ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

The use of FEM tools for the design, control and optimization of high-speed electrical drives

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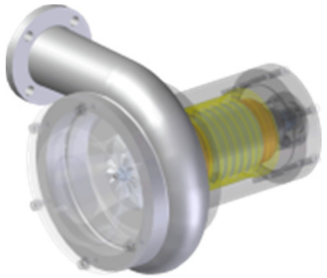
Outline

- Ultra-high-speed drive systems
  - Applications
  - Machine design
  - Drive strategies
- Lateral stator machine
  - Applications
  - Modeling and optimization
  - Active torque ripple compensation
- Airborne wind turbines
- Conclusions

Ultra-high-speed drives

➢ Application areas

Application areas



Turbocompressors
(fuel cells, turbochargers,
cryogenics)

Heating, ventilation and
air conditioning

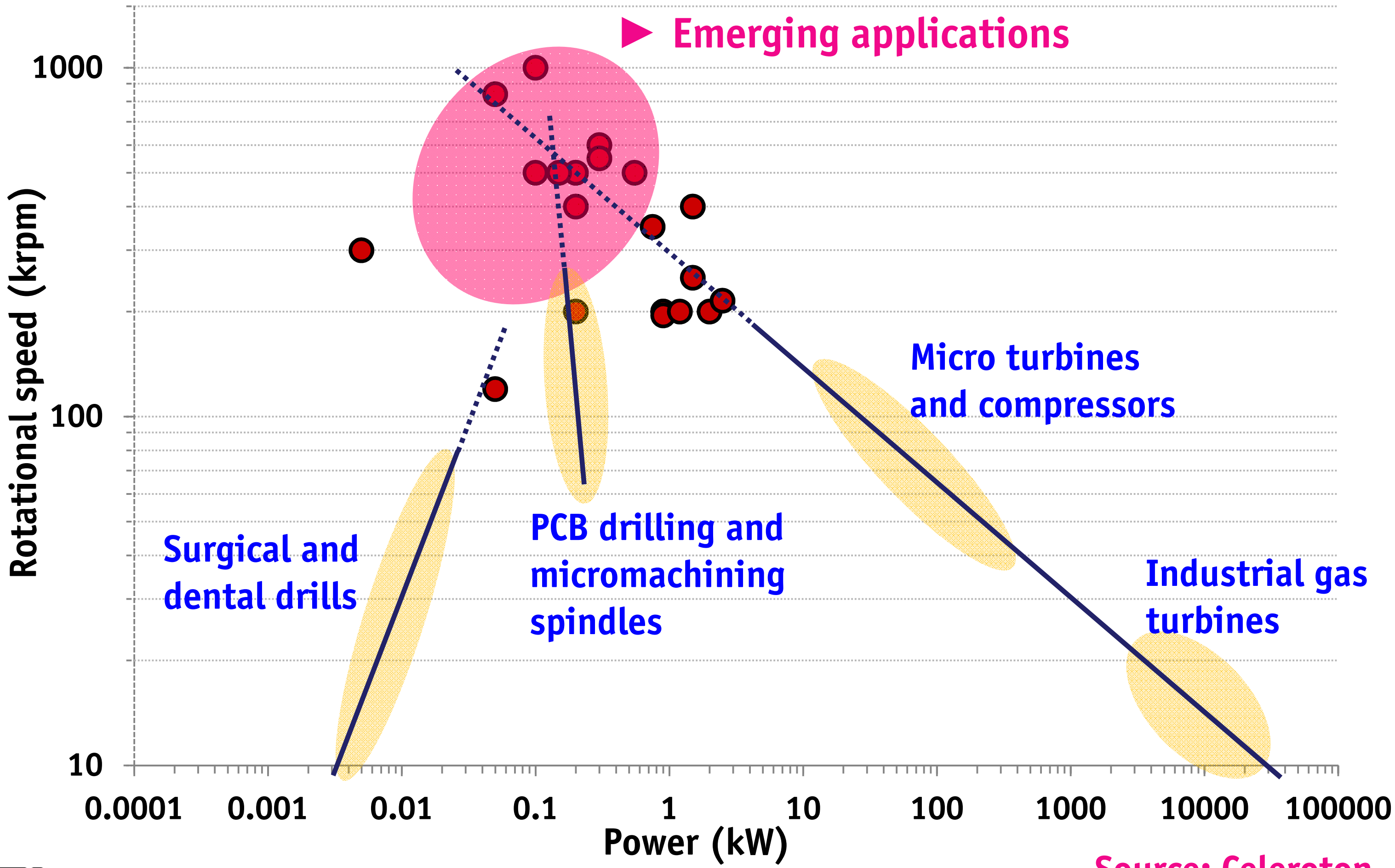
Satellite
reaction wheels

Surgical and dental
drills

Drilling spindles

Optical scanning
systems

Application areas

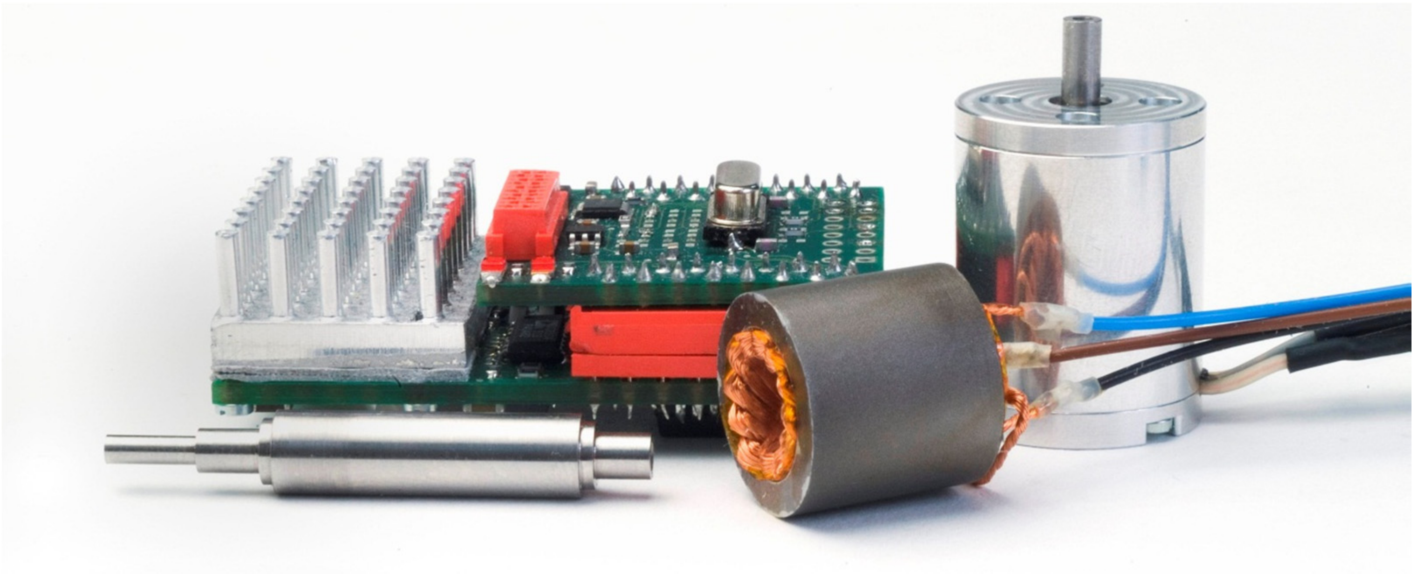


Source: Celeroton

Ultra-high-speed drives

➢ Application examples

Application examples

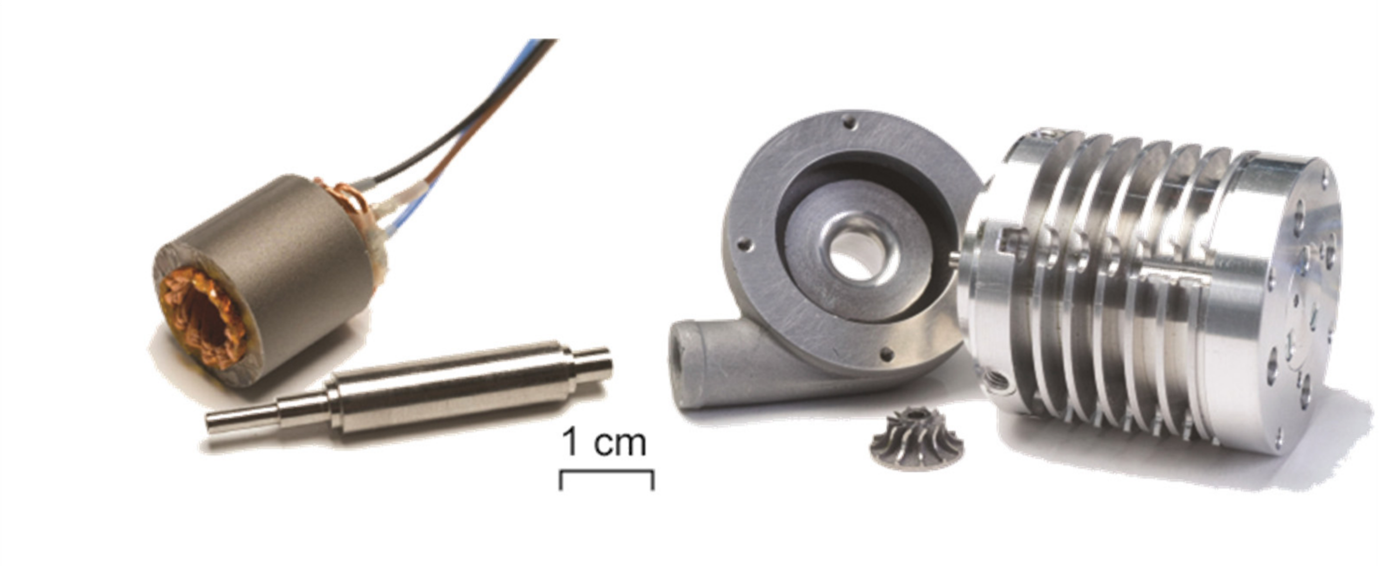


► World Record !

