18th International Symposium on Magnetic Bearings

18 – 21 July 2023 Lyon France

Bearingless motors: the future of magnetically levitated motor systems?

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Introduction

Presenter

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fractional horsepower systems

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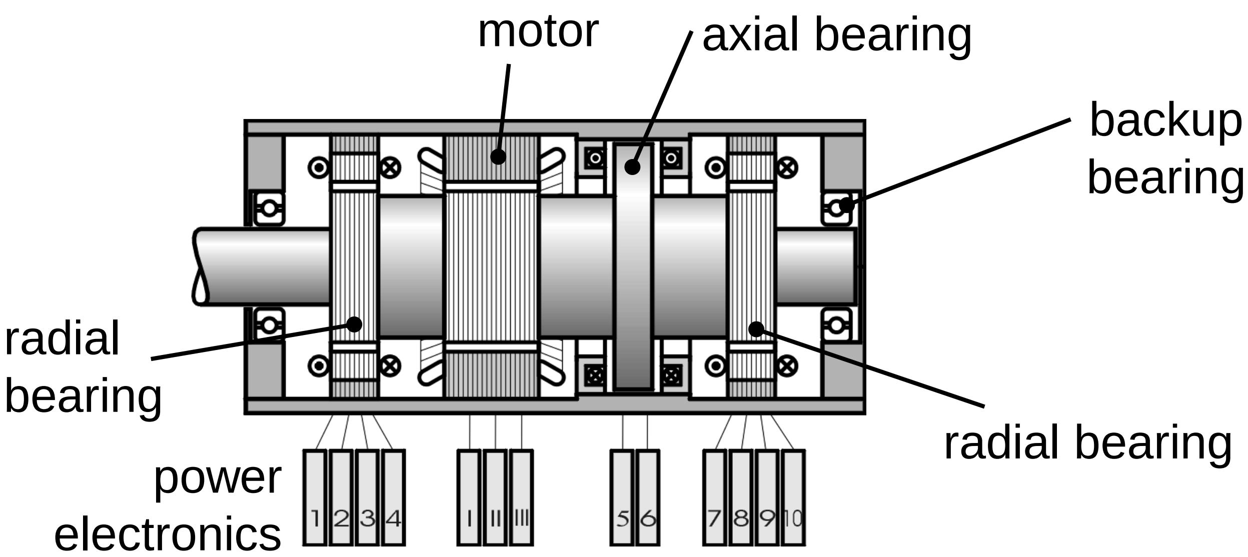
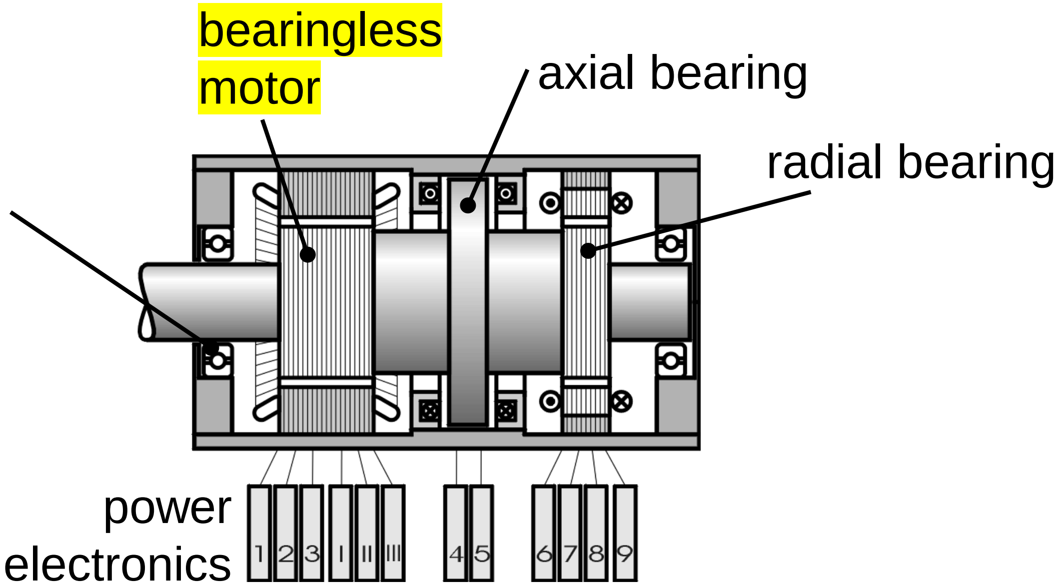
University of Wisconsin – Madison, USA
severson@ieee.org

integral horsepower systems

Outline

Bearingless motors:





Magnetically suspended drive

- drive and suspension is decoupled
- separated design of drive and suspension is possible
- typically larger and higher electric and mechanical demand

Bearingless motor

- very cost-effective setup for smaller systems
- drive and suspension are often on a common lamination stack
- more complex control structure

Outline

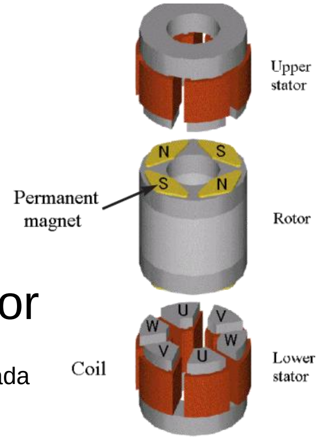
Bearingless motors:

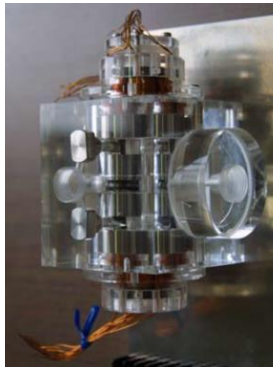
Torque and **radial** forces (often used)

Torque and **axial** forces (seldom)

Axial Self-Bearing Motor

Ibaraki Univ. Y. Okada





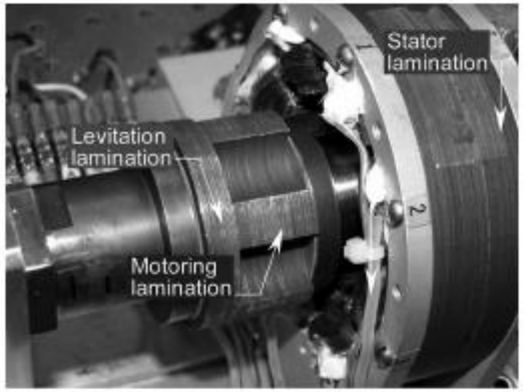
Bearingless Induction Machines

TIT, A. Chiba

PMSM

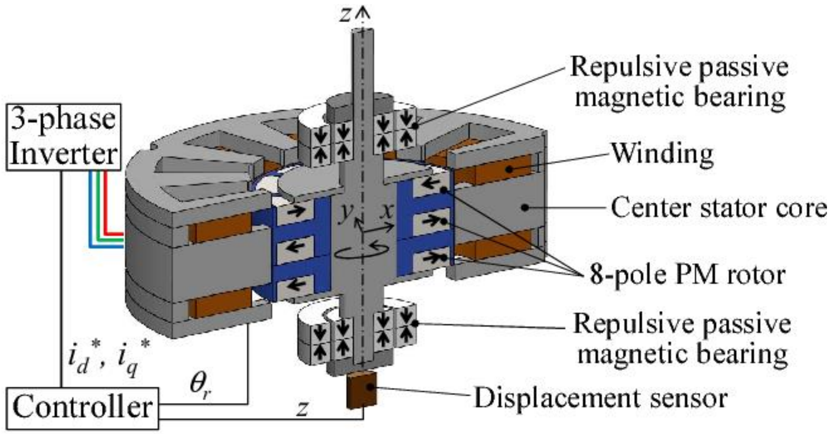
TU Darmstadt, A. Binder

Magnetic Bearing SR-Motor



NASA, C. R. Morrison

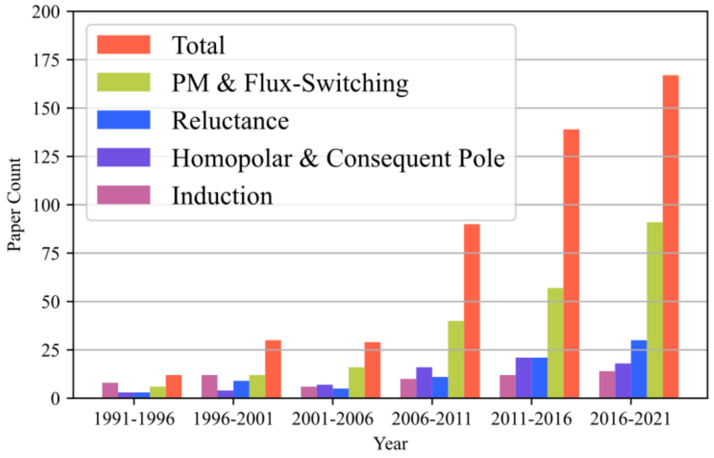
Single-Drive Bearingless Motor

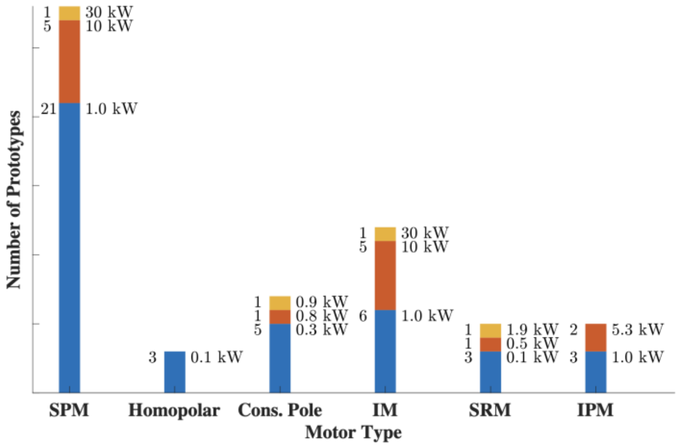


TDU, H. Sugimoto

Outline

Bearingless motor research is increasing significantly!





J. Chen, J. Zhu and E. L. Severson, "Review of Bearingless Motor Technology for Significant Power Applications," in *IEEE Transactions on Industry Applications*, March-April 2020

Industrial applications
(still a small market)

LEVITRONIX®

BPS-1

HeartMate 3

BFS-i10

SKF

Amber Kinetics

Outline

Academic research focus to develop bearingless motors for the broader market at JKU and WEMPEC:

- Reducing drive cost

- Improving performance

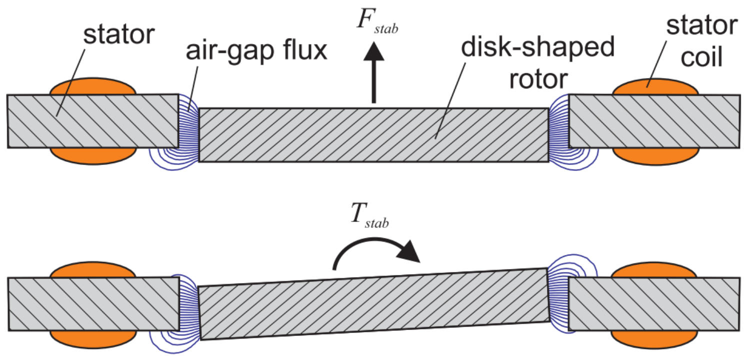
- Exploiting high speeds

Reducing drive cost

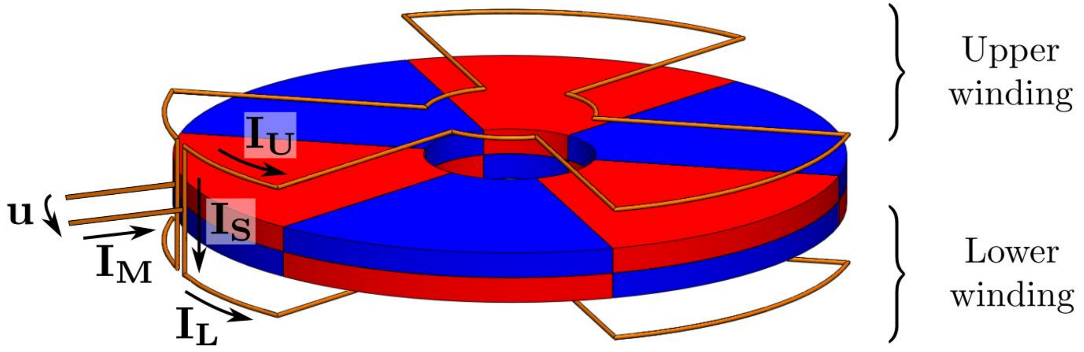
Reducing drive cost

Passive stabilization:

Slice motor concept

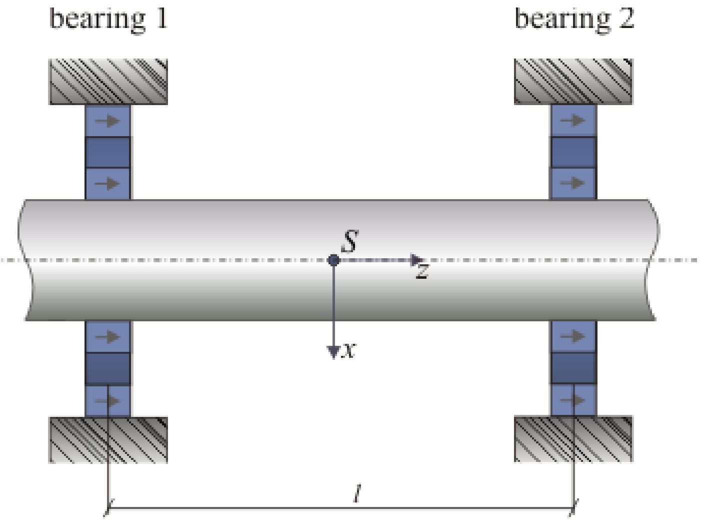


Electrodynamic bearings



UDL, J. Van Verdeghem

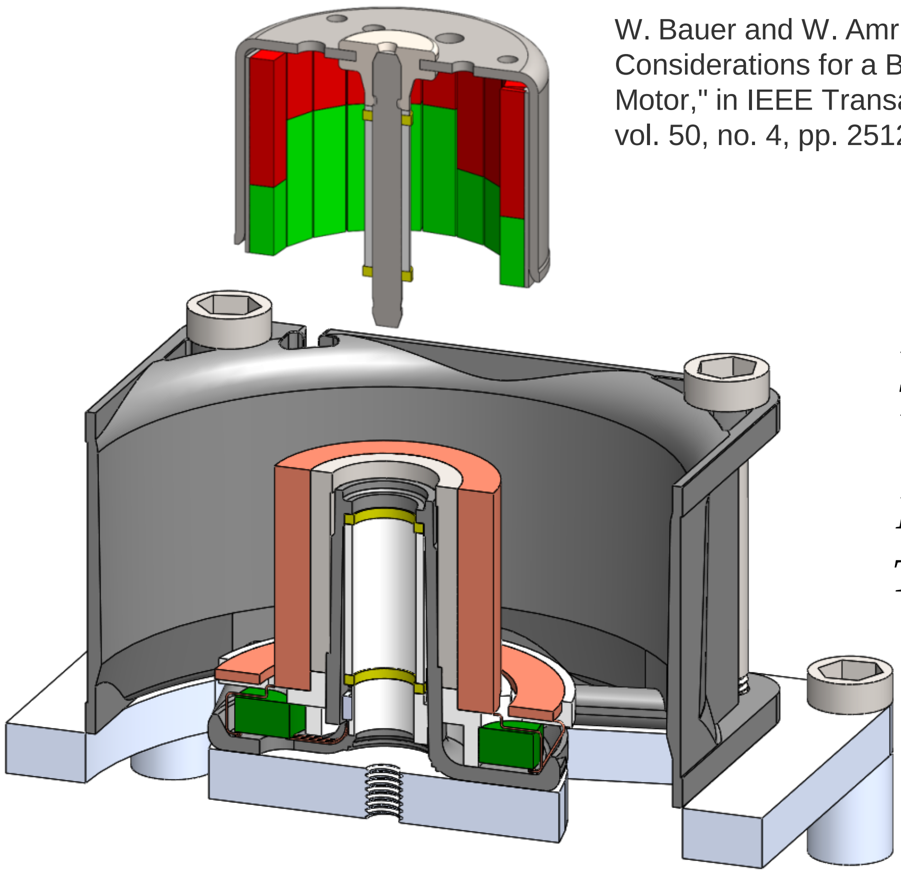
Permanent magnetic bearings



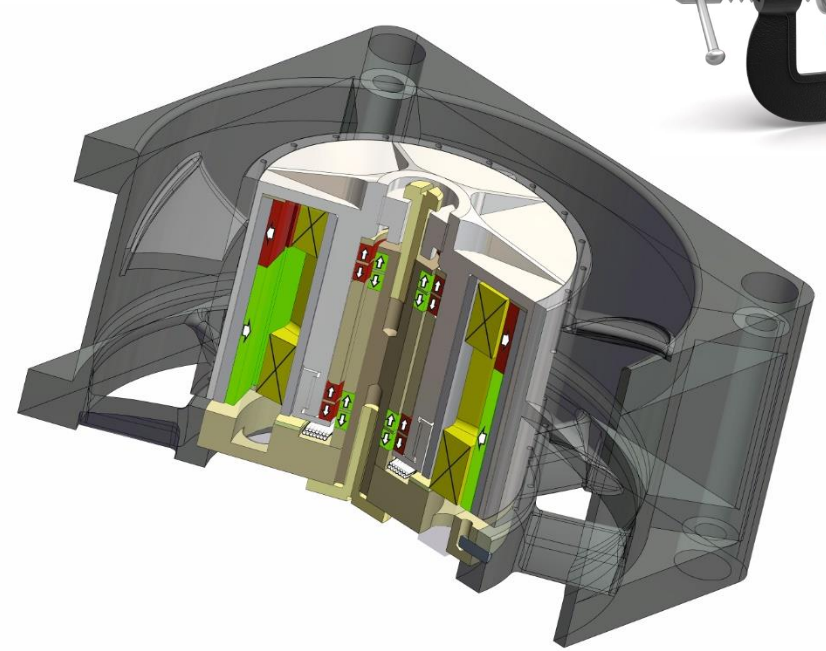
radial suspension of a shaft

Reducing drive cost

Bearingless axial-force motor as fan application:

