Innovative Low-Cost Sub-Fractional HP BLDC Claw-Pole Machine Design for Fan Applications

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Christian Doppler Laboratory for Brushless Drives for Pump and Fan Applications
Electric Drives and Machines Institute, TU Graz

What We Will Be Discussing

- Context
- Motivation
- The Design
- Auxiliary Teeth and Stator Claw Skewing
- Manufacturing Imperfections, Design Parameters, and Radial Magnetic Forces
- Experimental Challenge: Investigations with a Rheometer
- Final Comments

Context

City of Graz

United States Central Intelligence Agency - CIA World Factbook, public domain, https://commons.wikimedia.org/w/index.php?curid=19007

Both pictures
© Graz Tourismus
- Harry Schiffer

Graz University of Technology

Students

- Total: 13 375 (winter term 2018)
- New admissions: 2 007 (winter term 2018)
- Graduations: 2 003 (academic year 2017/18)

Staff (31.12.2018)

- Total: 3 485
- Scientific: 2 490, of which 1 018 third-party funded.
- Nonscientific staff: 995, of which 329 third-party funded.

Campus Alte Technik
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Christian Doppler Laboratory for Brushless Drives for Pump an Fan Applications

- Austrian funding scheme to fund application-oriented fundamental research.
- Laboratory established in April 2016.
- Since its establishment, the lab's team has grown to three PhD. students, two current master students, and its head of laboratory.
- The industrial partner MSG was founded in June 2005.
  - 250 members of staff and 75 million Euro turnover in 2018.
  - Offers customized mechatronic systems with a special focus on actuator and sensor systems produced on its own highly innovative and versatile production lines.

Motivation

Research Motivation 1/2

- Small low-cost motors typically have suboptimal designs ($)
  - Single-phase instead of three phase
  - Starting difficulties (remedy: asym. air-gap)
  - Large manufacturing tolerances
- More than 100 of such drives within a typical mid-sized car; increasing.
  - Includes performance-, safety-, and comfort-related drives.
  - Around 10 % are used as parts of pumping and fan systems.

Research Motivation 2/2

- "Small drives," i.e., fractional horsepower (FHP), where volume, mass, and efficiency have so far only been attributed secondary importance.
- Focus: auxiliary drives used within the fan and pump systems of automotive applications.
- Renewed interest not only in the "conventional" performance parameters of these small drives, such as energy conversion efficiency, size, and cost, but also in electromagnetic emission, noise, and fault tolerance.

The Design

Research Motivation

- Sub-FHP drives are cost driven.

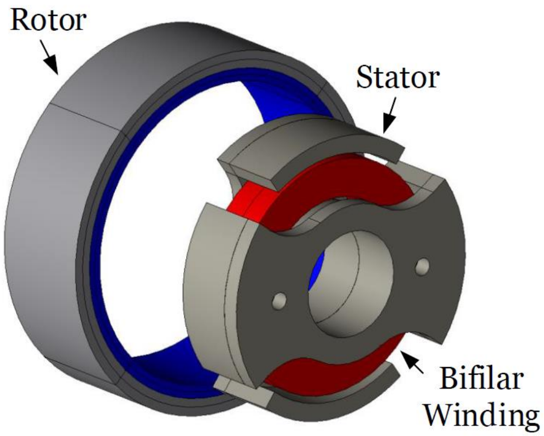
  This results in suboptimal motor behavior
  - Single-phase instead of three-phase motors
  - Fluctuating power and torque
  - High cogging torque (possible noise source, but cogging torque reduction is expensive)

Aim:

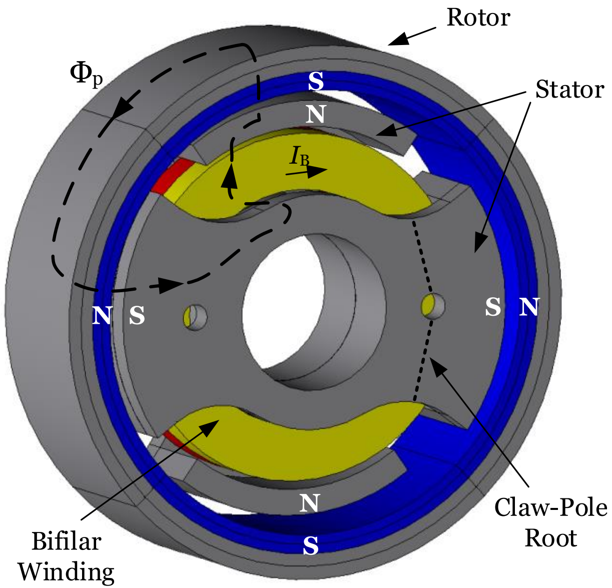
Cogging torque reduction with little/no increase in manufacturing cost.

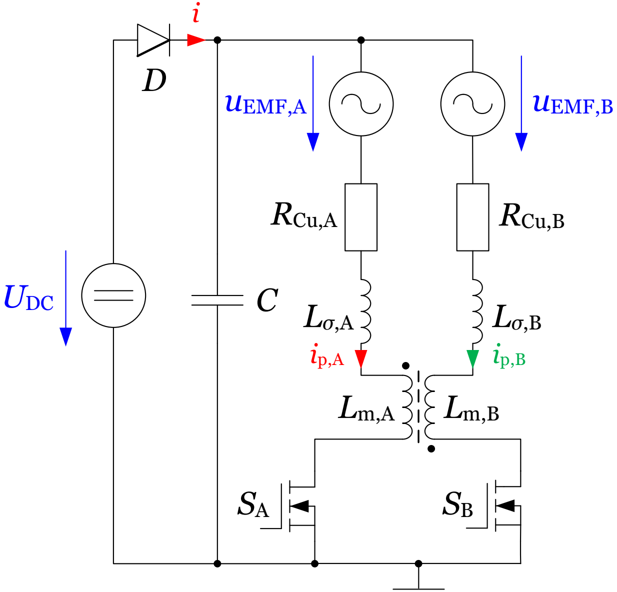
The Claw-Pole Motor

- Outer-rotor
- Single-phase
- Bifilar ring winding
- Low-cost
- Deep-drawn stator parts
- Air-gap asymmetry (for starting)
- Sub-fractional HP (approx. 1W)
- Application: automotive fan



