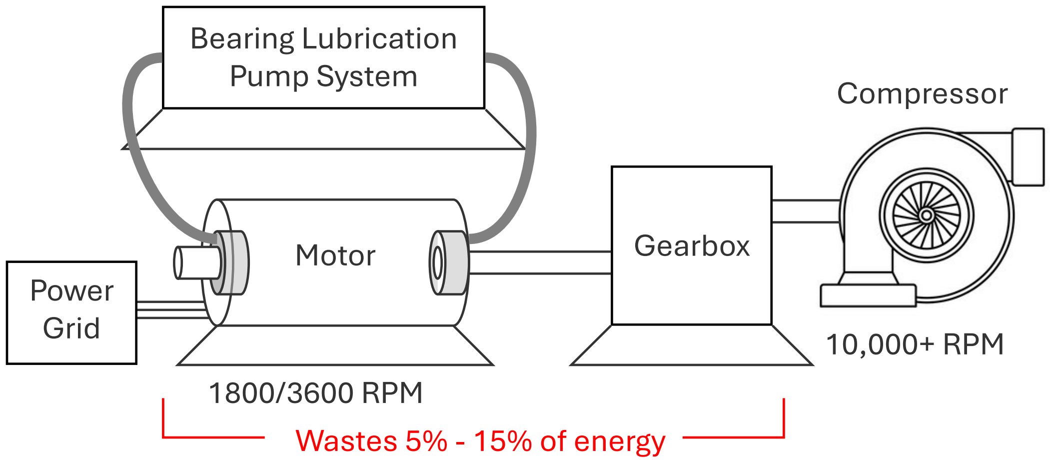


Overview

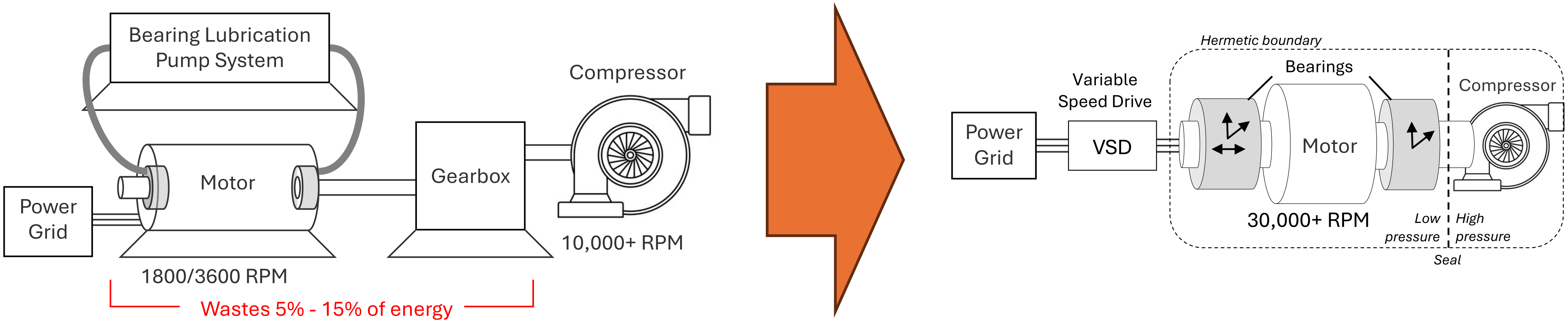
- Motivation for Hermetic Turbomachinery
- Commercial Bearing Solutions
- Existing Highspeed Motor Solutions
- Bearingless Motor Technology
- Proposed Motor/Bearing Solutions

Legacy Approach to Electrifying Turbomachinery

- Requires physically large components
  - Electric machine
  - Lubrication system
- Efficiency challenges
  - Induction motor
  - Bearings
  - Seals
  - Gearbox
- Can add variable speed drive
  - Leads to bearing failures!



Movement Toward Hermetic Turbomachinery



Potential benefits:

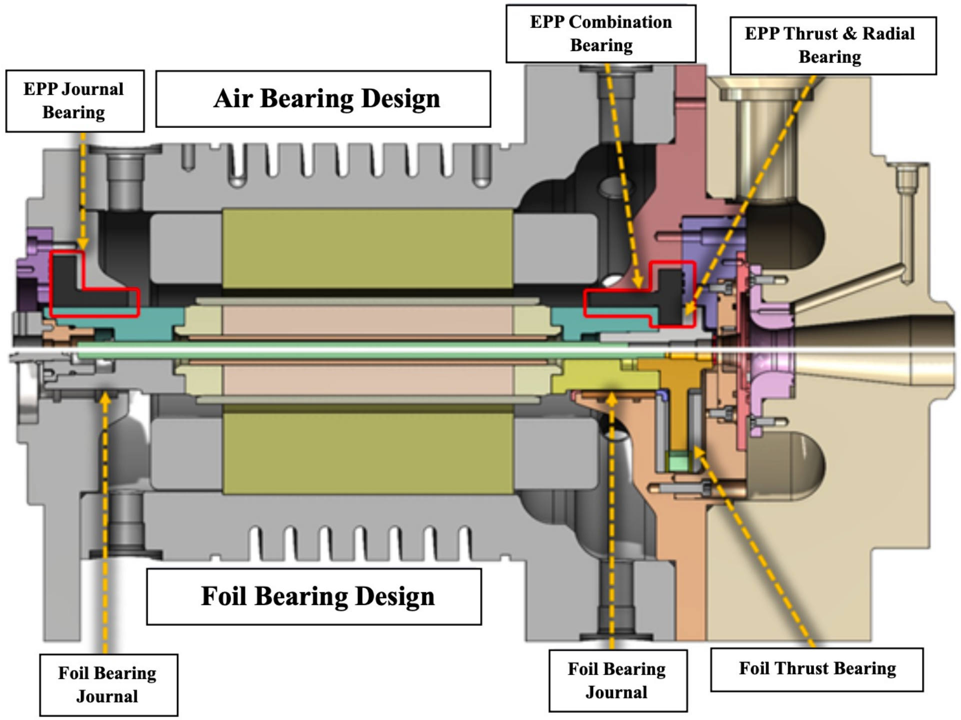
- Lower cost
- Longer lifetime
- Increased efficiency
- Higher power density

Challenges:

- Component compatibility with process fluid
- High speed drive electronics
- Rotor dynamics

Hermetic Turbomachinery in sCO_2

- Example SNL Turbo-Alternator-Compressor
- Low pressure & temp motor/bearing cavity
  - Scavenger pump to recover leakage
- Challenges for motor and bearings
  1. sCO2 incompatibility with oil lubrication
  2. Elevated pressure
     - Viscous losses on rotating surfaces, even in cavity
     - Extreme dynamic bearing loads
       - Oil-free bearings have lower specific load capacity
  3. High operating temperature
     - Permanent magnet demagnetization
     - Winding insulation limitations



Commercial Bearing* Solutions

*Oil-Free

Gas Foil Bearings

Shaft supported by air film induced by rotation

- Completely passive operation
  - No pass-throughs into cavity required
- Minimum speed required to lift-off
  - Wear during start/stop
  - Limits maximum shaft weight, or lifetime is reduced
    - Typically limits use up to a few hundred kW
- Reputation for low damping