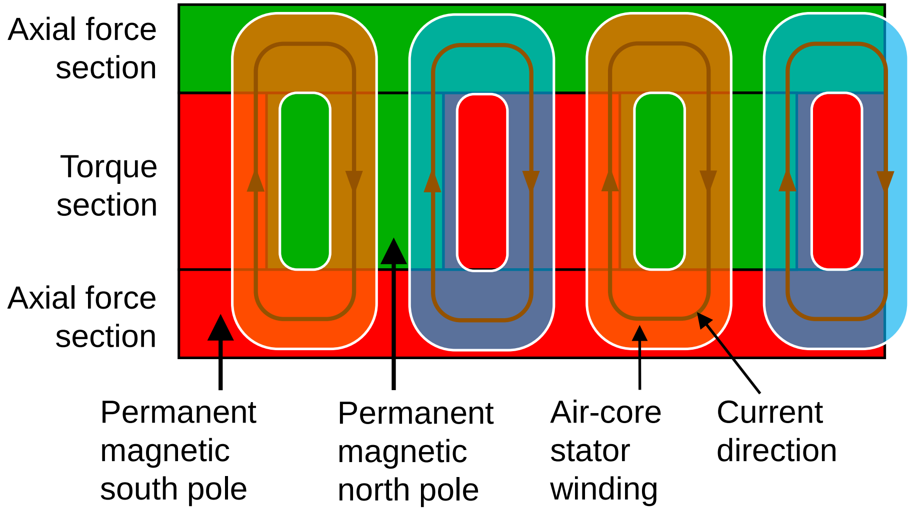


W. Bauer and W. Amrhein, "Electrical Design Considerations for a Bearingless Axial-Force/Torque Motor," in IEEE Transactions on Industry Applications, vol. 50, no. 4, pp. 2512-2522, July-Aug. 2014



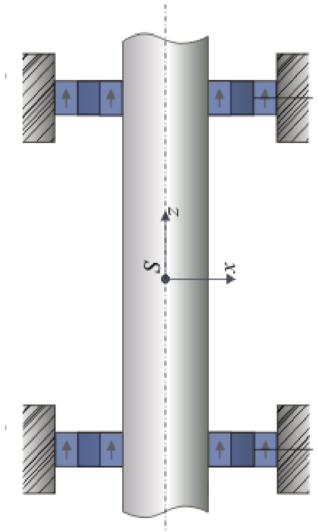
$$F_{z,phase1} = k_z \cdot i_1$$
$$T_{z,phase1}(\varphi_r) = k_t \cdot \sin(\varphi_r) \cdot i_1$$

$$F_{z,phase2} = k_z \cdot i_2$$
$$T_{z,phase1}(\varphi_r) = -k_t \cdot \sin(\varphi_r) \cdot i_2$$

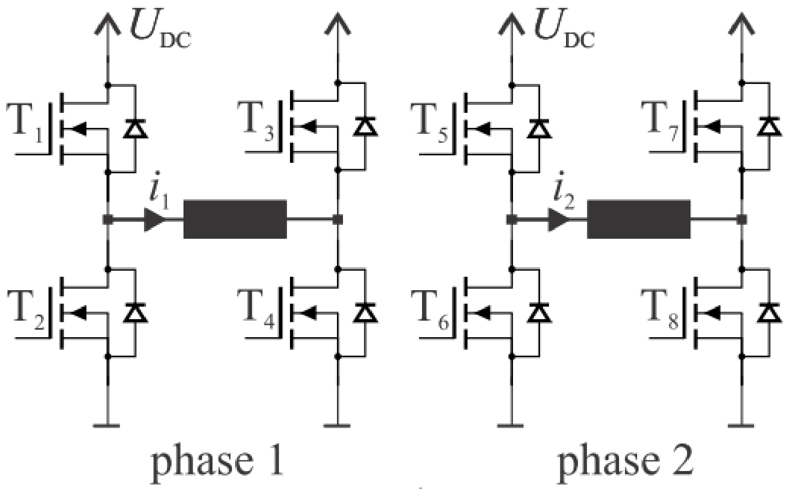


$i_1=i_2$ leads to force generation only
$i_1=-i_2$ leads to torque generation only

Reducing drive cost



Power electronics used:



- **Force Generation:**

  Split capacitor voltage drifts

  $i_1+i_2>0$: potential increases
  $i_1+i_2<0$: potential decreases

- **Torque Generation:**

  Split capacitor voltage unaffected

  $i_1+i_2=0$: potential unchanged

$i_1=i_2$ leads to force generation only
$i_1=-i_2$ leads to torque generation only

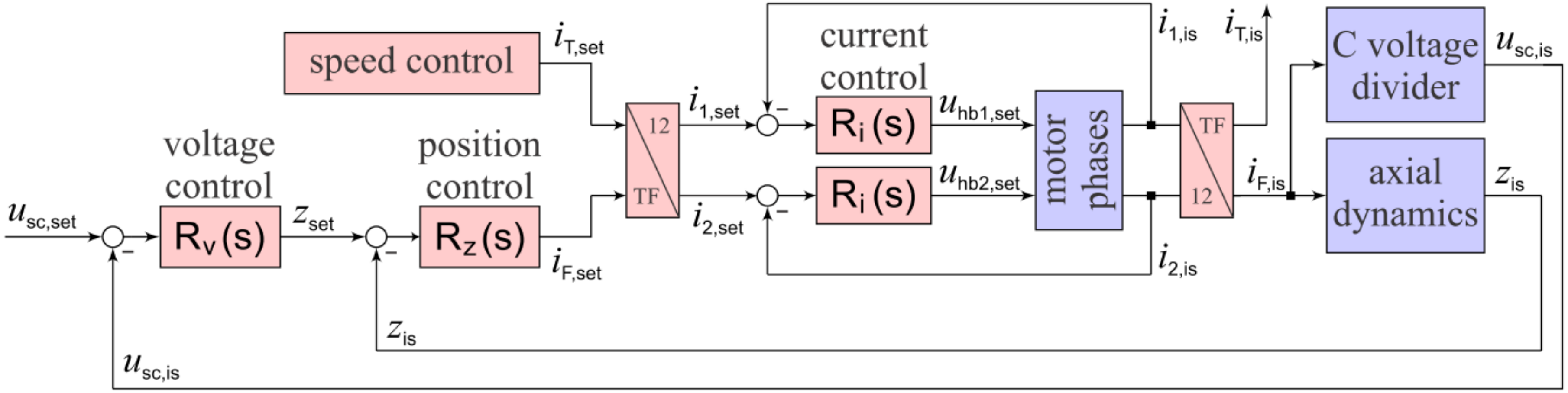
W. Gruber, S. Hell, "Bearingless Axial-Force/Torque Motor with Reduced Number of Power Switches," International Electric Machines & Drives Conference (IEMDC) 2023

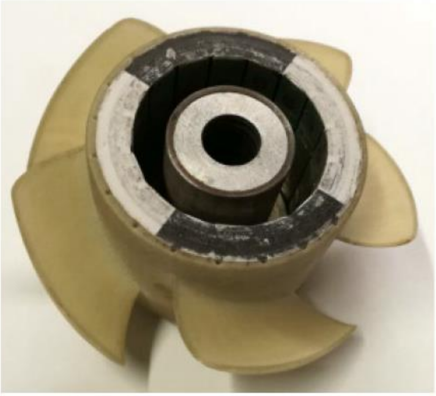
Force equilibrium z_{opt}

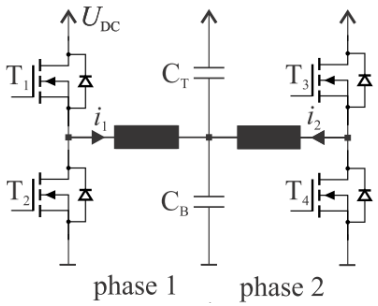
- $z=z_{opt}$
  - $f_{mag}=m_R g \rightarrow f_i=0 \rightarrow i_F=0$
  - Split capacitor voltage unchanged
- $z<z_{opt}$
  - $f_{mag}<m_R g \rightarrow f_i > 0 \rightarrow i_F>0$
  - Split capacitor voltage increases
- $z>z_{opt}$
  - $f_{mag}>m_R g \rightarrow f_i<0 \rightarrow i_F<0$
  - Split capacitor voltage decreases

Reducing drive

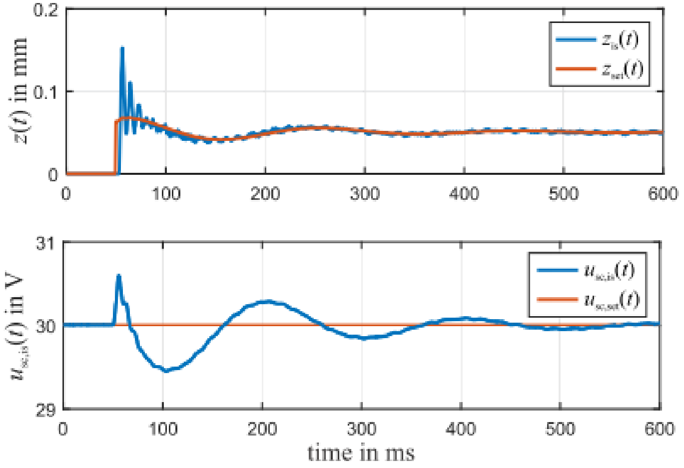
Bearingless axial-force motor as fan application:







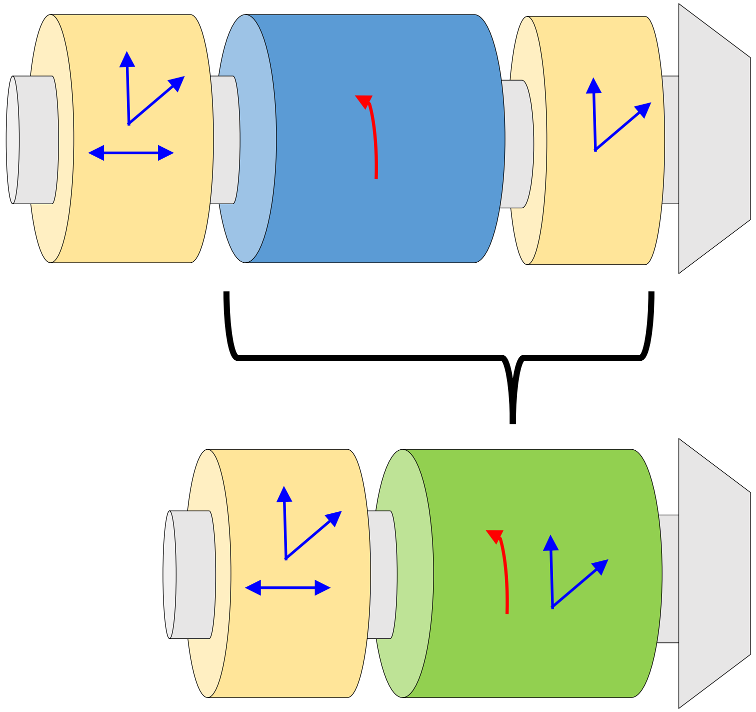
680µF spit capacitor



First bearingless motor operating with only two half bridges!

Integral Horsepower Bearingless Motor Topolog

Use electromagnetism to actively control force and torque in one actuator



Maglev Motor
(2 AMB + 1 motor)

Bearingless Motor
(1 AMB + 1 motor)

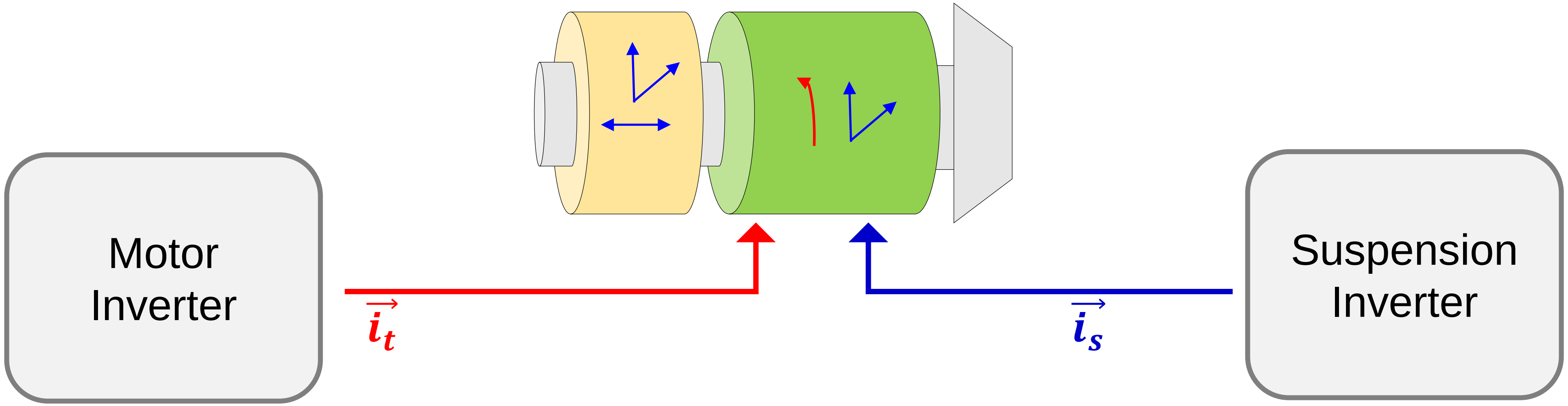
Gains
- >10x peak force capability
- Reduced axial length
- Fewer components

Challenges
- Increased control complexity
- Design must be optimized as a motor and bearing
- Motors and bearings often siloed or separate business units

Motor + AMB = Integral Horsepower Bearingless Motor

AMB: Active Magnetic Bearing

How it works



Standard motor operation

- Can use standard motor drive

  (does not need to know motor is levitated)

Low power suspension inverter

- <1% power rating of motor
- Motor magnetizing field is the bias field

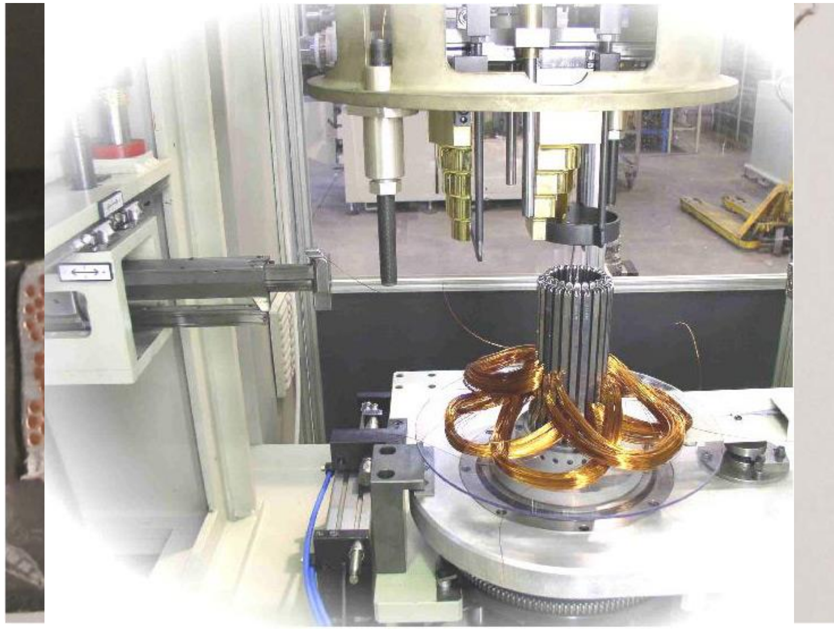
  (*replaces AMB bias current*)

$$\vec{F} = \overline{k_i}\,\overrightarrow{i_s} + k_\delta \vec{\delta}$$

Legacy approach: separate windings

- Reduce torque/power
  - by 25% – 40%
- Decrease efficiency
  - Longer flux paths
  - More conduction loss

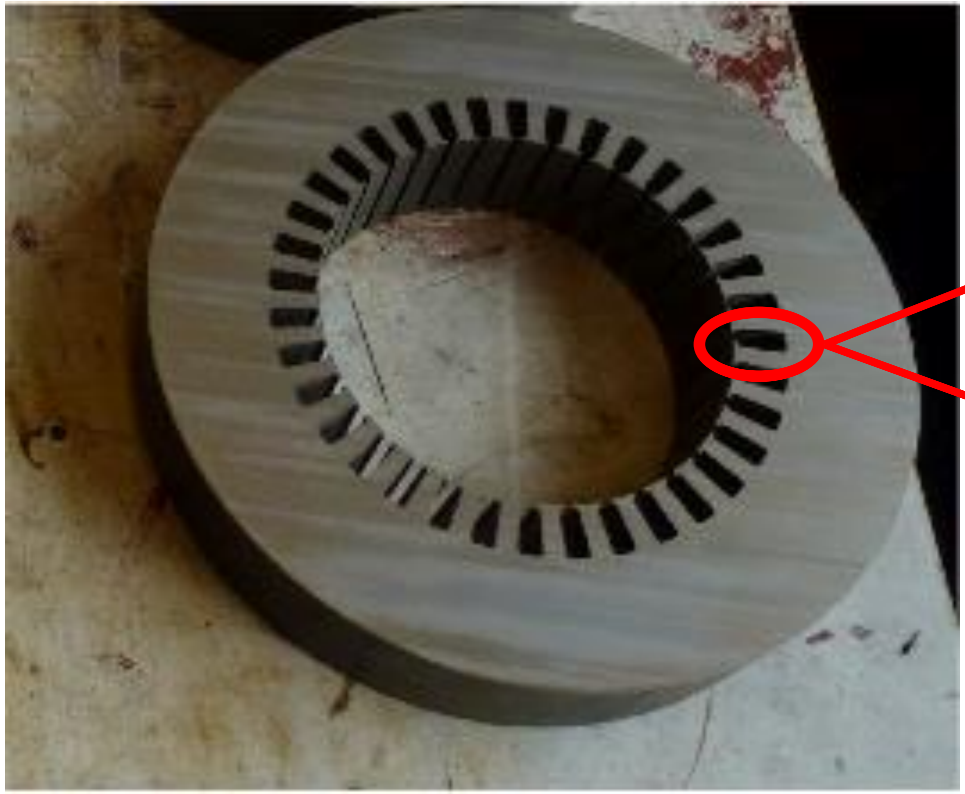
- Expensive to manufacture
  - Add additional winding layers
  - Non-standard winding equipment