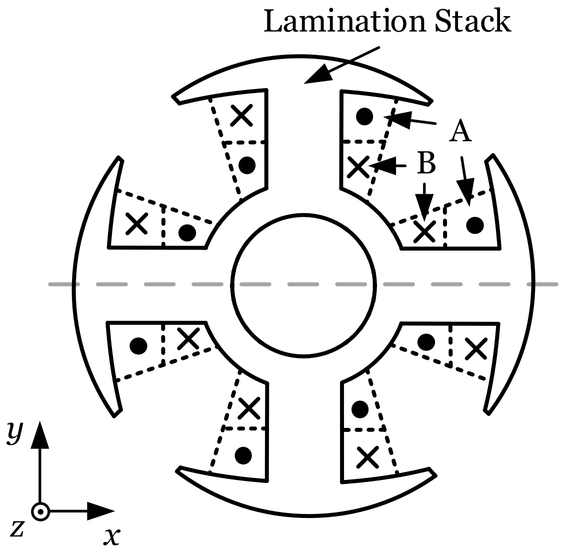
BLDC Claw-Pole Motor Drive Topology

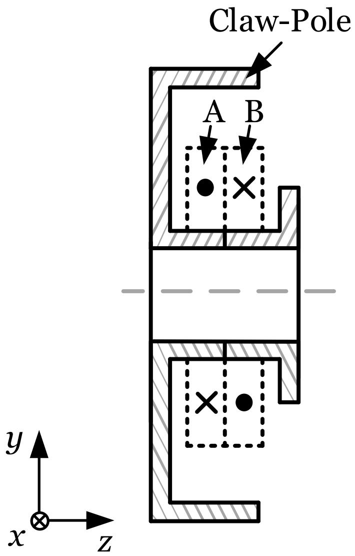




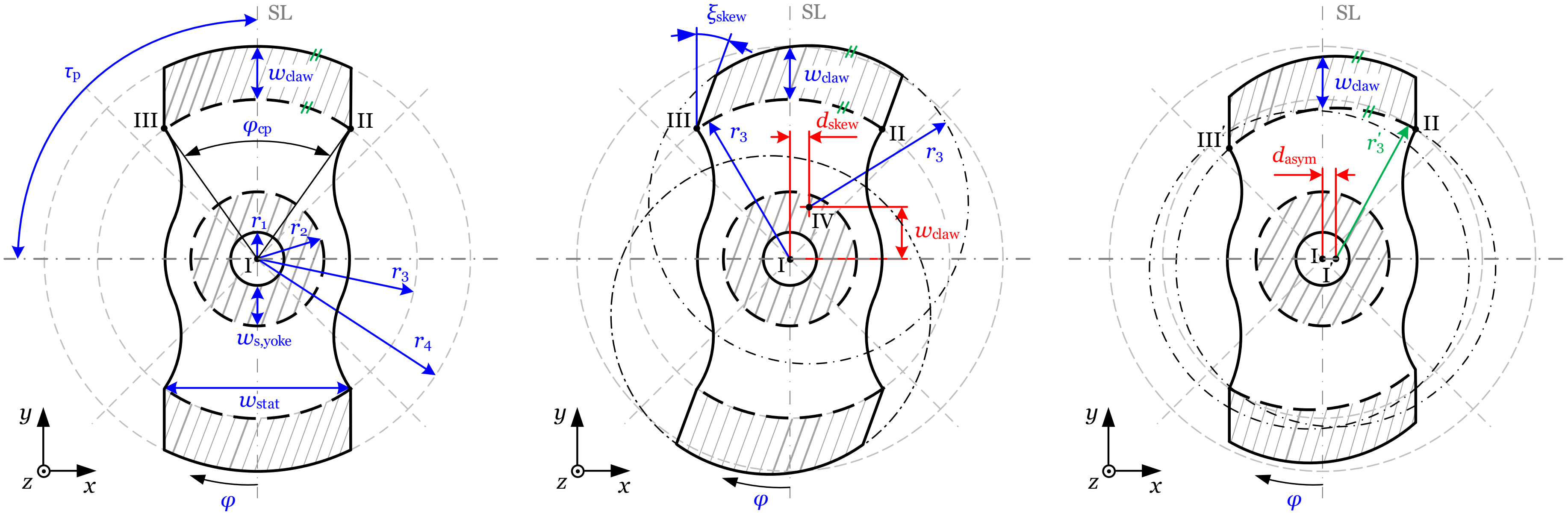
Winding Comparison

4 windings on 4 salient poles versus 1 global ring winding





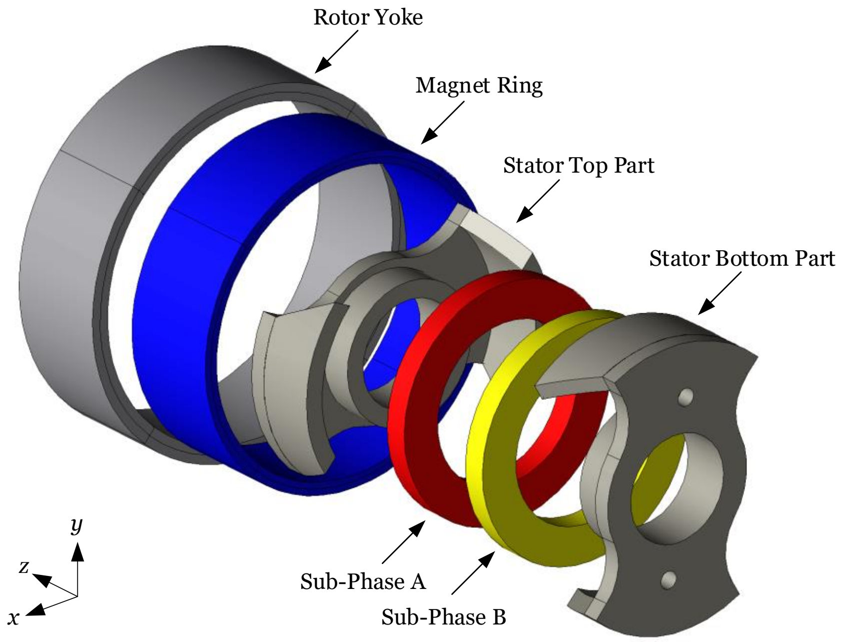
Steel Sheet Layouts for Punching and Deep-Drawing



Stator Claw Skewing

Skewing angle of 30º reduces the

- Cogging torque peak-to-peak value by 23% (sim.) and 28% (exp.)
- Back-EMF fundamental by 1.7% (sim.) and 1.9% (exp.)

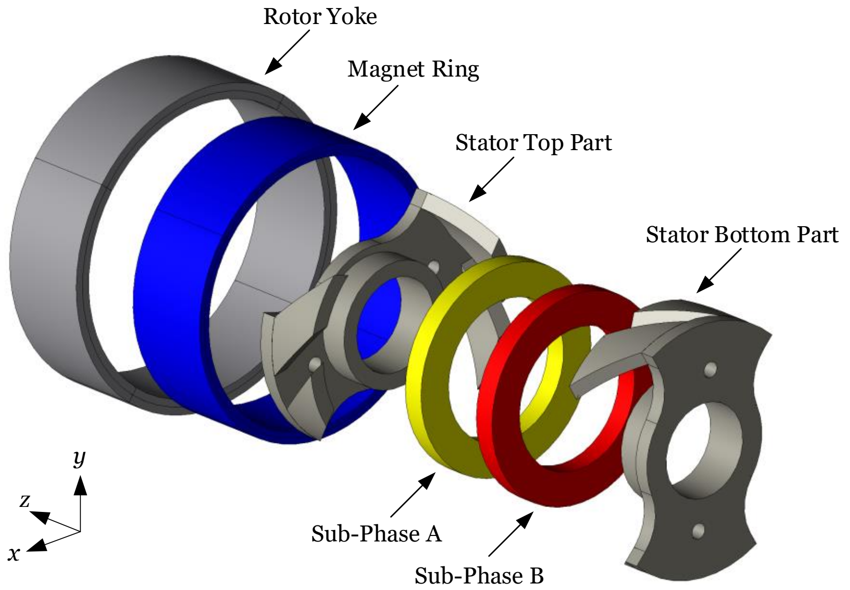


Auxiliary Teeth and Stator Claw Skewing

Auxiliary Slots and Claw Skewing

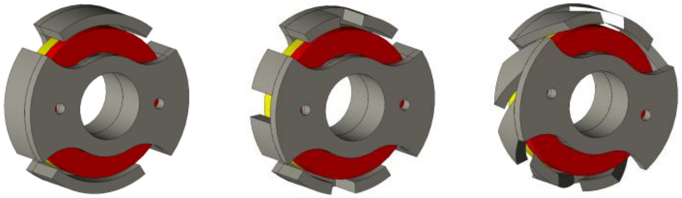
Auxiliary slots and a skewing angle of 45º reduces the

