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

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ABSTRACT

The demand for increased export power generation and ground vehicle electrification are escalating trends due to the warfighter's expanding mission requirements. Today's low-voltage alternators used in some fielded ground vehicle's power systems supply up to 650ADC, or 18kW. Future demand for vehicle export power generation is expected to reach and exceed 100kW. A majority of electric machines capable of meeting this level of power generation rely on rare-earth elements such as Neodymium (Nd), Samarium (Sm), Dysprosium (Dy) and Terbium (Tb). Due to diminished reserves in the United States, availability abroad and price volatility, continued use of rare-earth permanent magnet materials may not be viable. The expanding demand for vehicle power is on a trajectory which surpasses the U.S. ability to reliably harvest or procure rare-earth magnet materials. As such, electric machine topologies that utilize zero rare-earth magnet materials are being considered for ISG (integrated-starter-generator) applications. This paper investigates alternative permanent magnet materials and motor topologies for the design of an ISG capable of 100kW of output power and a continuous/peak torque of 1200Nm/1800Nm that do not include rare-earth elements. A comparative analysis detailing the zero rare-earth permanent magnet material selection process along with accompanied motor topology will be given.

INTRODUCTION

Today's military ground vehicles have an increased demand for electrical power with some applications reaching and surpassing the leading high-performance low-voltage (28-volt) alternators that are capable of supplying 18kW of power. Engine compartment packaging volume and front-end accessory drive capability are approaching their physical limits for conventional alternators. With electrical power requirements of future vehicles significantly in excess of today's fielded systems, sustained growth of low-voltage systems to meet future power demands will not be possible. The majority of high-performance electric machines capable of meeting future power generation requirements traditionally rely on rare-earth permanent magnets – NdFeB (*neodymium iron boron*) and SmCo (*samarium cobalt*) – to maximize their power and torque densities. Additionally, the rare-earth element, Dy (*dysprosium*), is also used to improve the high-temperature capabilities of NdFeB magnets. The military ground vehicle's escalating demand for increased onboard and export power generation make it extremely difficult to achieve the targeted performance and reliability requirements using materials outside of the rare-earth category. Due to their favorable properties, rare-earth permanent magnets, mainly NdFeB, have become the primary permanent magnet for hybrid motor applications. The rare-earth permanent magnets offer the highest coercivity and energy products available in modern permanent magnets, and depending on the specific material chosen, are usable over a wide temperature range. Rare-earth elements, such as *dysprosium*, present significant challenges for the development of high-density permanent magnets due to their rising prices, price instability and foreseeable shortages [1].

China is currently the primary supplier of rare-earth oxides and processed rare-earth metals (Figure 1). The existence of a single primary supplier location, as well as volatile political and economic conditions, brings future mass availability of rare-earths for permanent magnet development into question. Also, large scale rare-earth demand must be considered, given that some projections forecast demand outpacing rare-earth supply in the medium term, under present consumption rates.

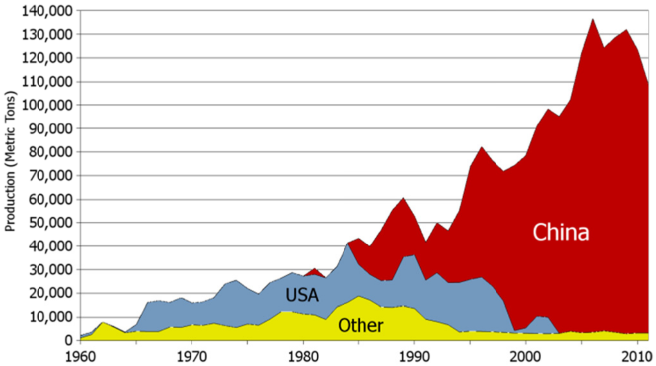

Figure 1: Global Production of Rare Earth Metals.

The USDOE (*U.S. Department of Energy*) 2011 Critical Materials Strategy Report identified materials critical to the future usage and development of clean energy within the United States. The report ranked the criticality of materials for the short and medium terms, based upon projected supply and importance to energy development. Figure 2 shows that five rare-earth (RE) elements (*dysprosium*, *terbium*, *europium*, *neodymium* and *yttrium*) were found to be critical in the short term (*present–2015*), with near-critical RE supply risks for elements such as *cerium, indium, lanthanum* and *tellurium.* While *neodymium, dysprosium* and *terbium* maintain their medium term critical state (2015-2025), the report indicates that potential new sources of light rare-earth elements, with significant supply, could be entering the market. Thus, reducing the criticality of some of those elements (*cerium, lanthanum)* [2].