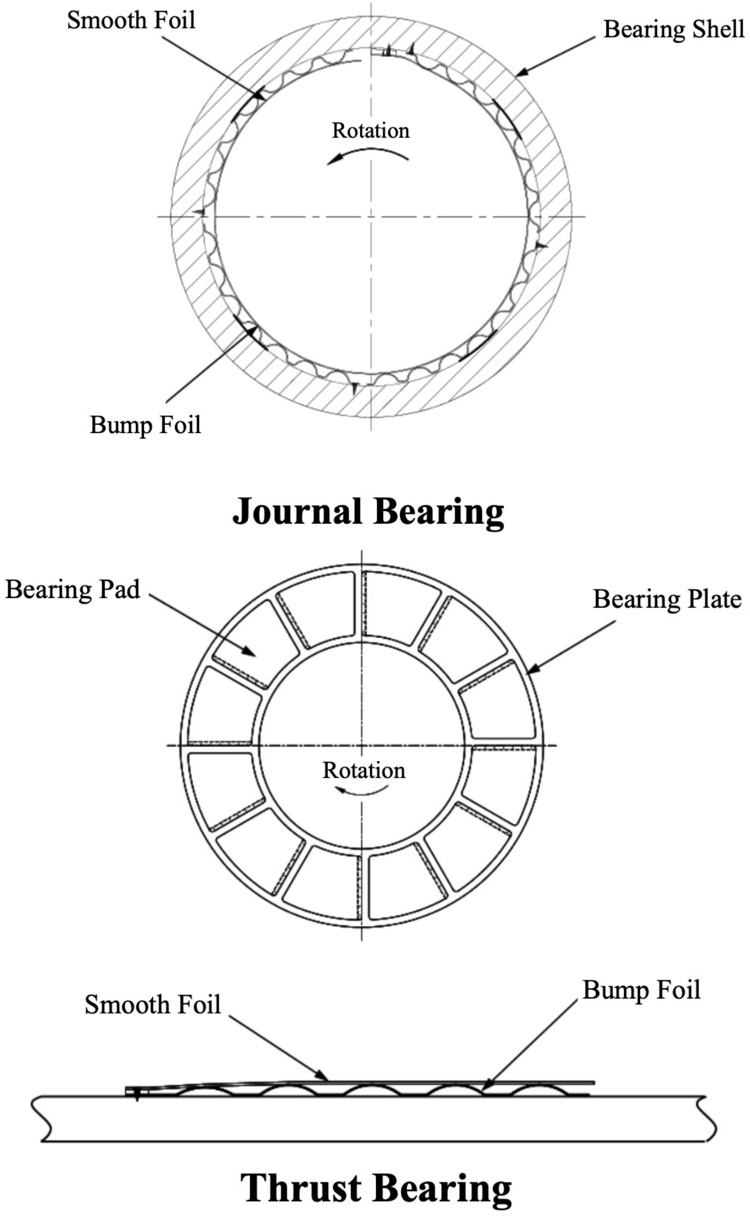
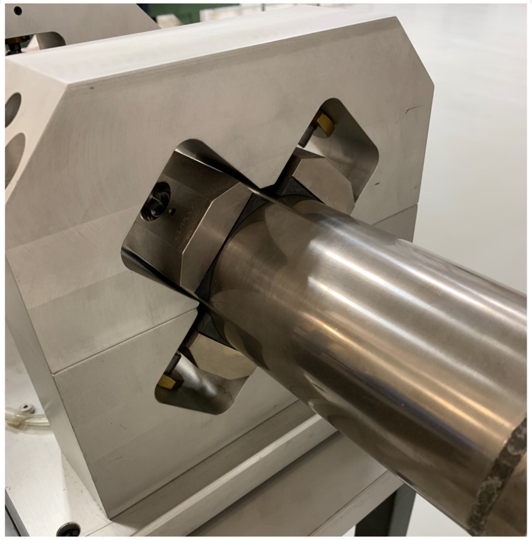


Image from M. Walker, D. Fleming, J. Pasch, “Gas foil bearing coating behvior in environments relevant to s-co2 power system turbomachinery,” SNL, 2018.

Externally Pressurized Porous Bearings

Shaft supported by air film from external source

- Very low friction, even at standstill
- Requires pressurized air supply
  - Passthroughs for hoses into cavity
  - Pressurized gas pump, or use high pressure fluid
- Can act as cavity seal
- Reputation for low damping
  - Recent research seeks to address this
  - I.e., compliant gas bearing in [17]



Images used with permission from D. Devitt, "Radial air bearings." https://www.newwayairbearings.com/catalog/radial-air-bearings

[17] B. Ertas, J. Powers, K. Gary, D. Torrey, J. Zierer, P. Baehmann, V. Rallabandi, T. Adcock, N. Anandika, and R. A. Bidkar, "Test rig concept for evaluating the performance of a co2 immersed electro-mechanical rotor system utilizing gas bearings: Part-1 mechanical and electric machine design," in Turbo Expo: Power for Land, Sea, and Air, ASME, 2023

Active Magnet Bearings

Shaft supported by electromagnetism

- Friction-free
- Employs active feedback control
  - Optimal rotor dynamics over wide range of operating conditions
  - Requires large number of sensors and passthroughs into cavity
- Requires large amount of shaft length
- Can be used for health monitoring

Comparison of Solutions

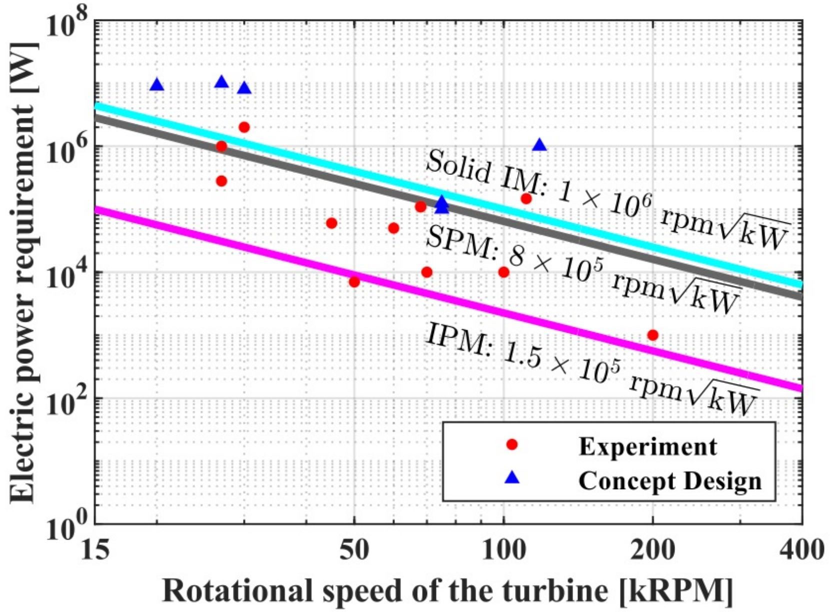
	Gas Foil	*EPP*	*Magnetic*
Max. Shaft Weight	Low	High	High
# of Passthrough	Low	Medium	High
Cost	Low	Medium	High
Complexity	Low	Low	High
Active / Passive	Passive	Passive	Active

Existing Motor* Solutions

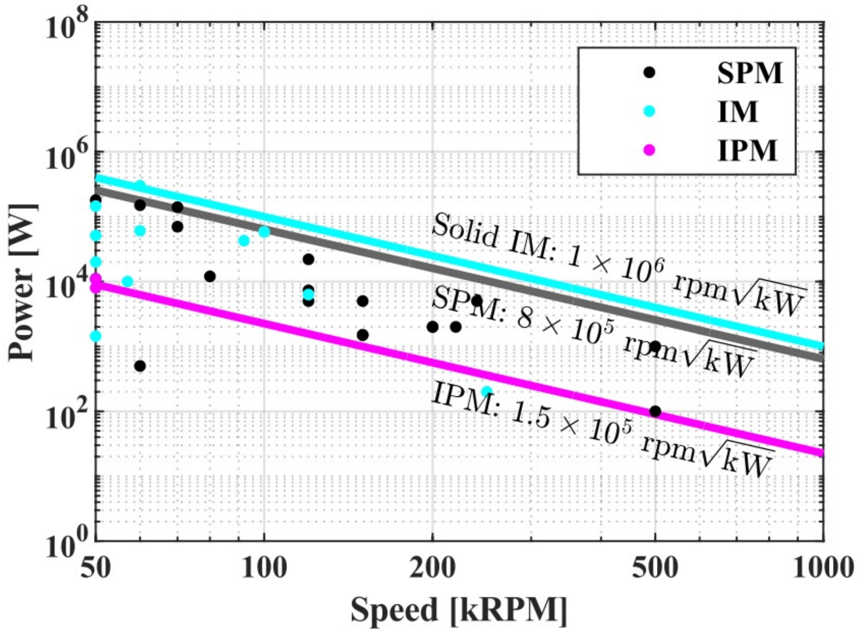
*High Speed

Motors

sCO2 turbomachinery designs [25-29]



