ZERO RARE-EARTH MAGNET INTEGRATED STARTER-GENERATOR DEVELOPMENT FOR MILITARY VEHICLE APPLICATIONS

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<td>06-03-2013 to 06-08-2013</td>
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<td>Remy International, 600 Corporation Drive, Pendleton, IN, 46064</td>
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<td>U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000</td>
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**Abstract**

**Briefing Charts**

**Subject Terms**

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Outline

• Introduction
• Permanent Magnet Materials
• Motor Topology Comparison
• Comparative Down-Selection Process
• Results
• Future Work
• Conclusion
• Questions
Introduction

• Today’s military ground vehicles require more electrical power than ever before.
• Current high-performance alternators – 28V, 18 kW.
• Future demand for vehicle export power generation is expected to reach and exceed 100kW.
• Many electric machines capable of (≥ 100kW) output power rely on rare-earth elements such Nd, Sm, Dy and Tb.
• Diminished U.S. reserves, uncertain availability abroad and price volatility limit rare-earth based PM material viability.
• These factors drive electric machine design towards high-voltage and Zero-Rare-Earth (ZRE) magnet Integrated-Starter-Generator (ISG) designs.
Consider and evaluate machine topologies for application to a 3-phase, brushless, integrated starter-generator (ISG) that does not use rare-earth (RE) metals, for:

- Continuous on-board power generation and engine starting in a military vehicle platform.
- Support of on-board hybrid electric features such as regenerative braking, torque assist and stop-start operation.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
<th>Units</th>
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<tbody>
<tr>
<td>Steady-State Output Voltage</td>
<td>600 ± 35</td>
<td>VDC</td>
</tr>
<tr>
<td>Output Power</td>
<td>100</td>
<td>kW</td>
</tr>
<tr>
<td>Cont. Torque</td>
<td>1200</td>
<td>Nm</td>
</tr>
<tr>
<td>Peak Torque (30 sec)</td>
<td>1800</td>
<td>Nm</td>
</tr>
<tr>
<td>Base / Max Speed</td>
<td>800 / 4250 RPM (objective)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1100 / 3200 RPM (threshold)</td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>WEG</td>
<td></td>
</tr>
<tr>
<td>Max Flow Rate</td>
<td>30</td>
<td>LPM</td>
</tr>
<tr>
<td>Inlet Temp</td>
<td>110</td>
<td>ºC</td>
</tr>
<tr>
<td>Operating Air Temp</td>
<td>-50 - 125</td>
<td>ºC</td>
</tr>
<tr>
<td>Housing</td>
<td>SAE #1 Compatible OD: 22 inch, Length: 120mm</td>
<td></td>
</tr>
</tbody>
</table>
Permanent Magnet Materials
Permanent Magnet History

- 1900’s – Magnetic Steel
- 1940’s – Alnico
- 1950’s – Ferrite
- 1960’s – Alnico 9
- 1960’s – SmCo
  - First RE PM’s
- 1980’s – NdFeB
- 2007 – LaCo Ferrite
• Traditional PM machines use rare-earth permanent magnets – NdFeB or SmCo.
• RE materials present challenges because of rising prices, price instability and foreseeable shortages.
• Because of these factors, this project considers designs that utilize zero-rare-earth magnets.
Permanent Magnet Materials

**Rare-Earth**
- NdFeB
- SmCo
- LaCo
- Ferrite

**Zero Rare-Earth**
- Ferrite
- Alnico

Developmental Materials
# Permanent Magnet Materials

**Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>NdFeB</th>
<th>SmCo 2:17</th>
<th>Alnico 9</th>
<th>Ferrite</th>
<th>Favorability Indicator</th>
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<tbody>
<tr>
<td>Flux Density [Br]</td>
<td>T</td>
<td>1.23</td>
<td>1.12</td>
<td>1.12</td>
<td>0.4</td>
<td>&gt; better</td>
</tr>
<tr>
<td>Coercivity [Hcb]</td>
<td>kA/m</td>
<td>931</td>
<td>820</td>
<td>109</td>
<td>290</td>
<td>&gt; better</td>
</tr>
<tr>
<td>Intrinsic Coercivity [Hcj]</td>
<td>kA/m</td>
<td>≥ 2228</td>
<td>≥ 1600</td>
<td>109</td>
<td>318</td>
<td>&gt; better</td>
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<tr>
<td>Energy product [BH\text{max}]</td>
<td>kJ/m\text{³}</td>
<td>240</td>
<td>230</td>
<td>83.6</td>
<td>31.8</td>
<td>&gt; better</td>
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<tr>
<td>Usable Temperature Range</td>
<td></td>
<td>up to 200 °C</td>
<td>up to 520 °C</td>
<td>up to 520 °C</td>
<td>-40 °C to 150 °C</td>
<td>Min: -50 °C to 150 °C</td>
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<tr>
<td>Relative Cost</td>
<td></td>
<td>Highest</td>
<td>High</td>
<td>Medium</td>
<td>Lowest</td>
<td>&lt; better</td>
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<tr>
<td>Grade</td>
<td></td>
<td>S38EH</td>
<td>Recoma 30</td>
<td>Alnico 9</td>
<td>NMF-9G</td>
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Significant magnetic performance difference between **rare-earth** and **zero-rare-earth** materials.
Motor Topology Comparison
Motor Topologies

Permanent Magnet
- IPM
- SPM
- AFPM

Non-Permanent Magnet
- Spoke IPM
- SRM
- SynRM
- TFPM
- IM
Permanent Magnet Topologies

- Requires more magnetic material when using non-rare-earth magnets to achieve similar torque density.
- If a flux concentrating magnet arrangement, ferrite magnets can be used otherwise, utilizes Alnico magnets.
- Flux concentrating requires a high magnet length to pole pitch ratio which requires high rotor thickness.
Non-PM Topologies

- Brushless, do not require active rotor windings.
- No requirement for permanent magnets.
- Low cost.