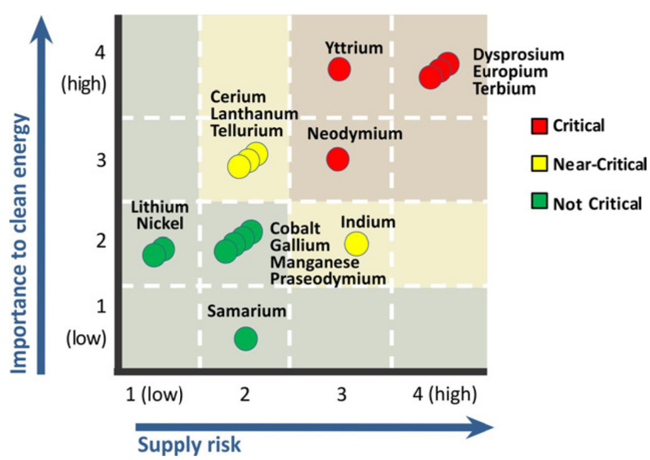

Figure 2: Short term critical materials.

The potential increase in rare-earths, especially with the re-opening of the Mt. Pass, California mine by Molycorp, provides a more positive outlook for the rare-earth markets, especially in the United States [3]. While only moderate increases appear on the horizon for the heavy rare-earth elements (*e.g., dysprosium*, *terbium*), fairly sizable increases are projected for the light rare-earths (*neodymium*, *cerium*, *lanthanum*) which are considered to be in a less critical state (Figure 3). This makes light-rare-earth element utilization an attractive future consideration.

	2010 Production[69]	Potential Sources of Additional Production between 2010 and 2015										Total 2015 Production Capacity
		United States		Australia			Vietnam	South Africa				
		Mt. Pass Phase I[72]	Mt. Pass Phase II	Mt. Weld[73]	NolansBore[74]	Dubbo Zirconia[75]	Dong Pao[76]	Steenkamps-kraal[77]	Russia & Kazakhs-tan[70]	India[71]		
La	**31,000**	5,800	6,800	5,600	2,000	510	970	1,100	140	560		54,000
Ce	**42,000**	8,300	9,800	10,300	4,800	960	1,500	2,300	290	1200		81,000
Pr	**5,900**	710	840	1,200	590	110	120	250	20	140		9,900
Nd	**20,000**	2,000	2,300	4,100	2,200	370	320	830	44	460		33,000
Sm	**2,800**	130	160	510	240	56	27	125	5	68		4,000
Eu	**370**	22	26	88	40	2		4	1			550
Gd	**2,400**	36	42	176	100	56		83	1	30		3,000
Tb	**320**	5	6	22	10	8		4	0.4			370
Dy	**1,600**	9	10	22	30	53		34	1			1,700
Y	**10,500**			66		410	21	250				11,300
Others	**2,000**	73	86			75	25	12	3	25		2,300
Total	**120,000**	17,000	20,000	22,000	10,000	2,600	3,000	5,000	500	2,500		200,000

Figure 3: Rare-Earth estimated supply 2010 – 2015.

To address the foreseeable rare-earth material supply challenges along with the military ground vehicle's increased demand for onboard and export power generation, a project to explore the design and development of a Zero Rare-Earth (**ZRE**) Magnet Integrated Starter-Generator (**ISG**) was undertaken. The ZRE ISG design/development effort and its findings serve as the basis for this paper. The basic performance requirements for the anticipated ISG are presented in Table 1.

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	

Table 1: ZRE ISG Performance Criteria.

Most importantly, the ISG's motor topology <u>shall not</u> utilize rare-earth (RE) permanent magnet materials, such as *neodymium* (Nd), *samarium* (Sm), *praseodymium* (Pr), *dysprosium* (Dy) or *terbium* (Tb). Forthcoming sections of this paper will discuss trade studies for alternative non rare-earth permanent magnet (PM) materials as well as associated motor topologies that are expected to meet the ZRE ISG design criterion (Table 1). Additionally, the process for down-selecting to an appropriate non rare-earth material and motor topology, results and future work will be presented.

PERMANENT MAGNET MATERIALS SELECTION

Given the criticality and limited availability within the United States, the usage of NdFeB and SmCo magnets has been discounted for this study. After rare-earth materials have been eliminated, alnico (first developed 1940's) and ferrite (first developed 1950's) are the commercially available materials of note.

