Zero Rare-Earth Magnet Integrated Starter-Generator Development For Military Vehicle Applications

Katherine Riley[Ψ], ShanShan Conway[Ψ], Seong T. Lee Ph.D.[Ψ],
Yong-Bae Jung Ph.D.[Ψ], Wesley G. Zanardelli Ph.D.[Ω], Ronnie L. Wright Ph.D.[Δ]

Ψ- Remy International, Inc. Ω- U.S. Army TARDEC Δ- DCS Corporation

14 August 2013

GVSETS

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **12 AUG 2013**	2. REPORT TYPE **Briefing Charts**	3. DATES COVERED **06-03-2013 to 06-08-2013**

4. TITLE AND SUBTITLE **ZERO RARE-EARTH MAGNET INTEGRATED STARTER-GENERATOR DEVELOPMENT FOR MILITARY VEHICLE APPLICATIONS**	5a. CONTRACT NUMBER **W56HZV-09-D-0148** 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Katherine Riley; ShanShan Conway; Seong Lee; Yong-Bae Jung; Wesley Zanardelli**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Remy International,600 Corporation Drive,Pendleton,IN,46064**	8. PERFORMING ORGANIZATION REPORT NUMBER **; #24094**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000**	10. SPONSOR/MONITOR'S ACRONYM(S) **TARDEC** 11. SPONSOR/MONITOR'S REPORT NUMBER(S) **#24094**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM (GVSETS), SET FOR AUG. 21-22, 2013

14. ABSTRACT
Briefing Charts

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Public Release**	**20**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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.

Introduction

ZRE ISG Requirements

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.

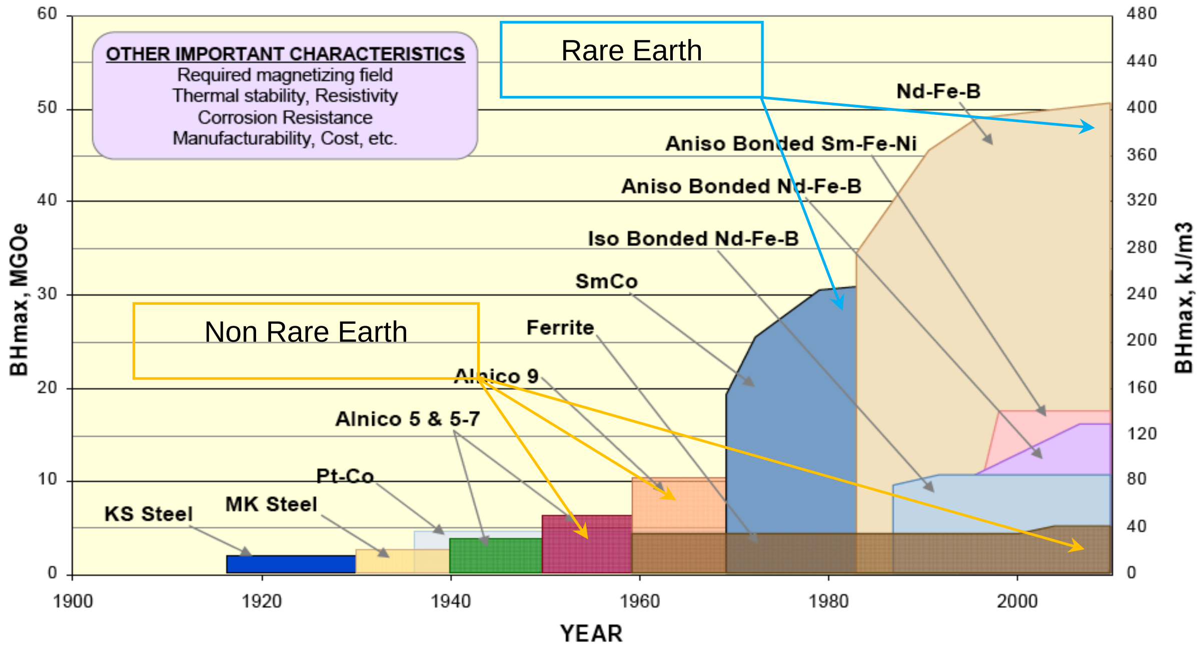
Requirement	***Value***	***Units***
Steady-State Output Voltage	600 ± 35	VDC
	MIL-PFR-GCS600A (ARMY)	
Output Power	100	kW
Cont. Torque	1200	Nm
Peak Torque (30 sec)	1800	Nm
Base / Max Speed	800 / 4250 RPM (objective)	
	1100 / 3200 RPM (threshold)	
Cooling	WEG	
Max Flow Rate	30	LPM
Inlet Temp	110	°C
Operating Air Temp	-50 - 125	°C
Housing	SAE #1 Compatible OD: 22 inch, Length: 120mm	