- Cogging torque peak-to-peak value by 70% (sim.) and 70% (exp.)
- Back-EMF fundamental by 12% (sim.) and 12.3% (exp.)
- 3pp reduction in efficiency (from 36% to 33%)

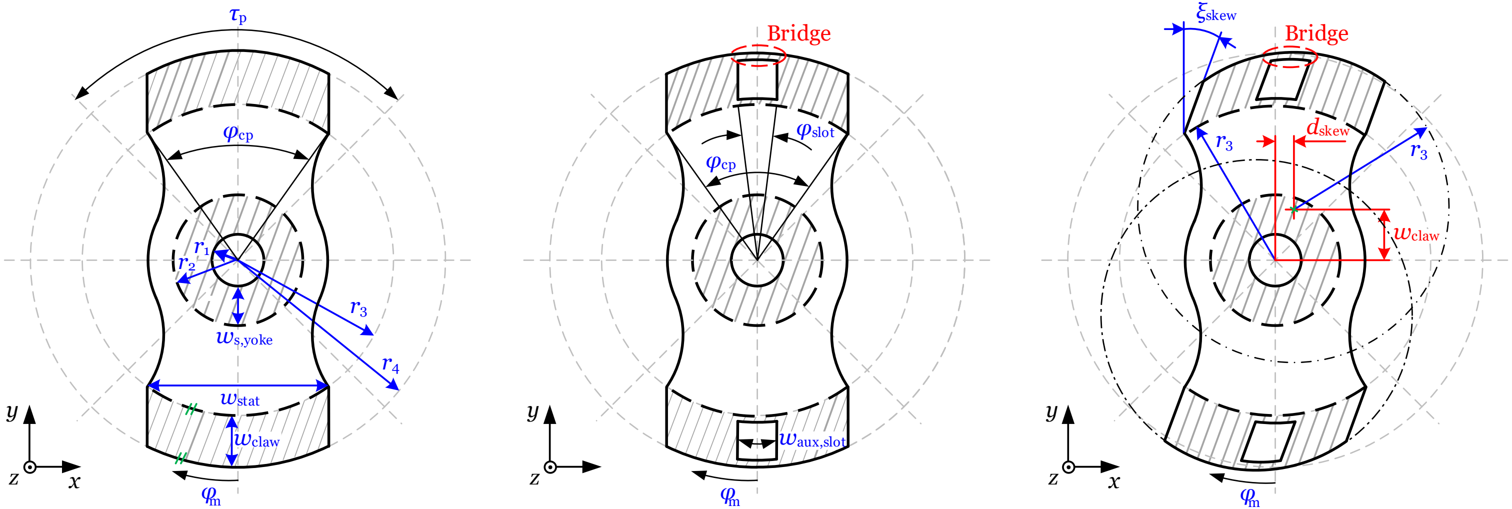


Steel Sheet Layouts for Punching and Deep-Drawing

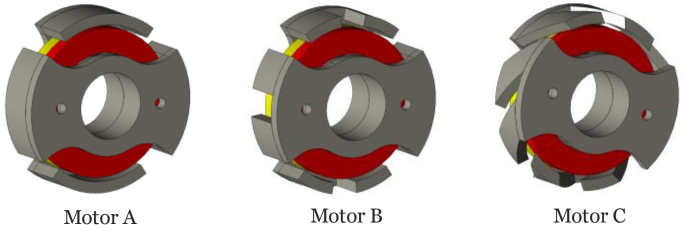
Implementation of improvements for free!



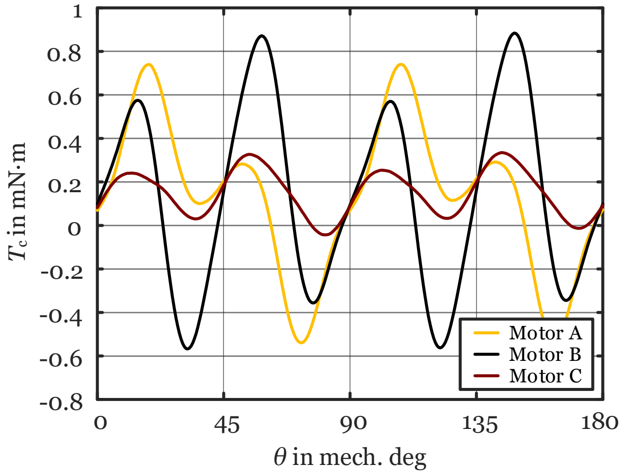
Motor A Motor B Motor C



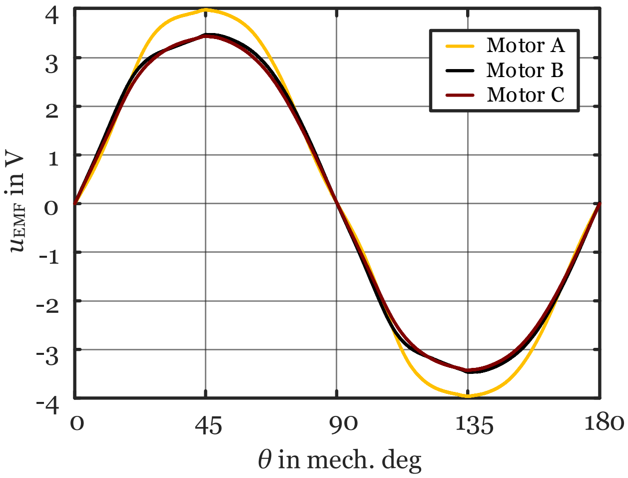
Experimental Results



Cogging torque



Back-EMF



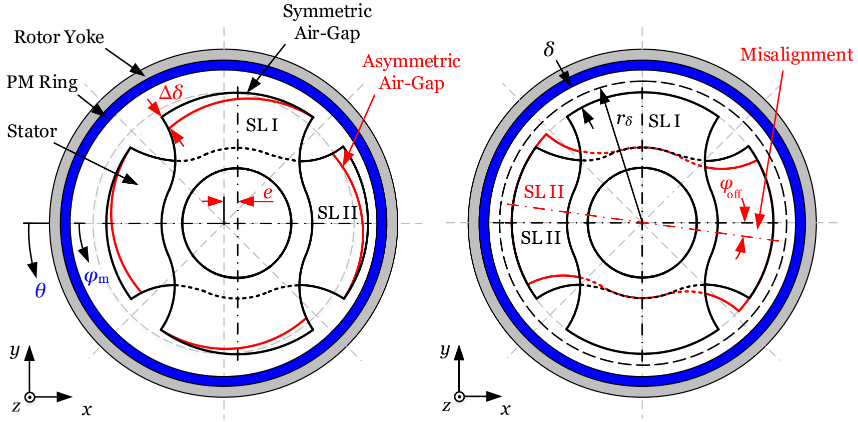
Manufacturing Imperfections, Design Parameters, and Radial Forces

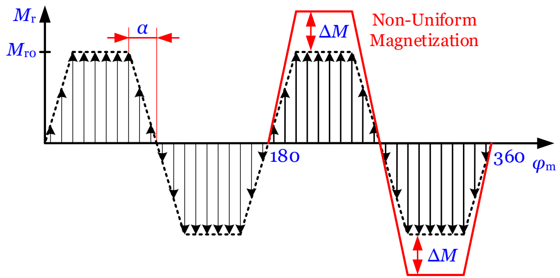
Research Motivation

- Trends
  - Cars are becoming quieter.
  - The number of auxiliary drives is increasing (approx. 100/car).
- Noise of auxiliary drives often is no longer masked by the noise of
  - Internal combustion engine
  - Road noise
- Knowledge of radial magnetic forces in auxiliary drives is thus increasingly important.

