FEAAM GmbH Forschungszentrum für Elektrische Antriebstechnik und Aktorik München
Research Center for Electrical Drives and Actuators Munich

Different Novel Electric Machine Designs for Automotive Applications

evs 27

The 27th **INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION.**
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FEAAM GmbH
Neubiberg, Germany

Drive Innovations

Overview

- Introduction, Concentrated Winding
- New Stator Design with Flux-Barriers
- Self-Excited Synchronous Machine
- Different Novel Winding Topology for PMSMs and ASMs
- ASM with Concentrated Windings
- Conclusions

Introduction

- Main Requirements

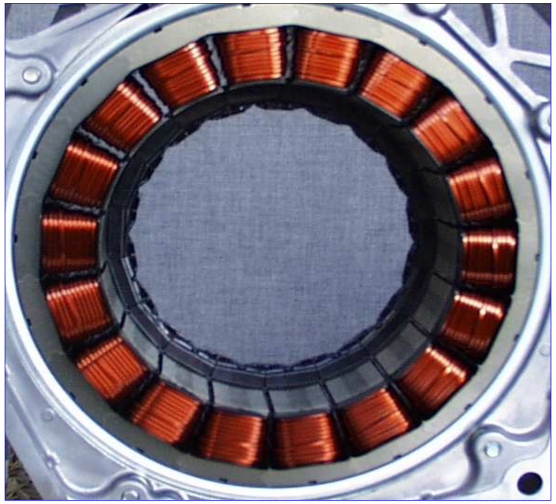
FSCW - Fractional slots tooth concentrated winding

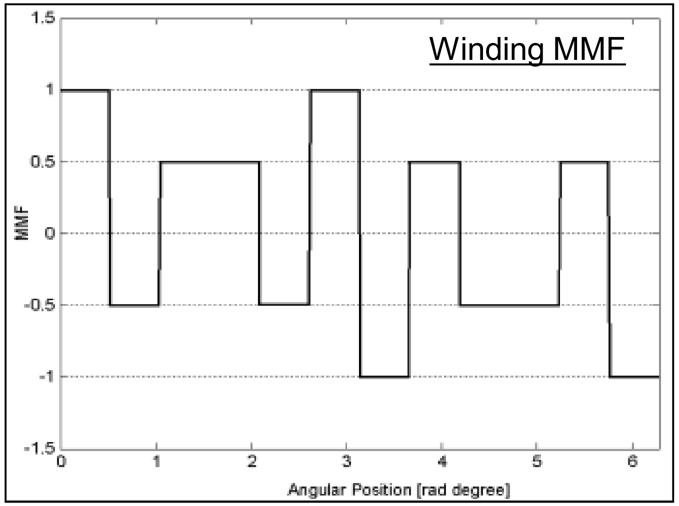
High Power Density	High Efficiency	Low Costs
➢ Limited volume ➢ Weight	➢ Energy price & Co2 ➢ Battery capacity	➢ Materials ➢ Manufacturing
SOLUTIONS – State of the Art		
▪ PM machines (NdFeB, SmCo) ▪ **FSCW** - High winding factor - Short end-winding	▪ Low losses (iron, copper, magnets) ▪ **FSCW** - Short end-winding - High filling factor	▪ **FSCW** - Simple manufacturing - Short end-winding ▪ **Other machine types** (ASM, CESM, SynRel, etc.)

- **FSCW are increasingly used in several industry application !!**

Concentrated Windings

- Main Characteristics





- Advantages
  - Compact design
  - Simple manufacturing
  - Short end winding
  - High winding factor
  - Low copper losses

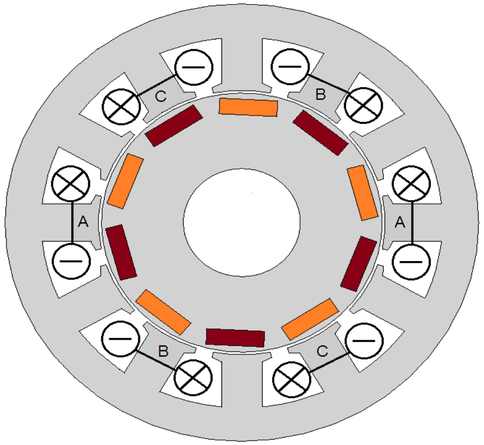
- Disadvantages
  - High space harmonics
    - **Rotor losses**
    - **Noise and vibrations**