- Motors above 3600 RPM are custom
- Two primary technologies:
  - Induction motors (especially solid rotor)
  - Surface permanent magnet
- Inherent speed-power mismatch for direct drive of sCO2 turbomachinery

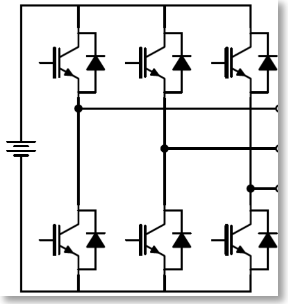


Example high speed motors [30]

Variable Speed Motor Drives

Difficult to find significant power + high speed

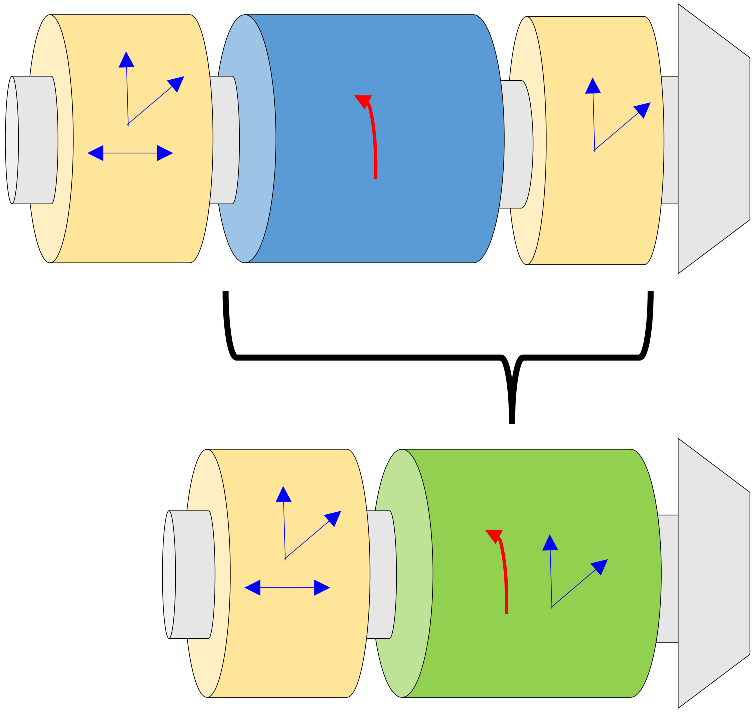
- Drives above 600 Hz are export controlled
  - 36,000 RPM for 2 pole motor
  - 18,000 RPM for 4 pole motor
- Even higher speeds require WBG devices
  - Expensive
  - Prone to electromagnetic interference
- Require specialized digital control
  - Default drive software configuration not capable of driving ultra-high speed loads



Bearingless Motor Technology

Bearingless Motor Technology

Use electromagnetism to actively control force and torque in one actuator



Maglev Motor
(2 AMB + 1 motor)

Bearingless Motor
(1 AMB + 1 motor)

Advantages

- 10x peak force capability
- Reduced axial length
- Fewer components

Challenges

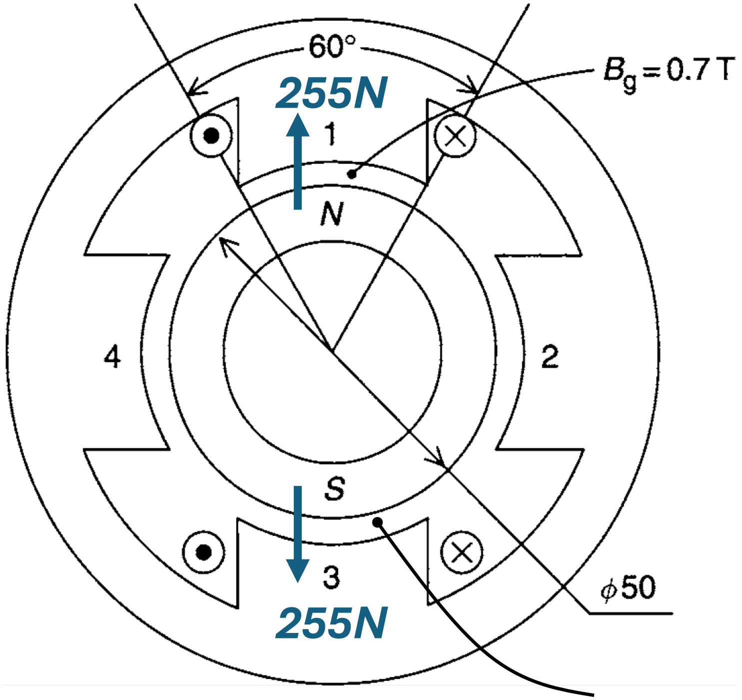
- Increased control complexity
- Design must be optimized as a motor and bearing
- Motors and bearings often siloed

Motor + AMB = Bearingless Motor

AMB: Active Magnetic Bearing

Illustrative Example from [1]

- Airgap diameter of 50mm and rotor length of 50mm
  - Assume average mass density of 7.65g/cm^3
- Force under tooth 1 and 3 calculated using MST
  - $T_{r,r} = \frac{B_r^2}{2\mu_0}$
  - $F_{t1,y} = -F_{t2,y} = \int T_{r,r} da$



[1] Chiba, Akira, Tadashi Fukao, Osamu Ichikawa, Masahide Oshima, Masatugu Takemoto, and David G. Dorrell. *Magnetic bearings and bearingless drives*. Elsevier, 2005.

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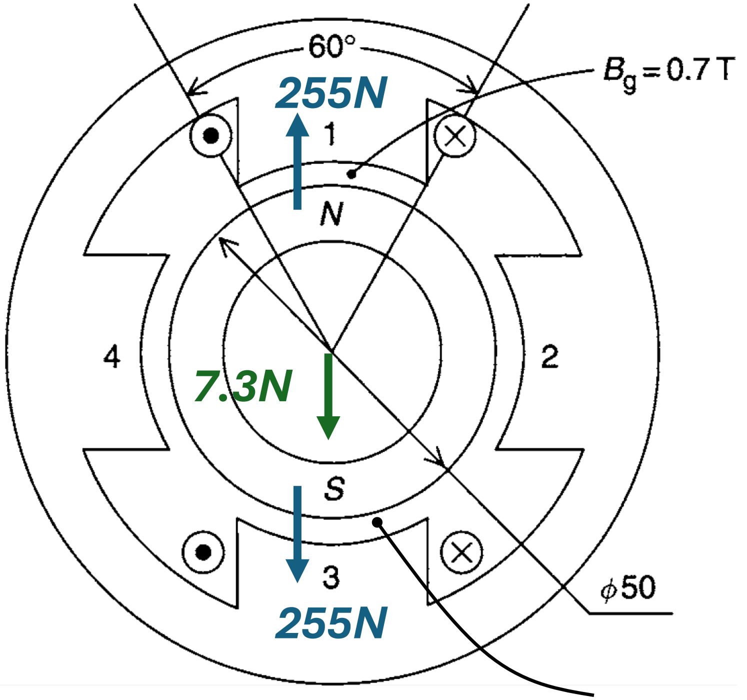
  - $F_{t1,y} = -F_{t2,y} = \int T_{r,r} da$
- Rotor weight: only 7.3 N
  - Each stator tooth experiences **35 times** the rotor weight!
  - Cancels out: no net force on rotor



[1] Chiba, Akira, Tadashi Fukao, Osamu Ichikawa, Masahide Oshima, Masatugu Takemoto, and David G. Dorrell. *Magnetic bearings and bearingless drives*. Elsevier, 2005.