Overview of Unbalanced Magnetic Force (UMF) Analysis

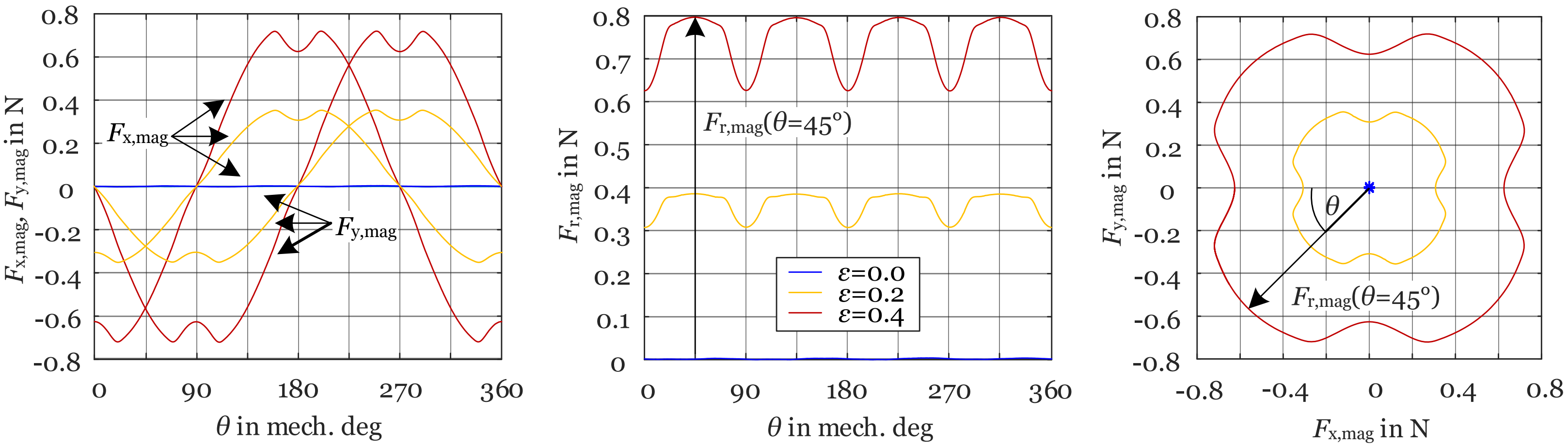
- Manufacturing imperfections
  - Eccentricity
  - Misalignment
  - Non-uniform magnetization
- Design parameters
  - Air-gap asymmetry
  - Magnetization pattern





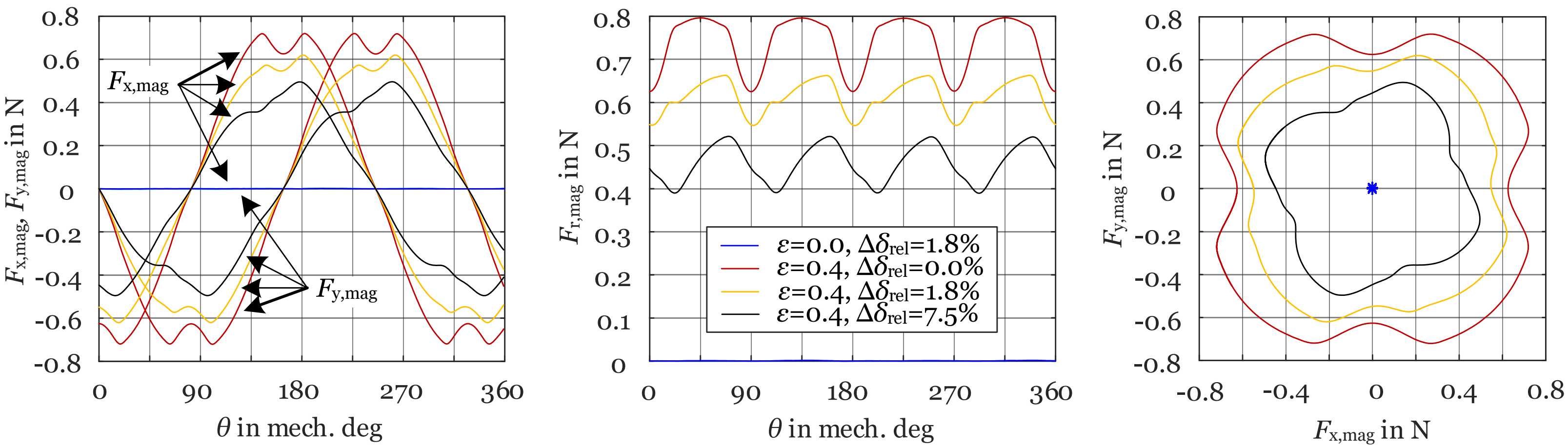
Eccentricity – Symmetric Airgap

- UMFs increase linearly with increasing eccentricity.
- Resultant radial force pulsates → may trigger resonances.