Permanent Magnet Materials

Permanent Magnet History

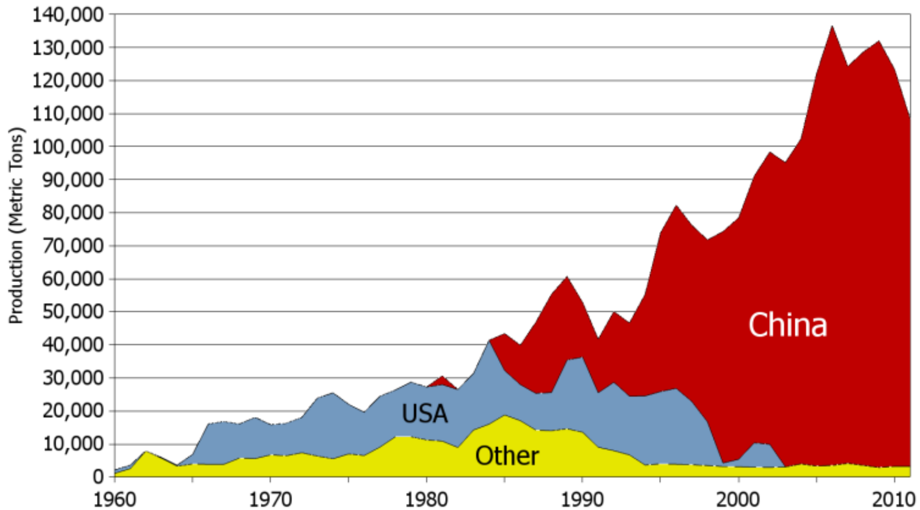
POWER AND MOBILITY

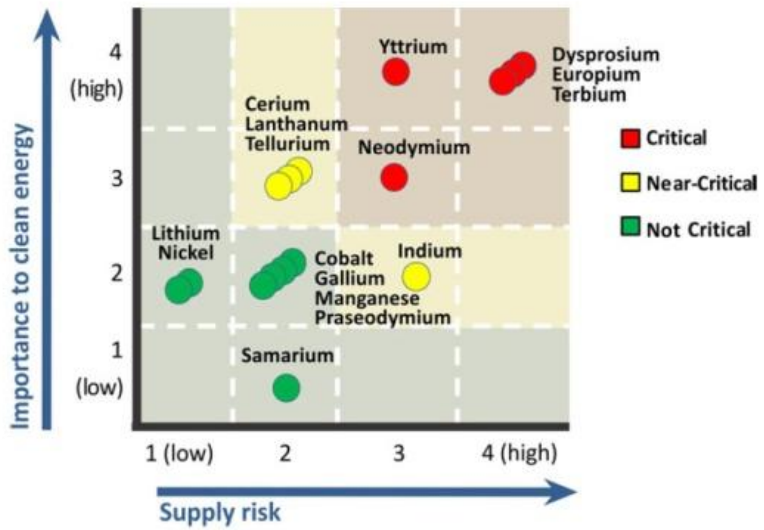
- 1900's – Magnetic Steel
- 1940's – Alnico
- 1950's – Ferrite
- 1960's – Alnico 9
- 1960's – SmCo
  - First RE PM's
- 1980's – NdFeB
- 2007 – LaCo Ferrite