- Realization
  - Single- or double-layer
  - Tooth concentrated

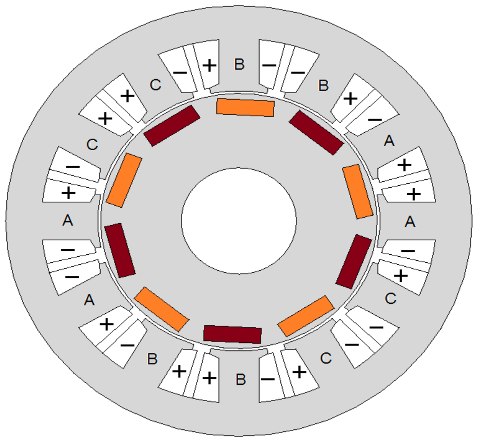
Concentrated Windings

➤ Realization: 12-Teeth/10-Poles

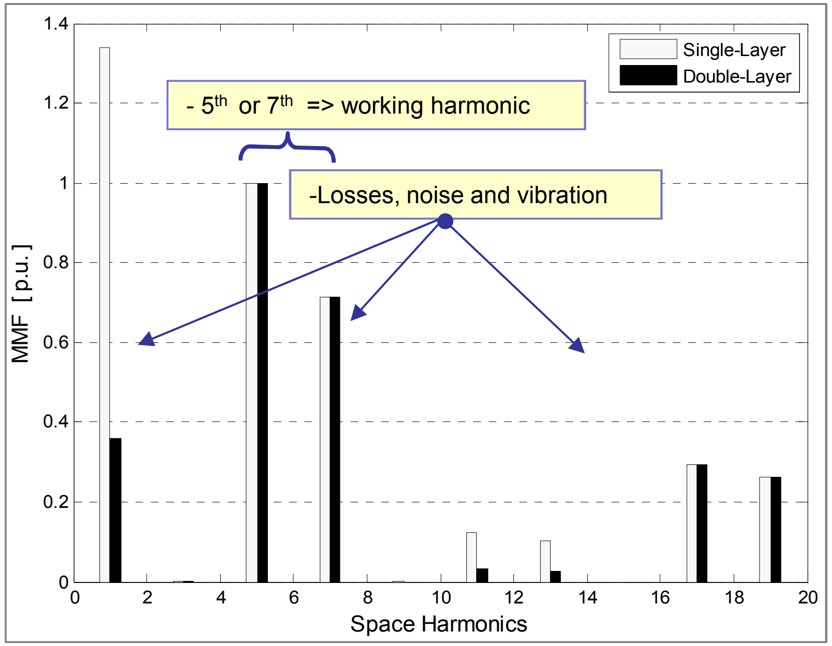
1. Single-layer



2. Double-layer



MMF Winding Characteristics



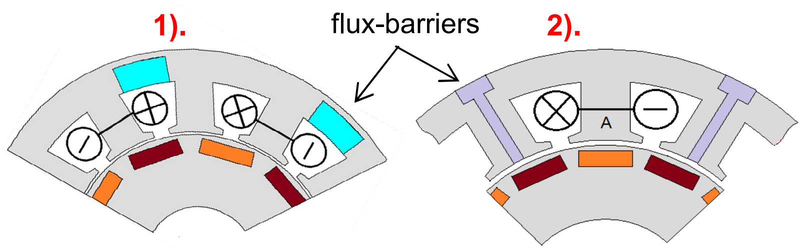
++High winding factors:

SL	DL
ξ_5 =0.966	ξ_5 =0.933
ξ_7 =0.966	ξ_7 =0.933

Reduction of the Winding MMF-harmonics

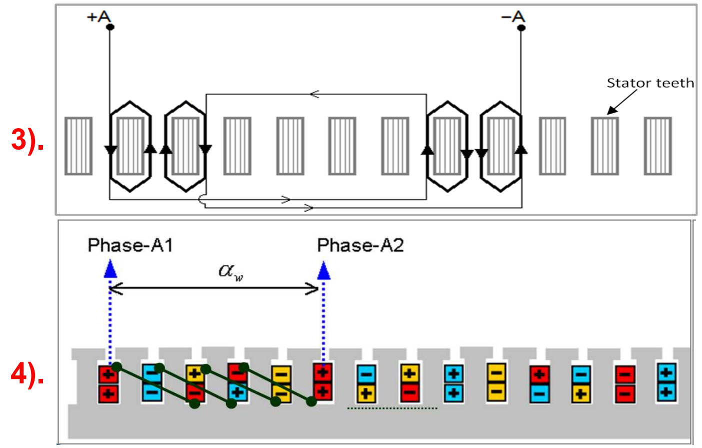
Using magnetic flux-barriers

1. Flux-barriers in stator yoke* (*ICEM-2012)
2. Flux-barriers in stator teeth* (*EDPC-2012)



Modifying winding

3. Different turns per coil-side* (*ICEMS-2011)
4. 24-Teeth/10-Poles* (*IEMDC-2011)
5. 18-Teeth/10-Poles* (*IEMDC-2013)
6. 36-Teeth/10-Poles