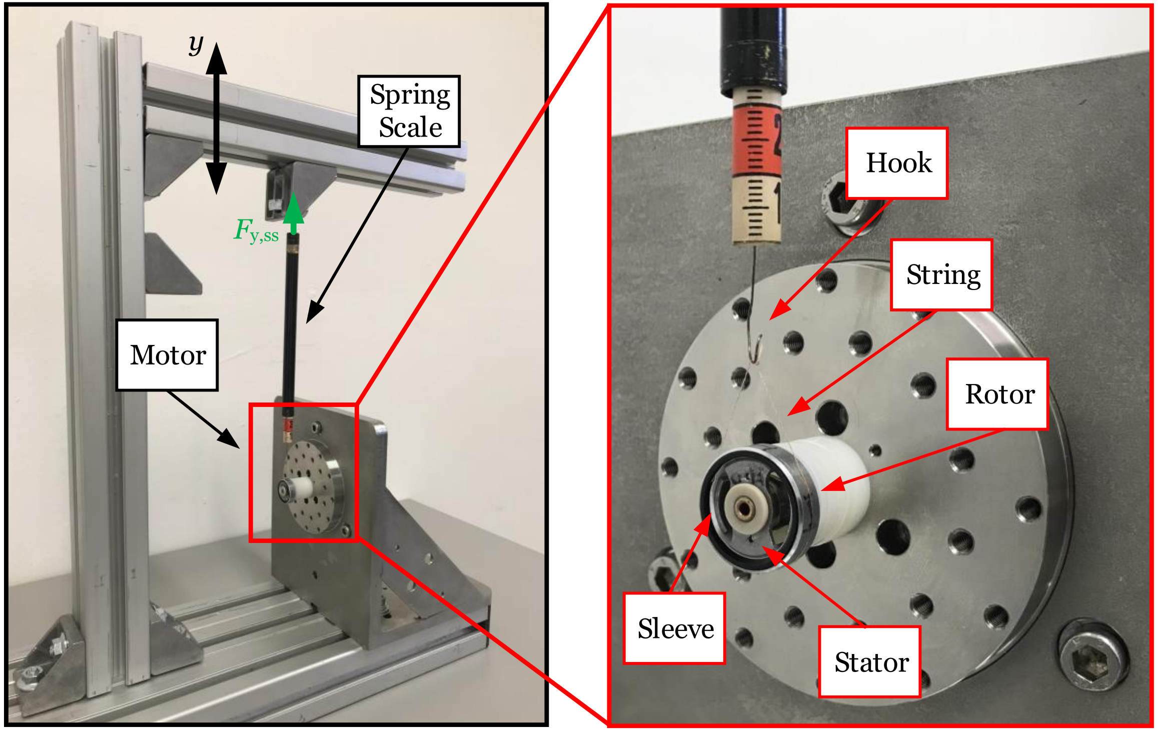


Eccentricity – Asymmetric Airgap

- UMFs increase linearly with increasing eccentricity.
- Resultant radial force pulsates → may trigger resonances.
- UMF magnitude decreases with increasing air-gap asymmetry.

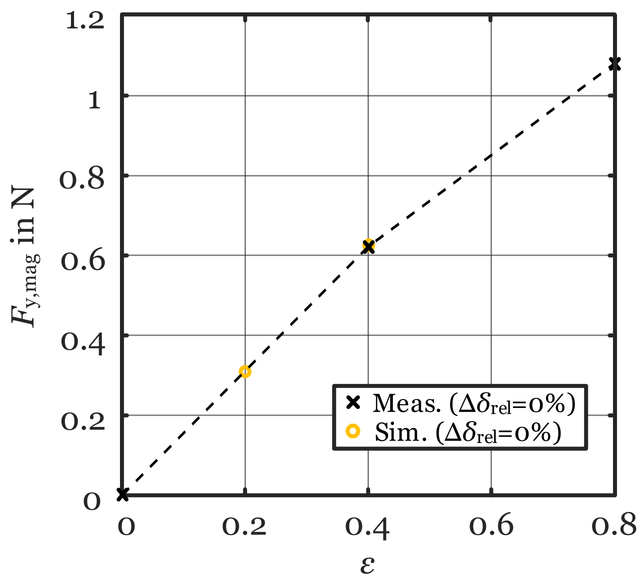


UMF Measurement Test Setup: Static Eccentricity

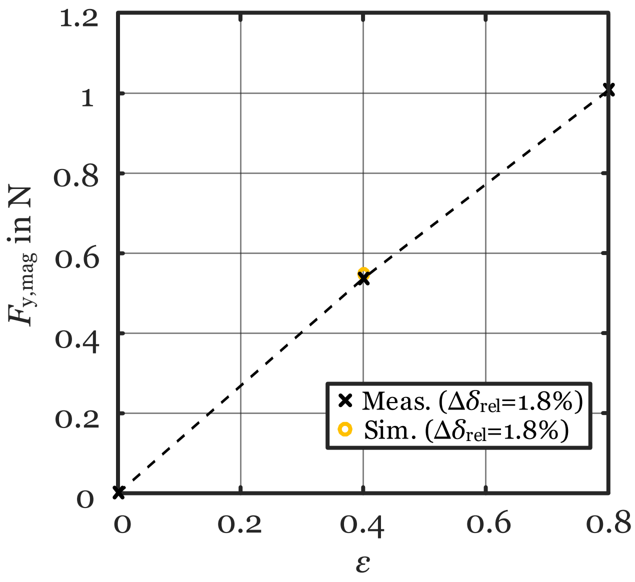


Measured Versus Simulated UMFs: Static Eccentricity

Symmetric air-gap



Asymmetric air-gaps



Experimental Challenge: Investigations with a Rheometer

Introduction

Knowledge of the cogging torque waveform is essential

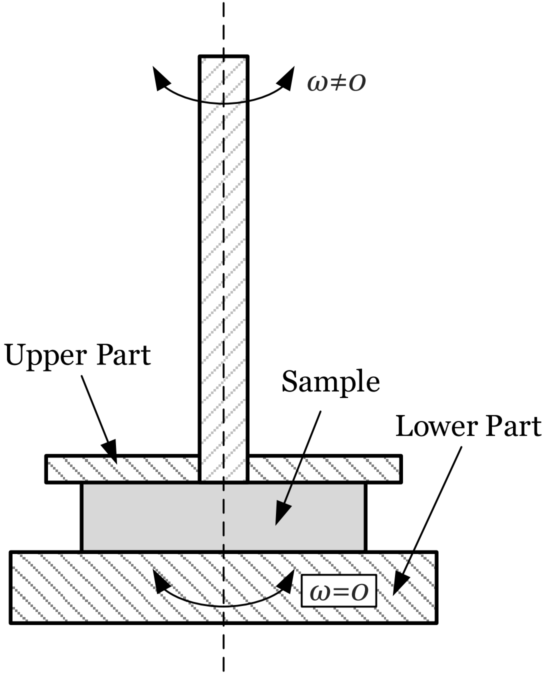
- Because it is in the same range as the alignment torque.

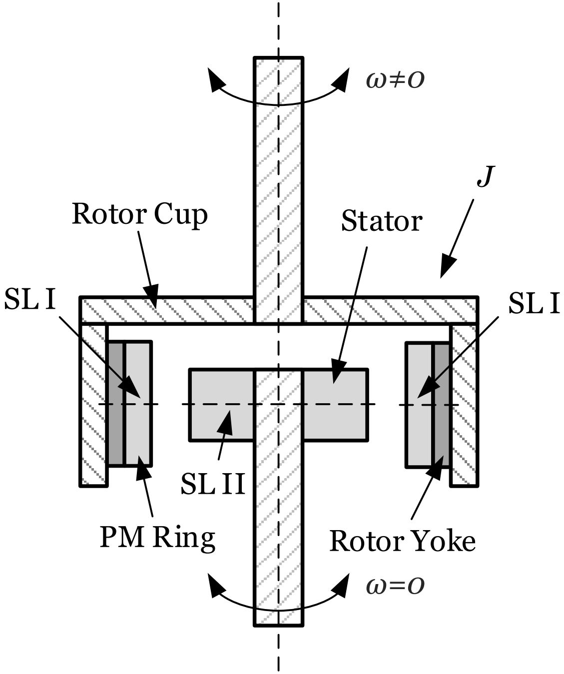
Measuring small torque is in general very hard.

- Cogging torque of sub-FHP motors is in the sub-milli-Newton meter range.
- A rheometer-based method is proposed.