GVSETS

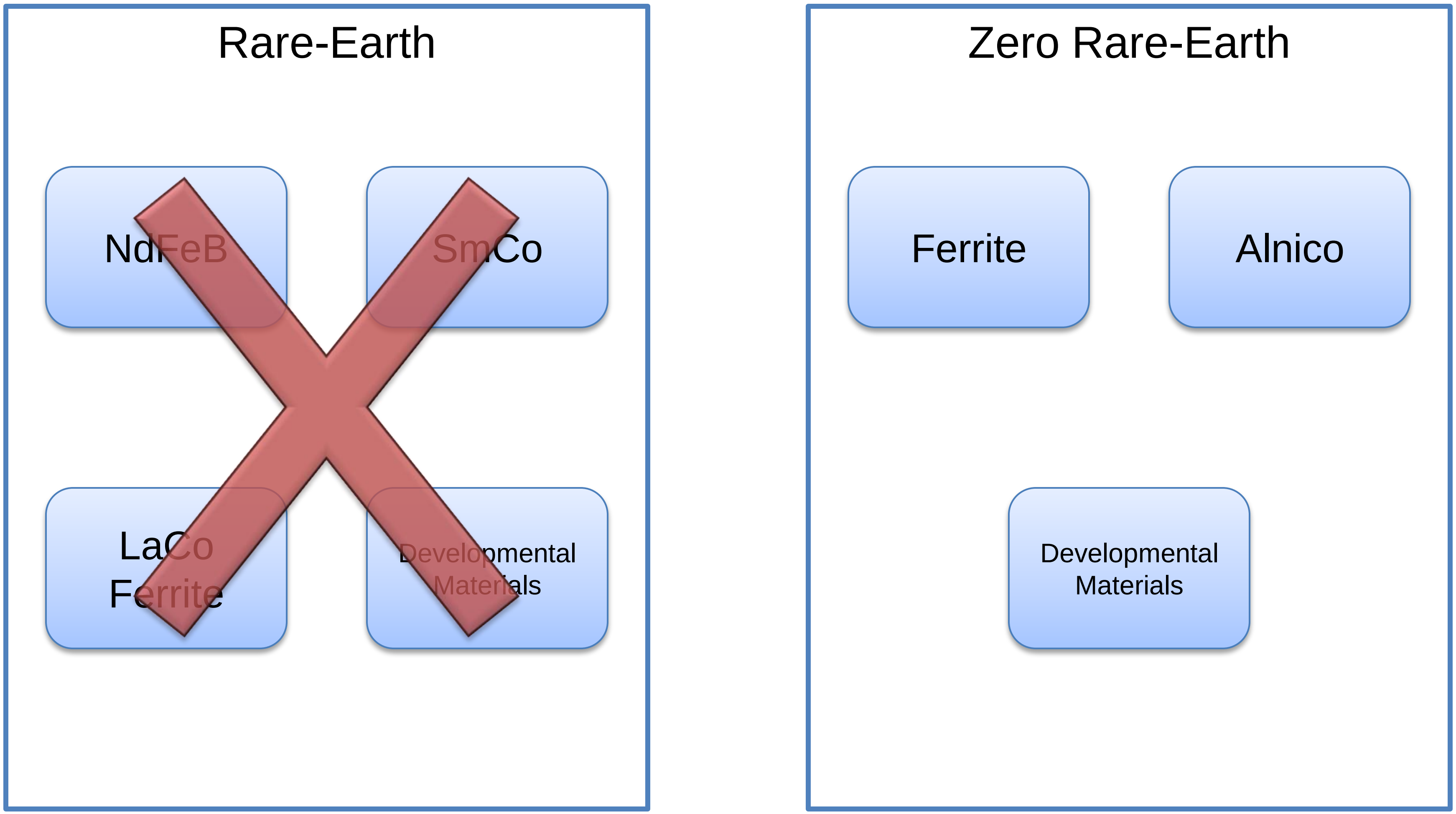
Permanent Magnet Materials





- 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

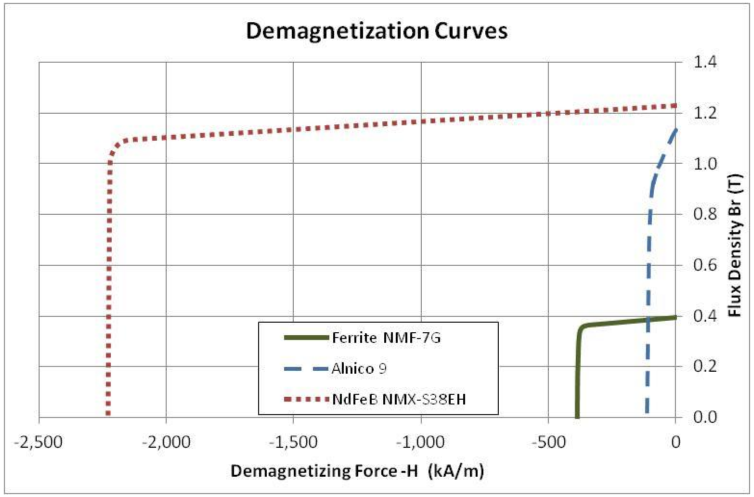


Permanent Magnet Materials

POWER AND MOBILITY

Characteristic	Units	NdFeB	SmCo 2:17	Alnico 9	Ferrite	Favorability Indicator
Flux Density [Br]	T	1.23	1.12	1.12	0.4	> better
Coercivity [Hcb]	kA/m	931	820	109	290	> better
Intrinsic Coercivity [Hcj]	kA/m	≥ 2228	≥ 1600	109	318	> better
Energy product [BH_{max}]	kJ/m^3	240	230	83.6	31.8	> better
Usable Temperature Range		up to 200 °C	up to 520 °C	up to 520 °C	-40 °C to 150 °C	Min: -50 °C to 150 °C
Relative Cost		Highest	High	Medium	Lowest	< better
Grade		S38EH	Recoma 30	Alnico 9	NMF-9G	

Significant magnetic performance difference between rare-earth and zero-rare-earth materials.