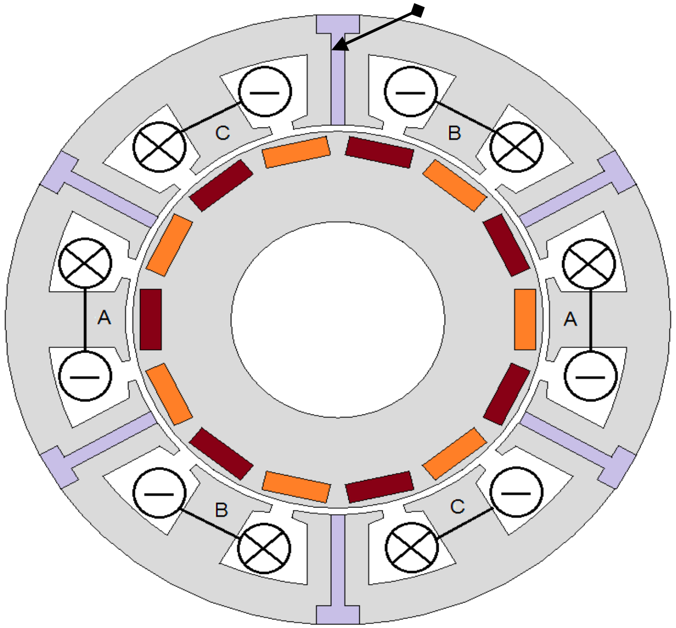


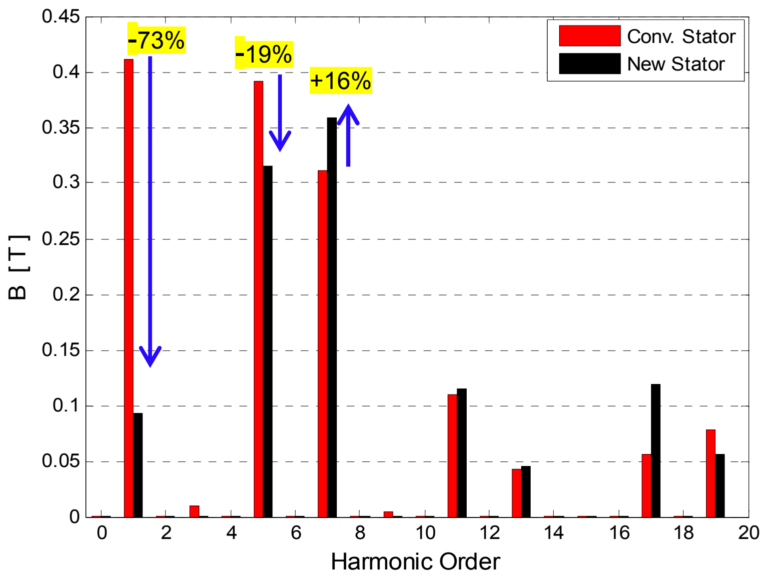
❖ **Self-excited SM:** Rotor excitation through MMF harmonics

Drive Innovations

Permanent Magnet Machines

➢ Flux-Barriers in Stator Teeth

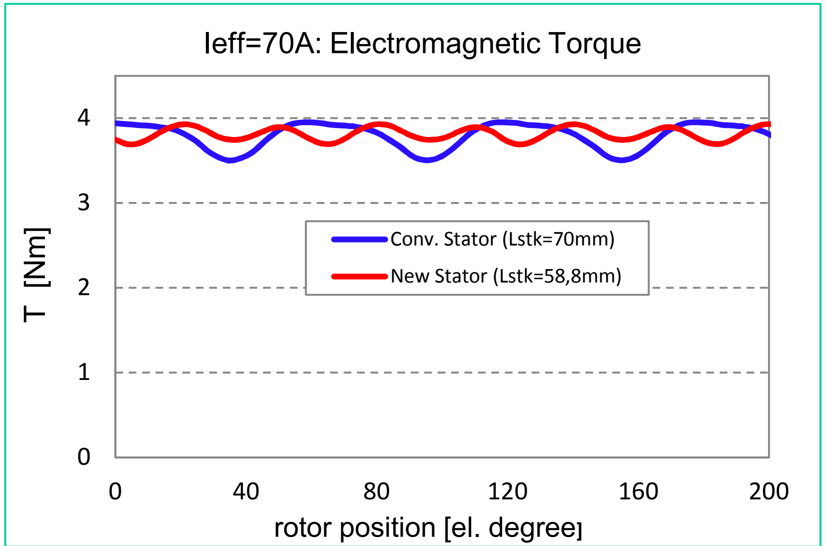


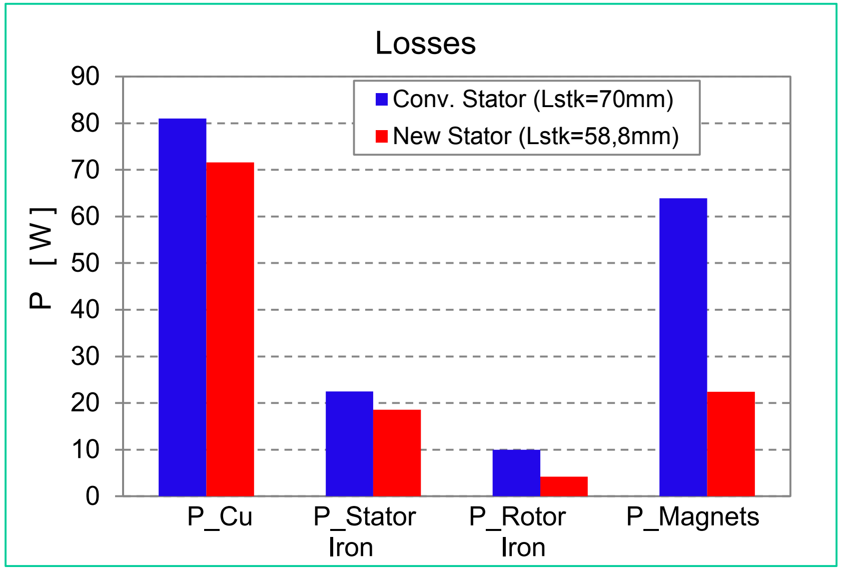


❑ Simple manufacturing; Efficiency cooling; Modular structure

Comparison of Results for a PM Machine

- Reduction of material costs and space up to 20%
- High Efficiency
- Improved field weakening
- Available efficiency cooling





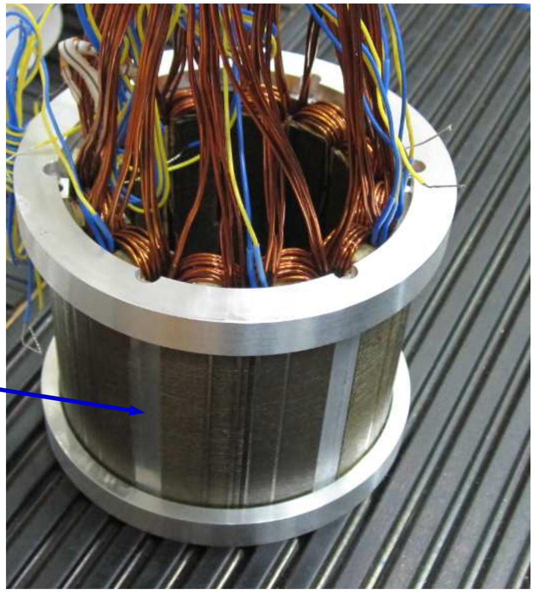
Volume:
- Conv. Design: Da = 80mm, Lstk = 70mm
- New Design: Da = 80mm, Lstk = 58.8mm