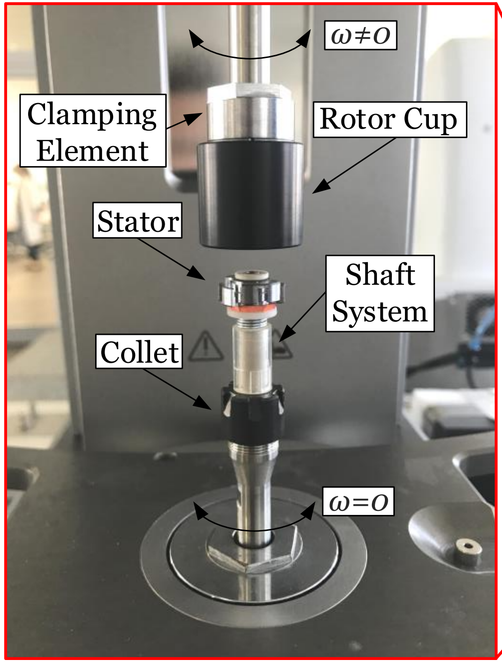
Turns out the rheometer can be used to determine the iron losses of the finished motor in addition to the cogging torque!

Classical Rheometer Setup Versus Adapted Setup





PM Motor Investigations with a Rheometer

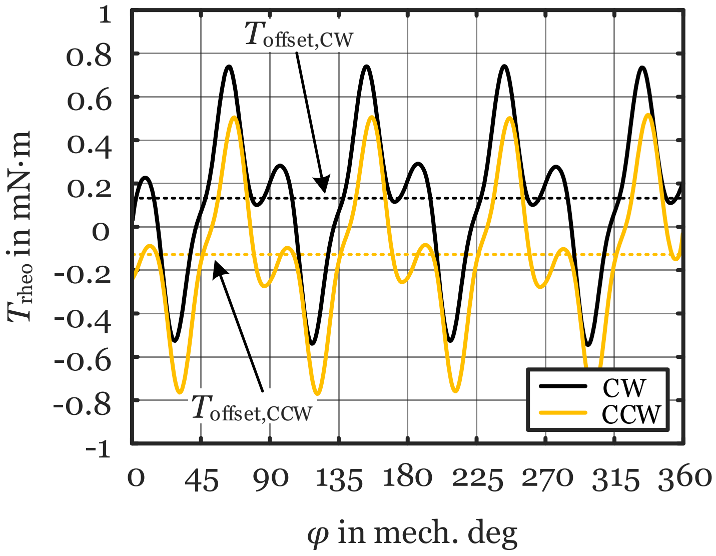


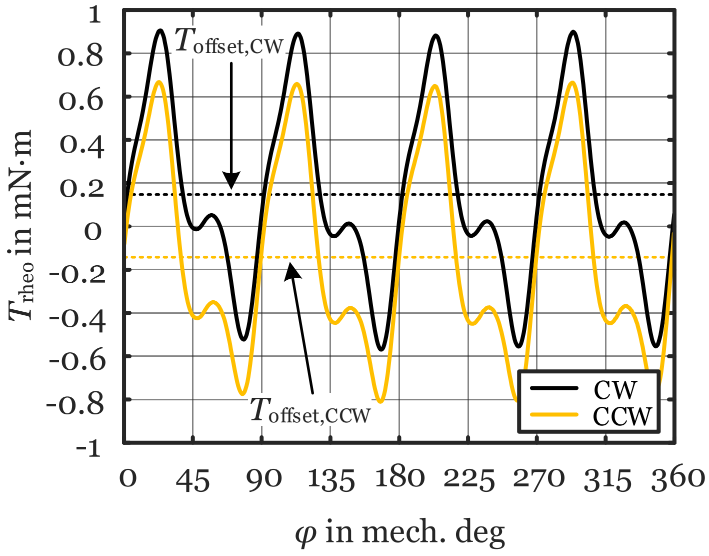
Rheometer test setup

- MCR502 WESP (Anton Paar GmbH)
- Axial and radial air bearings
- Resolutions
  T: ±0.05 nN·m
  φ: < 10 nrad
- Accuracy
  T: 0.5% (max.±0.2 μN·m)