[1] G. Munteanu, A. Binder and T. Schneider, "Loss measurement of a 40 kW high-speed bearingless PM synchronous motor," *2011 IEEE ECCE*

However…

- Very small suspension excitation needed for normal operation
  - Recent research on developing a “combined winding”



Normal Operation

$\leq$ 5% Suspension Current

$\geq$ 95% Available for Torque Current

Emergency Operation

25 – 40% Suspension Current

60 – 75% Available for Torque Current

[1] W. Gruber and S. Silber, "Dual Field-Oriented Control of Bearingless Motors with Combined Winding System," *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, Niigata, Japan, 2018

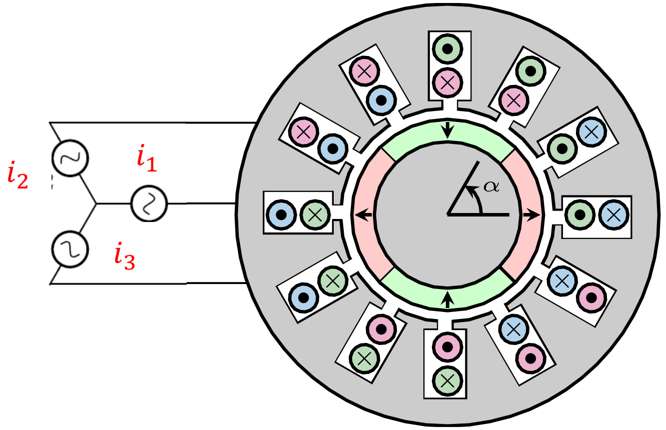
[2] D. Dietz and A. Binder, "Comparison between a bearingless PM motor with separated and combined winding for torque and lateral force generation," *2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe)*, Genova, Italy, 2019

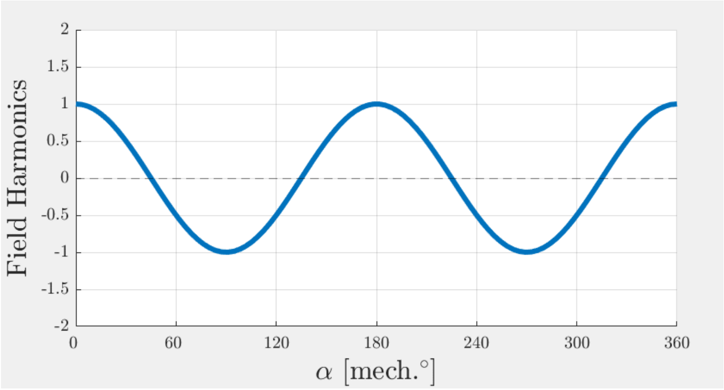
[3] M. Kang, J. Huang, J. -q. Yang and H. -b. Jiang, "Analysis and experiment of a 6-phase bearingless induction motor," *2008 ICEMS*

[4] G. Valente, L. Papini, A. Formentini, C. Gerada and P. Zanchetta, "Radial Force Control of Multisector Permanent-Magnet Machines for Vibration Suppression," in *IEEE Transactions on Industrial Electronics*, vol. 65, no. 7, pp. 5395-5405, July 2018

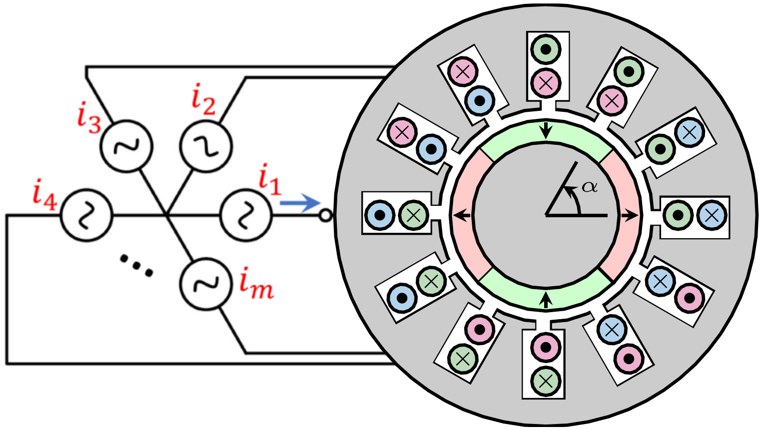
Add more phases to add more harmonics

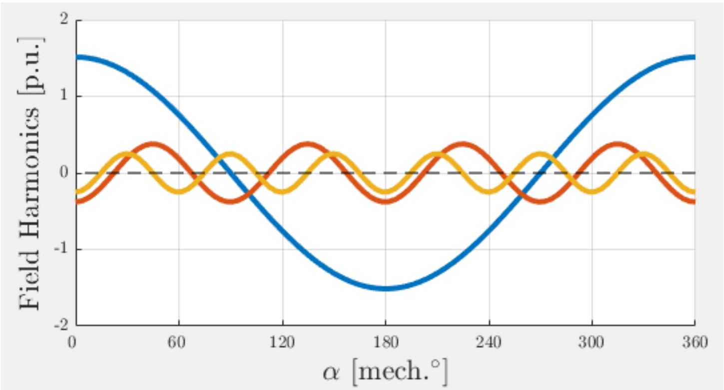
Standard Winding:





Combined Winding:





[1] Khamitov and Severson, "Design of Multi-Phase Combined Windings for Bearingless Machines," in IEEE Transactions on Industry Applications, May-June 2023

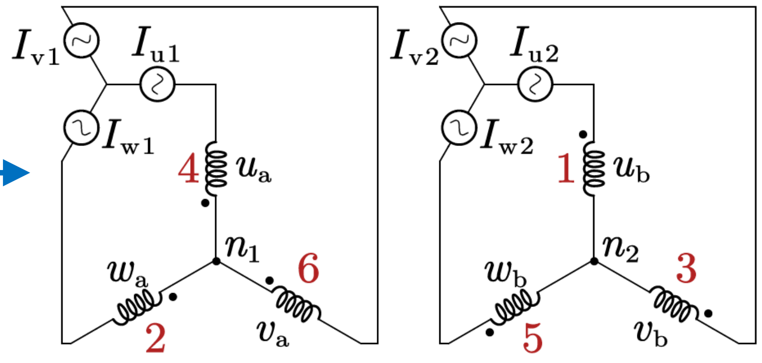
Drive Connection Option 1: “Double Star”

- Currents $i_k = \hat{I}_1 \cos\left(\phi_1 - [k-1]1\frac{\pi}{3}\right) + \hat{I}_2 \cos\left(\phi_2 - [k-1]2\frac{\pi}{3}\right)$

$$
\begin{aligned}
i_1 &= \hat{I}_1 \cos\phi_1 + \hat{I}_2 \cos\phi_2 \\
i_2 &= -\hat{I}_1 \cos\left(\phi_1 - \frac{4\pi}{3}\right) + \hat{I}_2 \cos\left(\phi_2 - \frac{2\pi}{3}\right) \\
i_3 &= \hat{I}_1 \cos\left(\phi_1 - \frac{2\pi}{3}\right) + \hat{I}_2 \cos\left(\phi_2 - \frac{4\pi}{3}\right) \\
i_4 &= -\hat{I}_1 \cos\phi_1 + \hat{I}_2 \cos(\phi_2) \\
i_5 &= \hat{I}_1 \cos\left(\phi_1 - \frac{4\pi}{3}\right) + \hat{I}_2 \cos\left(\phi_2 - \frac{2\pi}{3}\right) \\
i_6 &= -\hat{I}_1 \cos\left(\phi_1 - \frac{2\pi}{3}\right) + \hat{I}_2 \cos\left(\phi_2 - \frac{4\pi}{3}\right)
\end{aligned}
$$

Currents sum to 0! (i_1, i_3, i_5)

Currents sum to 0! (i_2, i_4, i_6)



Pros
- Can use 1 fewer current sensor
- Can use standard 3 phase inverters

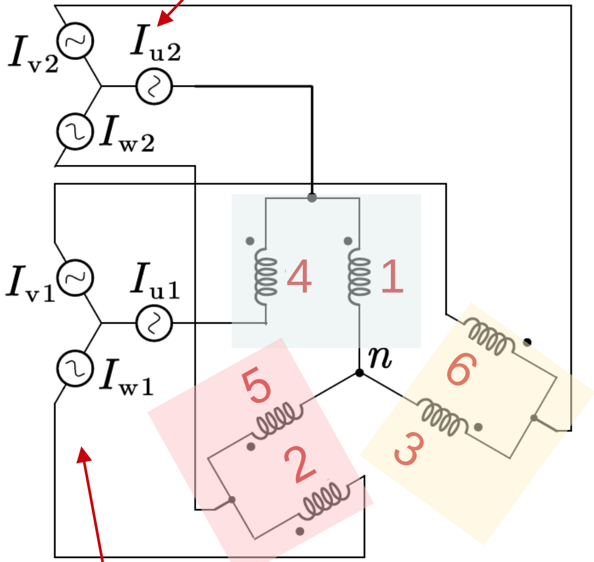
Drive Connection Option 2: “Parallel Circuit”

- Currents $i_k = \hat{I}_1 \cos\left(\phi_1 - [k-1]1\frac{\pi}{3}\right) + \hat{I}_2 \cos\left(\phi_2 - [k-1]2\frac{\pi}{3}\right)$

Looks like 3 phases

$i_1 =$	$\hat{I}_1 \cos\phi_1$	+	$\hat{I}_2 \cos\phi_2$
$i_4 =$	$-\hat{I}_1 \cos\phi_1$	+	$\hat{I}_2 \cos(\phi_2)$
$i_3 =$	$\hat{I}_1 \cos\left(\phi_1 - \frac{2\pi}{3}\right)$	+	$\hat{I}_2 \cos\left(\phi_2 - \frac{4\pi}{3}\right)$
$i_6 =$	$-\hat{I}_1 \cos\left(\phi_1 - \frac{2\pi}{3}\right)$	+	$\hat{I}_2 \cos\left(\phi_2 - \frac{4\pi}{3}\right)$
$i_5 =$	$\hat{I}_1 \cos\left(\phi_1 - \frac{4\pi}{3}\right)$	+	$\hat{I}_2 \cos\left(\phi_2 - \frac{2\pi}{3}\right)$
$i_2 =$	$-\hat{I}_1 \cos\left(\phi_1 - \frac{4\pi}{3}\right)$	+	$\hat{I}_2 \cos\left(\phi_2 - \frac{2\pi}{3}\right)$
	Differential mode current		*Common mode current*

$$I_{u2} = 2\hat{I}_2 \cos\phi_2$$
$$I_{v2} = 2\hat{I}_2 \cos\left(\phi_2 - \frac{4\pi}{3}\right)$$
$$I_{w2} = 2\hat{I}_2 \cos\left(\phi_2 - \frac{2\pi}{3}\right)$$



$$I_{u1} = \hat{I}_1 \cos\phi_1 - \hat{I}_2 \cos\phi_2$$
$$I_{v1} = \hat{I}_1 \cos\left(\phi_1 - \frac{2\pi}{3}\right) - \hat{I}_2 \cos\left(\phi_2 - \frac{4\pi}{3}\right)$$
$$I_{w1} = \hat{I}_1 \cos\left(\phi_1 - \frac{4\pi}{3}\right) - \hat{I}_2 \cos\left(\phi_2 - \frac{2\pi}{3}\right)$$

Pros
- Inverter 2 doesn’t care about harmonic 1 ← ***can use standard VFD!***
- Inverter 1 may see less back-EMF / Can size DC-link separately

Cons:
- Inverters carry more current!

[1] R. Oishi, S. Horima, H. Sugimoto and A. Chiba, "A Novel Parallel Motor Winding Structure for Bearingless Motors," in IEEE Transactions on Magnetics, vol. 49, no. 5, pp. 2287-2290, May 2013

Drive Connection Option 3: "Bridge Circuit"

- Currents $i_k = \hat{I}_1 \cos\left(\phi_1 - [k-1]1\frac{\pi}{3}\right) + \hat{I}_2 \cos\left(\phi_2 - [k-1]2\frac{\pi}{3}\right)$

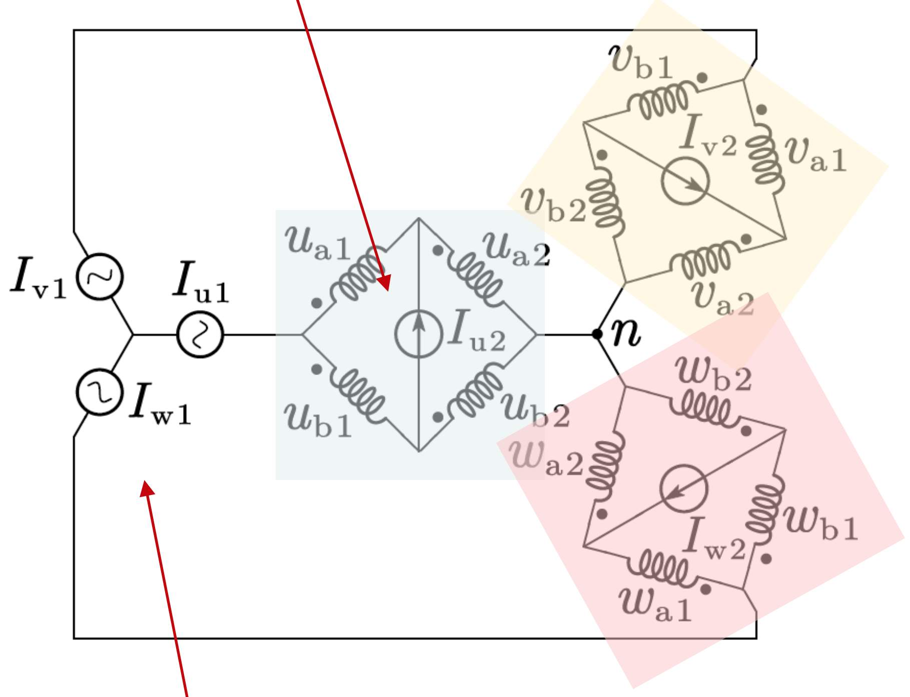
$I_{u2} = 2\hat{I}_1 \cos\phi_1$

$I_{v2} = 2\hat{I}_1 \cos\left(\phi_2 - \frac{2\pi}{3}\right)$

$I_{w2} = 2\hat{I}_1 \cos\left(\phi_2 - \frac{4\pi}{3}\right)$

$i_1 =$	$\hat{I}_1 \cos\phi_1$	+	$\hat{I}_2 \cos\phi_2$
$i_4 =$	$-\hat{I}_1 \cos\phi_1$	+	$\hat{I}_2 \cos(\phi_2)$
$i_3 =$	$\hat{I}_1 \cos\left(\phi_1 - \frac{2\pi}{3}\right)$	+	$\hat{I}_2 \cos\left(\phi_2 - \frac{4\pi}{3}\right)$
$i_6 =$	$-\hat{I}_1 \cos\left(\phi_1 - \frac{2\pi}{3}\right)$	+	$\hat{I}_2 \cos\left(\phi_2 - \frac{4\pi}{3}\right)$
$i_5 =$	$\hat{I}_1 \cos\left(\phi_1 - \frac{4\pi}{3}\right)$	+	$\hat{I}_2 \cos\left(\phi_2 - \frac{2\pi}{3}\right)$
$i_2 =$	$-\hat{I}_1 \cos\left(\phi_1 - \frac{4\pi}{3}\right)$	+	$\hat{I}_2 \cos\left(\phi_2 - \frac{2\pi}{3}\right)$
	Differential mode current		*Common mode current*

Looks like 3 phases



$I_{u1} = 2\hat{I}_2 \cos\phi_2$

$I_{v1} = 2\hat{I}_2 \cos\left(\phi_2 - \frac{4\pi}{3}\right)$

$I_{w1} = 2\hat{I}_2 \cos\left(\phi_2 - \frac{2\pi}{3}\right)$

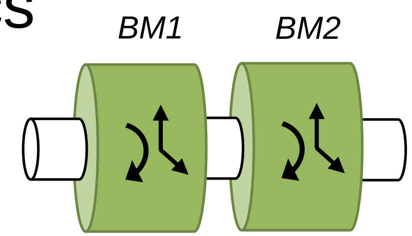
Pros
- Inverter 1 doesn't care about harmonic 2 ← ***can use standard VFD!***
- Inverter 2 doesn't care about harmonic 1 ← less coupling