100 W @ 1‘000‘000 rpm

C. Zwyssig, J. W. Kolar, S. D. Round, "Megaspeed Drive Systems: Pushing Beyond 1 Million r/min," IEEE/ASME Trans. on Mechatr., vol.14, no.5, Oct. 2009

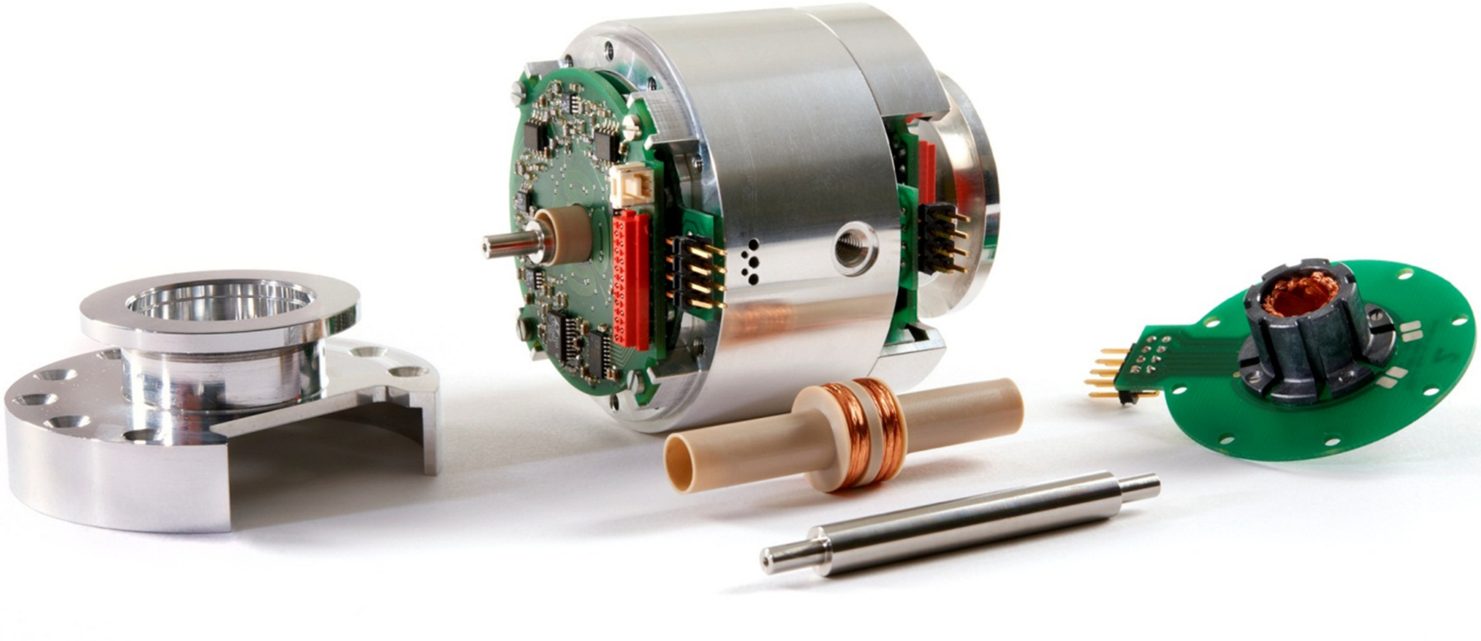
Application examples



► 500 000 rpm, 150 W Turbocompressor

C. Zwyssig, J. W. Kolar, S. D. Round, "Megaspeed Drive Systems: Pushing Beyond 1 Million r/min," IEEE/ASME Trans. on Mechatr., vol.14, no.5, Oct. 2009

Application examples



► World Record !

Magnetic bearing, 500 krpm

T. Baumgartner, J. W. Kolar, "Multivariable state feedback control of a
500 000 rpm self-bearing motor," IEEE IEMDC, 12-15 May 2013

Ultra-high-speed drives

➢ Machine design

Slotless Motor Design

Robust and simple rotor geometry

- ► One-piece cylindrical magnet
- ► Retaining titanium sleeve
- ► Interference fit

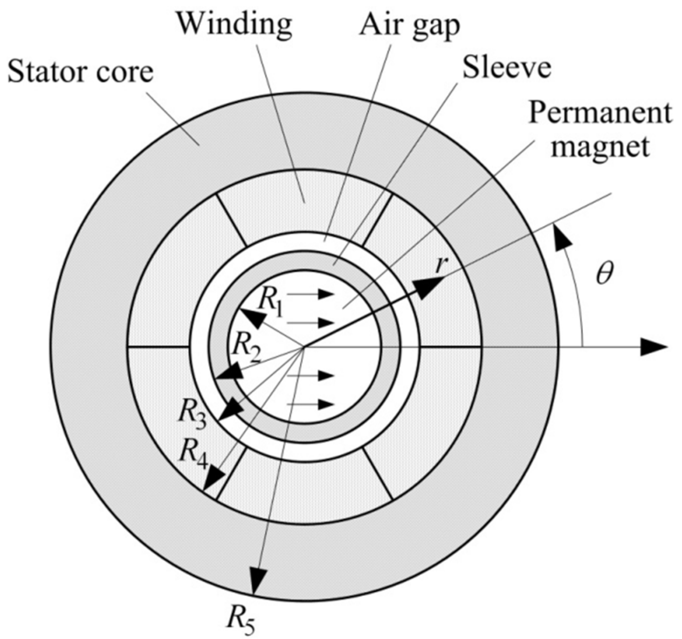
Lowest fundamental frequency

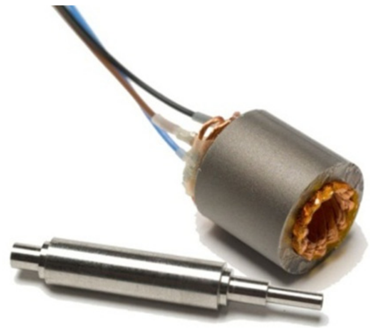
- ► 2 pole rotor
- ► 500 000 rpm -> 8.3 kHz

Low stator losses and simple construction

- ► 3-phase slotless litz wire winding
- ► Amorphous iron stator core

Low rotor losses low current reaction





C. Zwyssig, J. W. Kolar, S. D. Round, "Megaspeed Drive Systems: Pushing Beyond 1 Million r/min," IEEE/ASME Trans. on Mechatr., vol.14, no.5, Oct. 2009

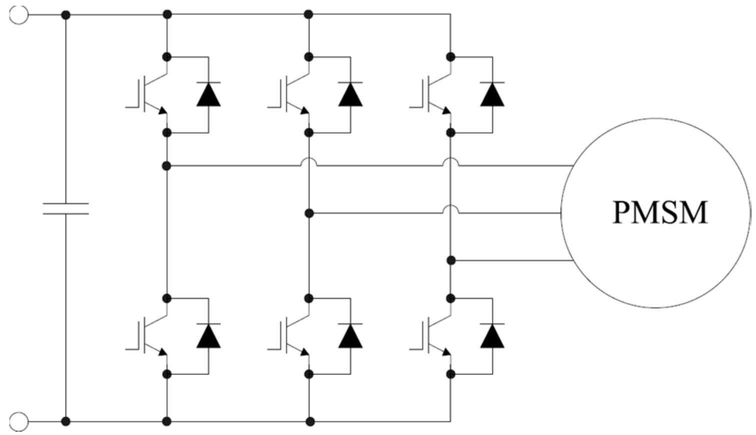
Ultra-high-speed drives

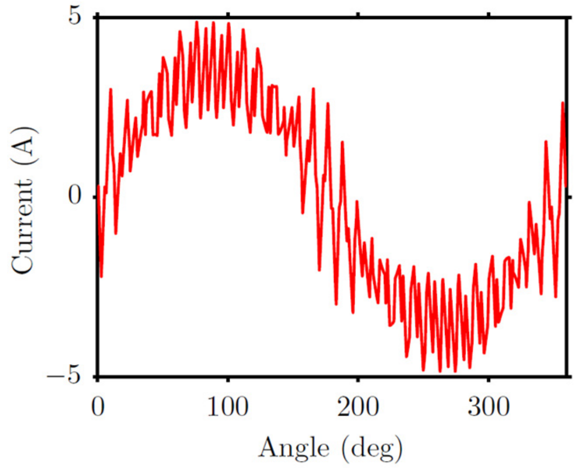
➢ Drive strategies

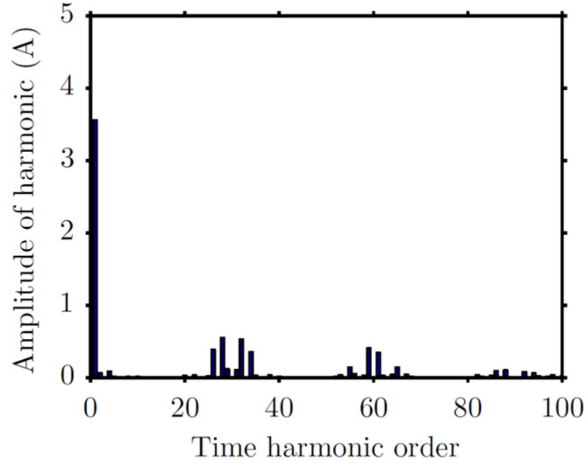
Drive strategies

Pulse-Width-Modulation (PWM)

- Only three-phase inverter
- Switching frequency > fundamental frequency
- High switching losses
- High current control bandwidth requirement

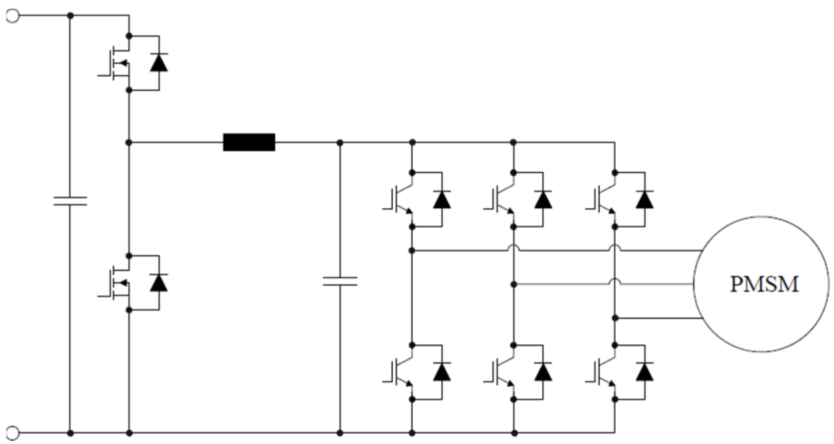






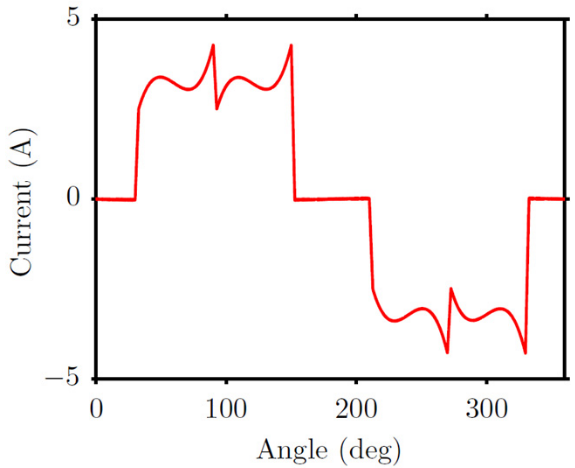
L. Schwager, A. Tuysuz, C. Zwyssig, J. W. Kolar, "Modeling and Comparison of Machine and Converter Losses for PWM and PAM in High-Speed Drives," IEEE Trans. on. Ind. Appl. vol.50, no.2, March-April 2014

