Evaluation of a Dual Half-Pitched Three-Phase Bearingless High-Speed Permanent Magnet Synchronous Motor Prototype
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Institute for Electrical Energy Conversion (EW, TU Darmstadt)
Content

• Introduction

• Working principle

• Prototype design

• Measurements on the test-bench

• Conclusions
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• Conclusions
What is a bearingless motor?

Bearingless (or self-bearing motors) are:
- Suitable for long lifetime high speed drives
- Work in clean atmosphere or vacuum

But suffer from:
- Increased size due to low magnetic vs. mechanical stiffness
- More complex motor design
- Additional power electronic required

(EW, TU Darmstadt)
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• Conclusions
Rotor field

- Stator
- Air-gap
- Rotor magnet
- Rotor field line
- $p_1 = 1$
- Rotor iron
Torque generation

Stator field line $p_1 = 1$

Rotor field line $p_1 = 1$

Three-phase drive winding

Drive winding
Force generation

- **Stator field line**
  \[ p_2 = 2 \]
- **Rotor field line**
  \[ p_1 = 1 \]

Three-phase levitation winding

Levitation winding
Winding arrangement

The two windings share the same motor slots:
- Partial copper utilization
- Two different windings should be inserted in the slots:
  - Winding processing more complicated

Typical slot partition:
- Drive winding: 80 - 85%
- Levitation winding: 15 - 20%
Winding modification:

Drive winding

Levitation winding
Step 1: Suppress the drive winding

Four-pole winding $\rightarrow$ two coils per phase (here connected in series)
Step 2: Split all the coils

Split of the coils

Levitation winding
Step 2: Split all the coils

Split of the coils

six isolated coils
Step 3: Recombine the coils

Split of the coils

Recombination of the coils
Step 3: Recombine the coils

Three-phase star-connected asymmetrical winding
Step 3: Recombine the coils (2)

Recombination of the coils (2)

Recombination of the coils
Step 3: Recombine the coils (2)

Coil pitch $W/\tau_p = 1/2$  ➞  Dual half-pitched three-phase winding
Positive-sequence current to generate torque (U-V-W)

Inverter B feeds the winding B with
\[ U_{B,1}, V_{B,1}, W_{B,1} \]

Inverter A feeds the winding A with
\[ U_{A,1}, V_{A,1}, W_{A,1} \]

Current systems A and B in phase opposition

Stator field line
\[ p_1 = 1 \]

Rotor field line
\[ p_1 = 1 \]
Negative-sequence current to generate radial forces (U-W-V)

Stator field line
\( p_2 = -2 \)

Rotor field line
\( p_1 = 1 \)

Inverter B feeds the winding B with
\[
\begin{align*}
W_{B,-2} &
\end{align*}
\]

Inverter A feeds the winding A with
\[
\begin{align*}
W_{A,-2} &
\end{align*}
\]

Current systems A and B in phase
# Current locus

<table>
<thead>
<tr>
<th>Positive sequence component</th>
<th>+</th>
<th>Negative sequence component</th>
<th>→</th>
<th>Unbalanced feeding</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Inverter B" /></td>
<td>+</td>
<td><img src="image" alt="Inverter B" /></td>
<td>→</td>
<td><img src="image" alt="Inverter B" /></td>
</tr>
<tr>
<td><img src="image" alt="Inverter A" /></td>
<td>+</td>
<td><img src="image" alt="Inverter A" /></td>
<td>→</td>
<td><img src="image" alt="Inverter A" /></td>
</tr>
</tbody>
</table>
Current locus

Measured elliptical current loci in stator reference frame for the operation point \((n, F, M) = (60000 \text{ rpm}, 5 \text{ N}, 160 \text{ mNm})\)
Content

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• Conclusions
## Motor rating