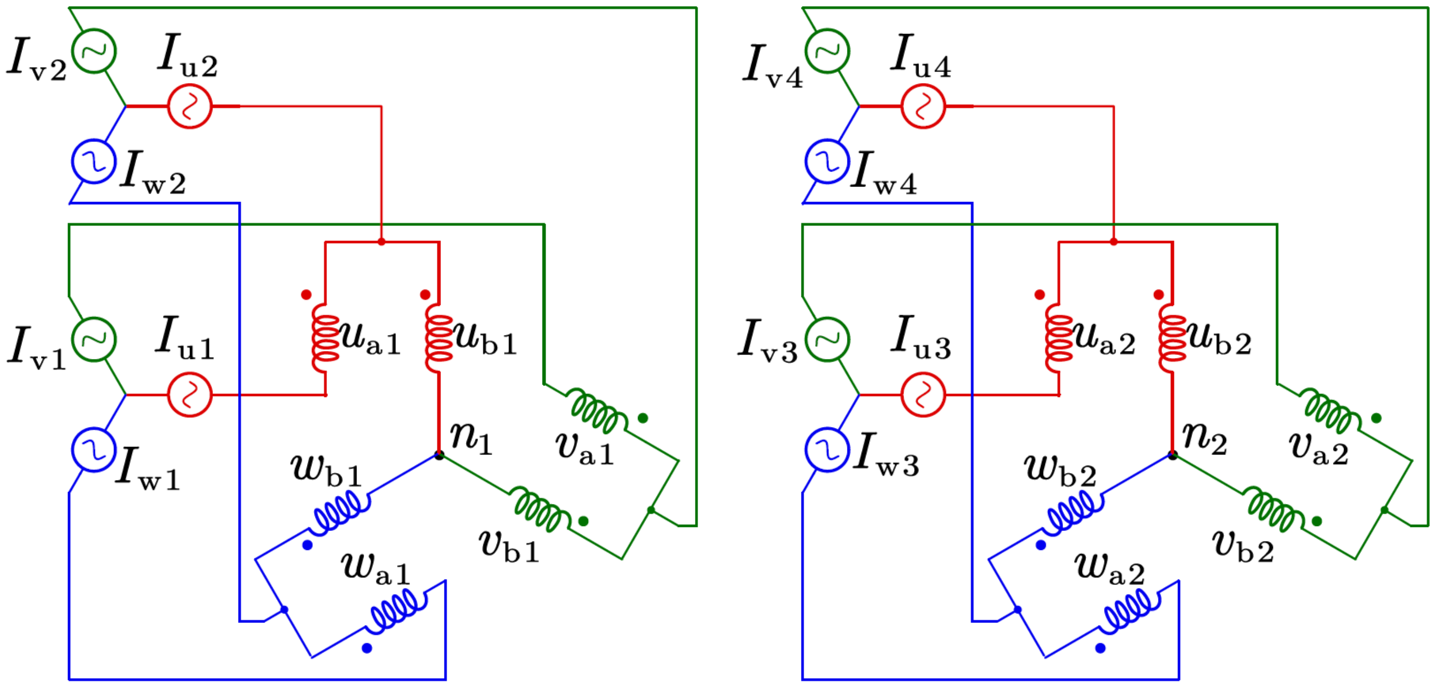
Cons:
- Inverter 2 must be isolated, single phase inverters…

[1] W. K. S. Khoo, K. Kalita and S. D. Garvey, "Practical Implementation of the Bridge Configured Winding for Producing Controllable Transverse Forces in Electrical Machines," in *IEEE Transactions on Magnetics*, vol. 47, no. 6, pp. 1712-1718, June 2011

What About Two Machines?

- Can double the power electronics



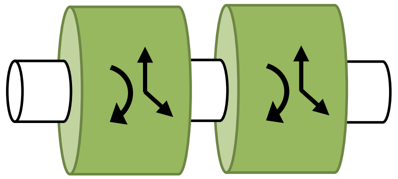


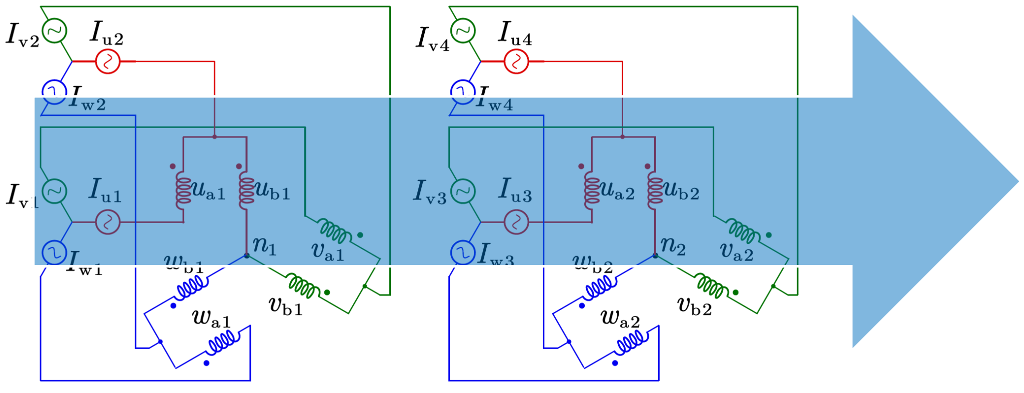
Bearingless machine 1

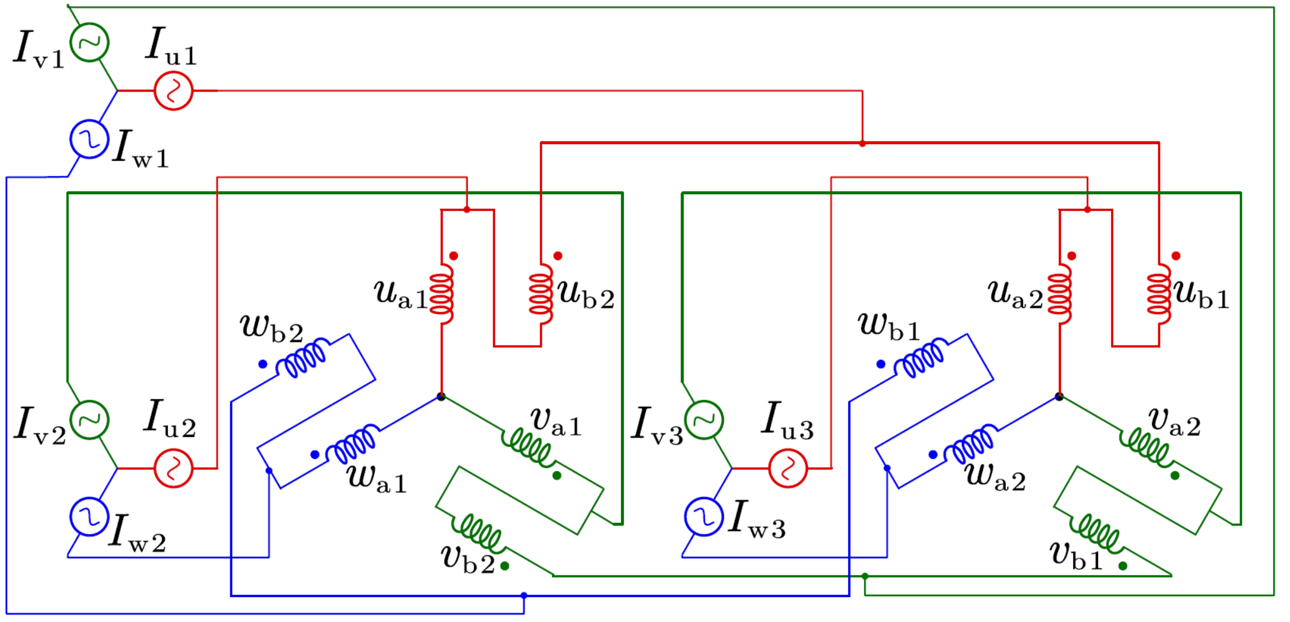
Bearingless machine 2

What About Two Machines?

- **Creatively use the circuit approaches to operate from 3 inverters!**
  - Only works if one of the fields can be the same in both machines → often is true







Control two bearingless motors by using only 3 inverters!

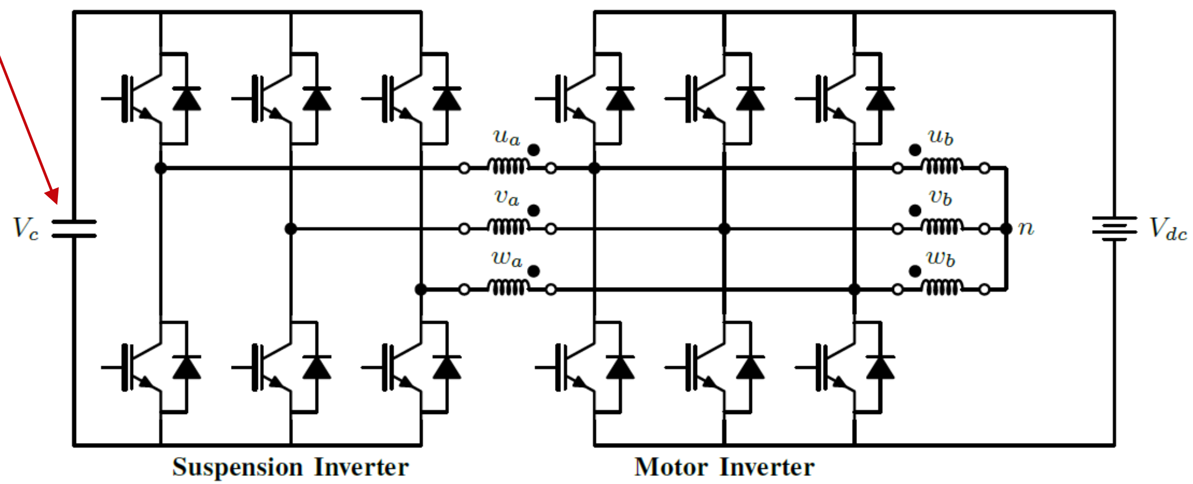
[1] Z. Wang and E. L. Severson, "Twin Bearingless Machine Drive Configurations With a Reduced Number of Inverters," in *IEEE Transactions on Energy Conversion*, vol. 38, no. 2, pp. 1130-1142, June 2023

Advanced Bearingless Drives

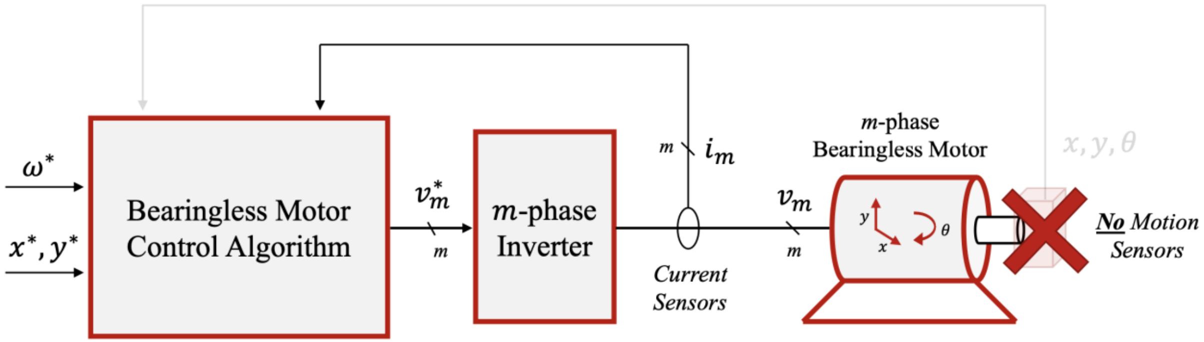
- Initiatives to reduce
  - Number of switches
  - Number of dc busses
  - Number of sensors
  - ***Cost***

- Self-Sensing
  - Back-EMF and inductance change with shaft position
  - New opportunities for self-sensing

Floating capacitor used for suspension inverter DC link



[1] Jiang and Severson, "Floating Capacitor Suspension Inverter for Parallel Combined Winding Bearingless Motors," in *IEEE Transactions on Industry Applications*, 2020

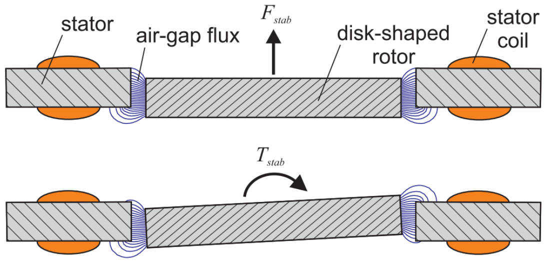


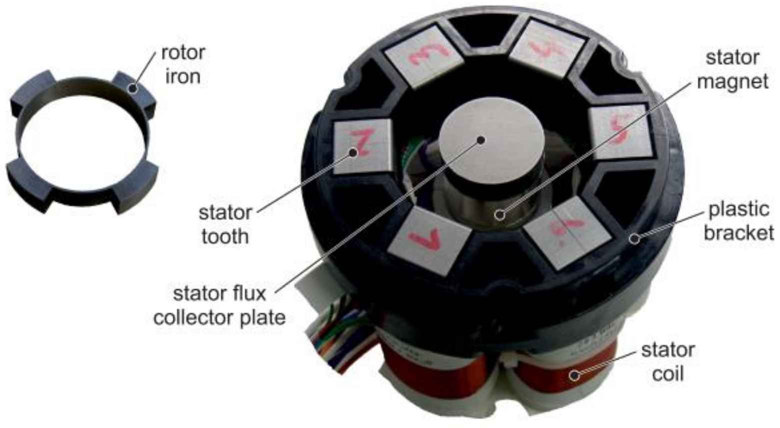
[1] N. Petersen and E. L. Severson, "Suitability of Bearingless Motor Windings for Non-Salient Rotor Displacement Self-Sensing," *2022 IEEE ECCE*.
[2] Kuwajima, Nobe, Ebara, Chiba, and Fukao, "An estimation of the rotor displacements of bearingless motors based on a high frequency equivalent circuits," in *IEEE ICPEDS*, 2001.
[3] Tera, Yamauchi, Chiba, Fukao, and Rahman, "Performances of bearingless and sensorless induction motor drive based on mutual inductances and rotor displacements estimation," *IEEE Transactions on Industrial Electronics*, 2006.
[4] Gruber and Stockler,"On the self-sensing technique based on the interlink voltage of two serially connected phase coils," 2015 IEEE ICPEDS.

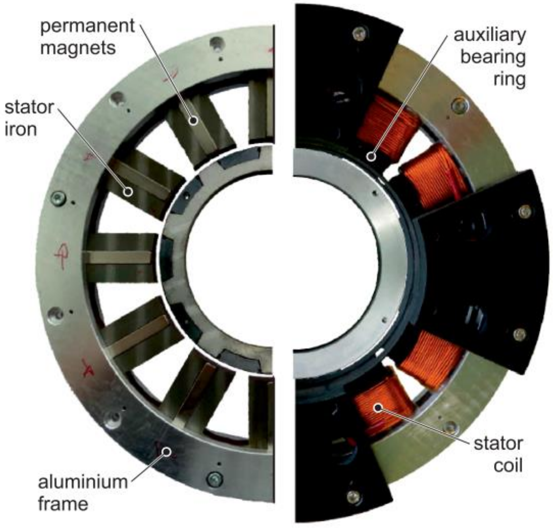
Improving performance

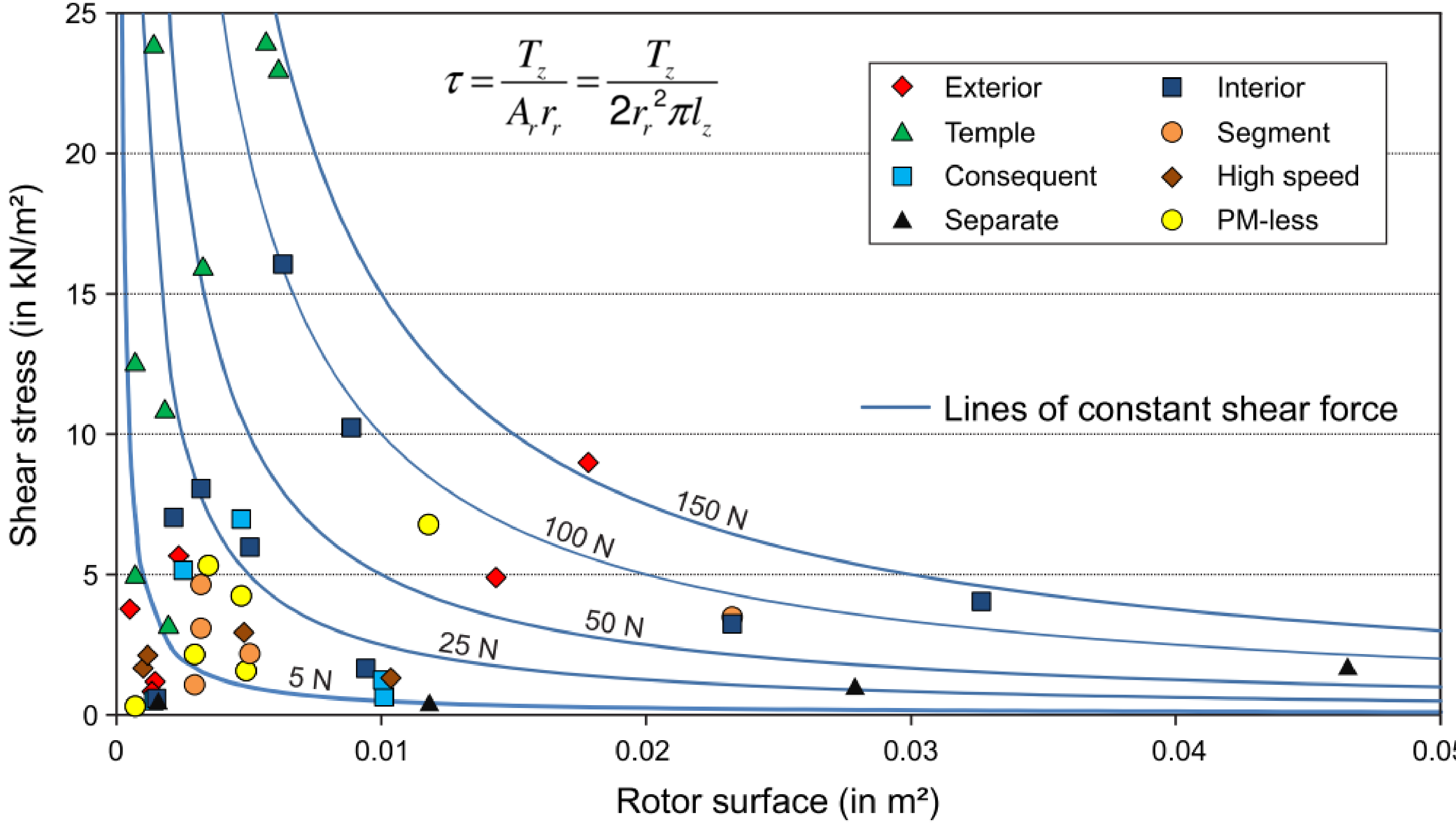
Improving performance

Bearingless slice motors without PM in rotor







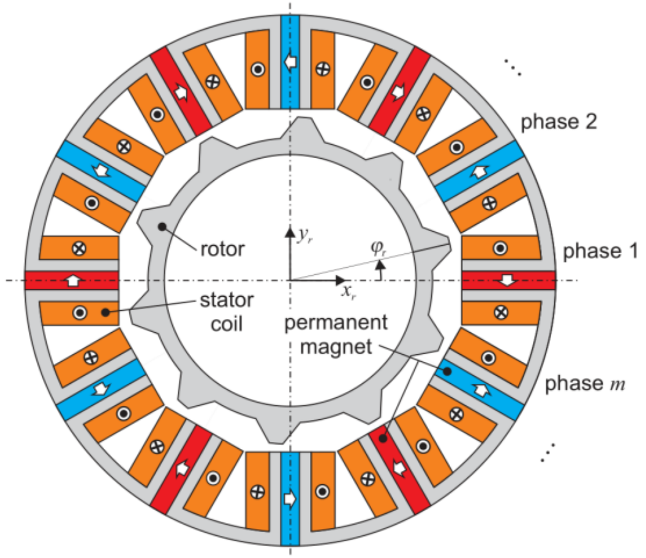


W. Gruber, "Bearingless slice motor systems without permanent magnetic rotors", LCM Journal Series ‚Advances in Mechatronics', ed. Trauner, ISBN 978-3-99062-439-5, 2019