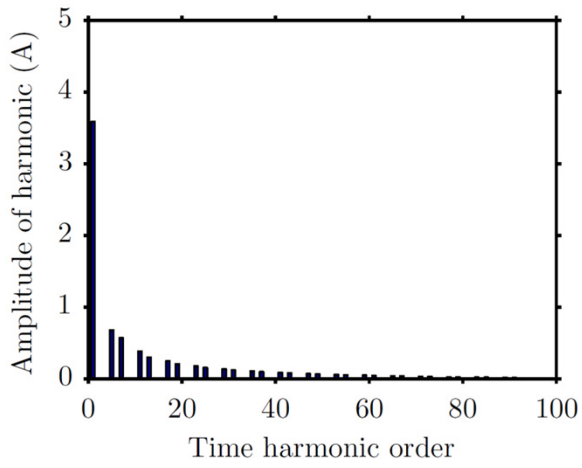
Drive strategies



Pulse-Amplitude-Modulation (PAM)

- Buck converter + three-phase inverter
- Inverter switches at fundamental frequency
- Low switching losses
- DC current control





L. Schwager, A. Tuysuz, C. Zwyssig, J. W. Kolar, "Modeling and Comparison of Machine and Converter Losses for PWM and PAM in High-Speed Drives," IEEE Trans. on. Ind. Appl. vol.50, no.2, March-April 2014

PAM or PWM, which one to use, and when?

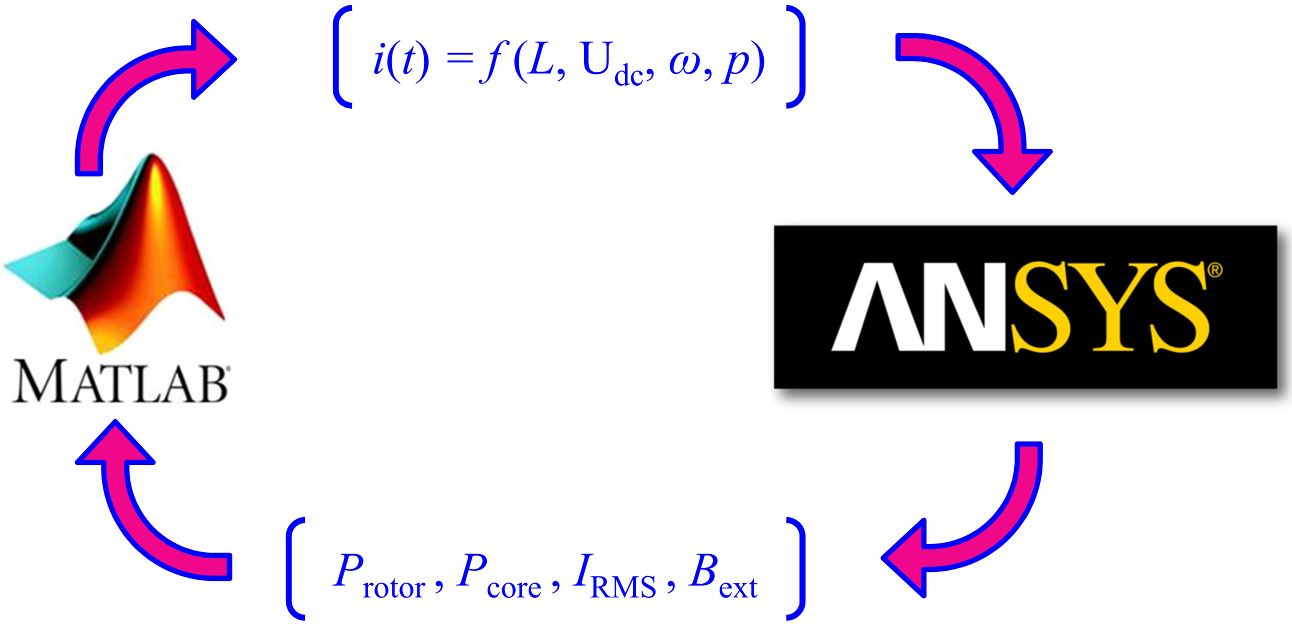
- PAM is typically used for speed above 200 krpm
- PWM is the typical industry solution up to 50 krpm

… but …

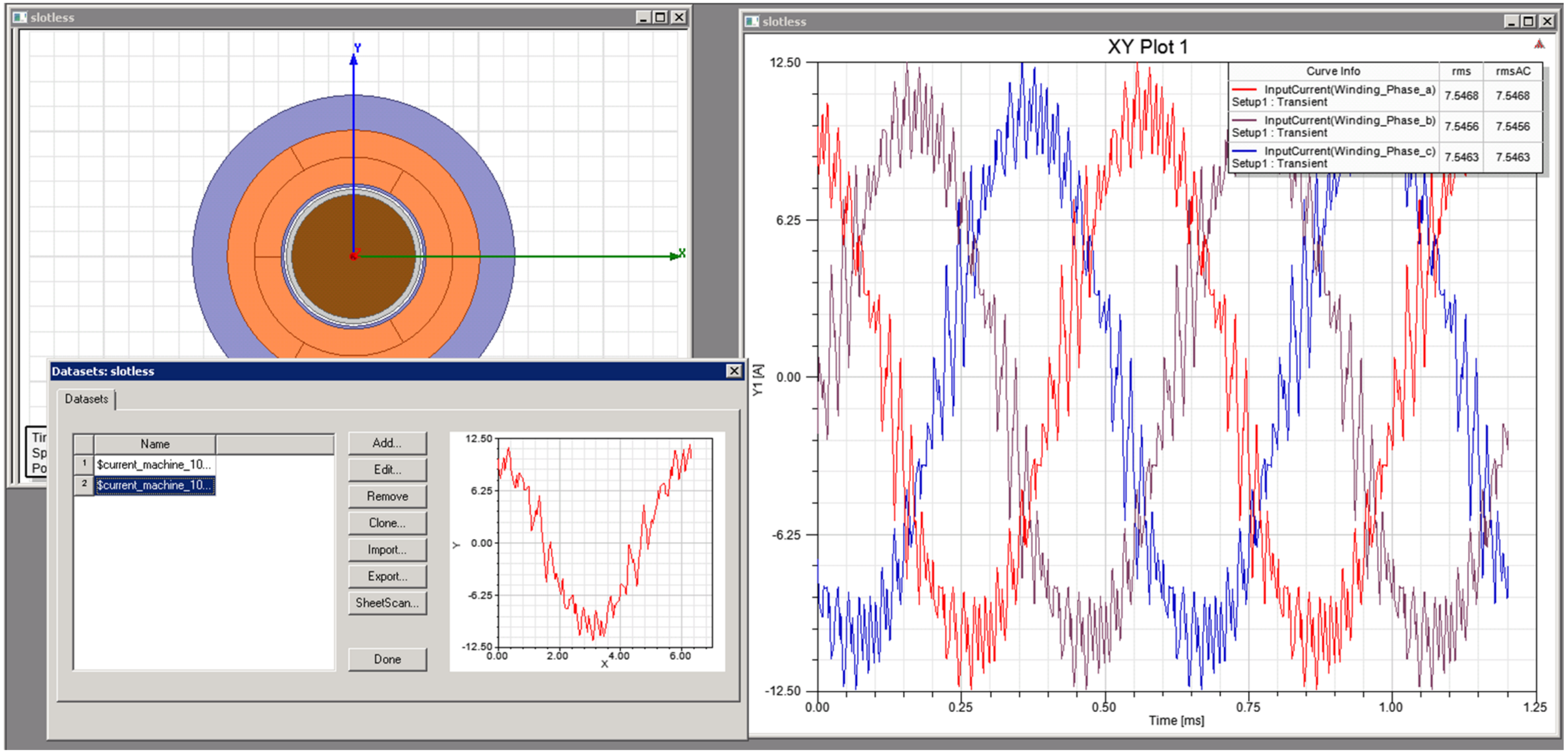
- What about between 50 – 200 krpm?
- How do PAM and PWM effect the drive system efficiency?
  - Machine losses?
  - Inverter losses?
- Do wide-band-gap (SiC, GaN) power switches change the game?