Measurement Results

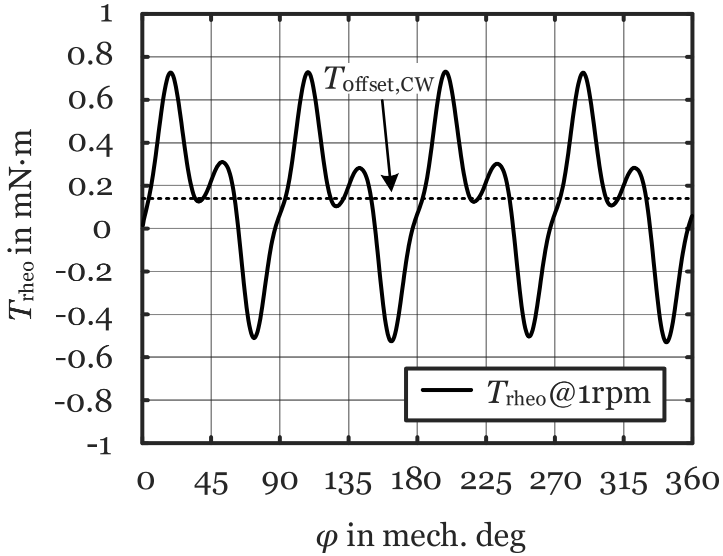
Symmetric versus asymmetric air-gaps

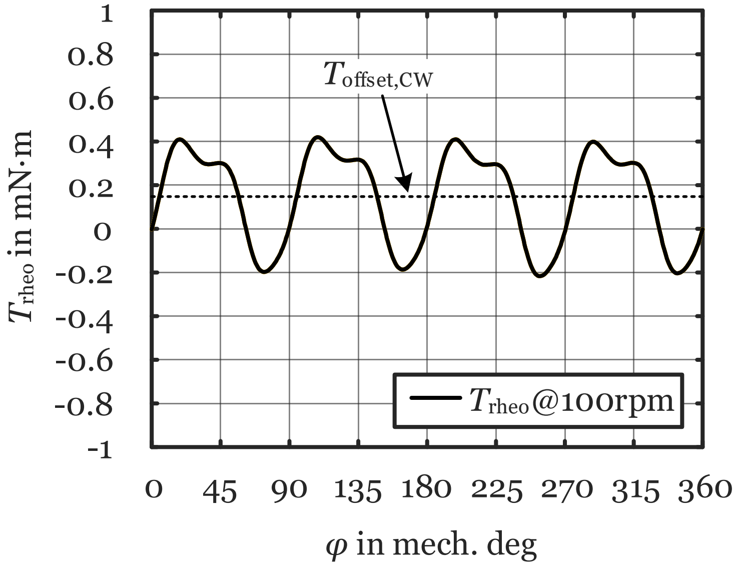




Measurement Results

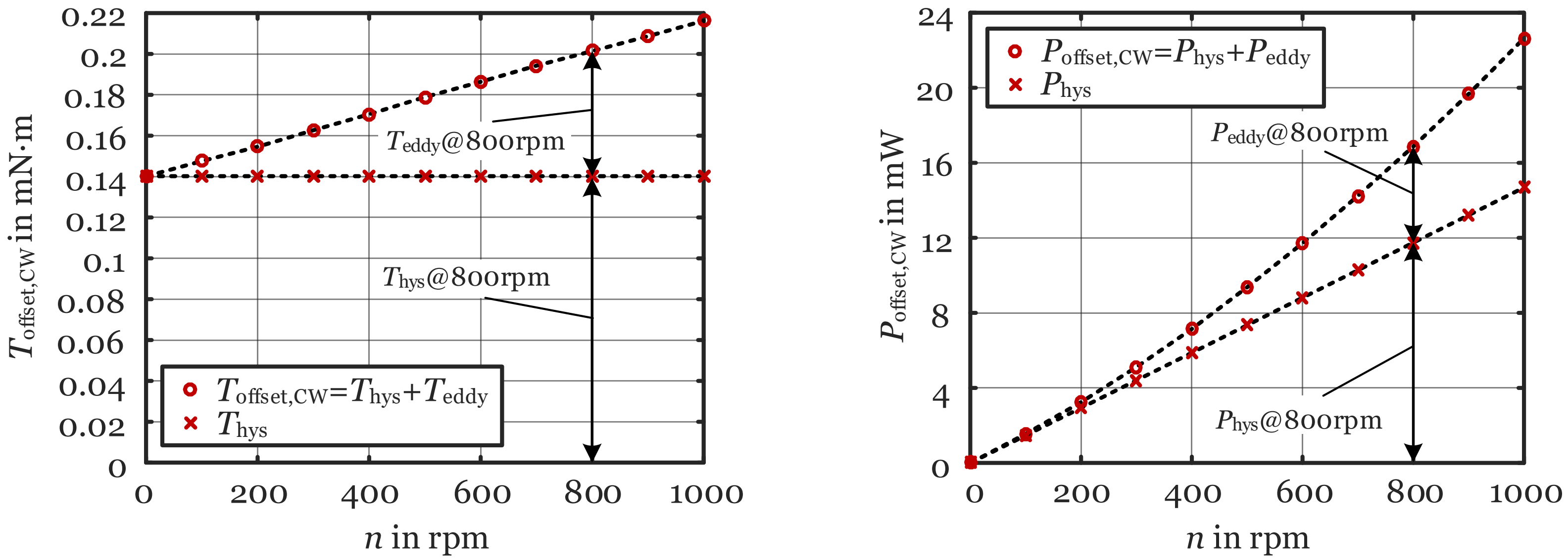
Investigation at different mechanical speeds





Iron Loss Determination

Iron loss measurement and separation from the measured torque-offset



(Almost) Final Remarks

(Almost) Final Remarks

- Auxiliary drives – the neglected stepchild of the research community?
- Auxiliary drives – mass produced commodity products with nothing to gain?

  OR

- Auxiliary drives – customized solutions produced in large numbers?
- There are many open questions and there is much room for improvement on the different fronts – e.g., modeling, design, control, …

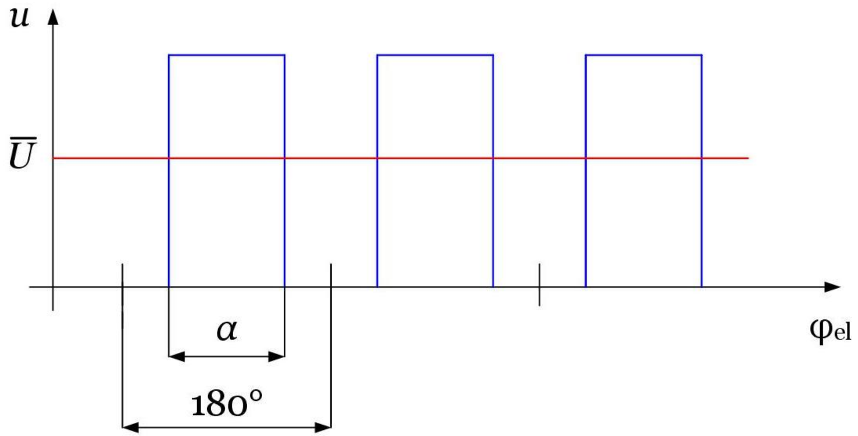
We showed you some examples!

“Simplicity Rediscovered” – Reduced Electromagnetic Emissions

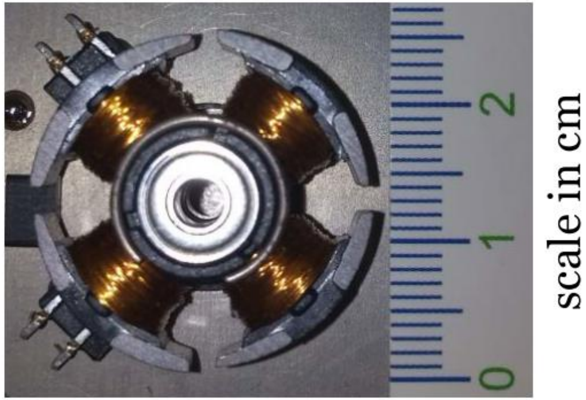
Angle Modulated Switching Strategy: Basic Frequency Re-Introduced

- Switching period longer than τ
- Speed dependent switching period
- Variable conduction angle α

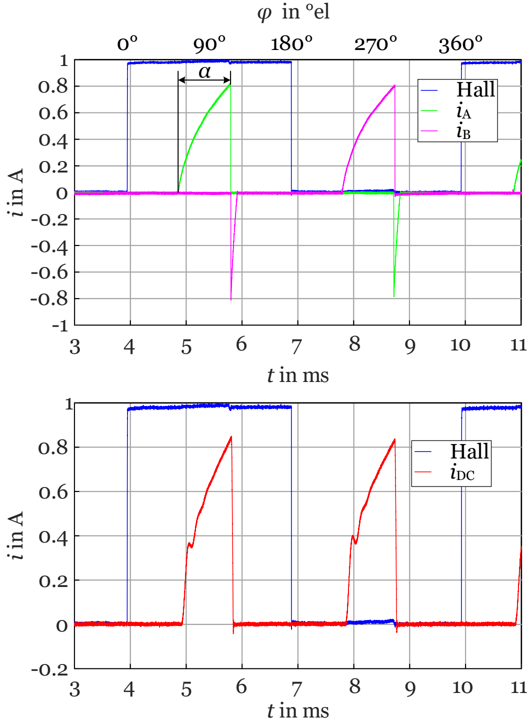
$$\alpha = \frac{\bar{U}}{U_{\mathrm{DC}}} 180^\circ$$