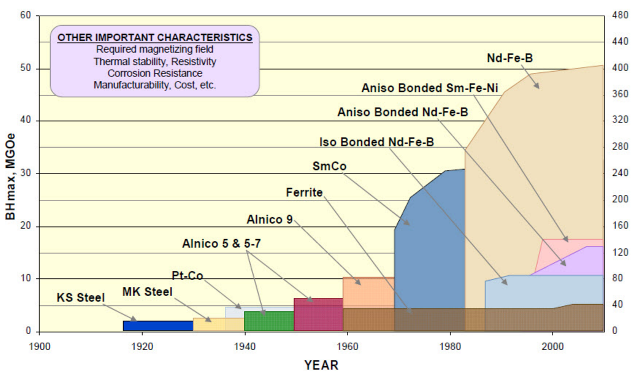

Figure 4: Historical trends in magnet materials.

Figure 4 details the historical trends for magnet materials, showing that most permanent magnets were Fe-based alloys from the early to mid-1900s. Ferrites comprise the largest class of permanent magnet materials produced worldwide [4]. Being composed primarily of inexpensive iron oxides, they are chemically inert, have high electrical resistivity and are considered to be important in a wide range of commercial applications [5].

While significant research has been undertaken to enhance the energy density of ferrites, ferrite-based magnets still have about half the energy density of alnico magnets and have significantly less energy density than rare-earth magnets. This low energy density means that ferrites have a high mass-to-magnetization ratio, requiring motor applications to have sufficient space for the large magnet mass. Due to their ferromagnetic properties, ferrites offer unique temperature characteristics. While most permanent magnet materials have negative temperature coefficients for both the induction change with temperature of Br and Hcj, ferrite has a positive temperature coefficient for Hcj. As such, the coercivity of ferrite increases as temperature increases which makes it a better material at higher temperatures versus lower temperatures [5].

Because ferrite magnets are used in high volumes across a wide variety of commercial applications, they are readily available from a range of suppliers. It is a mature magnet technology which provides for easy manufacturability in a variety of grades, sizes, and configurations.

Alnico magnets were among the first permanent magnets used for electric machines, but were quickly replaced as other permanent magnet materials became available. They offer a high remnant flux density (similar to NdFeB magnets), but have very low coercivities, making their demagnetization risk high. Alnico magnets derive their magnetic strength from the structural combination of iron-cobalt rich ferromagnetic phases and aluminum-nickel rich weak magnetic phases [5]. Alnico has generally favorable temperature properties for hybrid motor applications with a low induction change with temperature and a very wide usable temperature range. The thermal drawback of Alnico is the low coercivity, making it highly susceptible to demagnetization as temperature increases if special care is not paid to the position of the load line. Alnico magnets are considered to be mid-range in term of relative magnetic materials costs. They are part of a mature magnetic technology that lends itself to easy manufacturing of a wide range of sizes and configurations are readily available from multiple suppliers, both inside and outside the United States.

Table 2 provides a comparative view of key magnetic material properties of selected magnetic materials – mid grade rare-earth materials (NdFeB and SmCo) and high grade zero rare-earth materials (ferrite, alnico). As the provided data shows, the high grade zero rare-earth materials have significantly reduced properties compared to the mid-grade rare-earth materials.

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	

Table 2: Magnetic Properties Summary.

The selected alnico grade shown has a comparable flux density to that of the rare earth materials (Figure 5), but at a considerable coercivity and energy product deficit. This low coercivity does not preclude it from usage in electric motor applications, but care must be taken in the design process to isolate it from external fields that may cause demagnetization.

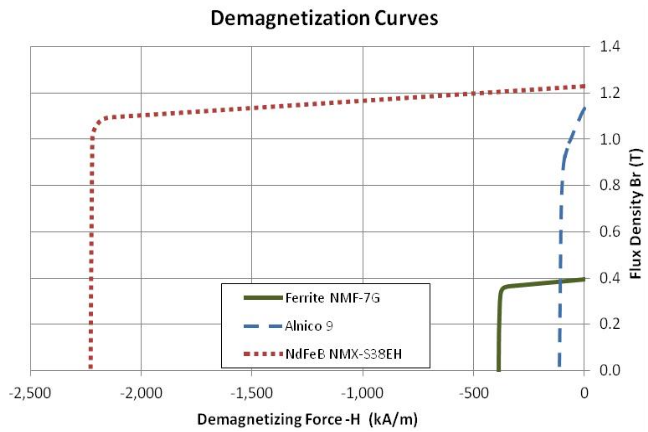

Figure 5: Example demagnetization curves for PM materials at 20° C.