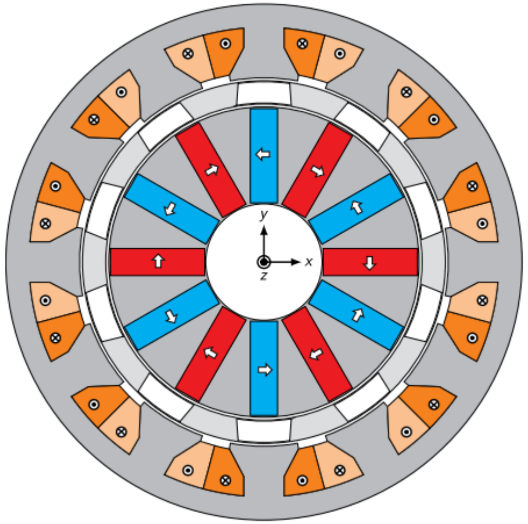
Improving performance

Bearingless slice motors without PM in rotor

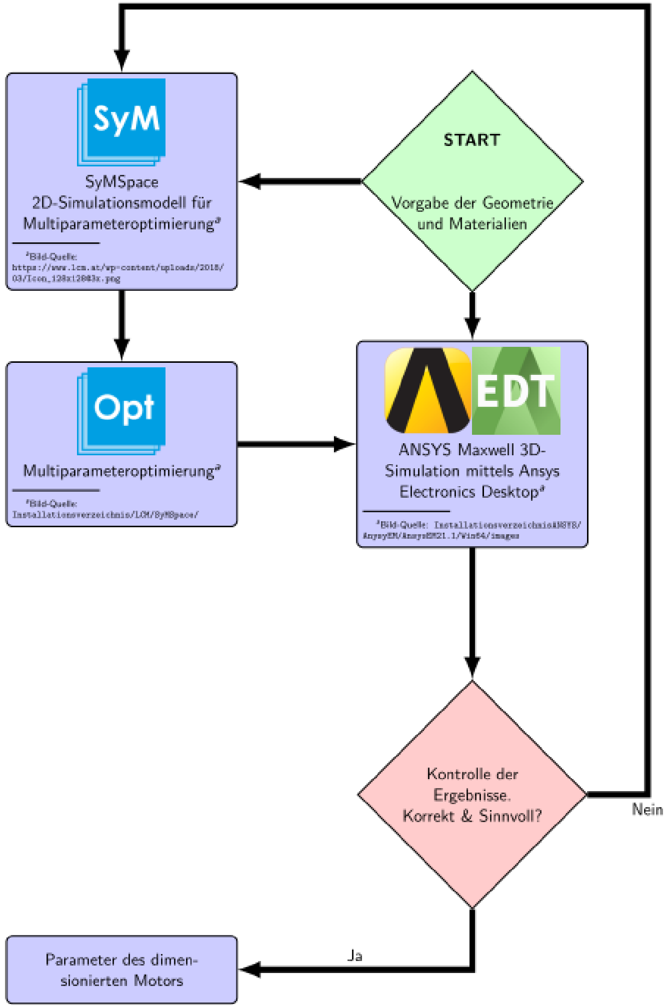
Novel topology: Dual-stator PM flux-switching motor



State of the art



Dual stator type



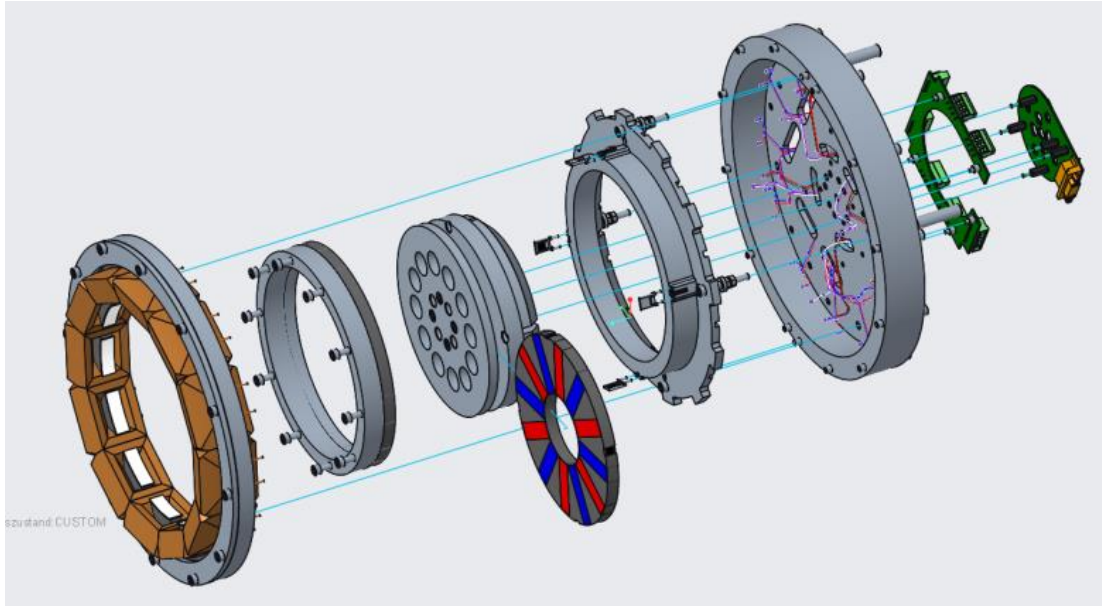
Optimization

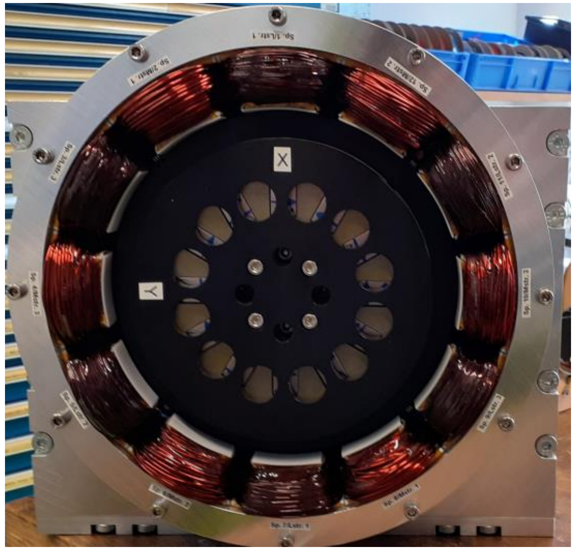
LUT University

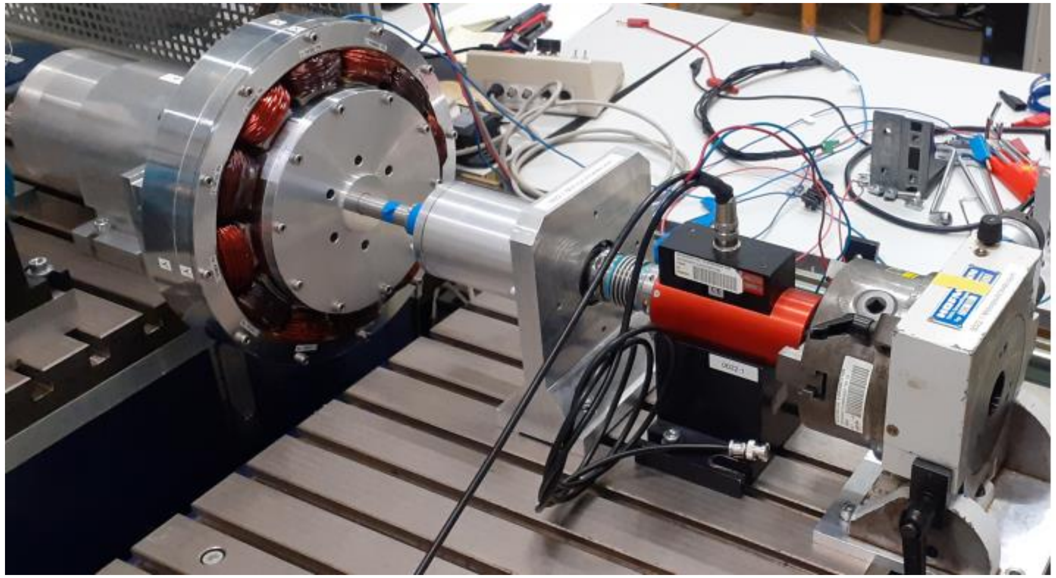
S. Madanzadeh, W. Gruber, A. Zhuravlev and R. P. Jastrzebski, "Self-Bearing Partitioned Stator Flux-Switching Permanent Magnet Motor," *2022 25th International Conference on Electrical Machines and Systems (ICEMS)*, Chiang Mai, Thailand, 2022

Improving performance

Dual-stator PM flux-switching motor prototype

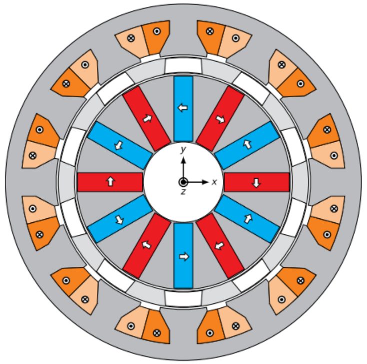




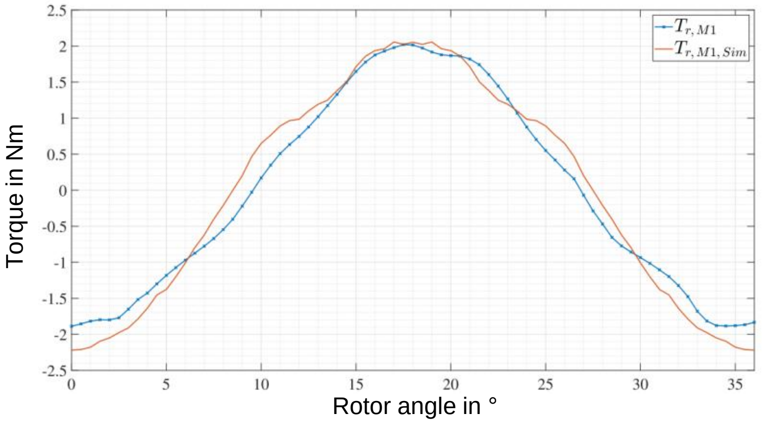


Improving performance

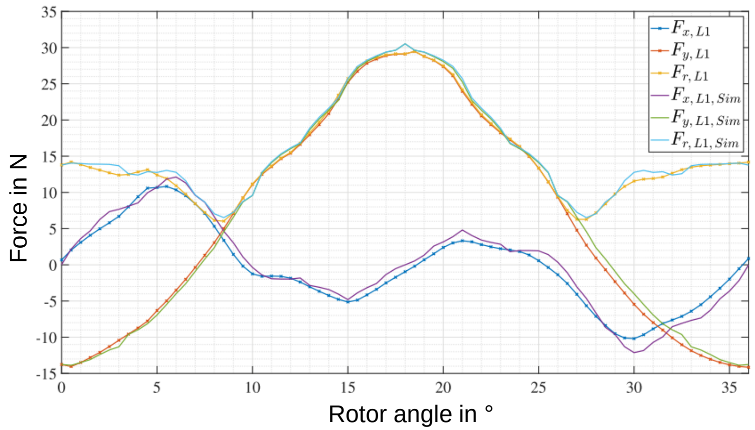
Dual-stator PM flux-switching motor prototype

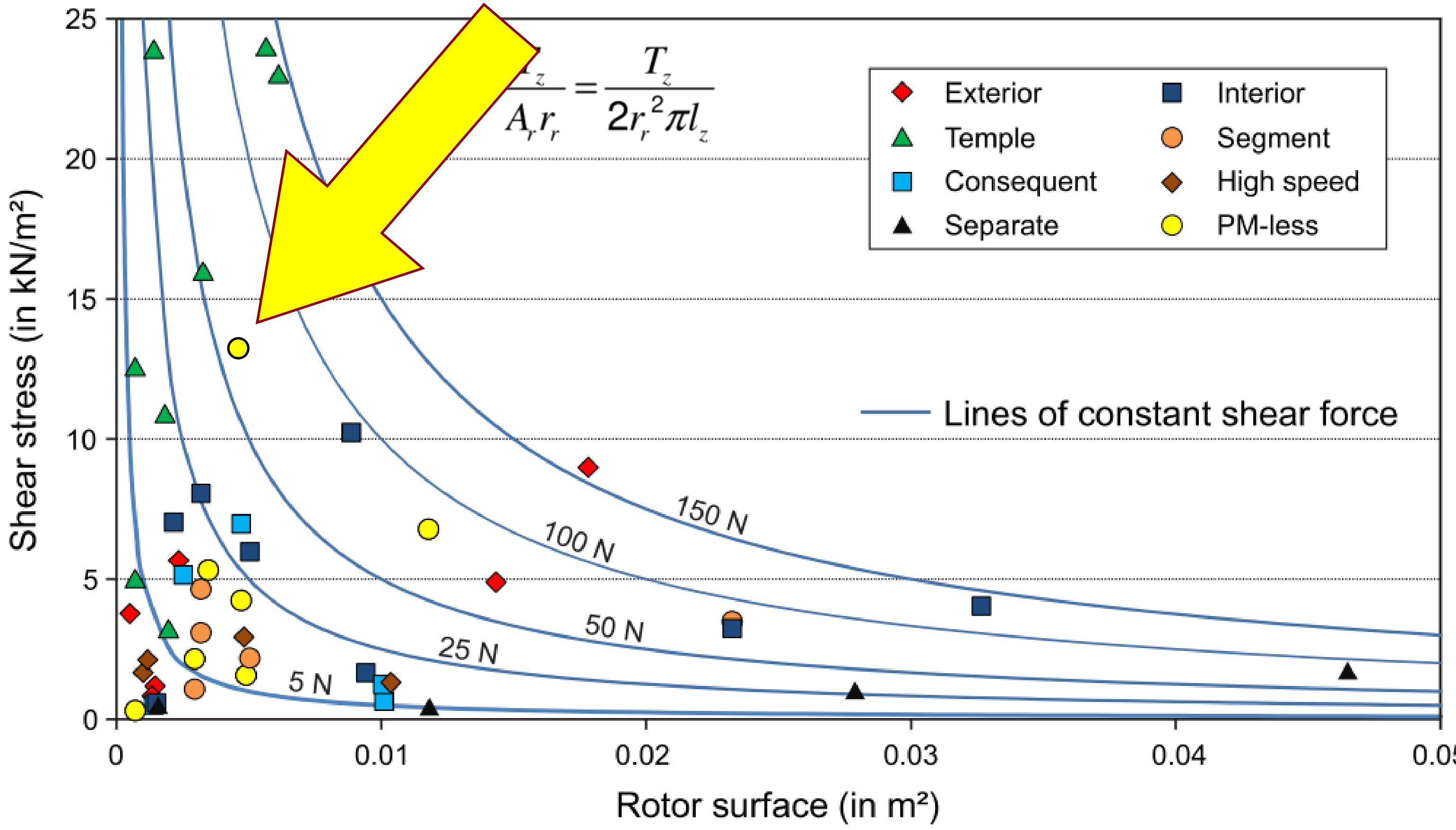


Single-phase torque measurement



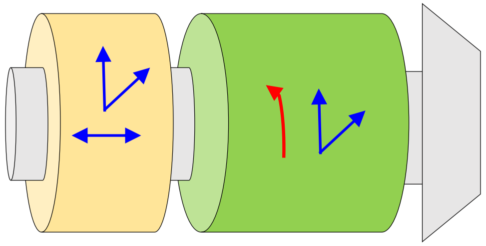
Single-phase force measurement





Torque performance was increased significantly!