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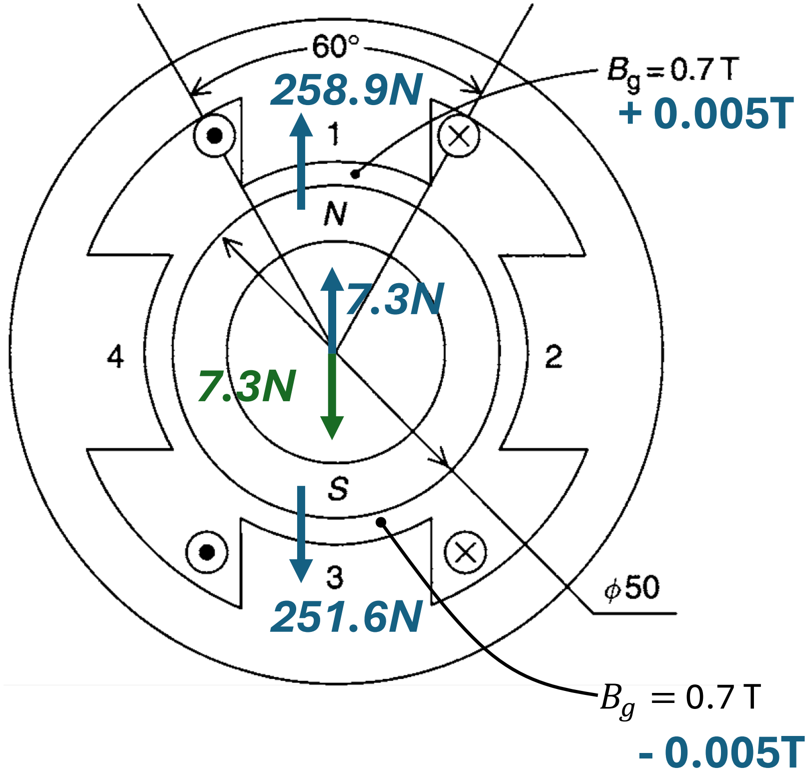
  - $F_{t1,y} = -F_{t2,y} = \int T_{r,r} da$
- Rotor weight: only 7.3 N
  - Each stator tooth experiences **<u>35 times</u>** the rotor weight!
  - Cancels out: no net force on rotor
- Disrupt the airgap field by adding/subtracting ΔB
  - Can support entire rotor weight with $\Delta B = 0.005$T!

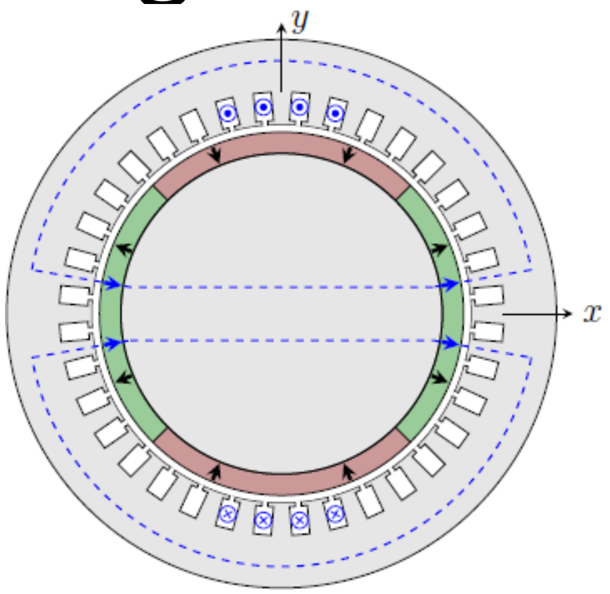


[1] Chiba, Akira, Tadashi Fukao, Osamu Ichikawa, Masahide Oshima, Masatugu Takemoto, and David G. Dorrell. *Magnetic bearings and bearingless drives*. Elsevier, 2005.

Basic Principles (1/3 radial bearingless motor)

$$f_x(\alpha) = \frac{B_r(\alpha)^2}{2\mu_0}\cos\alpha$$

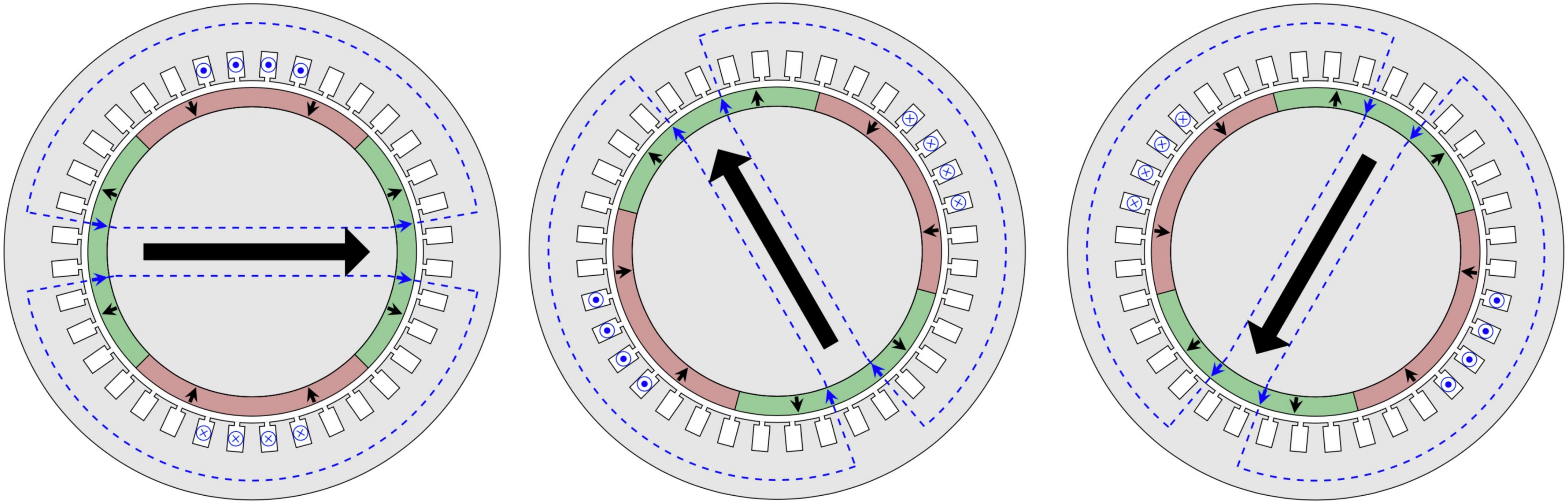
$$f_Y(\alpha) = \frac{B_r(\alpha)^2}{2\mu_0}\sin\alpha$$



- Disrupt the symmetry of motor's magnetic field
- Forces are created when $B(\alpha)$ has components which differ in the number of pole-pairs by 1