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated speed</td>
<td>$n$</td>
<td>60 000 rpm</td>
</tr>
<tr>
<td>Rated power (self-cooling /</td>
<td>$P_m$</td>
<td>0.66 / 2 kW</td>
</tr>
<tr>
<td>with propeller cooling)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated torque</td>
<td>$M_N$</td>
<td>0.15 / 0.45 Nm</td>
</tr>
<tr>
<td>Rated levitation force (equal</td>
<td>$F_N$</td>
<td>8.2 N</td>
</tr>
<tr>
<td>rotor weight force)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal phase voltage</td>
<td>$U_0$</td>
<td>45.4 V r.m.s</td>
</tr>
<tr>
<td>Two three-phase two-level</td>
<td>$S_N$</td>
<td>2 x 550 VA</td>
</tr>
<tr>
<td>MOSFET inverters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$f_{sw}$</td>
<td>31.25 kHz</td>
</tr>
<tr>
<td>Nominal current</td>
<td>$I_N$</td>
<td>3.9 A</td>
</tr>
<tr>
<td>Nominal torque current</td>
<td>$I_{N1}$</td>
<td>3.18 A</td>
</tr>
<tr>
<td>Nominal levitation current</td>
<td>$I_{N2}$</td>
<td>2.26 A</td>
</tr>
</tbody>
</table>

**Bearingless motors:**
- One dual half-pitched winding $W/\tau_p = 1/2$
- Two-pole drive winding
- Four-pole levitation winding
Stator iron stack

Prototype: Two double-layer winding, slot count $Q = 12$, $2p_1 = 2$, $2p_2 = 4$

+ Short winding overhang

Stator iron stack with windings (EW, TU Darmstadt)
Motor cut view

$l = 242 \text{ mm}$

- Emergency bearings
- Magnetic bearing
- Company Levitec GmbH (IP)
- Rotor angle sensors
- Bearingless rotor
- Stator
- Position sensors
- Prototype motor, Auto CAD (EW, TU Darmstadt)
- $m = 7.1 \text{ kg}$
- $d = 120 \text{ mm}$
- Propeller wheel
Rotor cut view

- Magnet bearing (rotor part)
- $d_{ra} = 32\text{ mm}$
- $m_r = 0.8\text{ kg}$
- Balancing holes
- SmCo$_5$ magnet
- Carbon fiber bandage

(EW, TU Darmstadt)
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- Measurements on the test-bench
- Conclusions
Test-bench

Additional compressor housing and propellers for overload operation

Battery supply (DC-link 155 V)

Drive cable and magnetic bearing cable

Bearingless motor with turbo-charger propeller as load

2 x 550 VA MOSFET inverters
2 x 12 VA for the levitation
2 x 538 VA for the drive

Additional compressor housing and propellers for overload operation

Battery supply (DC-link 155 V)

Drive cable and magnetic bearing cable

Bearingless motor with turbo-charger propeller as load

2 x 550 VA MOSFET inverters
2 x 12 VA for the levitation
2 x 538 VA for the drive

(EW, TU Darmstadt)
Measurements on the test-bench

Indirect estimation of output power: $\eta_N = 60000$ rpm, $M_N = 105$ mNm

<table>
<thead>
<tr>
<th>Losses / W</th>
<th>48000 rpm, 200 mNm</th>
<th>60000 rpm, 90 mNm</th>
<th>60000 rpm, 160 mNm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta \approx 85%$</td>
<td>$\eta \approx 75%$</td>
<td>$\eta \approx 83%$</td>
<td>Motor efficiency</td>
</tr>
<tr>
<td>$\eta \approx 78%$</td>
<td>$\eta \approx 69%$</td>
<td>$\eta \approx 77%$</td>
<td>Drive efficiency</td>
</tr>
<tr>
<td>$P_{out} \approx 1012$ W</td>
<td>$P_{out} \approx 567$ W</td>
<td>$P_{out} \approx 979$ W</td>
<td>Output power</td>
</tr>
<tr>
<td>33 K</td>
<td>42 K</td>
<td>51 K</td>
<td>Winding temp. rise</td>
</tr>
</tbody>
</table>

Motor copper losses
Additional losses
Inverter & MB copper losses
Iron and friction losses
Content

• Introduction

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• Conclusions
Conclusions

• Restricted to two-pole motors (four-pole motors possible)
• Relevant for small size high speed bearingless motors
• Simplified winding processing (equivalent to a single double-layer four-pole winding)
• Motor with reduced axial length

→ Further investigations on axial control with zero-sequence current.