Drive Innovations

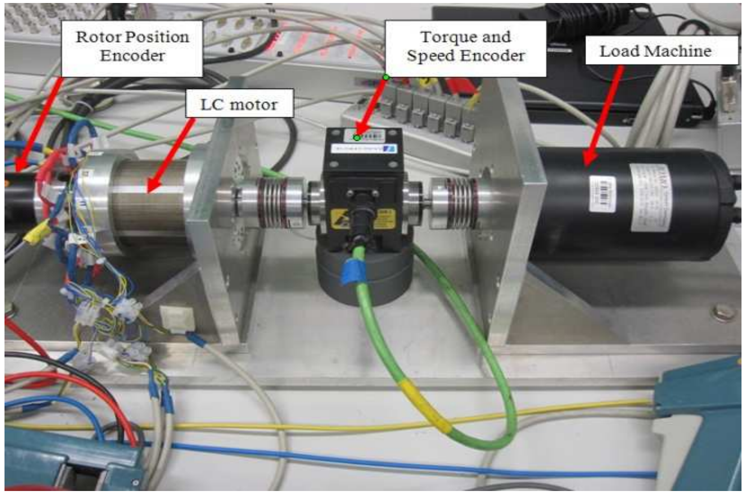
Analogous PM Machine with FB

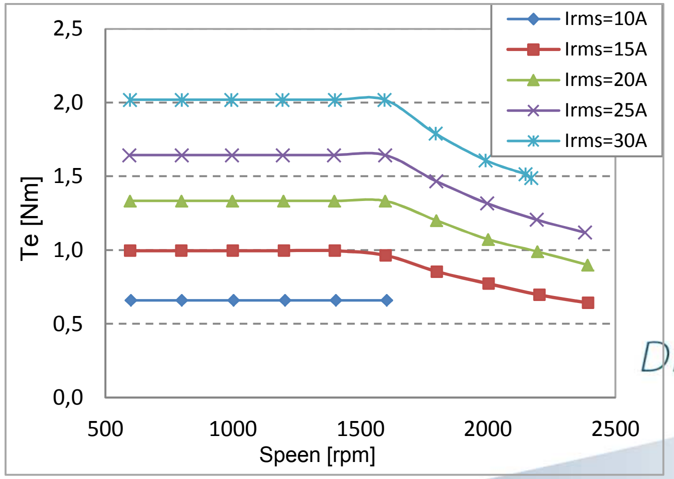
Requirements

- Maximum DC votage, $U_{DC,max}$ = 12 V
- Maximum short-time torque: T_{max}=4 Nm @ 1200 rpm
- Maximum speed n_{max} =3000 rpm
- Active volume (Dout=80mm, length =70 mm)
- **Pasive cooling**
- **Low cost**
- Low cogging torque & low torque ripple



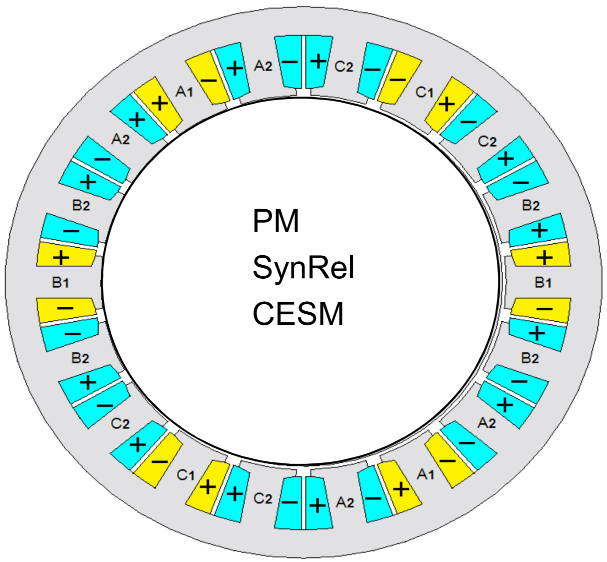
Flux-barriers (non-magnetic material)