Induction Machine

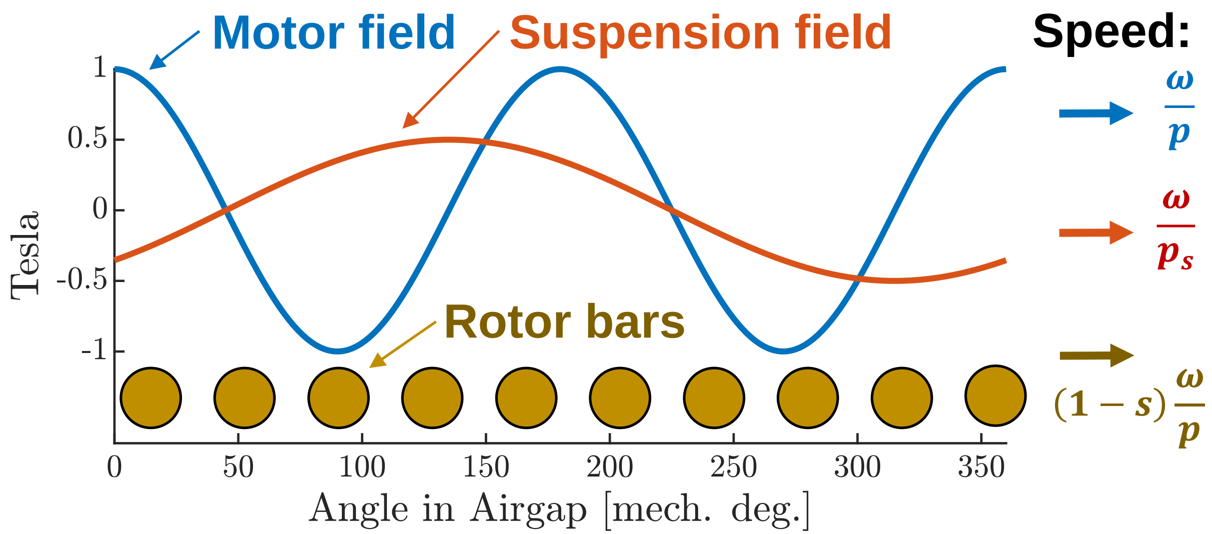


- Cage Rotor Induction Machines
  - “Workhorse of industry”
  - 90% of world’s installed motor systems > 1 hp

Challenges with Induction Machine Cage Rotors

- Suspension field rotates at a different speed than the motor field
  - Rotor sees a large slip
- Rotor currents induced by sus. field
  - **Create unwanted torque**
  - **Attenuate the suspension force**
  - **Create suspension force vector error**
  - **Create losses**
- Most problematic at high speeds

Example 4 pole motor, 2 pole suspension



[1] J. Chen and E. L. Severson, "Design and Modeling of the Bearingless Induction Motor," *2019 IEEE International Electric Machines & Drives Conference (IEMDC)*, 2019

Potential Solution: Pole-Specific Rotors

- Rotor that links motor field but not suspension field
  - ***Solves magnetic challenges***
- But extends axial length
  - ***Introduces rotor dynamics challenges***

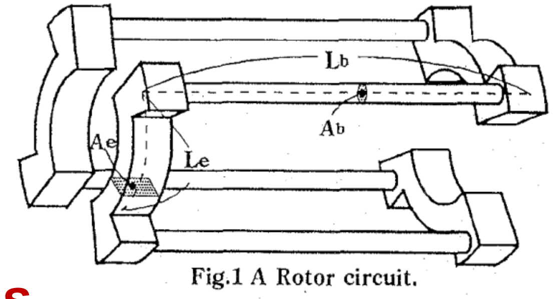


Image from [1]

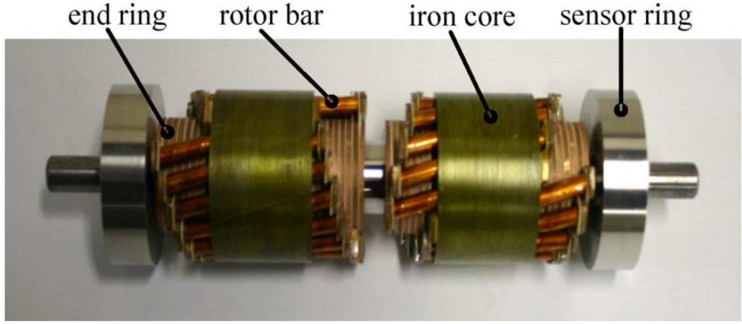
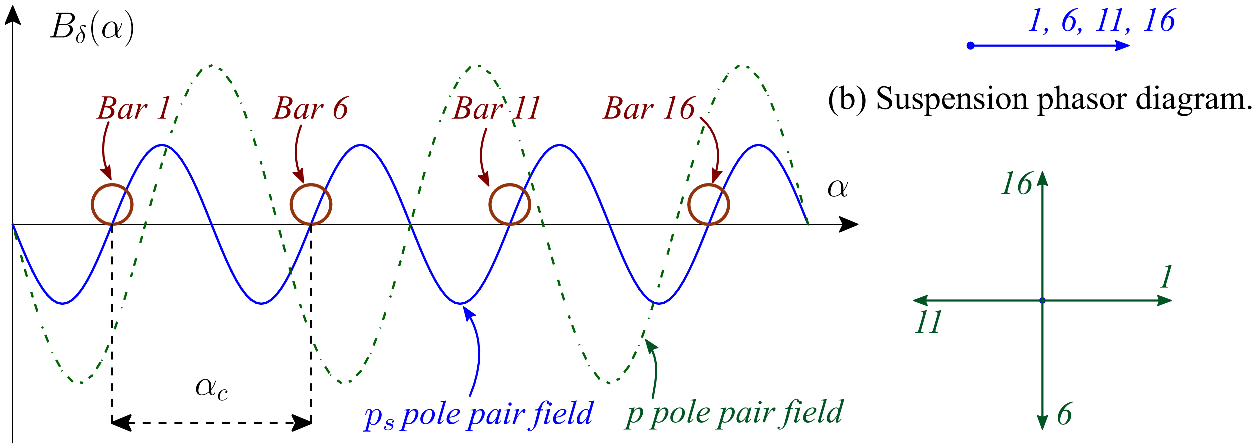


Image from [2]



(a) Magnetic field in the air gap at a time instant.

(b) Suspension phasor diagram.

(c) Torque phasor diagram.

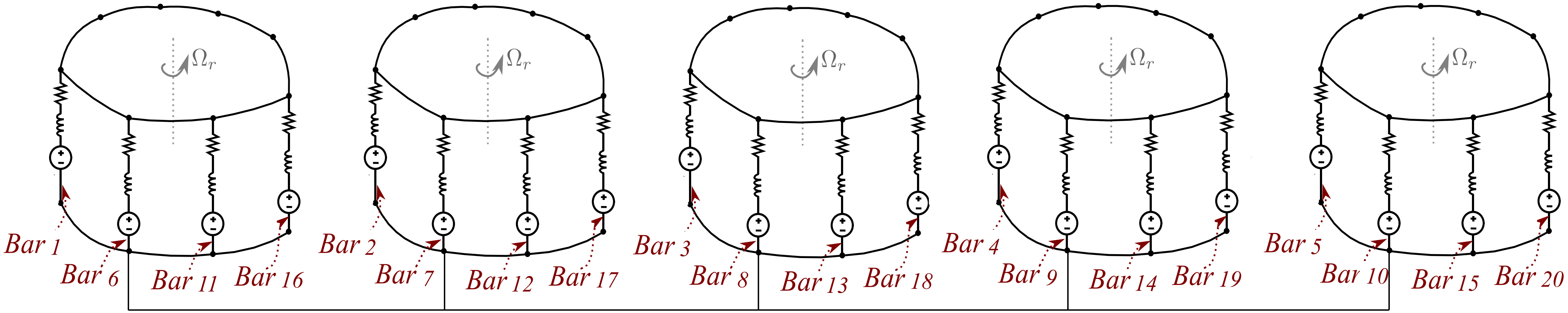
Image from [3]

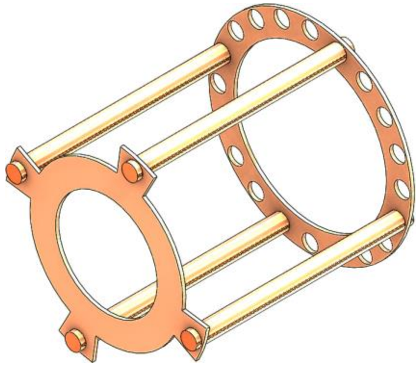
Image from [4]

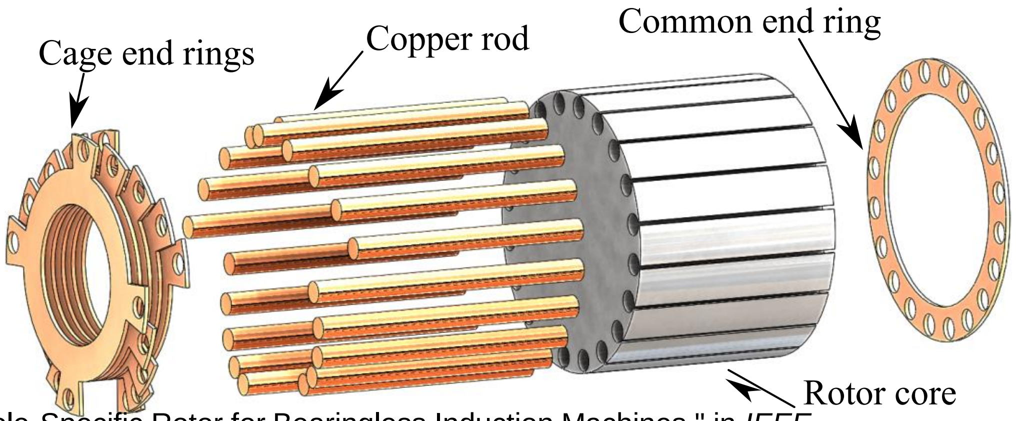
[1] A. Chiba and T. Fukao, "Optimal design of rotor circuits in induction type bearingless motors," in *IEEE Transactions on Magnetics*, vol. 34, no. 4, 1998
[2] A. Chiba and J. Asama, "Influence of Rotor Skew in Induction Type Bearingless Motor," in *IEEE Transactions on Magnetics*, vol. 48, no. 11, 2012
[3] X. Ye, Z. Yang, T. Zhang, “Modeling and Performance Analysis of a Bearingless Fixed-Pole Rotor Induction Motor,” *IET Electric Power App., 2018*
[4] J. Chen, Y. Fujii, M. W. Johnson, A. Farhan and E. L. Severson, "Optimal Design of the Bearingless Induction Motor," in *IEEE Transactions on Industry Applications*, 2021

Connecting the Cages

- State of the art is to have electrically isolated cages
  - ***Creates a long rotor!***
- Idea: electrically connect one side of the cages



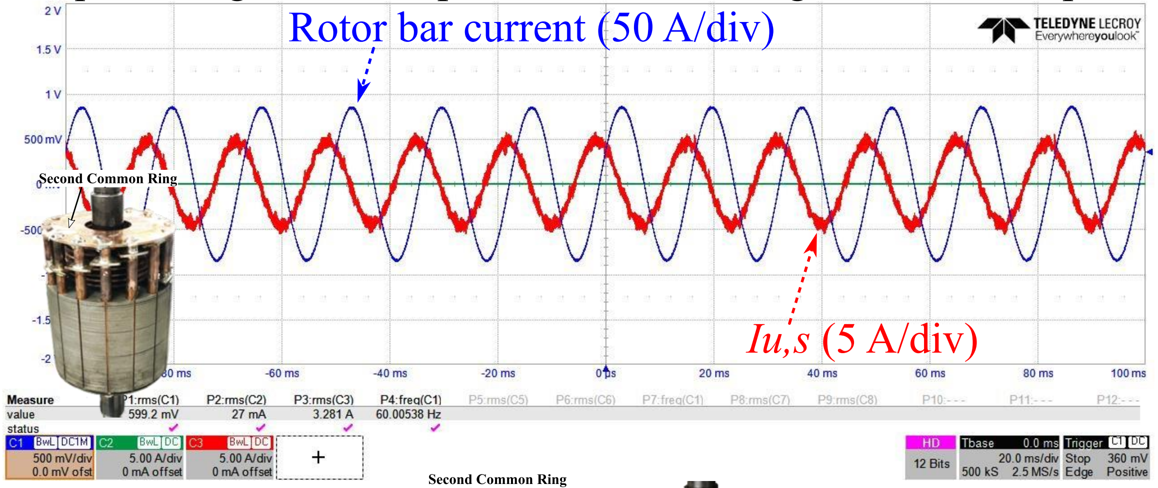




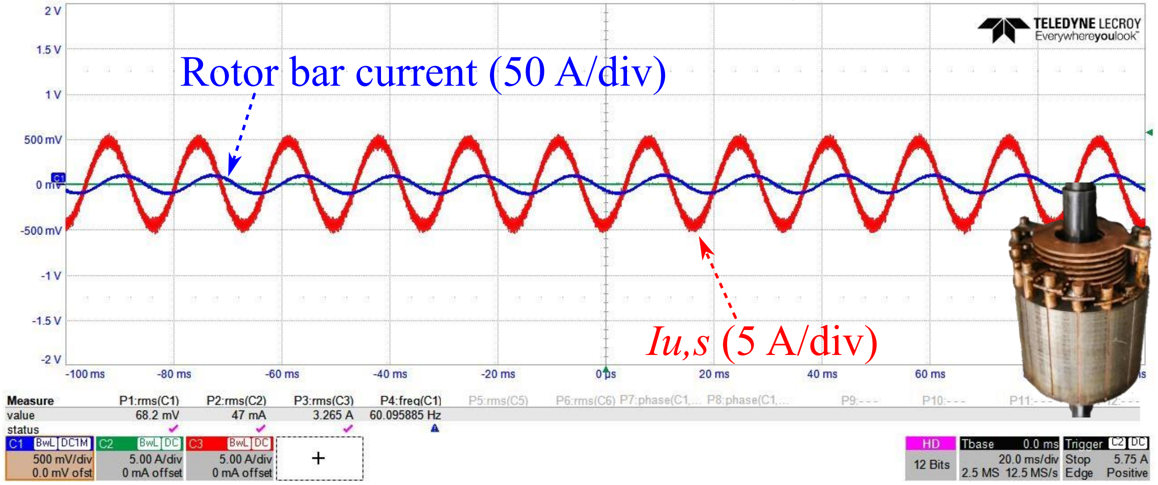
[1] J. Chen, M. W. Johnson, A. Farhan, Z. Wang, Y. Fujii and E. L. Severson, "Reduced Axial Length Pole-Specific Rotor for Bearingless Induction Machines," in *IEEE Transactions on Energy Conversion*, vol. 37, no. 4, pp. 2285-2297, Dec. 2022

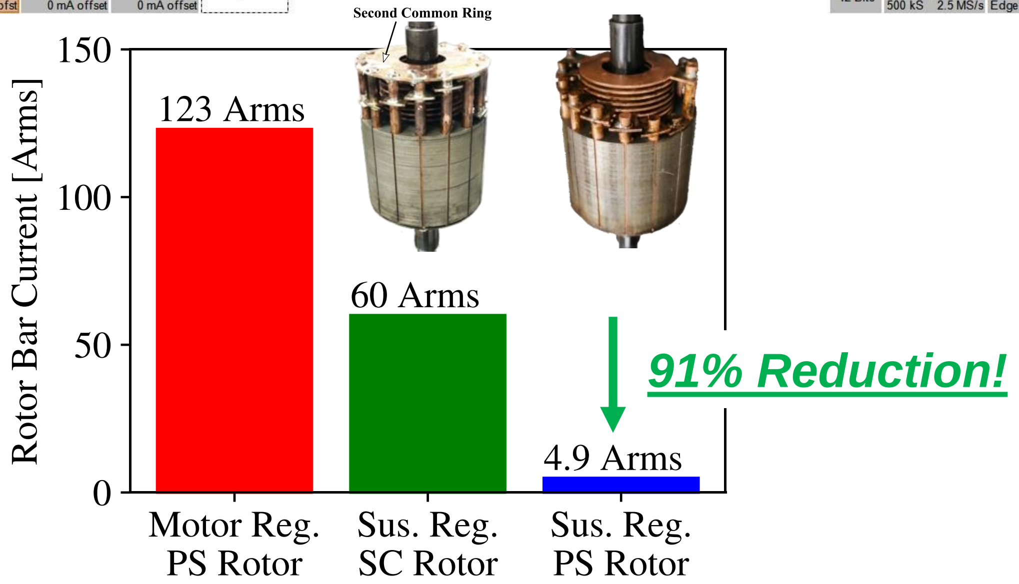
Results: 91% Reduction in Rotor Bar Currents