Cooperation project: LEViTEC GmbH, Lahnau, Germany
Evaluation of a Dual Half-Pitched Three-Phase Bearingless High-Speed Permanent Magnet Synchronous Motor Prototype

Thank you for your attention
Any questions?
List of motor parameters

<table>
<thead>
<tr>
<th>Motor Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power</td>
<td>$P_N$</td>
<td>660 W</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>$n_N$</td>
<td>60 000 rpm</td>
</tr>
<tr>
<td>Rated shaft Torque</td>
<td>$M_N$</td>
<td>105 mNm</td>
</tr>
<tr>
<td>Number of phases</td>
<td>$m$</td>
<td>6</td>
</tr>
<tr>
<td>Number of slots</td>
<td>$Q_s$</td>
<td>12</td>
</tr>
<tr>
<td>Iron stack length</td>
<td>$l_{Fe}$</td>
<td>40 mm</td>
</tr>
<tr>
<td>Magnet axial length</td>
<td>$l_M$</td>
<td>44 mm</td>
</tr>
<tr>
<td>Electrical steel sheet</td>
<td></td>
<td>M330-35A</td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>$d_{sa}$</td>
<td>75 mm</td>
</tr>
<tr>
<td>Stator inner diameter</td>
<td>$d_{si}$</td>
<td>35 mm</td>
</tr>
<tr>
<td>Rotor mass</td>
<td>$m_r$</td>
<td>0.80 Kg</td>
</tr>
<tr>
<td>Rotor inertia (approx.)</td>
<td>$J_z$</td>
<td>1e-4 kgm²</td>
</tr>
<tr>
<td>No-load phase voltage at $n_N$</td>
<td>$U_0$</td>
<td>45.4 V r.m.s</td>
</tr>
<tr>
<td>Nominal current (r.m.s)</td>
<td>$I_N$</td>
<td>3.9 A</td>
</tr>
<tr>
<td>Positive current component (r.m.s)</td>
<td>$I_{N1}$</td>
<td>3.18 A</td>
</tr>
<tr>
<td>Mechanical air-gap</td>
<td>$\delta_0$</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Permanent magnet ring</td>
<td></td>
<td>SmCo₅</td>
</tr>
<tr>
<td>Magnet ring magnetization</td>
<td></td>
<td>Parallel</td>
</tr>
<tr>
<td>Magnet height</td>
<td>$h_M$</td>
<td>2.75 mm</td>
</tr>
<tr>
<td>Magnet length</td>
<td>$l_M$</td>
<td>48 mm</td>
</tr>
<tr>
<td>Bandage thickness</td>
<td>$h_B$</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Winding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>$p$</td>
<td>1</td>
</tr>
<tr>
<td>Number of layers</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Coil pitch</td>
<td>$W/\tau_p$</td>
<td>1/2</td>
</tr>
<tr>
<td>Number of turns per coil</td>
<td>$N_c$</td>
<td>11</td>
</tr>
<tr>
<td>Slot fill factor</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Air-gap flux density (at $r_{si}$, 100°C)</td>
<td>$B_0$</td>
<td>0.48 T</td>
</tr>
<tr>
<td>Tooth flux density (100°C)</td>
<td>$B_{d,S}$</td>
<td>0.84 T</td>
</tr>
<tr>
<td>Yoke flux density (100°C)</td>
<td>$B_{y,S}$</td>
<td>0.82 T</td>
</tr>
</tbody>
</table>
Two simple *Park* transforms

Difference of phase currents $\rightarrow$ *Park* transform $\rightarrow$ Torque current
Sum of phase currents $\rightarrow$ *Park* transform $\rightarrow$ Levitation currents
Control scheme
Torque-force characteristic comparison

- Increased force potential.
- Keep levitating when one inverter stops.
- Inherent online current optimization for every working point.

Levitation possible with a single winding. The torque is pulsating but the rotor is safely kept in suspension.

Normalized torque-force characteristic due to inverter current limits:
Proposed winding in solid line and classical winding in dashed line
Torque-force characteristic

- Force
- Torque
- Inverters current limits
- Force + Torque

Combined inverter limit
Drive inverter limit
Force inverter limit

Radial force (p.u.)
Torque (p.u.)
Current locus

Calculated and measured elliptical current loci in stator reference frame with orthogonal main axis for the operation point \((n, F, M) = (n_N, 0.6 \cdot F_N, 1.5 \cdot M_N)\)
Determination of the coil pitch $W/\tau_p$

Prototype: two-layer winding, slot count $Q = 12$, $2p_1 = 2$, $2p_2 = 4$

Half-pitched $W/\tau_p = 1/2$ … …no field harmonic $\nu = 4$

(Torque) (Forces) (Disturbances)