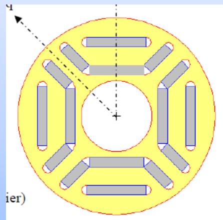
GVSETS

Motor Topology Comparison

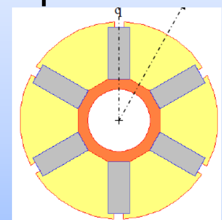
Motor Topologies

Permanent Magnet

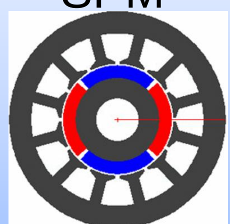
IPM



Spoke IPM

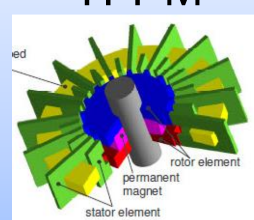


SPM



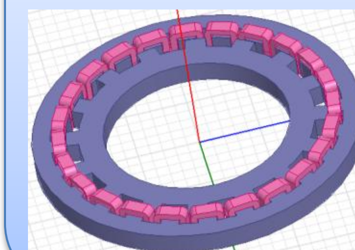
AFPM

TFPM

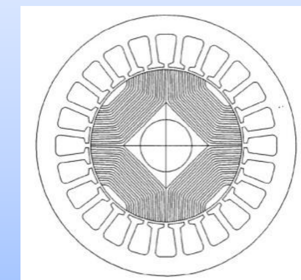


Non-Permanent Magnet

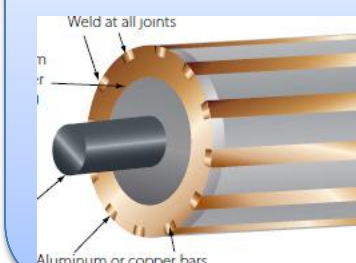
SRM



SynRM

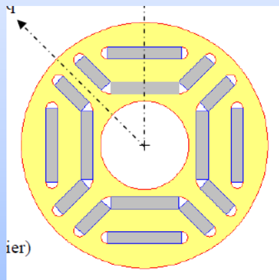


IM

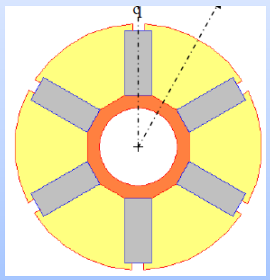


Permanent Magnet Topologies

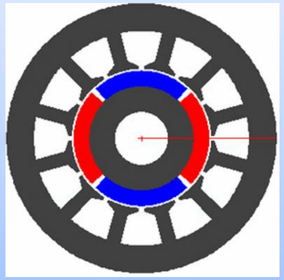
IPM



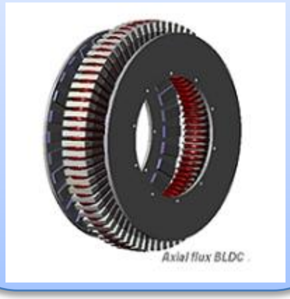
Spoke IPM



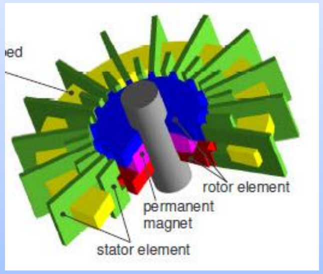
SPM



AFPM



TFPM



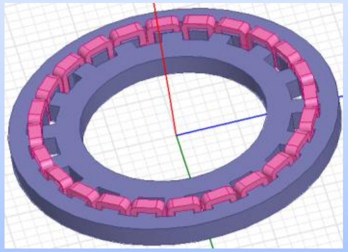
- Requires more magnetic material when using non-rare-earth magnets to achieve similar torque density.
- If a flux concentrating magnet arrangement, ferrite magnets can be used otherwise, utilizes Alnico magnets.
- Flux concentrating requires a high magnet length to pole pitch ratio which requires high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

Non-PM Topologies

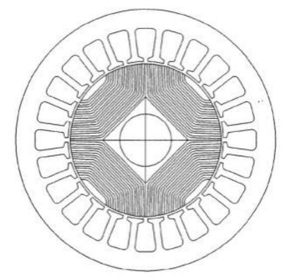
- Brushless, do not require active rotor windings.