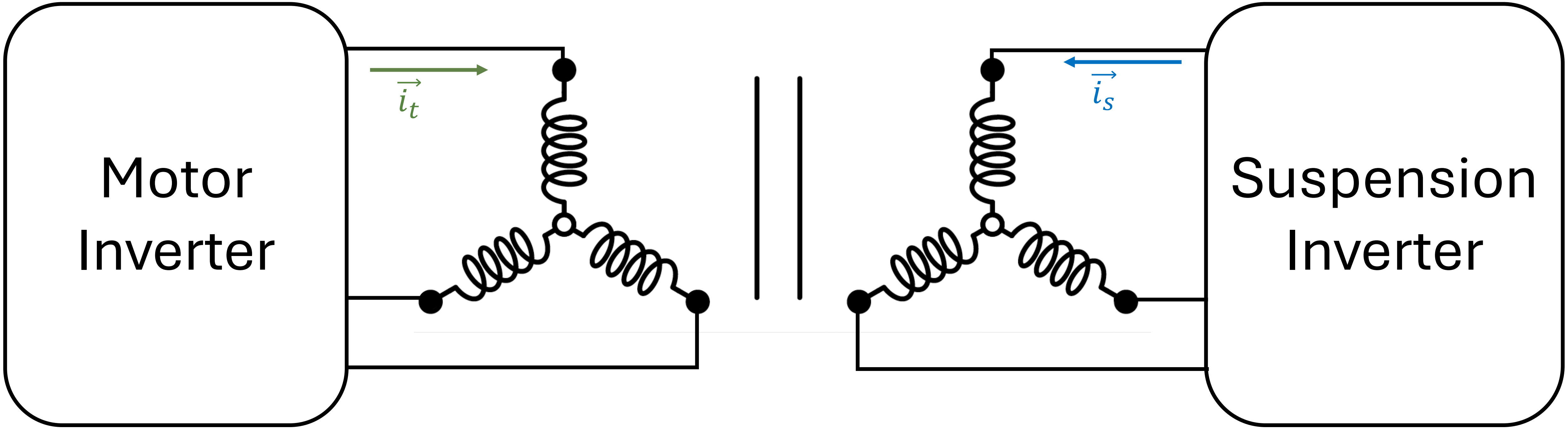
Basic Principles (2/3 force vector)

- Spatially displaced phases used to control force vector



Magnetizing field of the motor is used in place of the “bias” field in a magnetic bearing, eliminating most of the conduction losses found in magnetic bearings.

Basic Principles (3/3 drive operation)



Normal motor operation

Suspension Operation Based on Motor Type

- $\vec{F} = \overline{k_i}\vec{i_s} + k_\delta \vec{\delta}$
- $\angle \overline{k_i} = \begin{cases} -\theta, & p_s = p \pm 1 \\ 0, & p_s = 1 \end{cases}$

PM, Induction

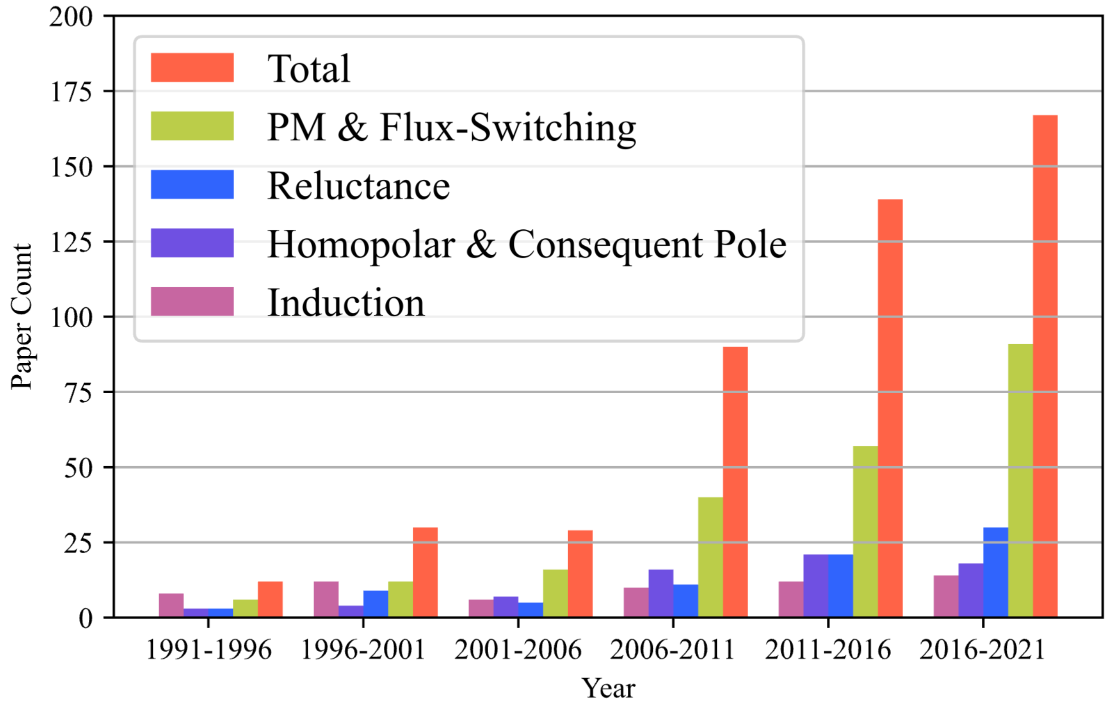
AC homopolar Consequent Pole

Similar to magnetic bearing force expression

This Technology is Rapidly Gaining Attention

- From review paper[1]
  - 467 papers reviewed
  - 1991 - 2021
- Growing research interest!

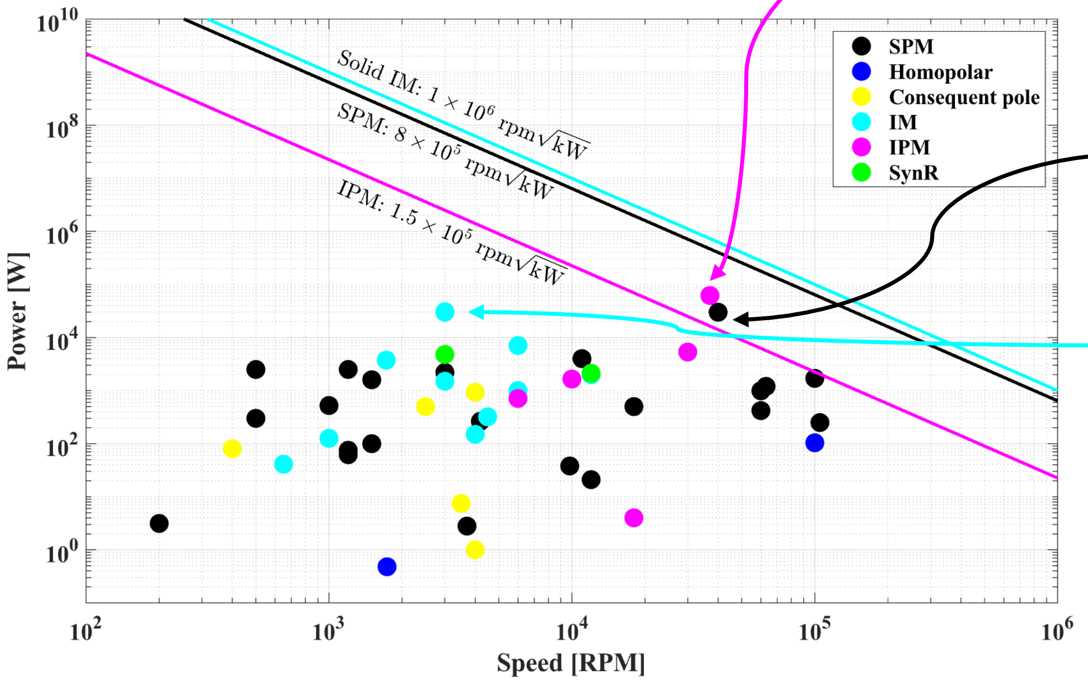
Bearingless Motor Publications with Experimental Results



[1] J. Chen, J. Zhu and E. L. Severson, "Review of Bearingless Motor Technology for Significant Power Applications," in *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1377-1388, March-April 2020,

Historically Focused on Low Power Applications

3 Bearingless Motors ≥ 30 kW[1]



2020 Tokyo Tech

- 61.9 kW, 37,000 r/min, 94.9% efficiency
- Buried PM machine
- Z. Liu, A. Chiba, Y. Irino and Y. Nakazawa, "Optimum Pole Number Combination of a Buried Permanent Magnet Bearingless Motor and Test Results at an Output of 60 kW With a Speed of 37000 r/min," in *IEEE Open Journal of Industry Applications*, vol. 1, pp. 33-41, 2020,