The selected ferrite shown is the highest grade available without the addition of *lanthanum*, a light rare earth. This ferrite has a flux density that is *one-half* to *two-thirds* of that of the rare-earth alternatives, and coercivities greater than that of alnico, but still lower than the rare-earth alternatives (figure 5). Given the unique temperature characteristics and increasing coercivity with temperature, ferrite can be successfully used for motor applications assuming that the motor design can accommodate the increased magnet mass needed to generate the required magnetic fields.

On a relative cost comparison, both alnico and ferrite are much lower cost alternatives to traditional rare-earth materials. Ferrite is generally the lowest cost magnet, being composed of low-cost, highly available oxides. Even though distinctly increased magnet mass is required to offset the lower magnetic properties, ferrite is still a much lower cost alternative to traditional rare-earth materials. Alnico has a moderately higher cost than ferrite, primarily caused by the cobalt content of the magnet, but is still much lower cost than rare-earth materials.

Ongoing research is focused on methods to increase the performance of both alnico and ferrite, as well as investigate new materials that have the potential to fill the magnetic performance gap between alnico / ferrite and the rare-earth materials. While this research is producing many promising materials, such as high coercivity *iron-nickel* alloys and *manganese-bismuth* [4], they are not expected to be commercially available in sufficient quantities in the next 3 to 5 years. As such, the current focus continues to be on finding ways to effectively utilize the lower properties of alnico and ferrite.

MOTOR TOPOLOGY TRADE STUDY

A qualitative review study was undertaken to determine the motor topologies that may be best suited to meet the performance criteria outlined in Table 1. The motor topologies fall into two categories: PM (*Permanent Magnet*) and Non-PM (*Non-Permanent Magnet*). For each motor topology, the following topics were considered:

- Inherent topology characteristics of the topology.
- New development required to meet technical target.
- Manufacturability of topology.
- Overall potential to meet technical target.

PM Topologies

Several permanent magnet motor topologies where identified as potentially viable solutions for this **ZRE** (*Zero Rare-Earth*) **ISG** (*Integrated Starter Generator*) application, such as ***(i)*** interior permanent magnet, ***(ii)*** surface permanent magnet, ***(iii)*** axial flux permanent magnet *and* ***(iv)*** transverse flux permanent magnet.

INTERIOR PERMANENT MAGNET (**IPM**) motors use a combination of reluctance torque (torque produced to minimize magnetic reluctance upon excitation of the stator windings) and magnetic torque (torque from the Lorentz force due to the interaction between the energized stator windings and rotor magnetic field) for torque and power production. Performance is highly dependent on the magnet material used. Many modern IPM motors utilize either NdFeB or SmCo magnets because their high energy products and high coercivities allow for smaller motors, but have an inherently higher material cost. Generally they are considered to have high torque and efficiency, combined with low torque ripple.

Assuming that appropriate design considerations are used to account for the lower energy products, ferrite magnets may be substituted into IPM machines. Between comparable performance IPM designs using ferrite and NdFeB magnets, the ferrite design will have a higher weight, increased magnet mass along with a rotor geometry that is more complex to support the increased magnet sizes.

Spoke IPM is a sub-type of the traditional IPM motor. Because of the flux concentrating aspects of the radial magnet orientation (Figure 6), it has the highest air-gap flux and subsequently the highest volumetric torque density [8] of the IPM variants. This high air-gap flux and a magnet flux concentrating structure makes it possible to achieve flux densities approaching that of rare-earth magnet motors using ferrite magnets [9].

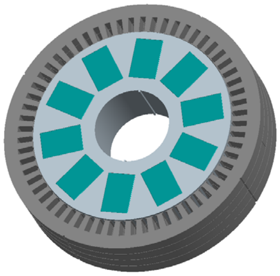

Figure 6: Example Spoke IPM Structure.

Generally, IPM motors are highly susceptible to partial demagnetization from stator currents, causing irreversible deterioration to motor performance. Since Spoke IPM can preferentially make use of ferrite magnets, this demagnetization risk can be reduced somewhat by careful magnet sizing and positioning to isolate them from the stator current forces [9].