Modeling the current shape dependent machine losses

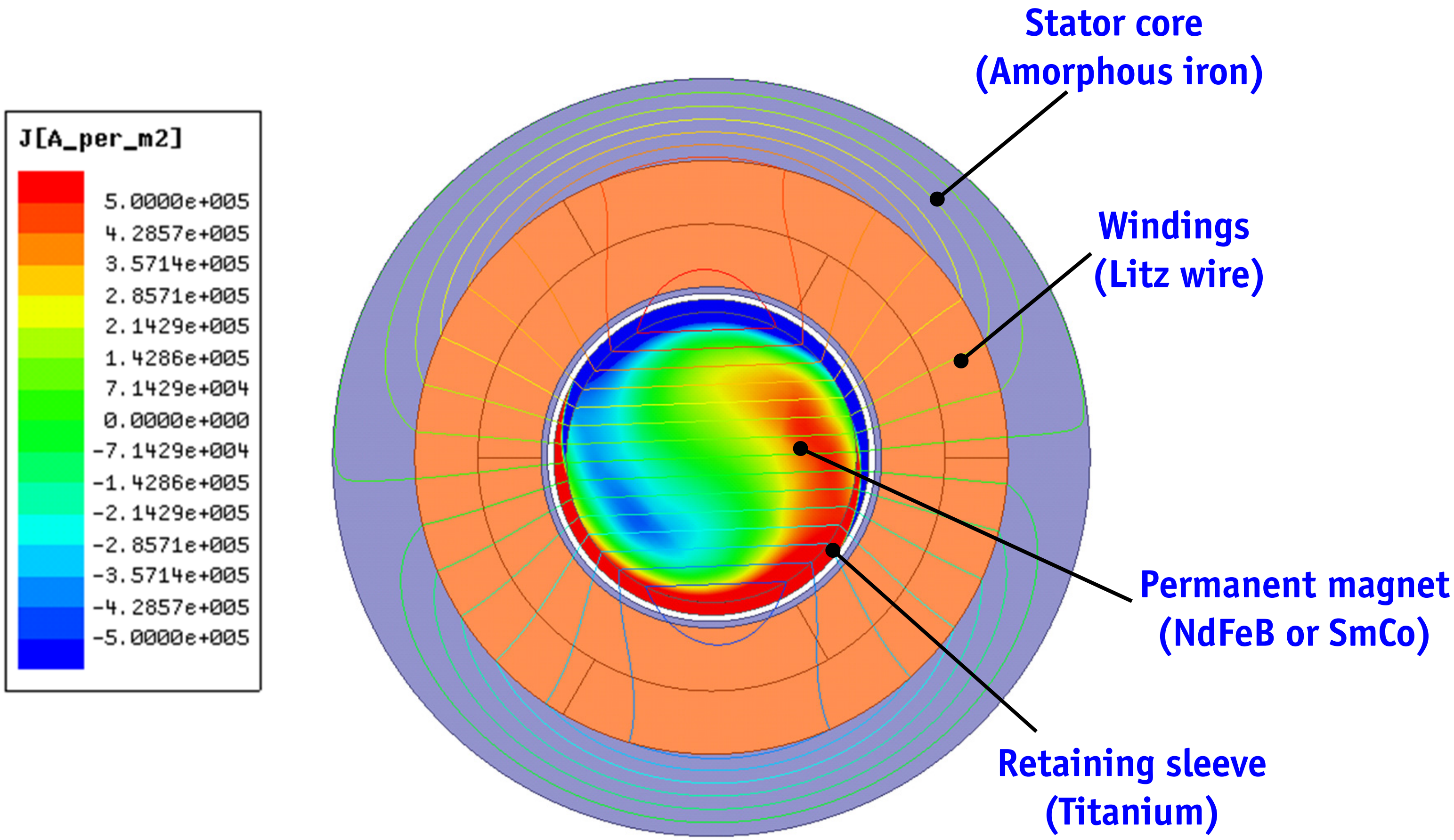
- Rotor eddy current losses
  - eddy effects, 2D
- Stator core losses
  - time domain formulation
- Copper losses (incl. skin and proximity effects)
  - RMS calculation
  - External field for proximity effect



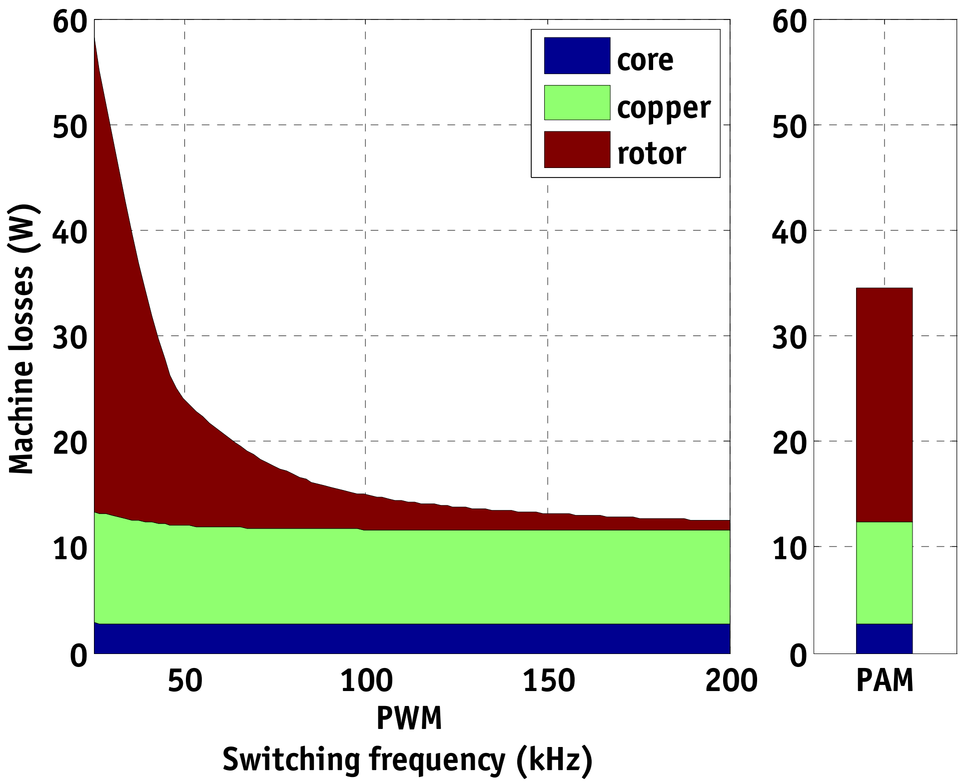
Modeling the current shape dependent machine losses



Rotor eddy current losses

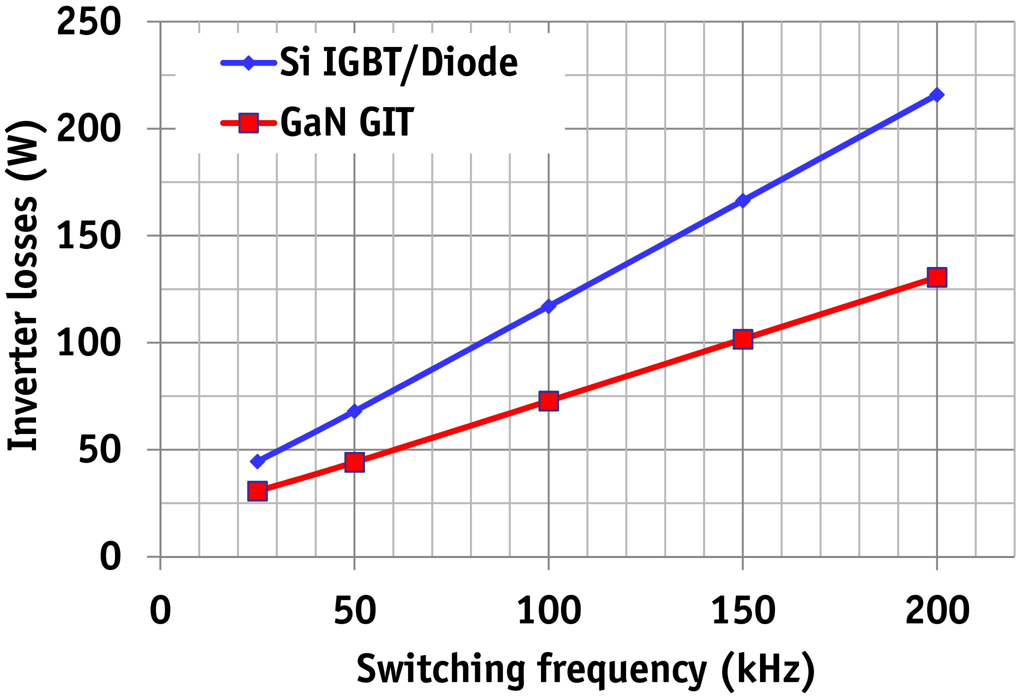


Case study: 100,000 rpm, 3 kW machine

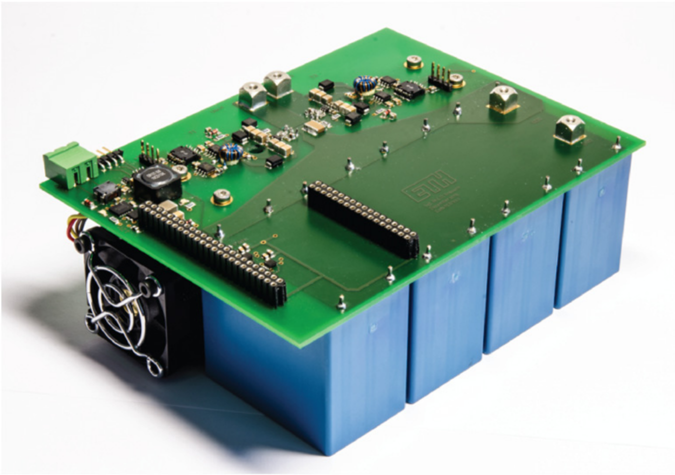


- I_{rated} = 7 A
- BEMF = 210 V (peak)
- B_{peak} = 1.2 T
- L = 130 uH

Modeling the inverter losses



- 600 V, 15 A GaN GIT
- 600 V, 15 A Si IGBT with antiparallel diode



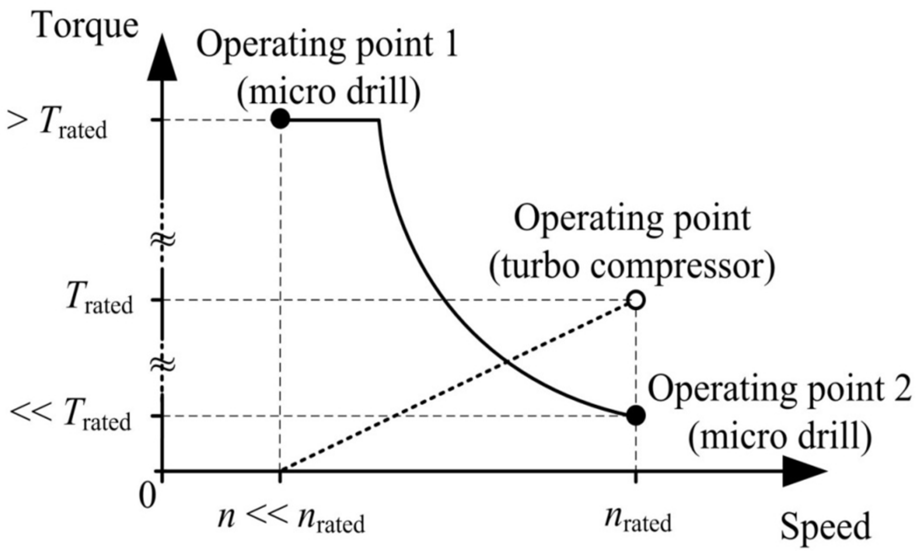
A. Tüysüz, R. Bosshard, J. W. Kolar, "Performance Comparison of a GaN GIT and a Si IGBT for High-Speed Drive Applications", IEEE ECCE Asia (IPEC), May 18-21, 2014