- IM & SynRM have significant end turn length because of low pole counts, making them less optimal for this application.
Qualitative Motor Comparison

### Specification

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<th>Non-PM Topologies</th>
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<td>Overall Housing Length</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Housing OD</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Maximum Operating Speed</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Base (corner) Speed</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Continuous Torque</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Continuous Power</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Peak Torque (800 RPM)</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Peak Power (800 RPM)</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>○</td>
<td>○</td>
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<tr>
<td>Operating Air Temperature</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

- **PM Topologies**
  - Spoke IPM
  - AFPM
  - TFPM
  - SRM
- **Non-PM Topologies**
  - SynRM
  - IM

### Used baseline specification and literature survey results to evaluate likelihood to topologies to meet requirements.

### More uncertainty in ability to meet specification for the PM topologies because of the limitations of the magnet materials.

### Selected for further consideration:
- Spoke IPM
- AFPM
- TFPM
- SRM
Comparative Down-Selection

- Designs provided a quantitative comparison between selected topologies.
- Criteria chosen based upon project technical targets and engineering assumptions.
- Designs generated using 2D and 3D FEA and preliminary thermal modeling.
## Comparative Down-Selection

<table>
<thead>
<tr>
<th>Specification</th>
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<th>AFPM</th>
<th>TFPM</th>
<th>SRM</th>
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<tr>
<td><strong>PHYSICAL</strong></td>
<td></td>
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<tr>
<td>Overall Housing Length</td>
<td>120 mm (T)</td>
<td>120 mm</td>
<td>120 mm</td>
<td>120 mm</td>
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<tr>
<td>Housing OD</td>
<td>&lt; 558 mm</td>
<td>530 mm</td>
<td>530 mm</td>
<td>530 mm</td>
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<tr>
<td>Pole Count</td>
<td>16</td>
<td>30 +</td>
<td>30 +</td>
<td>24/16</td>
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<td><strong>PEAK PERFORMANCE</strong></td>
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<td></td>
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<tr>
<td>Peak Torque (800 RPM)</td>
<td>1800 Nm</td>
<td>1057</td>
<td>550</td>
<td>1834</td>
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<tr>
<td>Peak Power (800 RPM)</td>
<td>150 kW</td>
<td>88.5</td>
<td>46</td>
<td>154</td>
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<td><strong>MAGNETIC REQUIREMENTS</strong></td>
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<tr>
<td>Magnetic Material</td>
<td>Ferrite</td>
<td>Alnico</td>
<td>Ferrite</td>
<td></td>
</tr>
<tr>
<td>Demagnetization Risk</td>
<td>Low</td>
<td>Guaranteed</td>
<td>Low</td>
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</tr>
<tr>
<td>General</td>
<td>Simple</td>
<td>Middle</td>
<td>Complex</td>
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<td>Controlability</td>
<td>Middle</td>
<td>Complex</td>
<td>Complex</td>
<td>Simple</td>
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<tr>
<td>Manufacturability</td>
<td>Middle</td>
<td>Complex</td>
<td>Complex</td>
<td>Simple</td>
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Results

• Spoke IPM
  – Unable to meet peak torque and power requirements.
  – Offers best performance for a permanent magnet machine.
  – Utilized ferrite magnets.
  – Unlikely that any PM topology will meet specifications using commercially available ZRE magnets.

• Switched Reluctance
  – Has the highest potential for meeting output torque and power requirements.
  – Requires no magnets.
  – Disadvantage of higher torque ripple and acoustic noise.
Future Work

• Detailed design ongoing to optimize electrical and mechanical designs for performance.
• After completion of mechanical design, prototypes will be built for testing and validation.
• Testing and validation anticipated to be completed by October 2014.
• Continued work for noise, torque ripple, performance improvement.
Conclusions

• As vehicle export power generation demands and ground vehicle electrification increase so does the U.S. dependence on rare-earth elements.

• Continued use of rare-earth permanent magnet materials for high-performance (≥ 100kW) military vehicle applications may not be viable.

• This paper offers alternative motor/machine topologies for ISGs that are rare-earth material independent and capable of meeting significant export power generation demands for military applications.

• The zero-rare-earth material study rated Ferrite and Alnico 9 as the preferred magnet material candidates due to their high commercial availability, low cost and suitable magnetic properties.

• The motor topology study rated the SWITCHED RELUCTANCE motor as the favored non-PM topology and found that the SPOKE IPM motor was the preferred ZRE PM topology.
Questions?