2011 Darmstadt

- 40 kW, 40,000 r/min, 92.7% efficiency
- Surface PM machine
- G. Munteanu, A. Binder and T. Schneider, "Loss measurement of a 40 kW high-speed bearingless PM synchronous motor," *2011 IEEE Energy Conversion Congress and Exposition*, 2011, pp. 722-729

2000 ETH/Sulzer

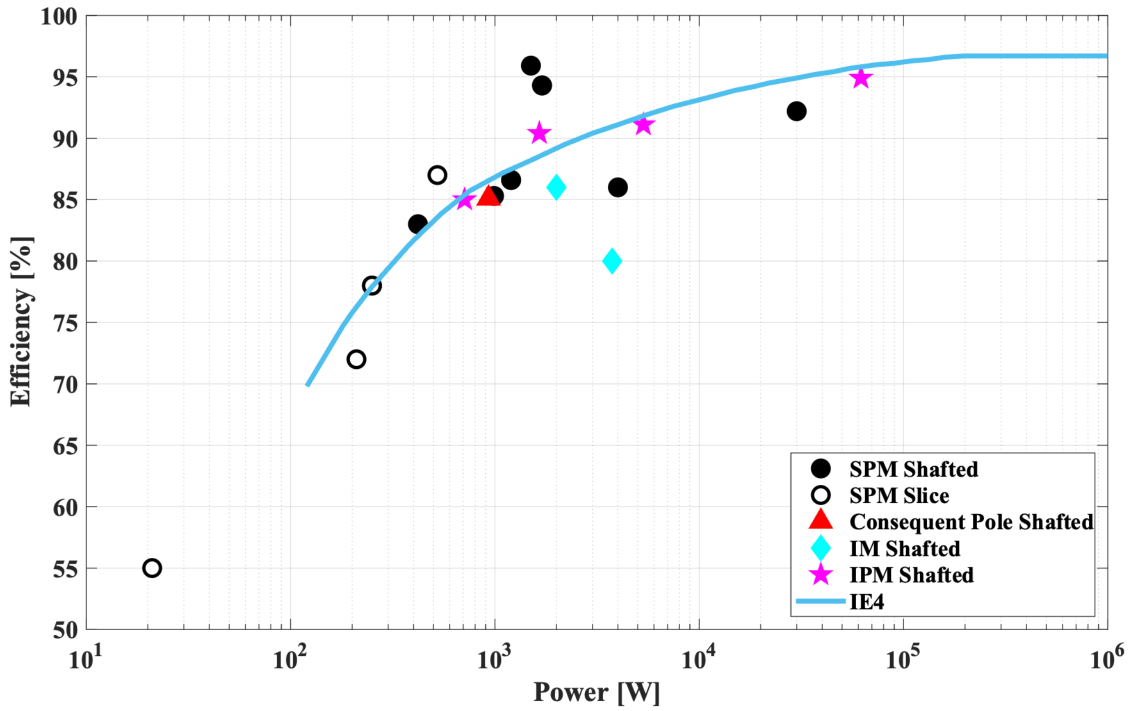
- 30 kW, 3,000 r/min
- Induction Machine
- C. Redemann, P. Meuter, A. Ramella, and T. Gempp, "30kw Bearingless Canned Motor Pump oin the Test Bed," *Seventh International Symposium on Magnetic Bearings (ISMB)*, 2000, pp. 189-194

[1] J Chen, J Zhu, E. Severson, "Review of Bearingless Motor Technology for Significant Power Applications," *IEEE Trans on Ind. App., 2020*

Efficiency

- Higher power prototypes have relatively low efficiency
- <u>**We can do better!**</u>

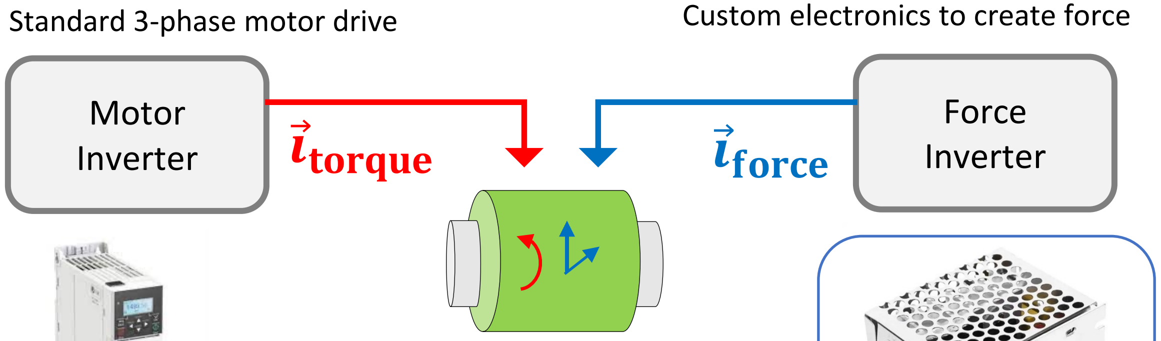
Bearingless Motor Publications with Experimental Results



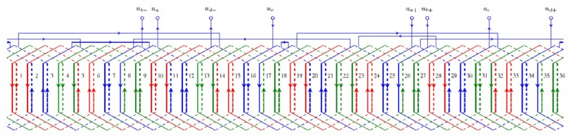
[1] J. Chen, J. Zhu and E. L. Severson, "Review of Bearingless Motor Technology for Significant Power Applications," in *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1377-1388, March-April 2020,

Recent Research for Significant Power

- Design innovations reach parity with highest performance motors
  - Combined stator windings
  - Innovative rotor design
  - Design optimization
  - Advanced controls

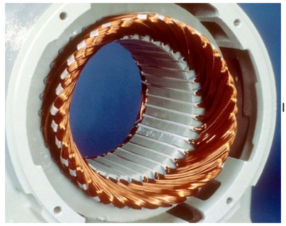


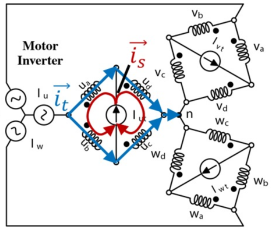
Source: ABB.com



Decoupled torque/force: Motor drive does not need to know machine is bearingless

Specialized stator winding configuration required in otherwise conventional motor





Design Studies for Turbomachinery

Bearingless PM Machine Design Space

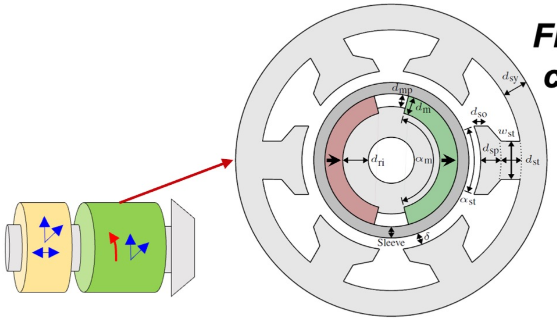
Machine Spec and Model

- Rating: 50 kW, 30,000 r/min
- Surface-mounted PM rotor
- Carbon fiber retaining sleeve
- DPNV Stator, 5% coil current for sus.
- 2D FEA + viscous windage loss + structural