For this application, the large rotor diameter with short axial length may still present advantages because of the large circumferential surface area can make optimal use of the flux concentrating effect of the spoke magnets.

SURFACE PERMANENT MAGNET (**SPM**) machines are similar to IPM machines, but utilize magnets attached to the rotor surface, instead of a radial orientation. Because of the proportional relationship between torque production and magnet flux, SPM uses significantly more magnetic material than traditional IPM. This increase in magnetic material can be offset when using rare-earth magnets. However, when ferrite magnets are used, it is not possible to maintain the high torque density within allowable magnetic material volumes [6]. Even though SPM has a simple physical rotor structure, at high speeds magnet retention can be difficult.

SPM has high power factor across its speed range and uses an easy control strategy, similar to traditional IPM machine control methods. However, it has limited field weakening capability at high speeds, which significantly limits the constant power speed range (CPSR).

AXIAL FLUX PERMANENT MAGNET (**AFPM**) machines have magnetic flux directed axially in the air gap and stator windings, where it then changes direction into the stator and rotor cores. Given this unique flux path, AFPM machines have the distinguishing feature of disk shaped rotor and stator structures and can be assembled in a wide variety of configurations to optimize volume, mass, power, and torque for a given application [10]. In general, these machines tend to be attractive for applications in which limited axial length is the driving design factor.

The axially-thin rotor of an AFPM machine is a packaging advantage for this application, but proves challenging from a structural vibration point-of-view. The thin rotor results in low axial rotor stiffness, low critical speeds, and mode shapes that deflect the rotor axially. This must be carefully managed in mechanical design, to avoid pole rub.

TRANSVERSE FLUX PERMANENT MAGNET (**TFPM**) machines operate based upon the principle that the path of magnetic flux is perpendicular (transverse) to the direction of rotor rotation. While transverse flux machines have their origins in the 1890's, they have previously been considered too difficult and overly complex to model and manufacturer, thus limiting their adoption, despite widespread research work [12].

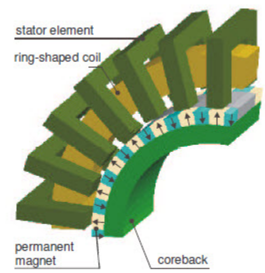

Figure 7: Basic TFPM Structure.

As shown in Figure 7, the TFPM motor structure is composed of stator elements wrapped around a ring-shaped current carrying coil and a rotor that has a ring of radially magnetized permanent magnets [13]. This structure requires no stator end turns (decreasing the axial length without compromising the available flux path space) and each phase in a TFPM machine is magnetically independent [12]. These basic characteristics of TFPM machines allow for a wide range of freedom in the physical design of these machines.

These same factors that allow for design flexibility also convey some distinct disadvantages. Because of the unique flux paths involved with TFPM machines, 3-D finite element analysis and custom coding is required to correctly size and model the electromagnetic behavior of the machine. Furthermore, the complex flux paths require the use of soft magnetic composites instead of traditional laminations for the active structure. Additionally, while TFPM offers short axial length per phase, that length can quickly multiply as the number of motor phases are increased, since traditionally phases are 'stacked' with an air-gap between each stack. In order to shorten the overall axial length of a multi-phase machine, structures not directly contributing to motor torque are removed. As a result, mutual flux sharing within the stator structure is achieved [14].

Non-PM Topologies

Several *non-permanent* magnet motor topologies where identified as potentially viable solutions for this **ZRE ISG** application, such as (***i***) switched reluctance, ***(ii)*** synchronous reluctance *and* ***(iii)*** induction.

SWITCHED RELUCTANCE (**SR**) motors have a long development history. The first reported switched reluctance motor was used to propel a locomotive between England and Scotland in the mid-1800s. The 1971 and 1972 patents by Bedford and Hoft first described the modern switched reluctance motor. Additional work has continued to build on those patents, including development of axial-gap switched reluctance designs and advances in controls and power electronics specifically for SRM drives. These motors have traditionally been used for industrial applications. However, recent applications have utilized them as generators and wheel motors in heavy mining and construction equipment.

A switched reluctance machine is doubly salient, brushless and does not require magnets or rotor windings. The lack of rotor windings and magnets means that the rotor can be made solely of laminated high silicon electrical steel, making it mechanically robust and durable over a wide speed range. Higher numbers of rotor poles increases the theoretical maximum torque produced of the motor, while increasing the number of stator poles can be used to reduce the coil end-turn lengths [18].