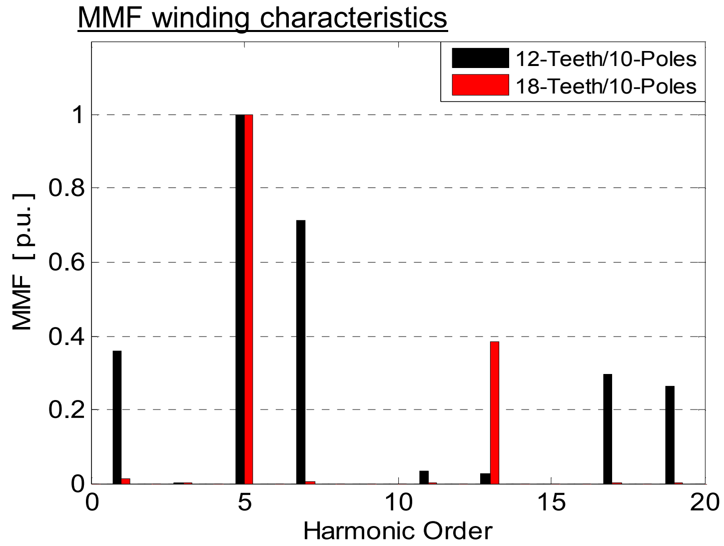




Self-Excited CESM with Concentrate Winding

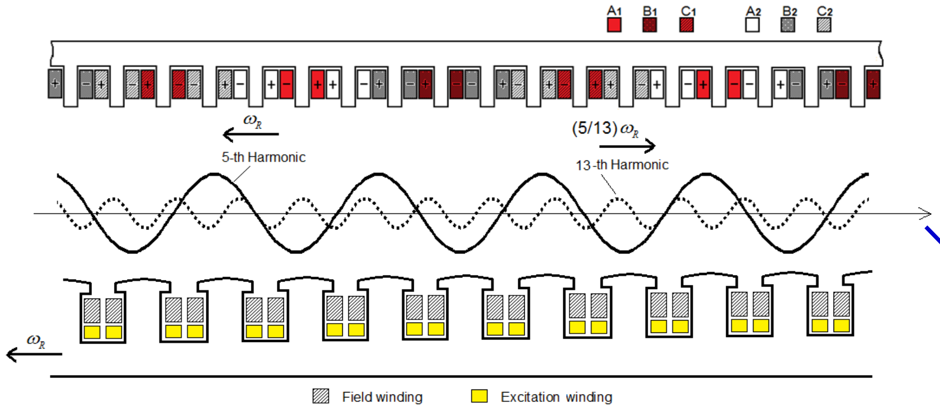
- New Concentrated Winding, **18-Teeth/10-Poles**
  - Low harmonic contents
  - High slot fill factor
  - Short end-winding length
  - Simple construction



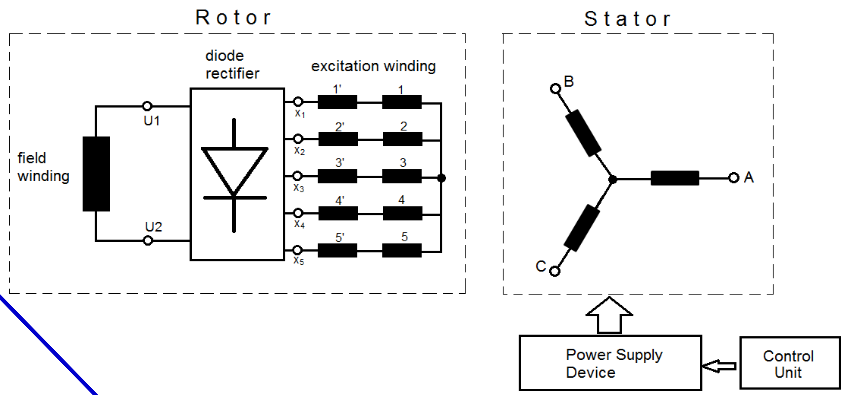


Self-Excited CESM with Concentrate Winding

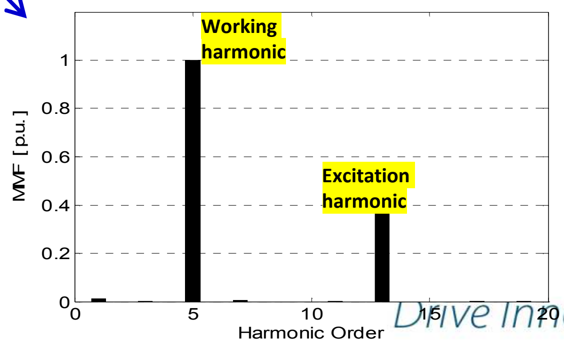
➤ Fundamental Construction



Block Circuit-Diagram for the New Machine



MMF 18T/10P

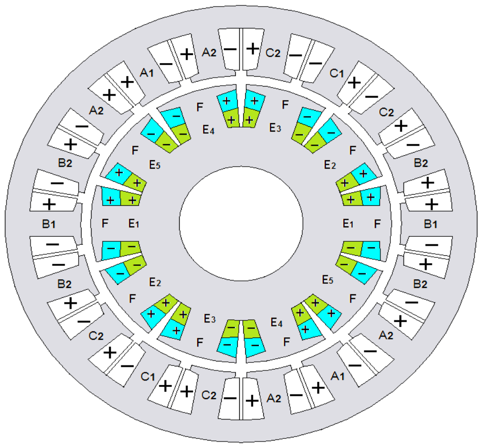


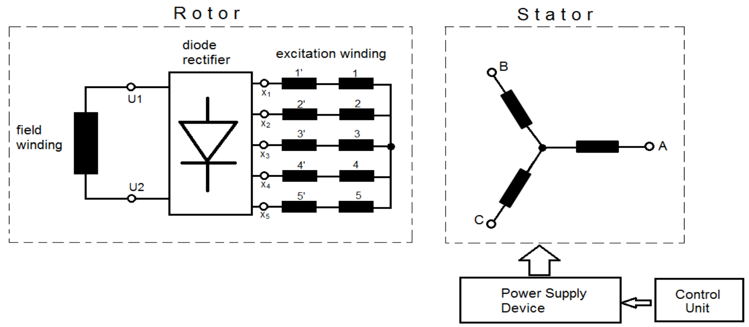
Main Characteristics

- ❑ Brushless current excited synchronous machine
- ❑ Simple tooth concentrate winding for the both stator and rotor
- ❑ The 5th MMF harmonic is used as working harmonic
- ❑ The 13th MMF harmonic is used as excitation harmonic