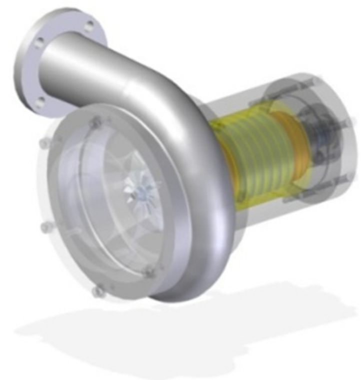
Novel Machine Topologies

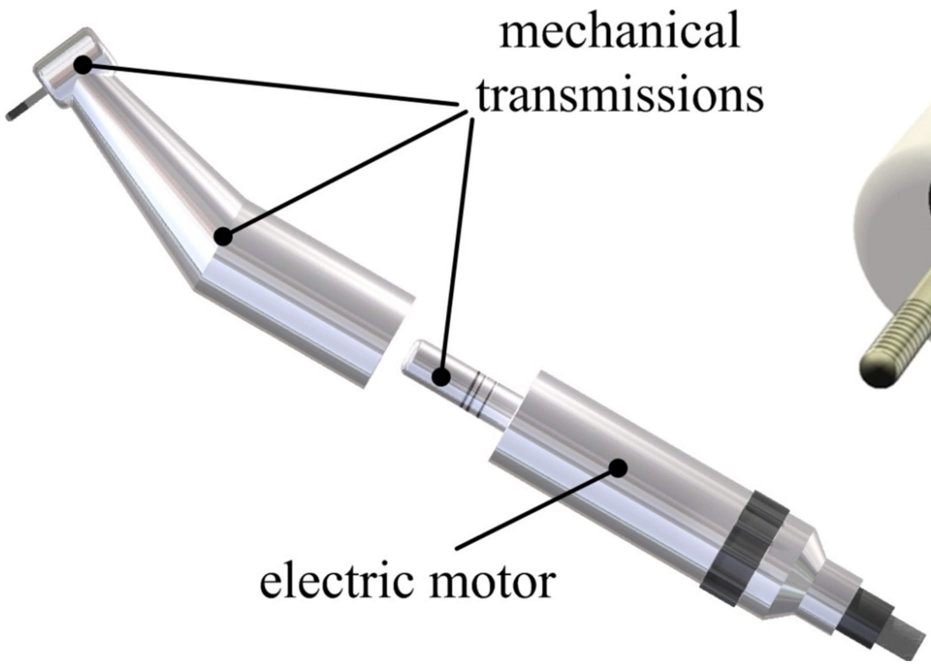
➢ Lateral stator machine

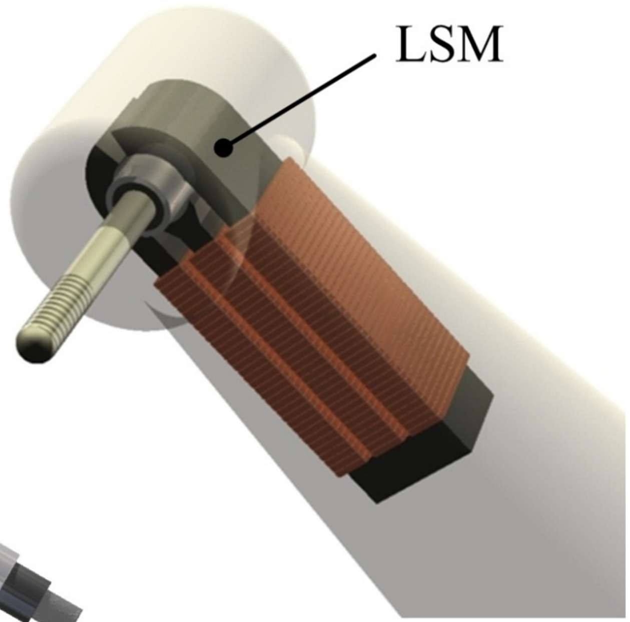
Requirements of different high-speed applications

- ▶ **Turbocompressors: Single operating point**
- ▶ **Drills – spindles: wide torque-speed range**





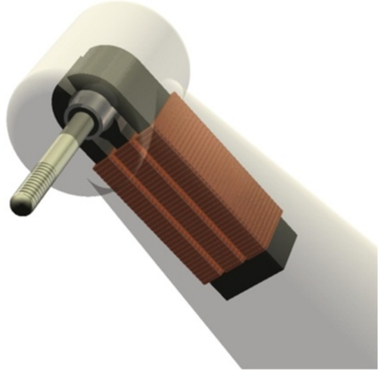




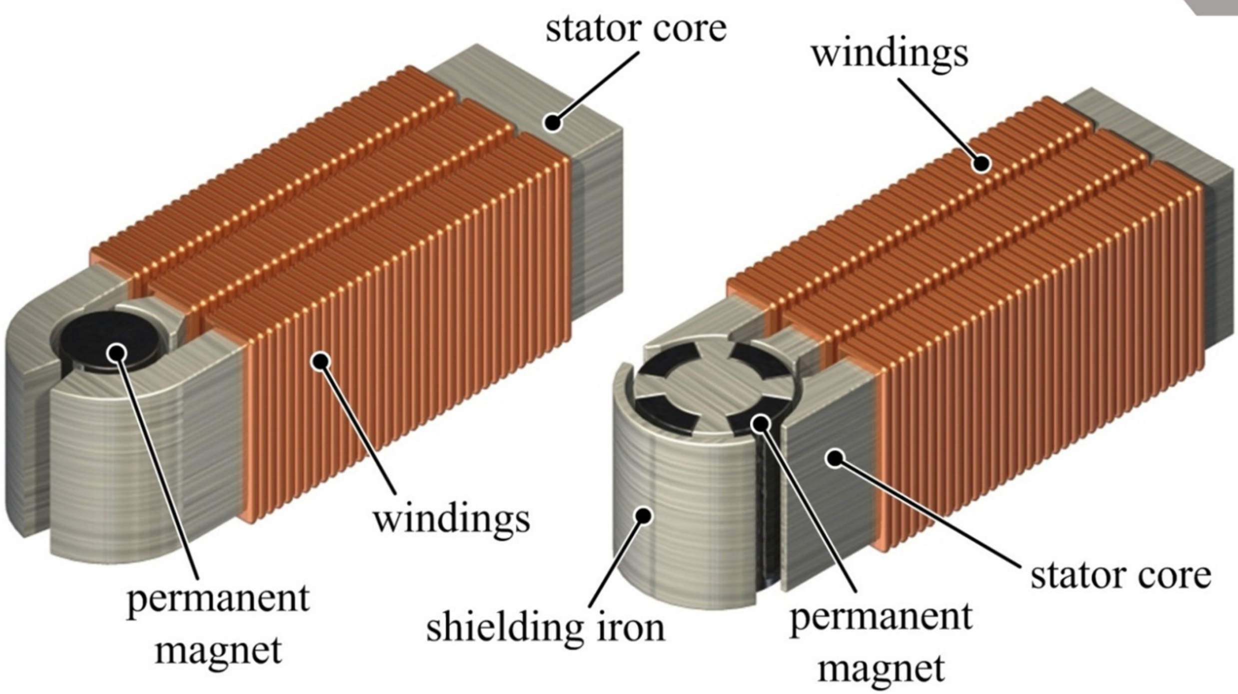
► state-of-the-art

► direct drive approach

A. Tuysuz, C. Zwyssig, J. W. Kolar, "A Novel Motor Topology for High-Speed Micro-Machining Applications," IEEE Trans. on Ind. Electr., vol.61, no.6, June 2014

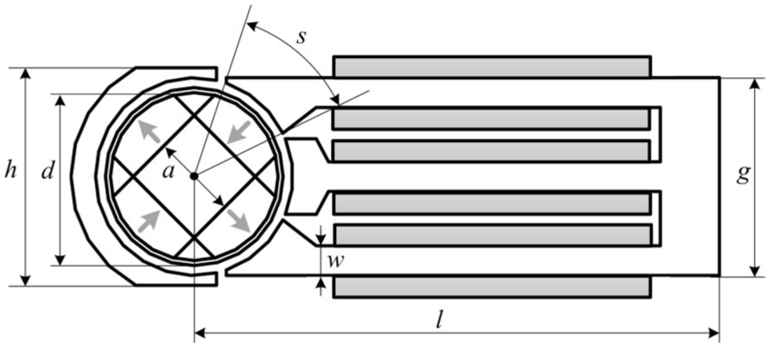


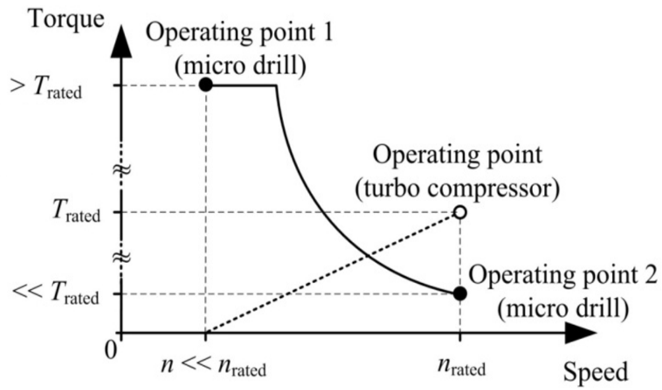
► Direct drive possible with
new machine topology



A. Tuysuz, C. Zwyssig, J. W. Kolar, "A Novel Motor Topology for High-Speed Micro-Machining Applications," IEEE Trans. on Ind. Electr., vol.61, no.6, June 2014

Geometric parametrization





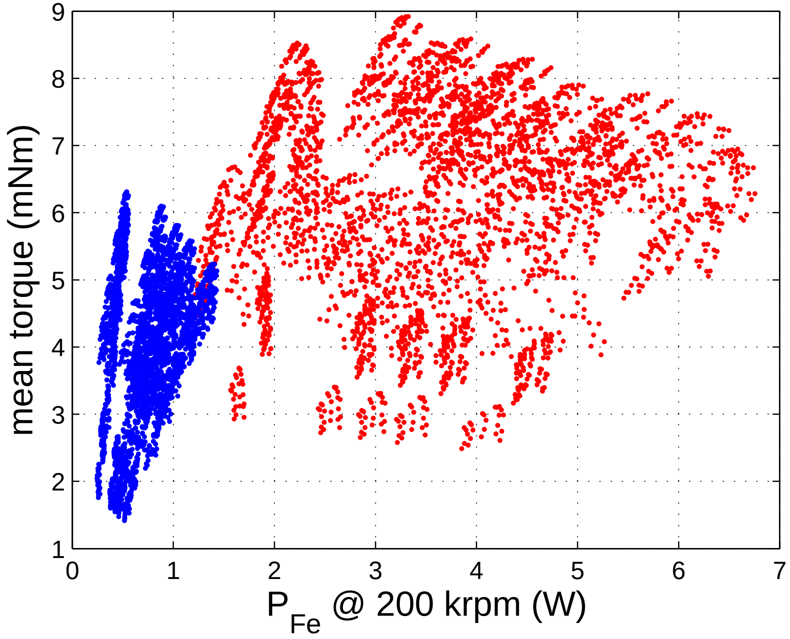
MATLAB → Geometry, materials
Operating point → ANSYS