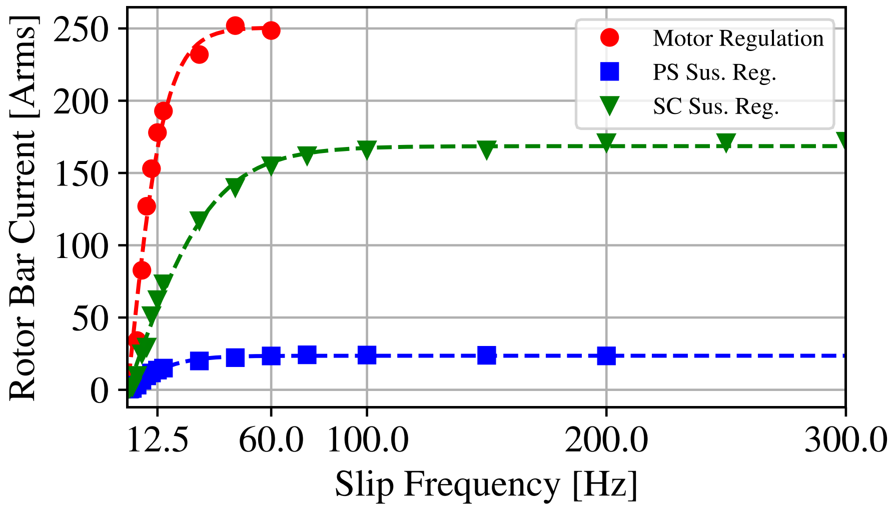
Squirrel cage rotor, suspension terminals regulated to 4.6 Apeak



Pole-specific rotor, suspension terminals regulated to 4.6 Apeak

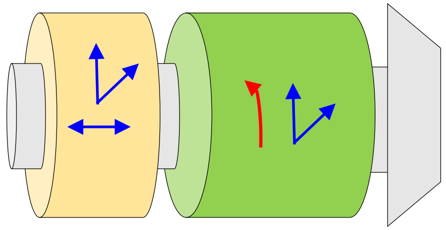


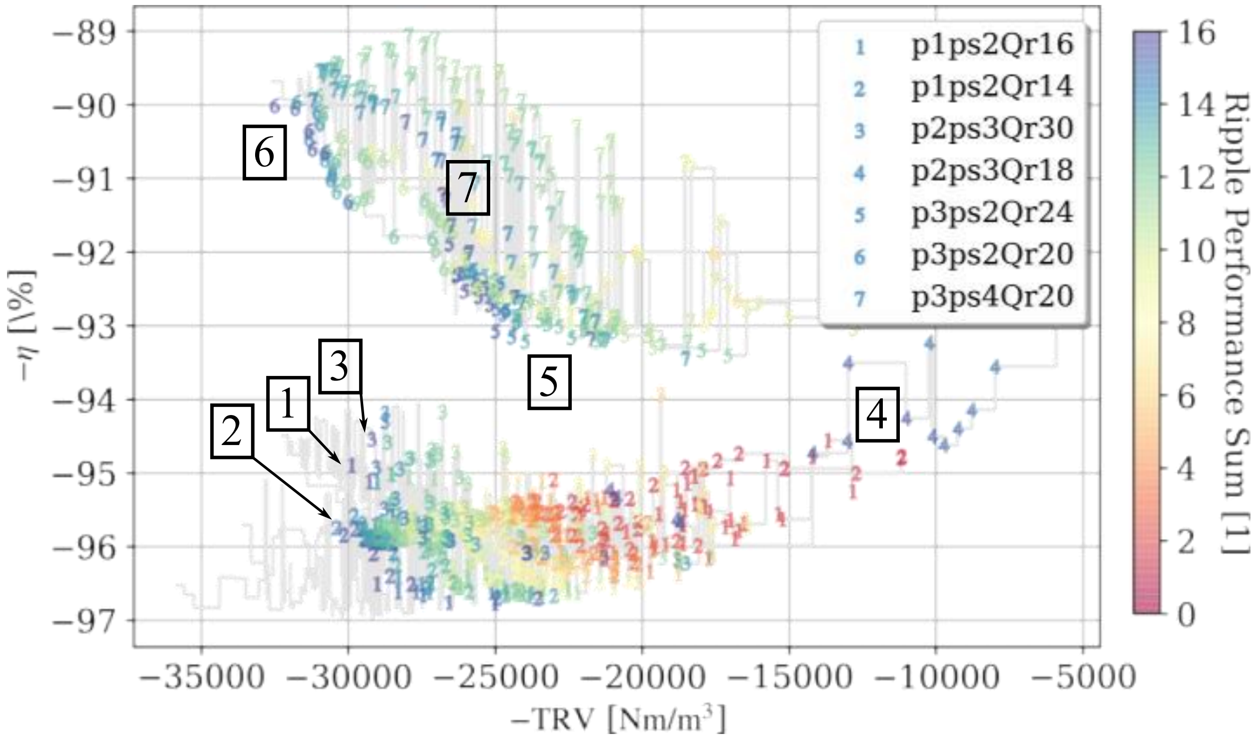




Design Space for Industrial Compressors

- Designs evaluated at:
  - 50 kW
  - 30,000 r/min
  - 2.5% suspension force
- Only showing designs that can support rotor's weight
- **High performance possible!**
  - >96% efficiency
  - $\mathrm{TRV} > 15\,\frac{\mathrm{kNm}}{\mathrm{m}^3}$



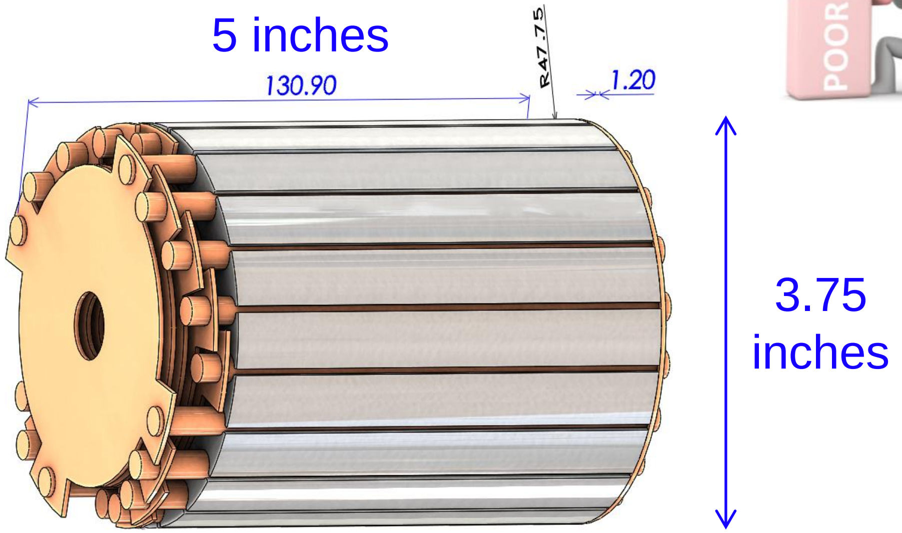


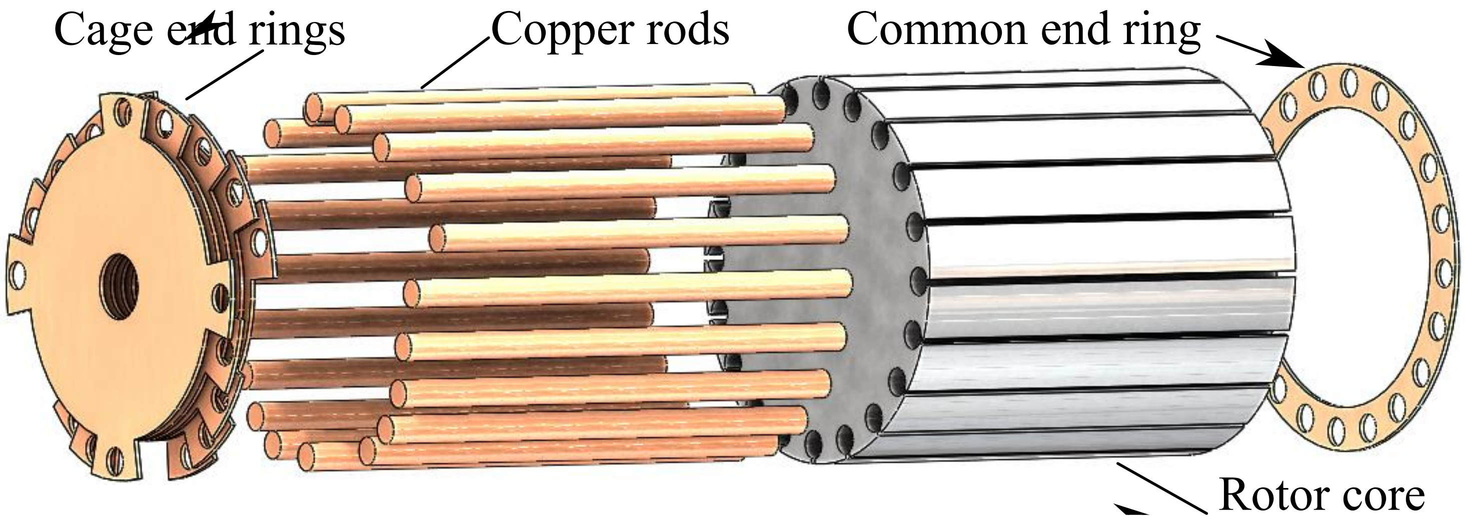
We can make high performance bearingless induction machines

[1] J. Chen, M. W. Johnson, A. Farhan, Z. Wang, Y. Fujii and E. L. Severson, "Reduced Axial Length Pole-Specific Rotor for Bearingless Induction Machines," in *IEEE Transactions on Energy Conversion*, vol. 37, no. 4, pp. 2285-2297, Dec. 2022

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
  - $\text{TRV} \approx 20\,\frac{\text{kNm}}{\text{m}^3}$





[1] J. Chen, M. W. Johnson, A. Farhan, Z. Wang, Y. Fujii and E. L. Severson, "Reduced Axial Length Pole-Specific Rotor for Bearingless Induction Machines," in *IEEE Transactions on Energy Conversion*, vol. 37, no. 4, pp. 2285-2297, Dec. 2022

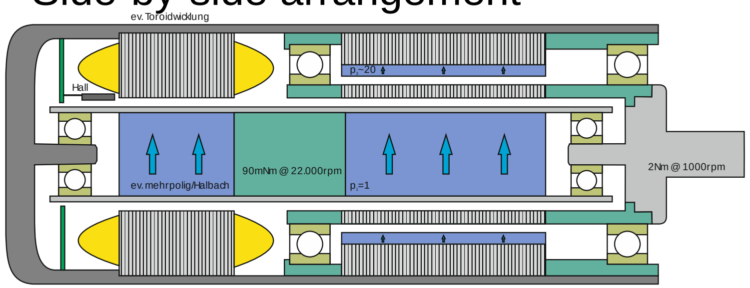
Exploiting high speeds

Exploiting high speeds

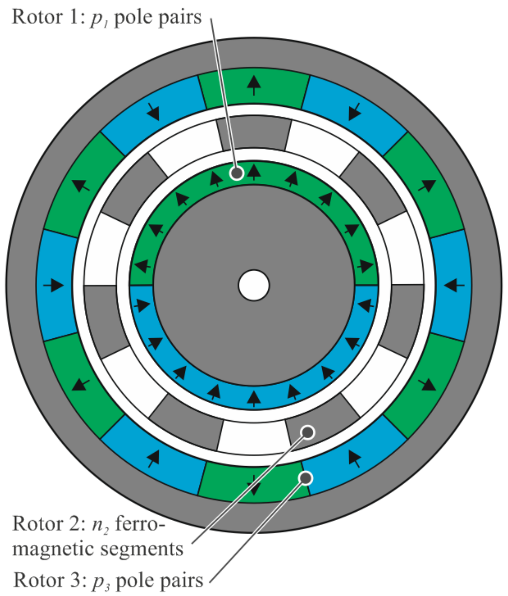
Bearingless magnetic gear motor

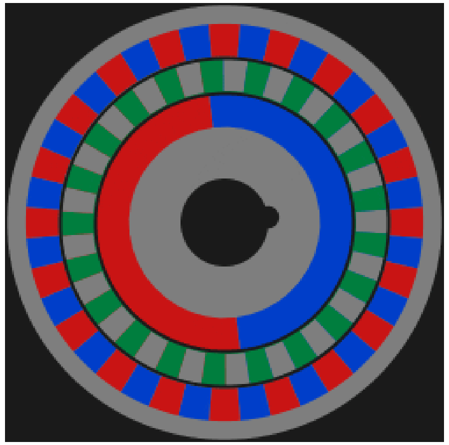
Combination of high speed drive and magnetic gear

Side-by-side arrangement

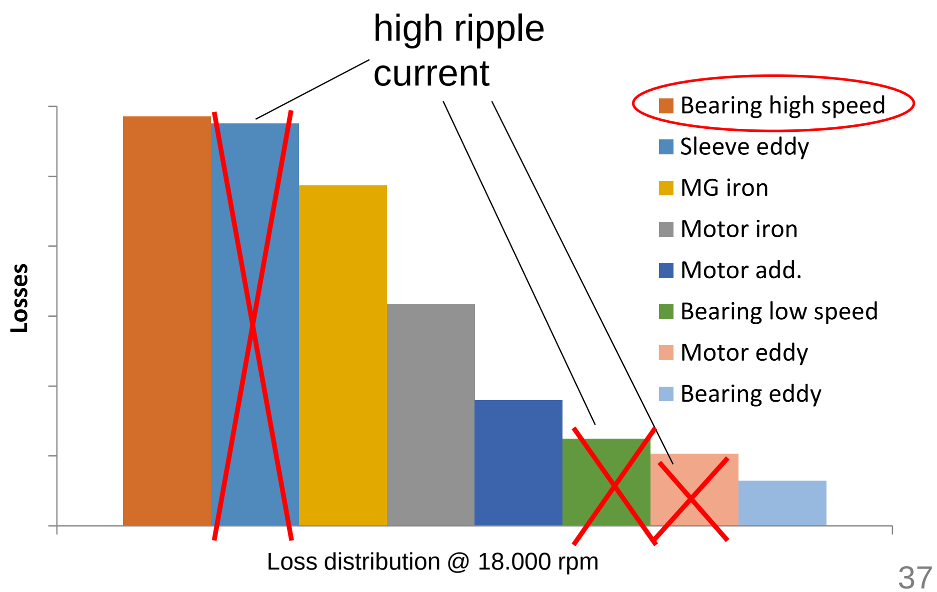


G. Jungmayr, E. Marth and G. Segon, "Magnetic-Geared Motor in Side-by-Side Arrangement - Concept and Design," 2019 IEEE International Electric Machines & Drives Conference (IEMDC), 2019, pp. 847-853





https://hackaday.com/?p=218196

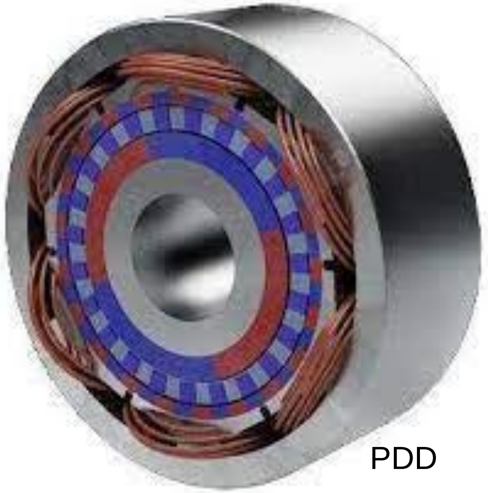


Exploiting high speeds

Cooperation with TIT, Jppan (Prof. Chiba)

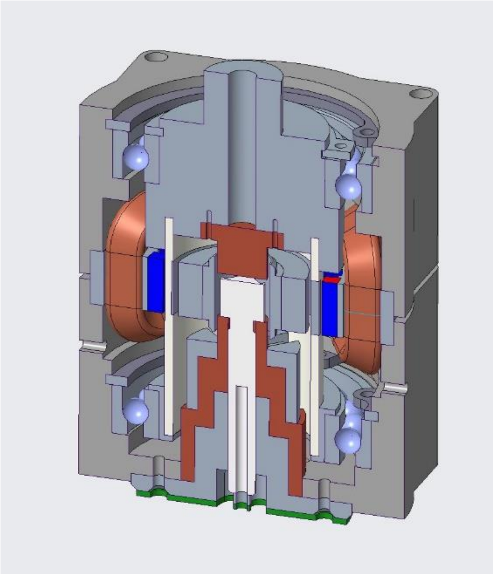
Bearingless magnetic gear motor

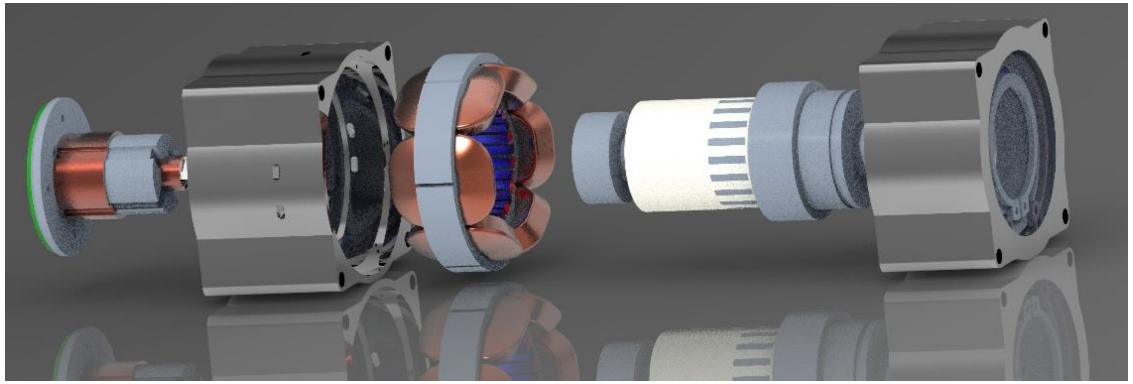
- PDD setup with a bearingless motor (for high-speed rotor)
- Force and torque generation is independent from modulator angle and only depends on high speed rotor angle
- Use a 6-phase combined winding system
- Low speed modulator keeps mechanical ball bearings