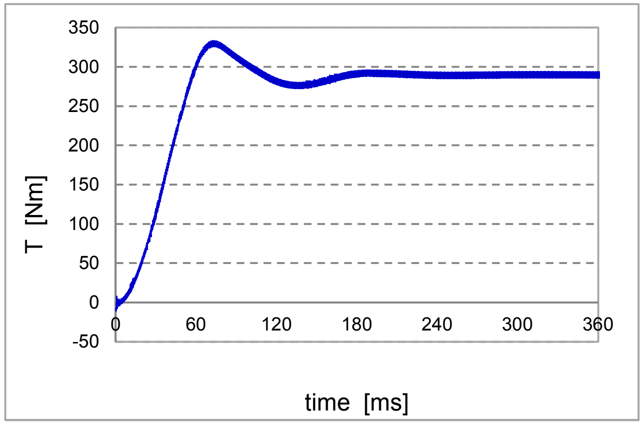
Simulation Results

- Exemplary Machine
  - Da = 230 mm
  - Lstk = 150 mm
  - U_{DC} = 400 V
  - Imax = 650 A
  - n_{max} =12000 rpm

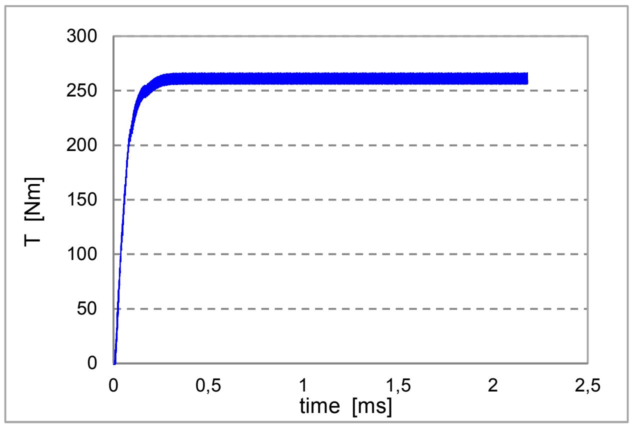


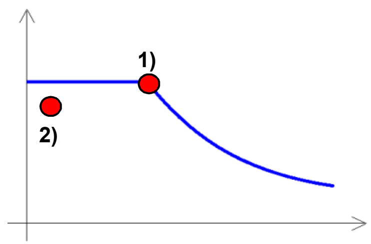


1). n = 5100 rpm, Ieff = 500A



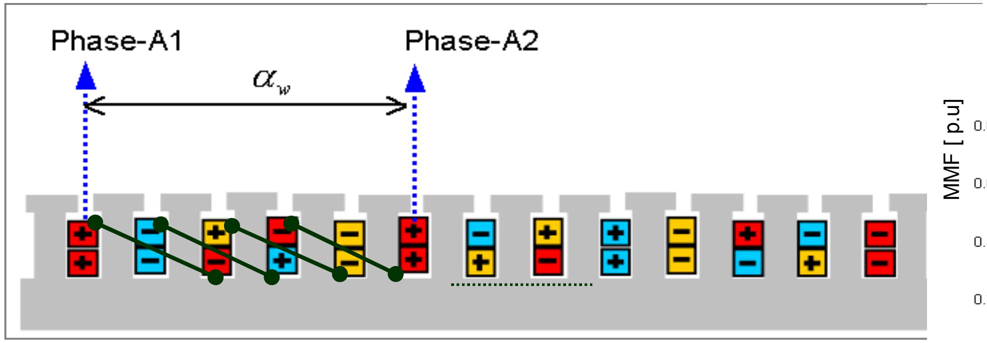
2). n = 600 rpm, Ieff = 650A

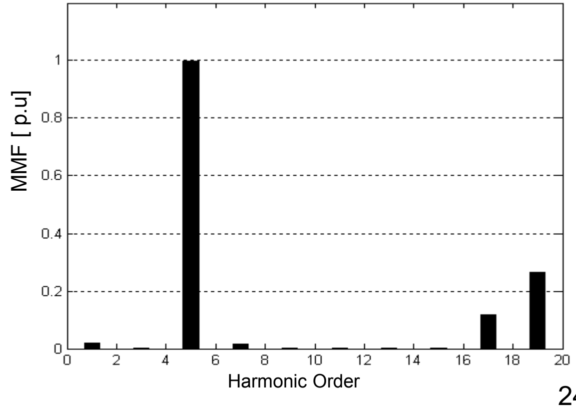