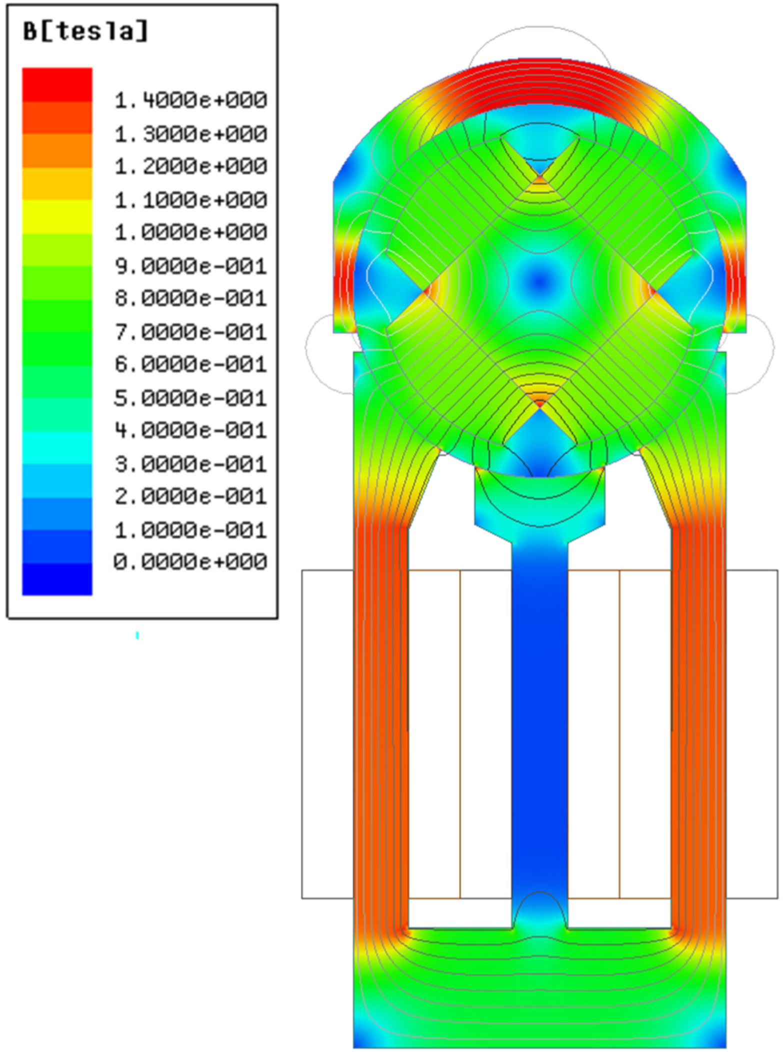
T_{mean} @ $P_{cu,max}$

$P_{no\text{-}load}$ @ n_{rated}

A. Tuysuz, C. Zwyssig, J. W. Kolar, "A Novel Motor Topology for High-Speed Micro-Machining Applications," IEEE Trans. on Ind. Electr., vol.61, no.6, June 2014

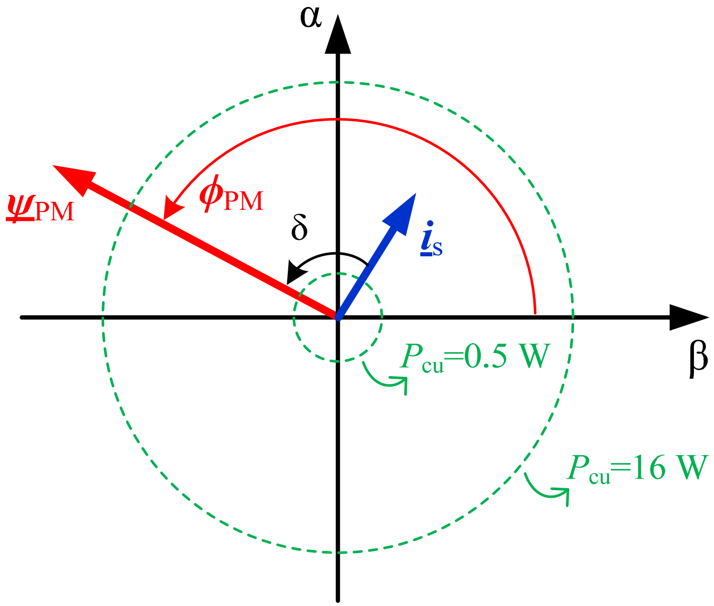
Simulation results

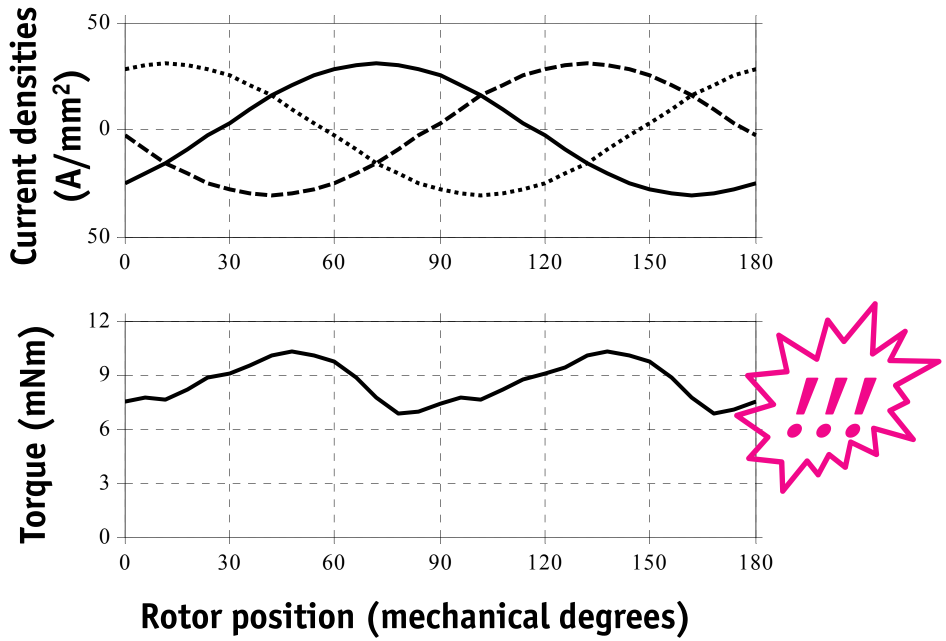




Active torque ripple compensation

► Torque ripple due to saturation, slotting, asymmetry

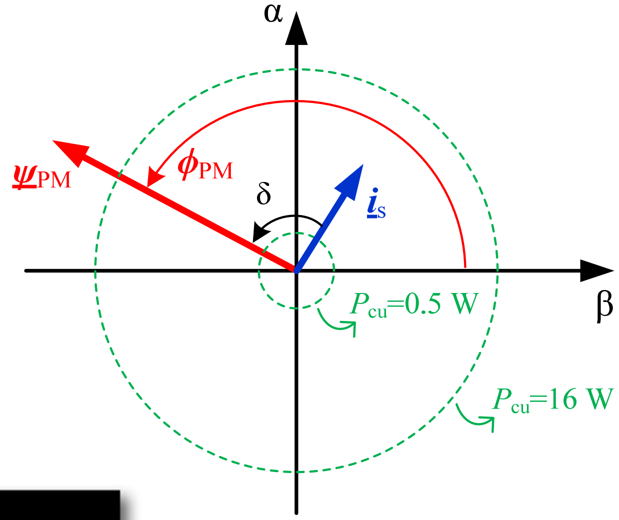


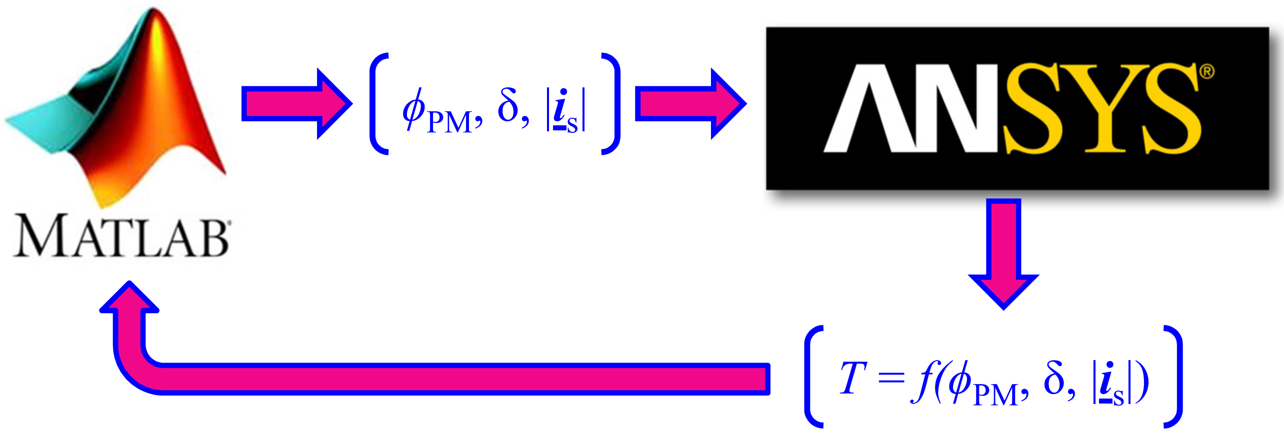


A. Tuysuz, A. Looser, J. W. Kolar, C. Zwyssig, "Novel miniature motors with lateral stator for a wide torque and speed range," IEEE IECON 2010, 7-10 Nov. 2010