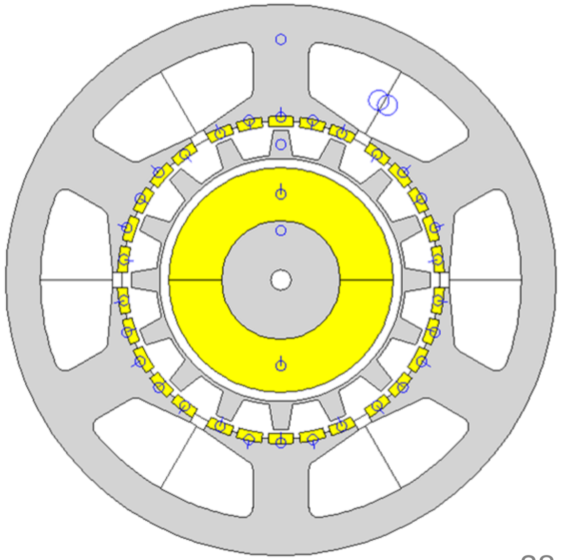


PDD

https://www.magnomatics.com/



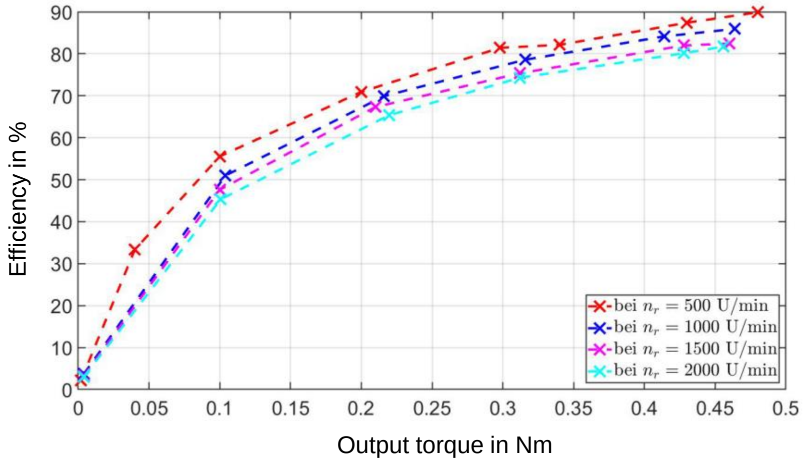




Exploiting high speeds

Bearingless magnetic gear motor prototype

First magnetic gear measurements



Stator iron with some permanent magnets

Modulator

Top stator part

Rotor magnet

Bottom stator part holding modulator ball bearing

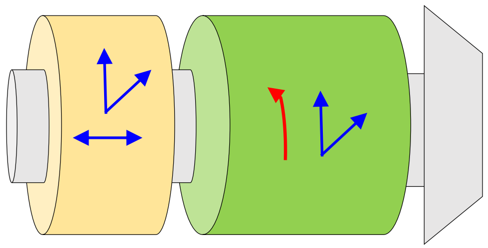
Stator sensor holder and lower auxiliary bearing

Sensor rod

Upper auxilairy bearing

Feasibility of system is shown by simulation – experimental proof is ongoing

Field Weakening



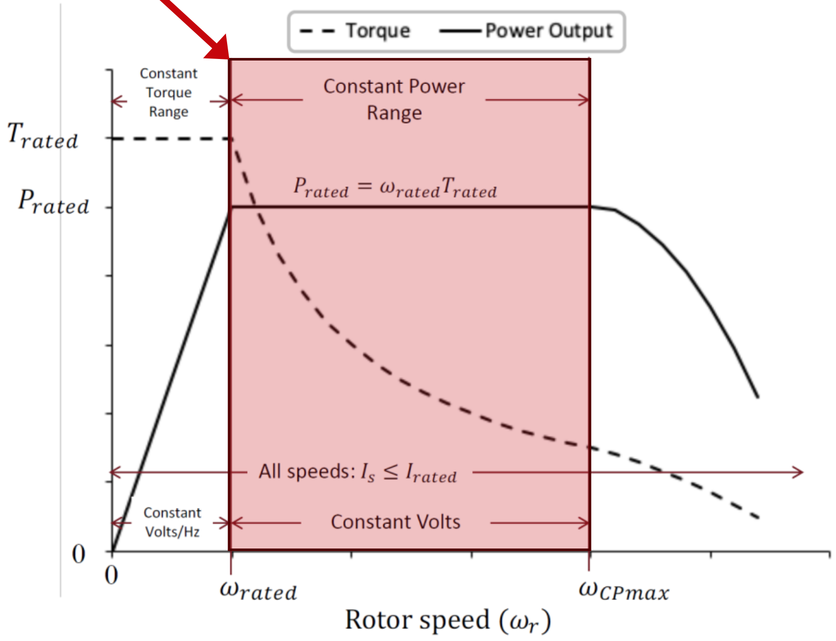
Widely used for high speed motors

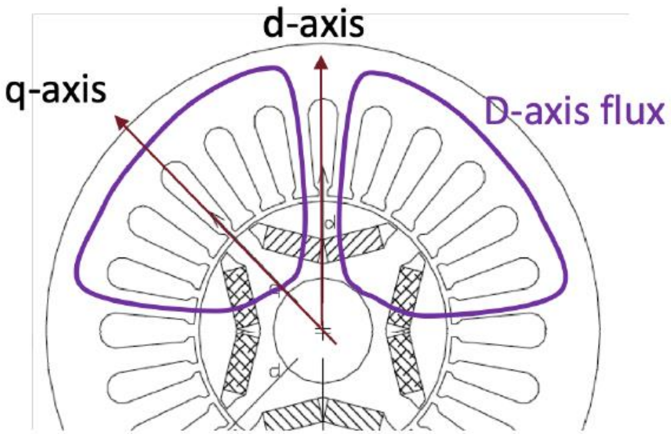
- $-I_d$ stator current to weaken magnets

Implications for bearingless motors

- **Reduce magnetizing flux → reduce force**
- Not typically used, except [1]

Field weakening





Flux paths due to stator d-axis current

- Through two magnets which act like a large air gap

Images from UW-Madison ECE511 Course Notes

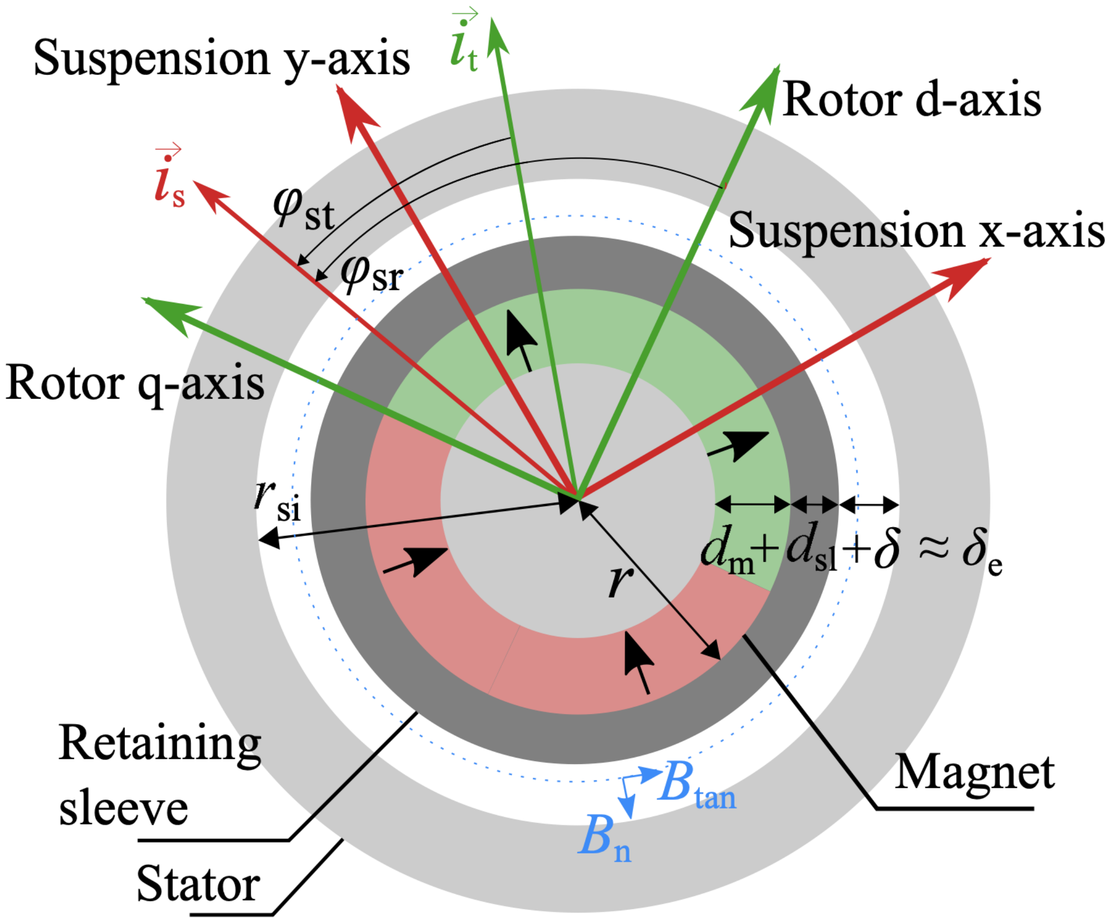
[1] T. Loutit and M. Noh, "Design of a dipole internal permanent magnet bearingless motor for flux-weakening control," in 2022 IEEE Energy Conversion Congress and Exposition (ECCE), 2022, pp. 1–8.

Challenging old assumptions…

- Rederiving force expression including radial **and tangential** airgap fields [1]:

Suspension current — Magnet field — Torque current

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \frac{V_{\mathrm{si}} \hat{A}_{\mathrm{s}}}{2} \left(\hat{B}_\delta K_1 \begin{bmatrix} \cos\phi_{\mathrm{sr}} \\ \pm\sin\phi_{\mathrm{sr}} \end{bmatrix} + \mu_0 \hat{A}_{\mathrm{t}} K_2 \begin{bmatrix} \cos\phi_{\mathrm{st}} \\ \pm\sin\phi_{\mathrm{st}} \end{bmatrix} \right)$$

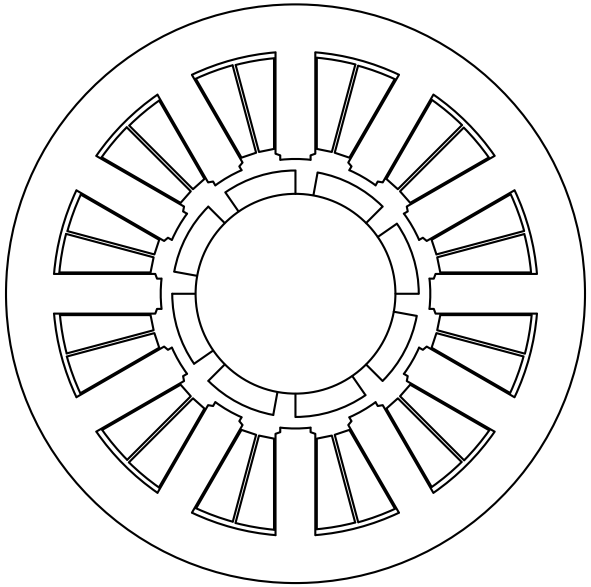


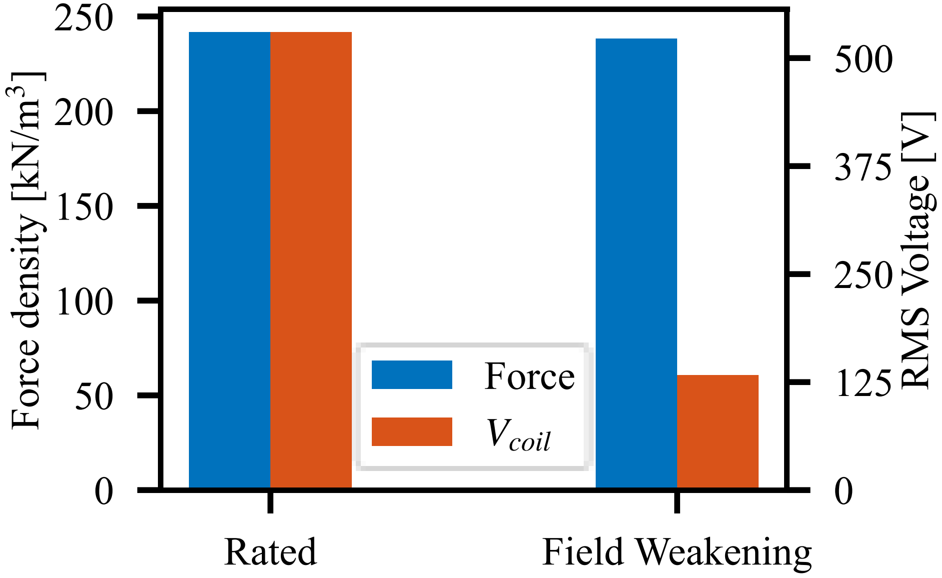
- **If $K_2 = 0$, we can field weaken!**
- **We can [sometimes] design this:** $\delta_e = \dfrac{r_{\mathrm{si}}}{\min(p, p_{\mathrm{s}})}$
- What is going on?
  - Lorentz and Maxwell forces from torque current are cancelling each other

[1] Ramadas and Severson, "Rethinking the Design of Non-Salient Bearingless Permanent Magnet Machines," in *IEEE Transactions on Industry Applications*, May-June 2023

Ex. Field Weakening Compatible Bearingless Motor

- 12 Slot, 8 pole torque, 10 pole suspension
- Design with $\frac{\delta_e}{r_{si}} \approx \frac{1}{\min(p,p_s)} = 0.125$ created
- JMAG simulation study



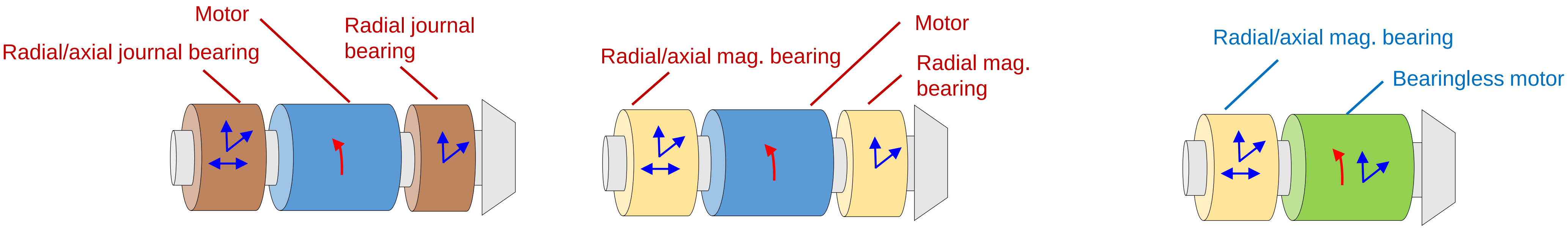


FEA on design example shows field weakening does not reduce force

[1] Ramadas and Severson, "Rethinking the Design of Non-Salient Bearingless Permanent Magnet Machines," in *IEEE Transactions on Industry Applications*, May-June 2023

Concluding thoughts

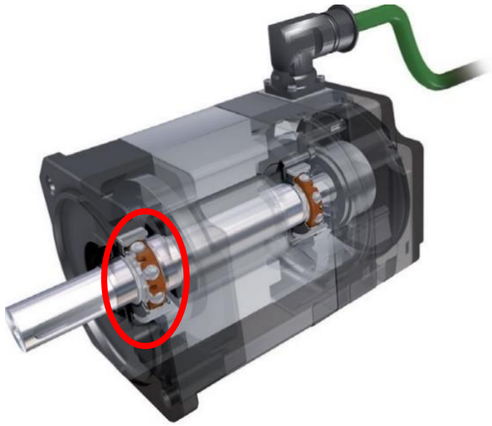
Technology Comparison

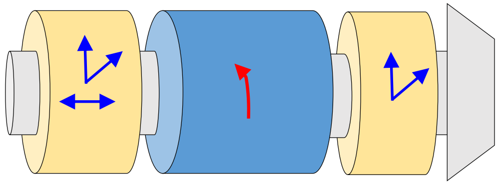


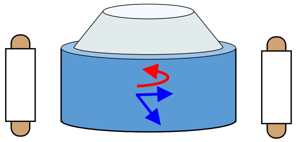
	Journal Bearing	Mag. Bearing Motor System	System with Bearingless Tech
Peak force	--	2.5 × Rated Force	20+ × Rated Force
System axial length	Baseline	> Baseline	20-30% Shorter than AMB Solution
# of Major Components	3	3	2
Motor drive (VFD)	Standard	Standard	Custom
Oil-Free / Zero Maintenance	No	Yes	Yes

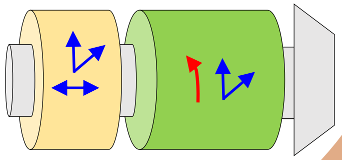
Bearingless motors can solve key challenges of mag. bearings

Motor Bearing Technology









Ball bearings &
Hydrodynamic journal bearings

+ Mature technology
- Oil interference
- Reliability / lifetime issues

Magnetic Bearings

+ Oil-Free
+ Zero maintenance
+ Low vibration
+ Health monitoring
- Increased axial length
- Difficult to integrate
- Long product dev. timeline

★ ***Small Bearingless Motors***

+ All benefits of mag bearings
+ Extreme peak force
+ Reduce axial length
+ Fewer components
- Limited power range
- Limited motor performance

?

Ongoing research focusing on these challenges

1988 2001 2023

1988: First ISMB!

2001: Levitronix is formed

Conclusion

- Bearingless concept proven at small-scale
- Feasibility studies indicate potential of this technology
- The time is right: supporting technologies rapidly maturing