Different Winding Topologies with Low MMF Harmonic Contents

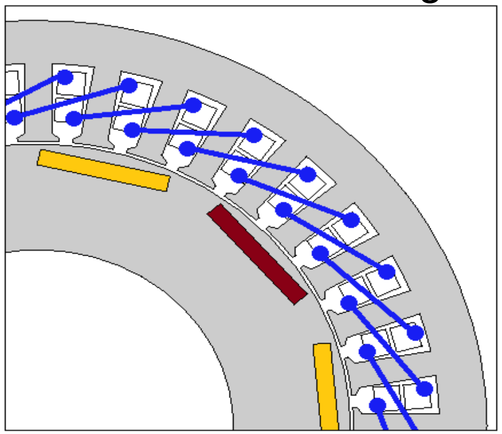
- 24-Teeth/10-Poles Winding

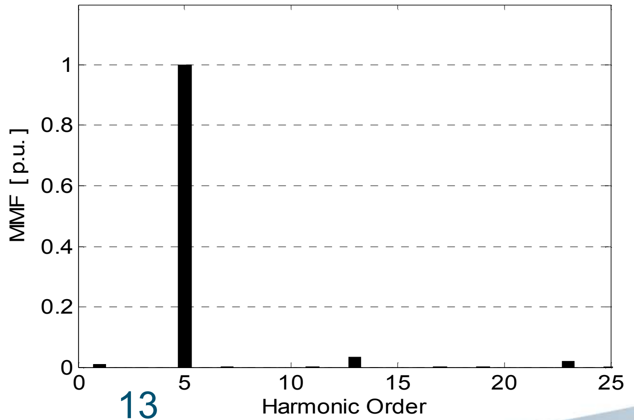




24-Teeth/10-Poles Machine

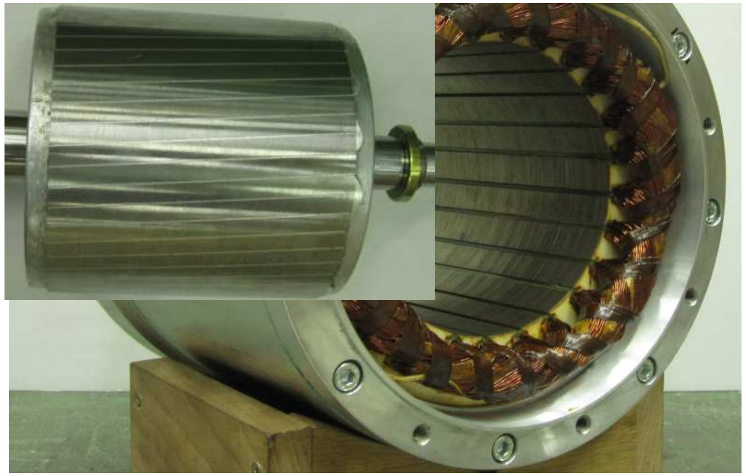
- 36-Teeth/10-Poles Winding



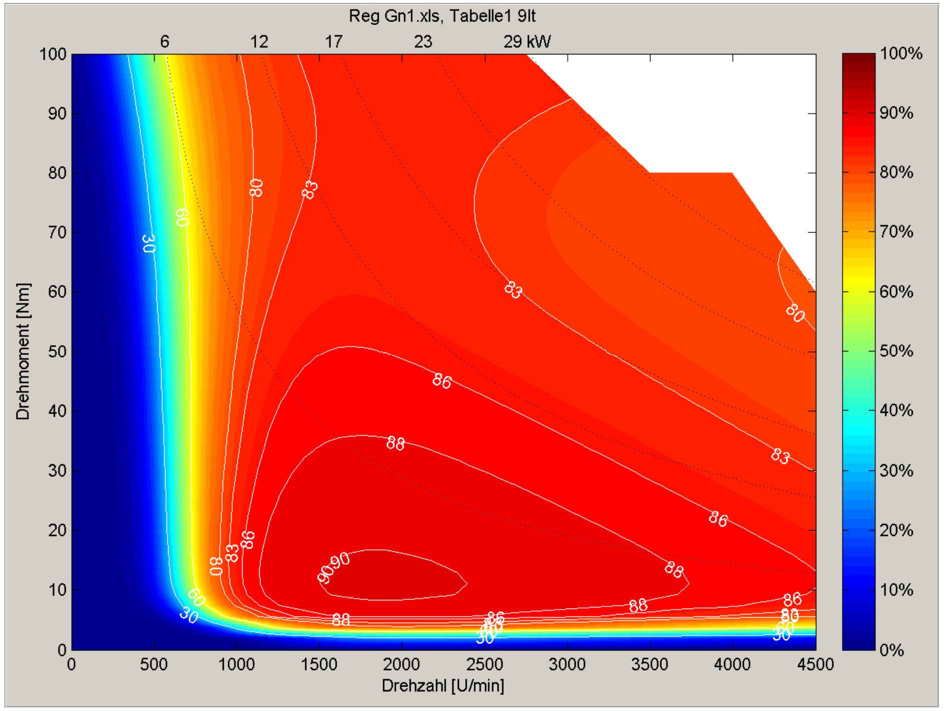


24-Teeth/10-Poles ASM

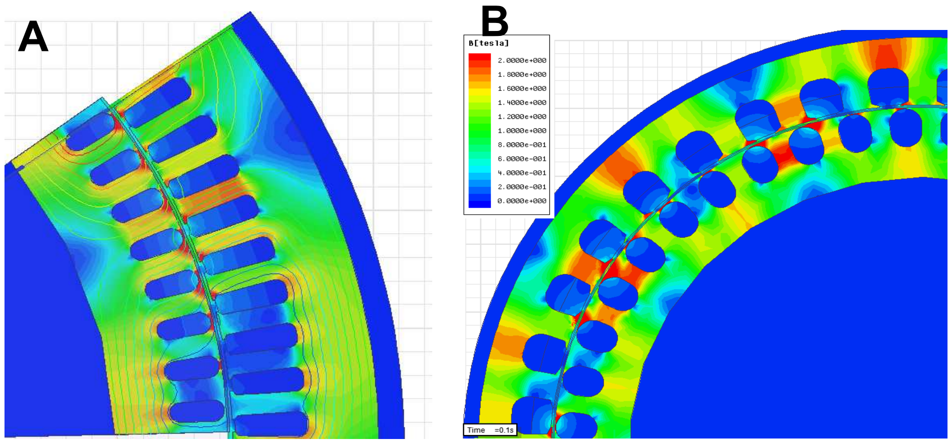
- ASM Prototype Machine



- Efficiency Map (Experimental Results)



