Different Novel Electric Machine Designs for Automotive Applications

G. Dajaku
FEAAM GmbH
Neubiberg, Germany
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

- High Power Density
- Limited volume
- Weight

- High Efficiency
- Energy price & Co2
- Battery capacity

- Low Costs
- 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

*Drive Innovations*
Concentrated Windings

Realization: 12-Teeth/10-Poles

1. Single-layer
2. Double-layer

++High winding factors:

- SL
  - $\xi_5 = 0.966$
  - $\xi_7 = 0.966$

- DL
  - $\xi_5 = 0.933$
  - $\xi_7 = 0.933$

MMF Winding Characteristics

- 5th or 7th => working harmonic
- Losses, noise and vibration

Drive Innovations
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
Permanent Magnet Machines

- Flux-Barrier 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

**Graph 1:**
- **I_{eff}=70A:** Electromagnetic Torque vs. Rotor position [el. degree]
- Conv. Stator (Lstk=70mm)
- New Stator (Lstk=58.8mm)

**Graph 2:**
- Losses
- Conv. Stator (Lstk=70mm)
- New Stator (Lstk=58.8mm)

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

Drive Innovations
Analogous PM Machine with FB

Requirements

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

![Image of flux barriers (non-magnetic material)]

![Graph showing torque vs. speed for different current levels (Irms=10A, 15A, 20A, 25A, 30A)]
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

[Diagram of PM SynRel CESM]

[Graph showing MMF winding characteristics for 12-Teeth/10-Poles and 18-Teeth/10-Poles]
Self-Excited CESM with Concentrate Winding

Fundamental Construction

- Brushless current excited synchronous machine
- Simple tooth concentrate winding for both stator and rotor
- The 5\textsuperscript{th} MMF harmonic is used as working harmonic
- The 13\textsuperscript{th} MMF harmonic is used as excitation harmonic
Simulation Results

- Exemplary Machine
  - $D_a = 230$ mm
  - $L_{stk} = 150$ mm
  - $U_{dc} = 400$ V
  - $I_{max} = 650$ A
  - $n_{max} = 12000$ rpm

1). $n = 5100$ rpm, $I_{eff} = 500$ A

2). $n = 600$ rpm, $I_{eff} = 650$ A

Drive Innovations
Different Winding Topologies with Low MMF Harmonic Contents

- 24-Teeth/10-Poles Winding

- 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

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<tr>
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<tbody>
<tr>
<td>Active length</td>
<td>63 mm</td>
<td>70 mm</td>
<td>65 mm</td>
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<tr>
<td>Nr. of poles</td>
<td>10</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Stator outer radius</td>
<td>151 mm</td>
<td>151 mm</td>
<td>151 mm</td>
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<tr>
<td>Shaft radius</td>
<td>99,5 mm</td>
<td>99,5 mm</td>
<td>99,5 mm</td>
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<tr>
<td>Max. Efficiency difference</td>
<td>-</td>
<td>+2,6%</td>
<td>+0,3%</td>
</tr>
<tr>
<td>Copper reduction</td>
<td>-</td>
<td>0%</td>
<td>15,5%</td>
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New Rotor Design for ASM with CW

- Series Connection of Rotor Bars

End-Ring Module

ASM: 9-teeth/8-poles

Winding MMF

Electromagnetic Torque

Rotor-Alu Losses
Conclusions

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<tr>
<th>High Power Density</th>
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<th>Low Costs</th>
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<tr>
<td>➢ Limited volume</td>
<td>➢ Energy price &amp; Co2</td>
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<td>➢ Weight</td>
<td>➢ Battery capacity</td>
<td>➢ Manufacturing</td>
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**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

Gurakuq Dajaku
FEAAM GmbH, Neubiberg, Germany

gurakuq.dajaku@unibw.de