Improvement of a Coreless Tubular Permanent Magnet Machine in Terms of Output Power Using Dual-Segment Magnets

Minh-Trung Duong, Yon-Do Chun, Pil-Wan Han, Byoung-Gun Park, Jin-Kyu Lee
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Geometry
Conventional Topology Using Halbach Array

Stony Brook University’s model

- **Application**: energy harvesting in vehicle suspension system.
- Double layers, coreless type.
- Using Halbach array for PMs.
- 16 slots – 8 poles
Conventional Topology Using Halbach Array

8 slots – 4 poles

- Number of segments/pole pitch: 2
- Segment: radial PM, axial PM
Novel Topology Using Dual-segment Magnet

- **Even segment**

- **Number of segments/pole pitch:** 4
- **Segment:** radial PM, axial PM, 45° PM
Novel Topology Using Dual-segment Magnet

- **Odd segment**

- **Number of segments/pole pitch**: 5
- **Segment**: radial PM, axial PM, $30^\circ$ PM

![Diagram of the novel topology using dual-segment magnet with indications of the segment types, number of segments, and specific dimensions.]
Design Configurations
### Permanent magnets

**Halbach array**

<table>
<thead>
<tr>
<th>4 segments</th>
<th>5 segments</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **Material:** NdFeB N50SH - $B_r = 1.4T; \mu_r = 1.05$ at 20°C
- **Magnetized angle:** randomly selected.
- **PMs width:** equally divided.
**External circuit**

(a) Flux distribution vs coil position

(b) External circuit

- **Maximum power:** $R_{Load} = \sum R_{coil}$

- **Coil 1 & coil 3:** series connection & positive winding direction

- **Coil 2 & coil 4:** series connection & negative winding direction.
Assumption
- Medium size car suspension system.
- Road class C.
- Speed: 60 mph (96 km/h)

Operating conditions
- Vibrating speed: 0.25 m/s
- Vibrating frequency: 10 Hz
- Peak to peak stroke length: 11.25 mm
## Design parameters

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Halbach array</th>
<th>4 segments</th>
<th>5 segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner PMs thickness, $t_{im}$ (mm)</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer PMs thickness, $t_{om}$ (mm)</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial PMs width, $w_{am}$ (mm)</td>
<td>24</td>
<td>12</td>
<td>9.6</td>
</tr>
<tr>
<td>Radial PMs width, $w_{rm}$ (mm)</td>
<td>24</td>
<td>12</td>
<td>9.6</td>
</tr>
<tr>
<td>Segment PMs width, $w_{sm}$ (mm)</td>
<td>---</td>
<td>12</td>
<td>9.6</td>
</tr>
<tr>
<td>Coil width, $w_c$ (mm)</td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Coil thickness, $t_c$ (mm)</td>
<td></td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Pole pitch, $\tau_p$ (mm)</td>
<td></td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>Mechanical airgap, $g$ (mm)</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Back iron thickness, $t_b$ (mm)</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Wire diameter, $d_w$ (mm)</td>
<td></td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Number of windings per slot, turns</td>
<td>408</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase resistance, $R$ ($\Omega$)</td>
<td></td>
<td>9.7*2=19.4</td>
<td></td>
</tr>
<tr>
<td>Material of iron</td>
<td></td>
<td>S20C</td>
<td></td>
</tr>
<tr>
<td>Material of PMs</td>
<td></td>
<td>N50SH: $B_r = 1.40T$; $\mu_r = 1.05$</td>
<td></td>
</tr>
</tbody>
</table>
Comparison
Flux distribution

At $t=0.3s$

- Halbach array
- 4 segments
- 5 segments
Flux density in the middle of coil

<table>
<thead>
<tr>
<th>Flux density</th>
<th>Halbach array</th>
<th>4 segments</th>
<th>5 segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum (T)</td>
<td>0.76</td>
<td>0.85</td>
<td>0.82</td>
</tr>
<tr>
<td>Waveform</td>
<td>Square</td>
<td>Sinusoidal</td>
<td>Sinusoidal</td>
</tr>
</tbody>
</table>
Output power

<table>
<thead>
<tr>
<th>Flux density</th>
<th>Halbach array</th>
<th>4 segments</th>
<th>5 segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum (T)</td>
<td>92.00</td>
<td>100.72</td>
<td>96.11</td>
</tr>
<tr>
<td>Average (T)</td>
<td>45.43</td>
<td>50.43</td>
<td>48.92</td>
</tr>
</tbody>
</table>
Conclusion

- **Dual-segment magnet topology:**
  - Higher flux density: nearly 10.6% (4-segment) & 7.3% (5-segment)
  - Higher maximum output power: 8.7% (4-segment) & 4.3% (5-segment)

- **Further study:**
  - Optimization of the magnetized angle.
  - Optimization of the number of PMs segments.
  - Optimization of the relative dimensions of PMs segments.
Thank you!