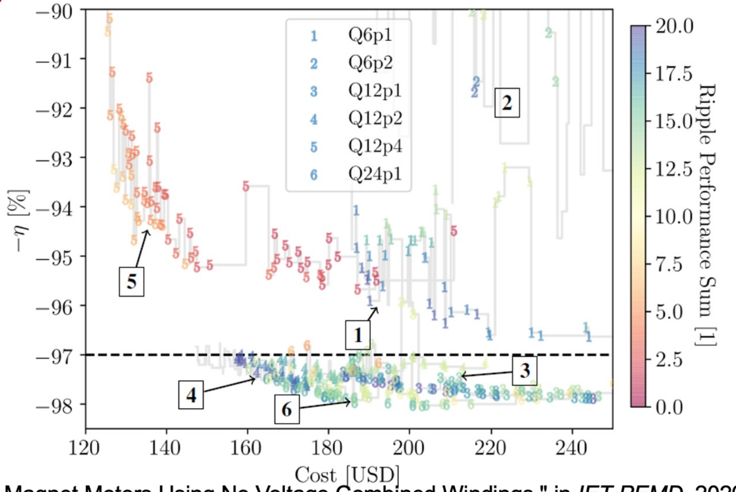
Design space is promising

- > 97% Efficiency

Design #	Stator Slots	Motor Poles	Sus. Poles
1	6	2	4
2	6	4	2
3	12	2	4
4	12	4	2
5	12	8	10
6	24	2	4



Fractional-slot concentrated windings



[1] J. Chen, A. Farhan, M. W. Johnson, and E. L. Severson, “Design of Bearingless Permanent Magnet Motors Using No Voltage Combined Windings," in *IET PEMD*, 2020

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Design Studies for Turbomachinery

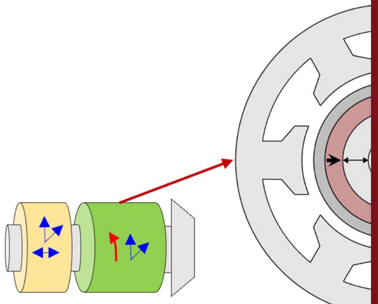
Bearingless

Machine Spec a

- Rating: 50 kW, 30
- Surface-mounted
- Carbon fiber retai
- DPNV Stator, 5%
- 2D FEA + viscous

Design space is

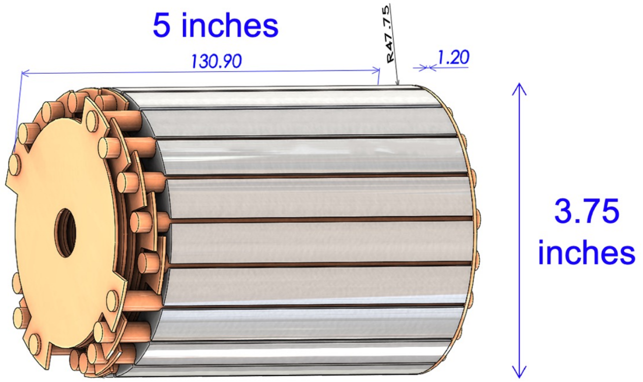
- > 97% Efficie

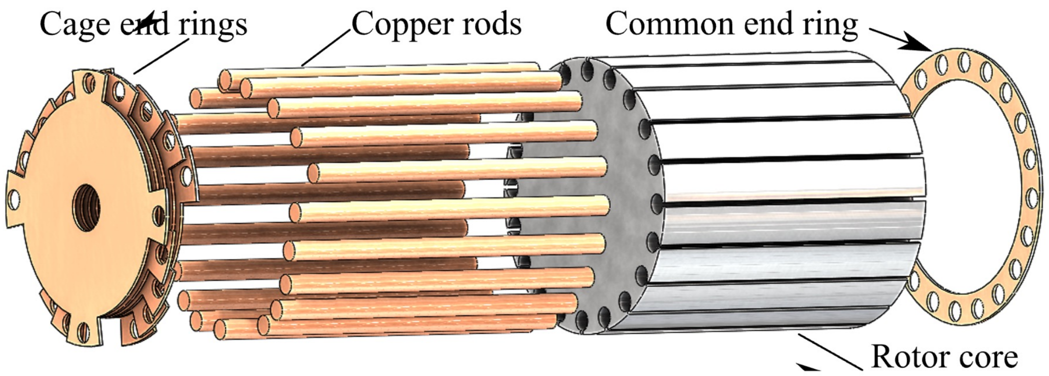


[1] J. Chen, A. Farhan, M. W. Johnson

Example Design

- Machine specs
  - 6 pole motor, 8 pole suspension
  - 50 kW, 30,000 RPM
- Axial length
  - <u>Only 15% length increase of SC rotor</u>
- Modeled performance
  - 96.8% efficiency
  - TRV $\approx 20\,\frac{\text{kNm}}{\text{m}^3}$





J. Chen, M. Johnson, A. Farhan, Y. Fujii, and E. Severson, "Reduced Axial Length Pole-Specific Rotor for Bearingless Induction Machines," *IEEE Trans on Energy Conv.*, Dec. 2022

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Our Prototype Testing (In Progress)

Bearingless PM Machines

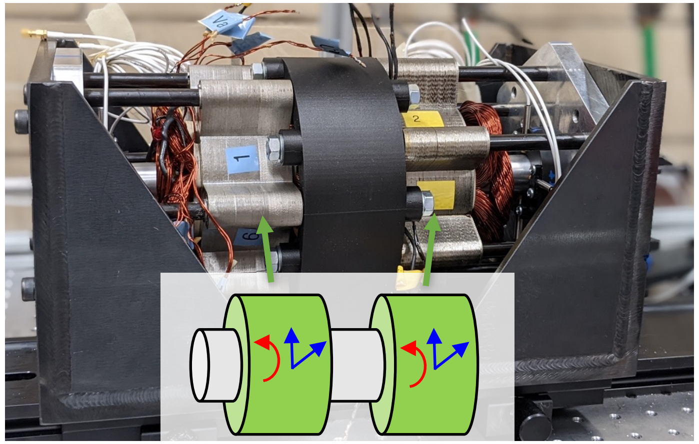
1. 1 kW, 30,000 r/min Motor
2. 10 kW, 160,000 r/min Motor
3. 3.4 kW, 35,000 r/min “Twin” Motor
4. 50 kW, 80,000 r/min Generator

Bearingless Induction Machines

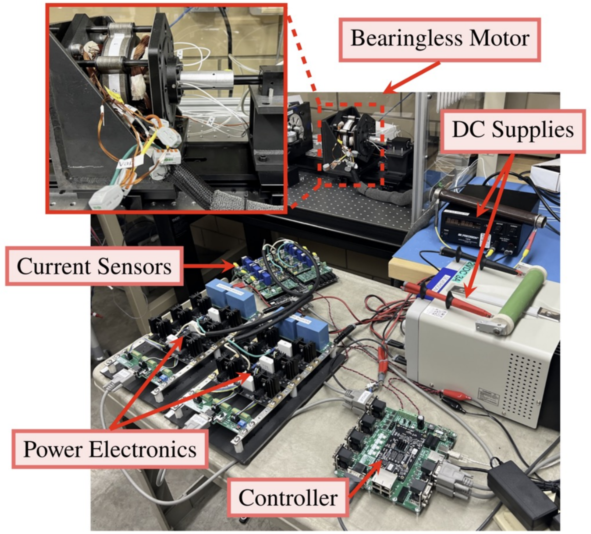
5. 3.6 kW, 30,000 r/min Motor
6. 4.7 kW, 30,000 r/min Motor

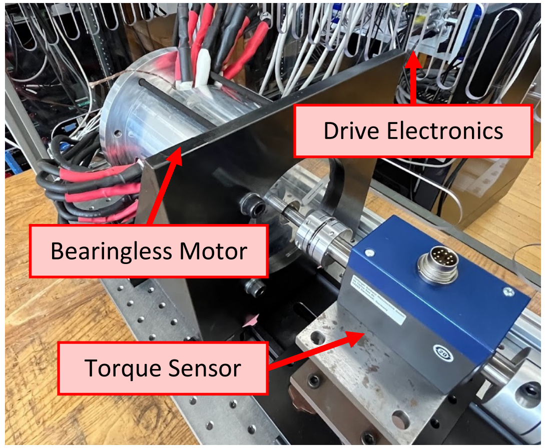
AC Homopolar Machines

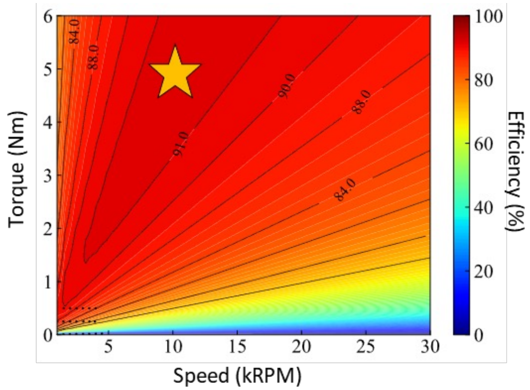
7. 1 kW, 3,600 r/min Motor
8. 6 kW, 10,000 r/min Motor/Generator