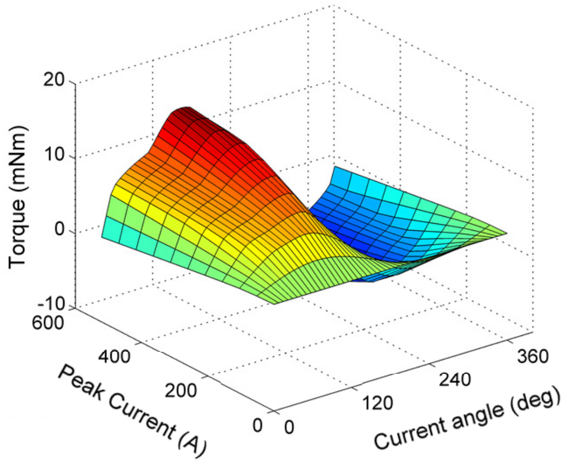
Active torque ripple compensation

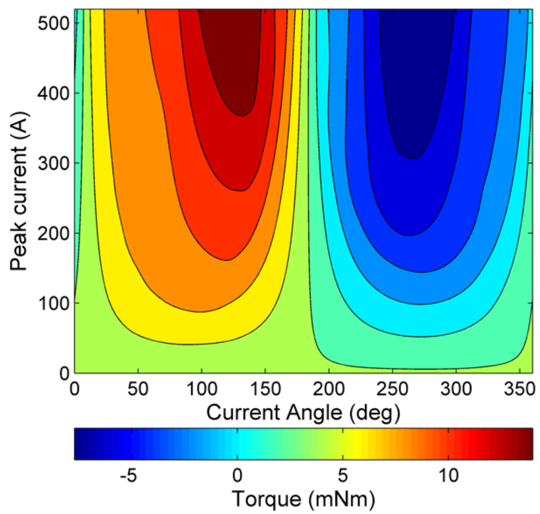
► **Matlab-Maxwell coupling used to calculate the optimum current profile**

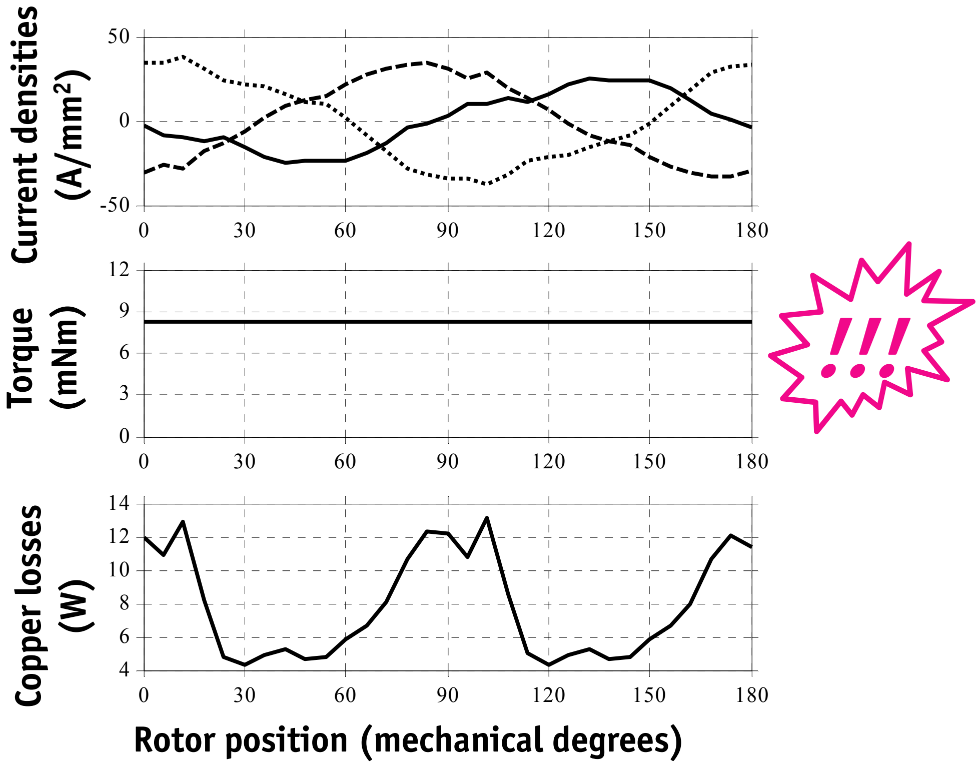




Active torque ripple compensation



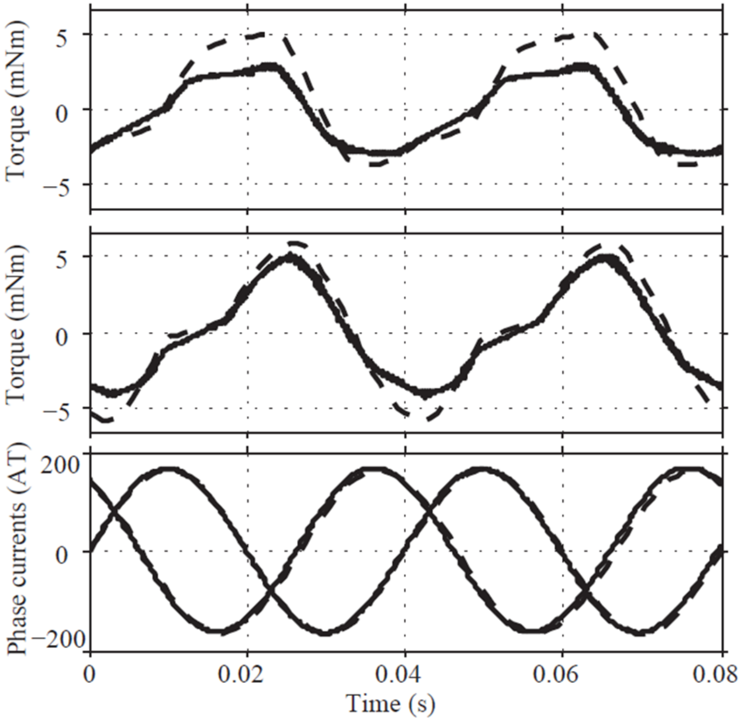




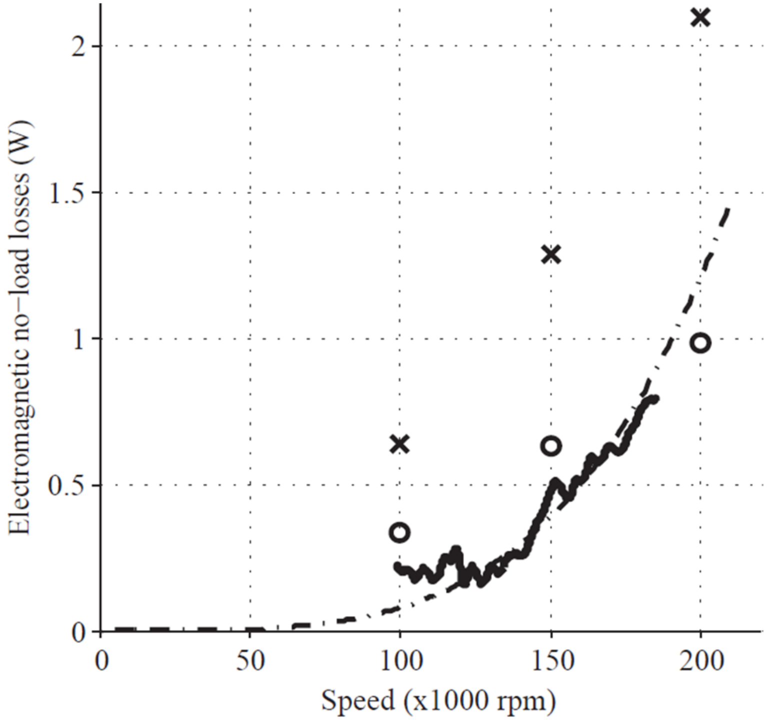
A. Tuysuz, A. Looser, J. W. Kolar, C. Zwyssig, "Novel miniature motors with lateral stator for a wide torque and speed range," IEEE IECON 2010, 7-10 Nov. 2010

Accuracy of models – experimental verification

▶ Standstill torque measurement



▶ No-load loss measurement



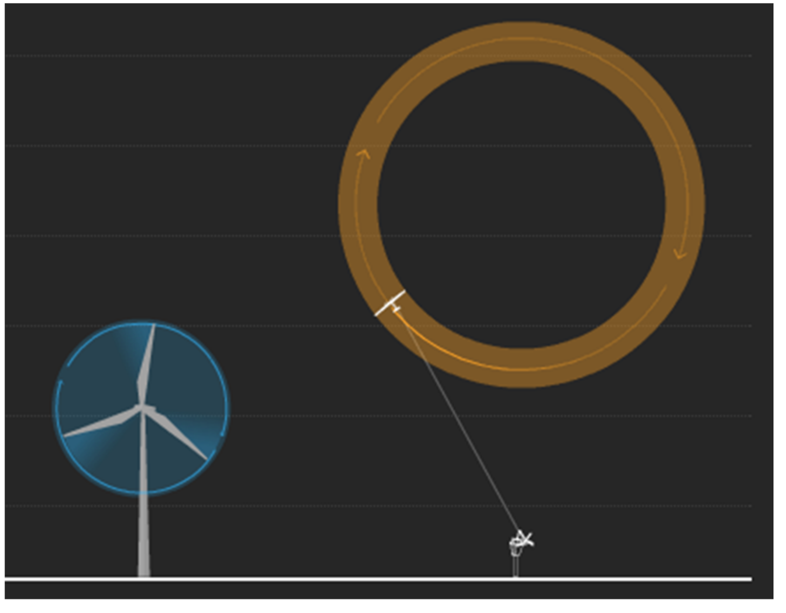
A. Tuysuz, C. Zwyssig, J. W. Kolar, "A Novel Motor Topology for High-Speed Micro-Machining Applications," IEEE Trans. on Ind. Electr., vol.61, no.6, June 2014