Comparison of Two ASM for Traction Applications



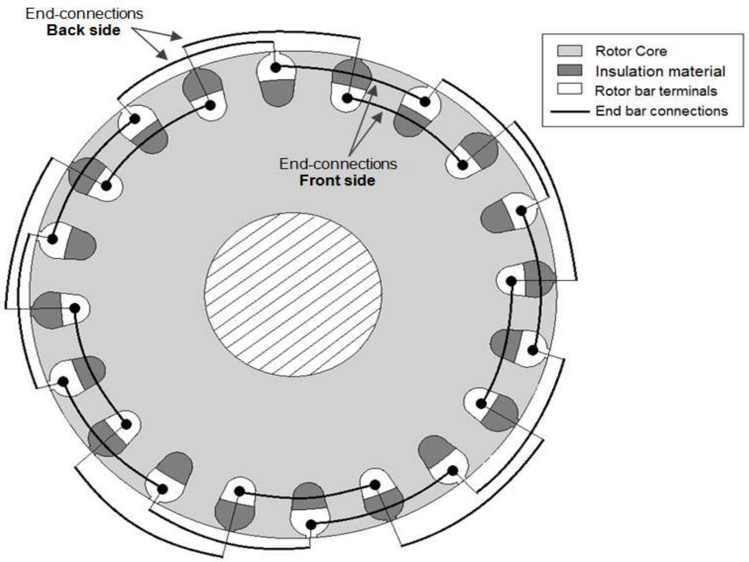
A). 90-Teeth/10-Poles ASM with the conv. winding

B). 36-Teeth/10-Poles ASM with the new winding

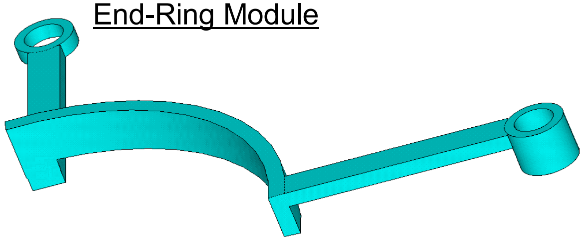
Machine specifications	Reference machine Conv. Design	New Design-1	New Design-2
Active langth	63 mm	70 mm	65 mm
Nr. of poles	10	10	10
Stator outer radius	151 mm	151 mm	151 mm
Shaft radius	99,5 mm	99,5 mm	99,5 mm
Max. Efficiency difference	-	**+2,6%** -0,3%	+0,3% -0,3%
Copper reduction	-	0%	**15,5%**

New Rotor Design for ASM with CW

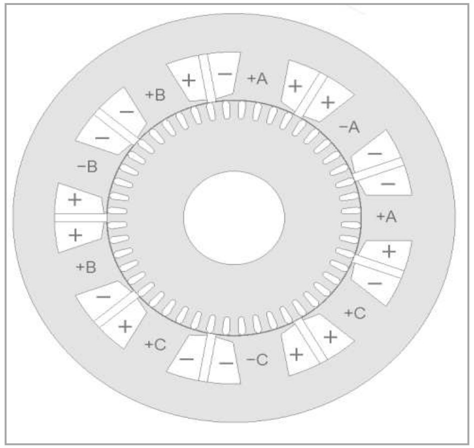
- Series Connection of Rotor Bars



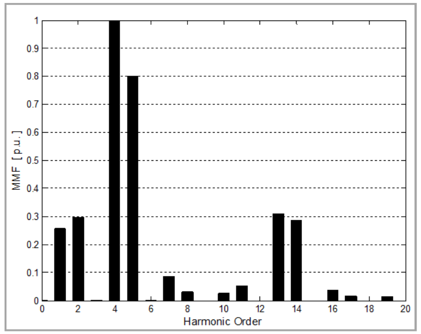
End-Ring Module

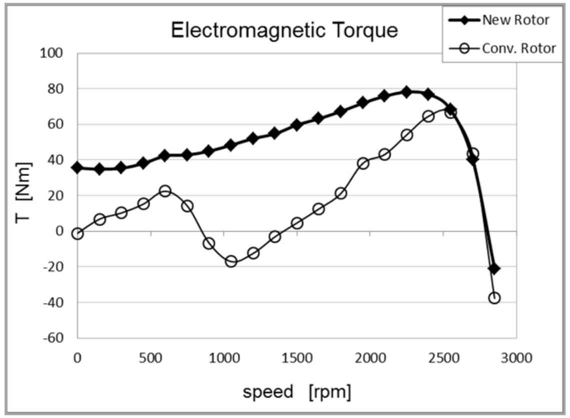


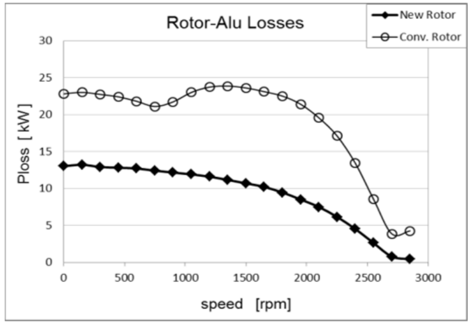
ASM: 9-teeth/8-poles



Winding MMF







Drive Innovations

Conclusions

High Power Density	High Efficiency	Low Costs
➢ Limited volume ➢ Weight	➢ Energy price & Co2 ➢ Battery capacity	➢ Materials ➢ Manufacturing

New SOLUTIONS: E-machines with Concentrated Windings and,

- Flux-barriers (PMSM, SynRel): >> up to 20% material costs and volume reduction, high efficiency
- Self-excitation (CESM): >> low costs design, small volume, high efficiency
- New Windings (PMSM, CESM, ASM, SynRel): >> high efficiency & power-density, low costs
- New ASM Rotor: >> low costs, high efficiency
- Torque Pulsations Reduction: >> low costs, high efficiency

Thank You for Your Attention

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