Bearingless motor 1   Bearingless motor 2

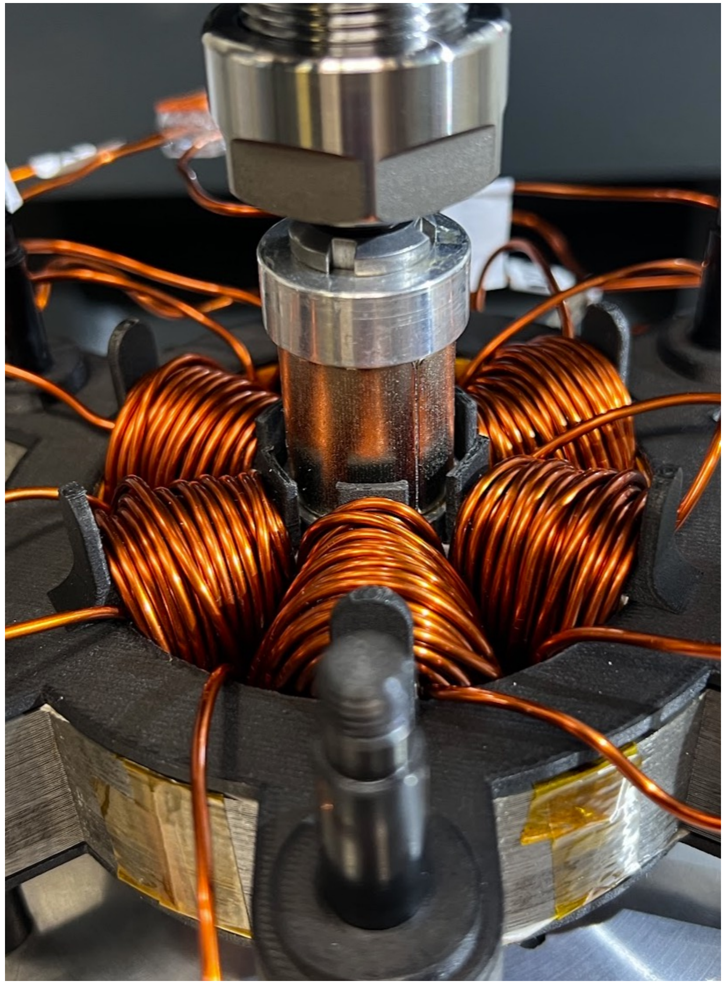






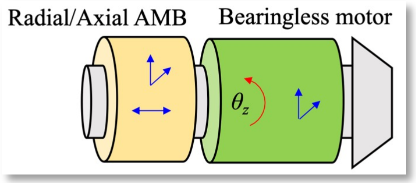
Making Radial Forces in Motors

- The technology is figured out
- Requires
  - Multiphase stator winding
  - Standard 3 phase drive for motor/generator
  - Additional inverter for forces (1-2 orders of magnitude smaller)
  - [Sometimes] Shaft proximity probes
- Larger scale demonstrations needed

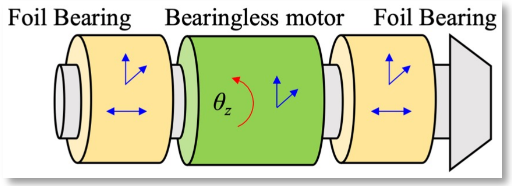


Proposed Solutions for sCO2

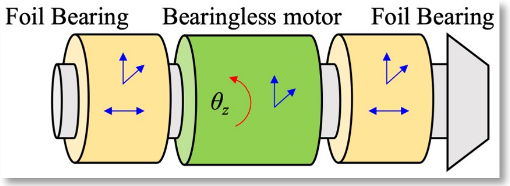
Two Fundamental Approaches

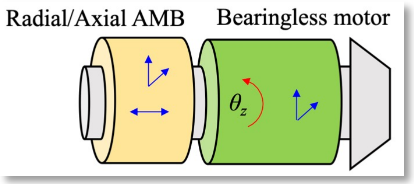


1. Replace one or more bearings
2. Supplement or enhance bearings
   - Static unloading
     - No additional sensors needed
     - No passthroughs into motor cavity needed
   - Dynamic unloading
     - Peak transient forces usually occur with surge when low torque is needed
     - Bearingless motor can be dynamically transformed into magnetic bearing to help



Potential for Improvements





	Conventional Motor			Bearingless Motor	
	Gas Foil	***EPP***	***Magnetic***	***Gas Foil***	***Magnetic***
Max. Shaft Weight	Low	High	High	High	High
# of Passthrough	Low	Medium	High	Low	Medium
Cost	Low	Medium	High	Low	Medium
Complexity	Low	Low	High	Medium	High
Active / Passive	Passive	Passive	Active	Passive	Active

Looking Further Out

- Thrust loading is particularly challenging in sCO2 turbomachinery
- Future electric motor will control axial forces as well as radial
- Emerging research in this space
    - Radial flux machine
        - Field weakening control + reluctance features
    - Axial flux machines
    - Passive coil

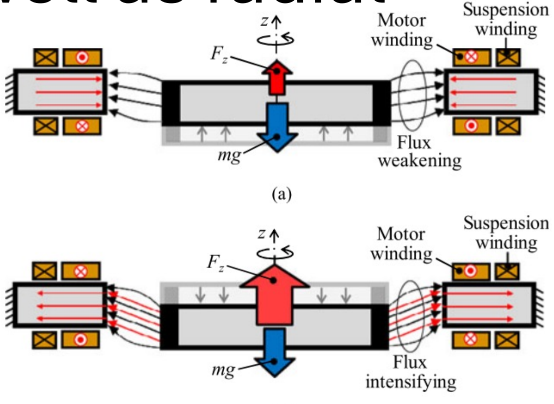


Image from H. Sugimoto, M. Miyoshi and A. Chiba, "Axial Vibration Suppression by Field Flux Regulation in Two-Axis Actively Positioned Permanent Magnet Bearingless Motors With Axial Position Estimation," in *IEEE Trans on Ind App*, vol. 54, no. 2, pp. 1264-1272, March-April 2018

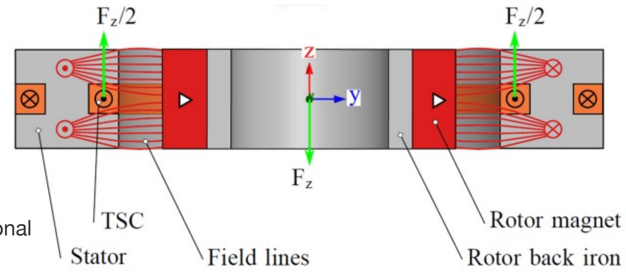


Image from H. Mitterhofer, G. Jungmayr, W. Amrhein and K. Davey, "Coaxial Tilt Damping Coil With Additional Active Actuation Capabilities," in *IEEE Trans on Ind App*, vol. 54, no. 6, pp. 5879-5887, Nov.-Dec. 2018

Conclusion

- Motor, drive, & bearings for hermetic sCO2 turbomachinery
  - Inherently custom, complex
- There is substantial potential for performance gains by using motor that can create radial forces
  - Bearing assist
  - Bearing replacement
- Bearingless motor research is rapidly maturing
  - Ready for at-scale demonstration