- No requirement for permanent magnets.
- Low cost.

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

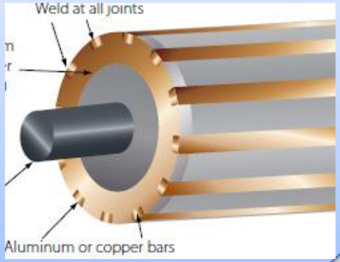
SRM



SynRM



IM



Qualitative Motor Comparison

POWER AND MOBILITY

	Specification	PM Topologies				Non-PM Topologies		
		Spoke IPM	SPM	AFPM	TFPM	SRM	SynRM	IM
HOUSING DIMENSIONS								
Overall Housing Length	120 mm (T)	●	●	●	●	●	○	○
Housing OD	< 558 mm	●	●	●	●	●	●	●
MECHANICAL PERFORMANCE								
Maximum Operating Speed	4250 RPM	●	⊙	○	⊙	●	●	●
Base (corner) Speed	800 RPM	●	●	●	●	●	●	●
CPSR								
Continuous Torque	1200 Nm	⊙	⊙	⊙	⊙	●	⊙	⊙
Continuous Power	100 kW	⊙	⊙	⊙	⊙	⊙	⊙	⊙
Peak Torque (800 RPM)	1800 Nm	⊙	⊙	●	●	●	⊙	⊙
Peak Power (800 RPM)	150 kW	⊙	⊙	●	●	●	⊙	⊙
THERMAL REQUIREMENTS								
Inlet Temperature	110°C	●	●	●	●	⊙	⊙	⊙
Operating Air Temperature	-50°C to 125°C	⊙	⊙	⊙	⊙	●	●	●
GENERAL								
Manufacturability		●	⊙	○	○	●	●	●

● Estimated to meet specification ○ Uncertain ability to meet spec

⊙ Strong potential to meet specification □ Unable to meet specification

- 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

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

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?