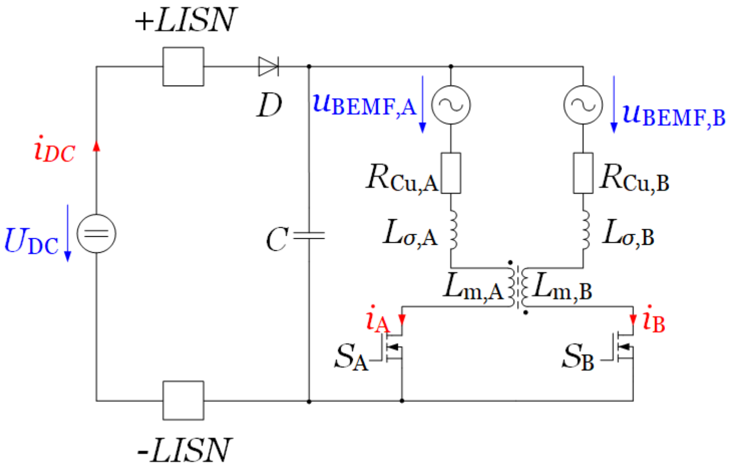


Example Case Drive



Currents AMSS





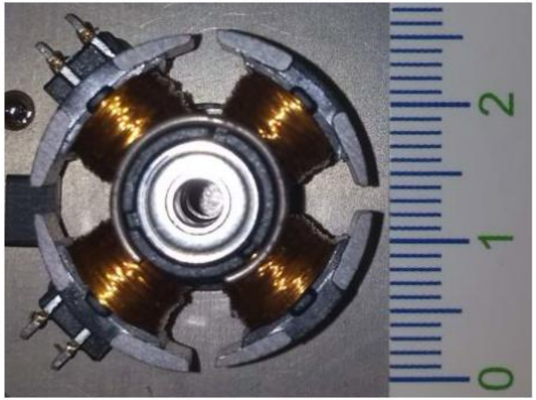
Simplification of Electronic Circuit

Original electronic circuit used

9 capacitors

→ reduced down to

4 capacitors

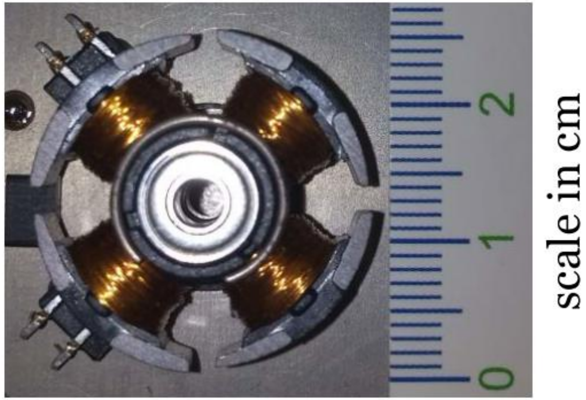


scale in cm

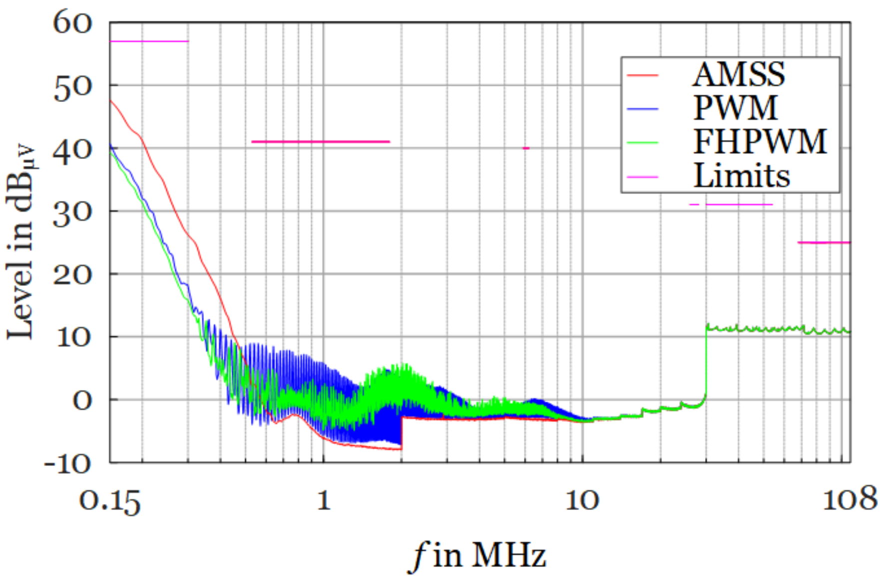
Simplification of Electronic Circuit

9 capacitors

4 capacitors



Conducted Emissions – qp Detector



AMSS: angle modulated switching strategy.

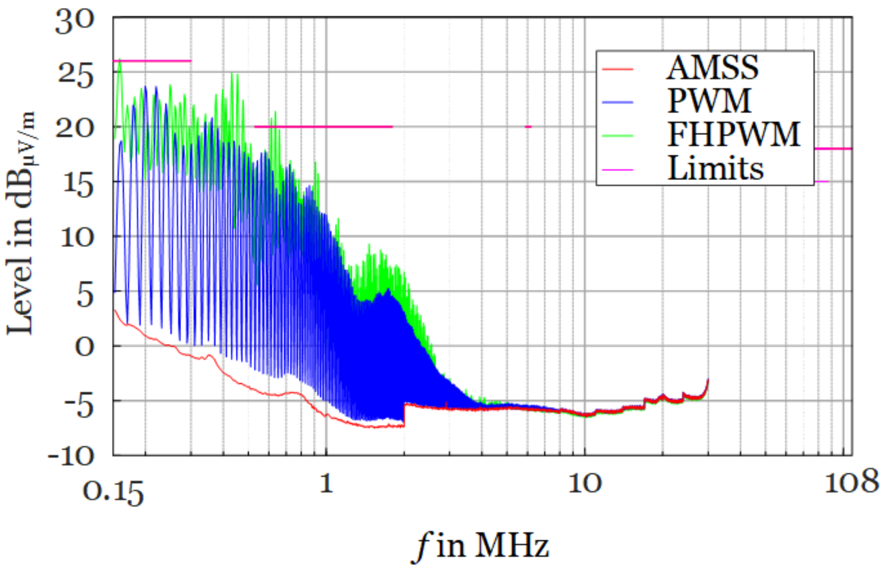
PWM: conventional PWM.

FHPWM: frequency hopping PWM.

Limits as per CIPSR 25 class.

All with four capacitors only.

Radiated Emissions – av Detector



AMSS: angle modulated switching strategy.

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All with four capacitors only.

Related Publications

S. Leitner et al., “Low-Cost Sub-FHP Brushless Direct Current Claw-Pole Machine Topology for Fan Applications,” IEEE APEC 2018.

S. Leitner et al., “Cogging Torque Minimization on a Mass-Produced Sub-FHP Brushless Direct Current Claw-Pole Motor,” IEEE ECCE 2018.

S. Leitner et al., “Effects of Manufacturing Imperfections and Design Parameters on Radial Magnetic Forces in the BLDC Claw-Pole Motor,” IEEE IEMDC 2019.

S. Leitner et al., “Rheometer-Based Cogging Torque Measurement for Sub-FHP Permanent Magnet Motors,” IEEE ITEC 2019.

S. Leitner et. al., “Innovative Low-Cost Sub-Fractional HP BLDC Claw-Pole Machine Design for Fan Applications,” *IEEE Transactions on Industry Applications*, 2019.

S. Leitner et. al., “Cogging Torque Minimization and Performance of the Sub-Fractional HP BLDC Claw-Pole Motor,” *IEEE Transactions Industry Applications*, 2019.

Other Work on “Small Drives” by the CD Laboratory

H. Gruebler et al.,“Improved Switching Strategy for a 1ph Brushless Direct Current Motor and its Impact on Motor Efficiency,” IEEE IEMDC 2017.

H. Gruebler et al., “Loss-Surface-Based Iron Loss Prediction for Fractional Horsepower Electric Motor Design,” IEEE EPE-ECCE 2018.

H. Gruebler et al., “Space Mapping-Based FHP Permanent Magnet Motor Design for Pump and Fan Applications,” IEEE IEMDC 2019.

F. Krall et al., “Angle Modulated Switching Strategy for FHP BLDC Motors for Improved Electromagnetic Compatibility,” IEEE EPE-ECCE 2019.

H. Gruebler et. al., “Improved Switching Strategy for a Single-Phase Brushless Direct Current Motor and its Impact on Motor Efficiency,” *IEEE Transactions on Industry Applications*, 2018.

Thank you