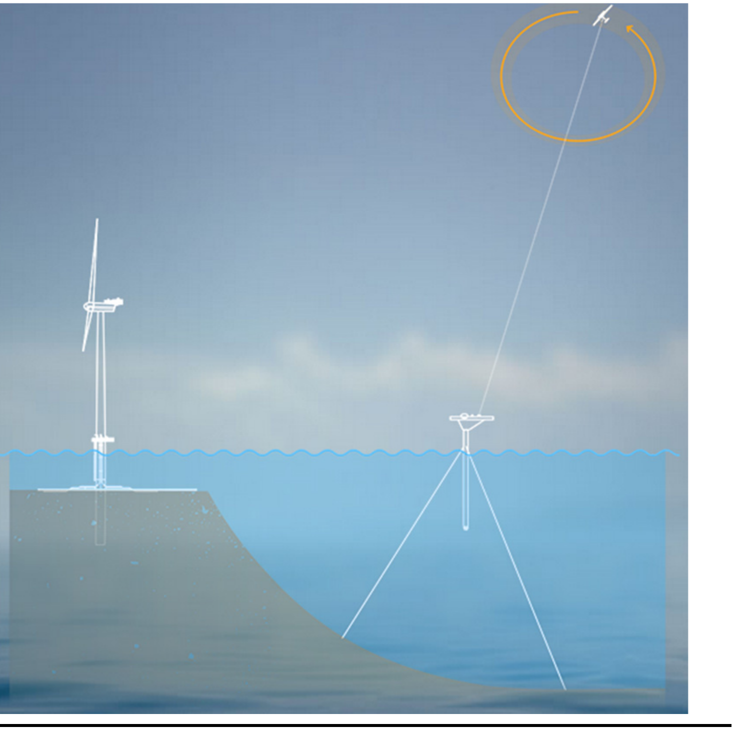
Airborne Wind Turbines

➢ Power density vs. efficiency

Airborne wind turbines

- Less material
- Cheaper
- Higher altitude winds

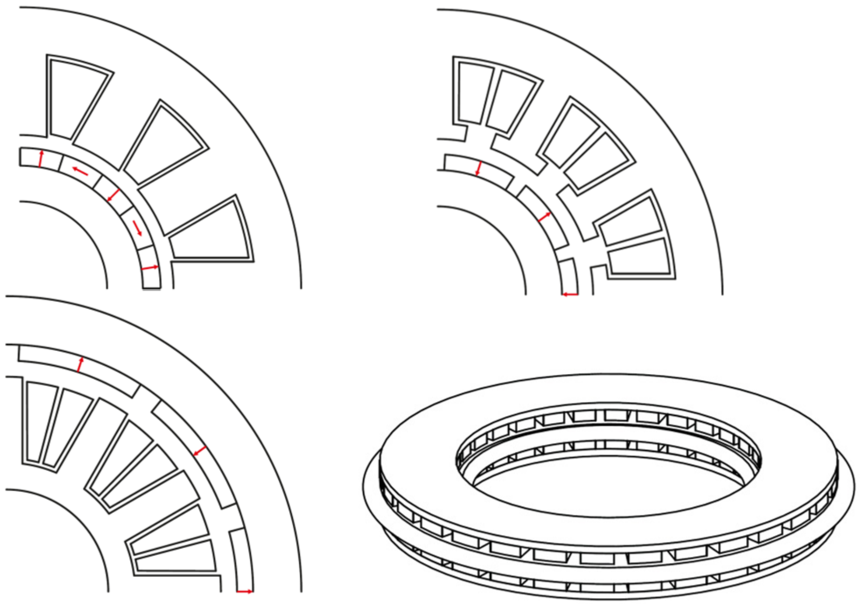


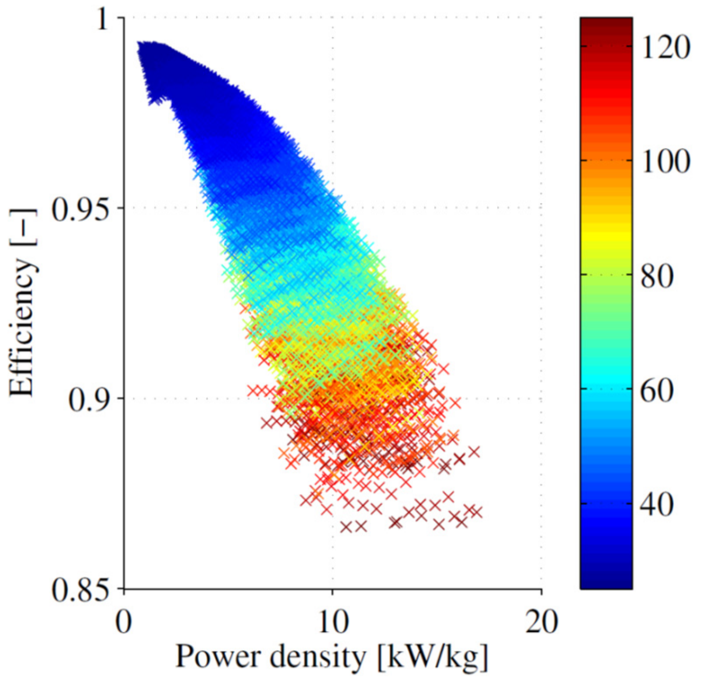


Source: Makani
google.com/makani/

Weight and efficiency optimized electrical machine

- Several different PM machine topologies
- Analytic models offer very high speeds and insight
- FEM offers high accuracy

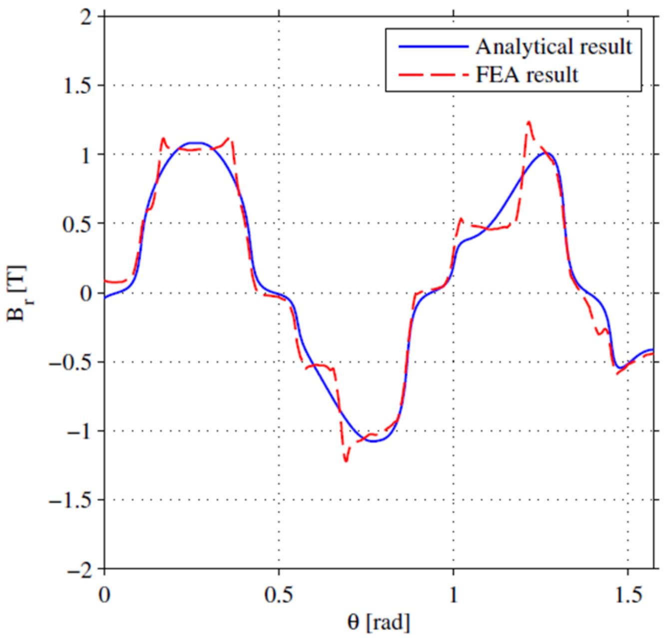


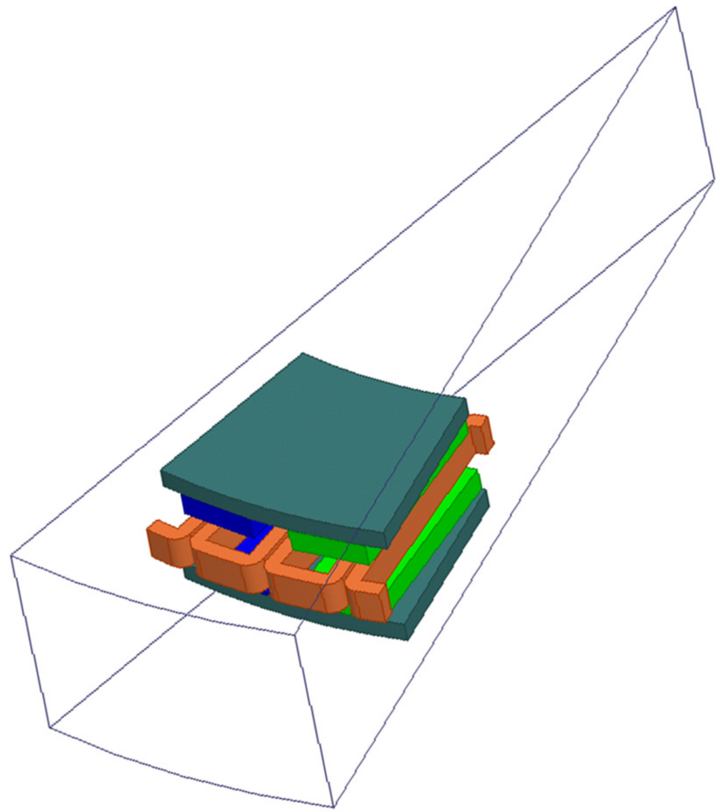


C. Gammeter, Y. Drapela, A. Tuysuz, J. W. Kolar "Weight Optimization of a Machine for Airborne Wind Turbines," IEEE IECON 28 Oct. – 1 Nov. 2014

Weight and efficiency optimized electrical machine

- FEM is used for
  - verification of analytic models
  - fine tuning – final design

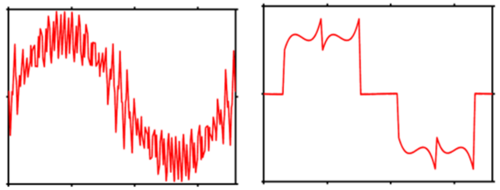




Y. Drapela, "Design and Construction of a Weight Optimized Electric Machine," Master's Thesis at Power Electronic Systems Lab., ETH Zurich, 2013

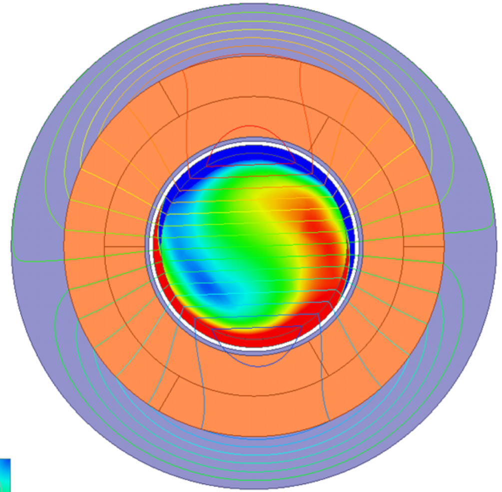
Conclusions

Conclusions



Ultra-high-speed drive systems

- Applications
- Machine – inverter interaction
- Loss models taking modulation into account

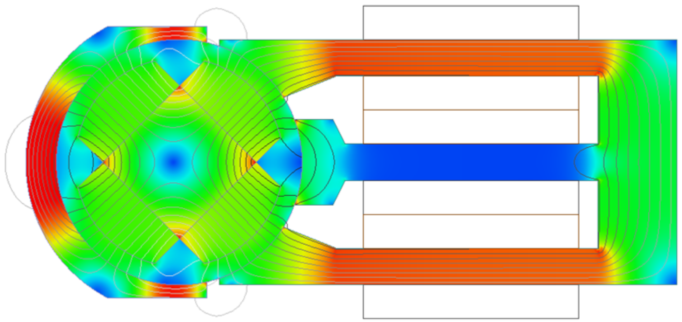


Lateral stator machine

- Geometric parameterization
- Active-torque ripple compensation

Benefits of Matlab-Maxwell coupling

Airborne wind turbines



Acknowledgement

The authors would like to thank ANSYS customer portal and support engineers

Questions ?