SR motors only use torque produced by the excitation of the stator coils (reluctance torque), and this torque is proportional to the phase inductance as varied by the rotor angle. The stator windings are excited via pulsed current applied in turn to each phase. The magnetic flux produced in the stator windings cause the rotor to move from an unaligned position (*min. inductance*) to an aligned position (*max. inductance*) producing reluctance torque [16].

SYNCHRONOUS RELUCTANCE (**SynRM**) motors are alternatives to induction or IPM motors. While synchronous reluctance is many times treated as an IPM machine without magnets, they solely generate reluctance torque. SynRM machines have a conventional poly-phase A/C sine wave excited stator, while the rotor has internal flux barriers shaped to maximize the ratio of ***d-axis*** (high-inductance axis) to ***q-axis*** (low inductance) reactance [19].

SynRM machines have the potential for good torque densities, but are dependent on the motor having a high saliency ratio (the ratio of ***Lq*** to ***Ld***) to do so. The saliency ratio is directly dependent on the motor pole count, and drops as the pole count increases. Low motor pole counts translate into increased stator and rotor yoke thickness and high end turn lengths.

INDUCTION MOTORS (**IM**) were invented by Nicola Tesla in 1882. It is the most widely used type of electric motor, mainly due to the IM's ability to run directly from an A/C voltage source without an inverter. The IM has been widely accepted for constant-speed industrial applications. In the past 30 years low-cost inverters have made variable-speed operation possible for traction drives.

In induction motors the electric current in the rotor needed to produce torque is induced by electromagnetic induction from the magnetic field of the stator winding. They do not require mechanical commutation, separate-excitation or self-excitation. Most induction rotors for traction or ISG applications are either aluminum or copper squirrel-cage type.

There are two primary drawbacks for induction motors in high torque, high power ISG applications – pole count and rotor heat rejection. Most induction motors traditionally use low pole counts, such as four or six poles.

Qualitative Topology Comparison

Based on a trade study review of the seven topologies described above, a qualitative comparison is outlined in Table 3. Using the data available from previous research and previous studies, each topology's performance potential from five categories, such as *housing*, *mechanical performance*, CPSR (*constant power speed range)*, *thermal requirements* and *general manufacturability* was considered.

This qualitative analysis showed that while each topology had potential for meeting the torque and power requirements, each presented additional concerns to be considered. The PM topologies presented more structural concerns, especially *AFPM* and *TFPM* which are very sensitive to air gap variation. Of the non-PM topologies, *SynRM* and *IM* both prefer low pole counts and long end-turn which increase the difficulty to meet the desired housing dimensions.

All of the permanent magnet topologies have an uncertain ability to meet performance and thermal requirement because of the limitations of the magnet material itself. NdFeB and other rare-earth permanent magnet materials used in modern hybrid motors are more susceptible to demagnetization at high temperatures than at low. Being ferrimagnetic, ferrite magnets are more susceptible at low temperatures; most ferrites are generally rated to -40°C, which is 10°C warmer than the specified cold start temperature of -50°C.

Specification		PM Topologies: Spoke IPM	PM Topologies: SPM	PM Topologies: AFPM	PM Topologies: TFPM	Non-PM Topologies: SRM	Non-PM Topologies: SynRM	Non-PM Topologies: 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

Table 3: Qualitative Topology Comparison.

Based upon this comparison, three permanent magnet topologies and one non-permanent magnet topology have been selected for further study. The permanent magnet topologies include: *Spoke IPM*, *AFPM*, and *TFPM*; the non-permanent magnet topology selected is *SWITCHED RELUTCANCE*. Two of the permanent magnet topologies favor the primary use of ferrite magnets over alnico, as they have better properties for the expected operating conditions (*Spoke IPM* and *TFPM*). *AFPM* is better able to offset the low coercivity of alnico. Table 4 offers a summary of the advantages and disadvantages of each selected topology.

Advantages	Disadvantages
Spoke IPM	
High torque	High cogging torque
High efficiency	Irreversible demagnetization risk
Can utilize ferrite magnets	Requires non-magnetic material inside rotor core
Large diameter optimal for using ferrite	Complex rotor geometry
No additional changes to traditional IPM control	Increased rotor inertia
AFPM	
Better torque density than traditional IPM machines	Large axial forces exerted on stator by magnets may cause rotor flex and variations in the air gap
Low armature reaction reduces demagnetization effects	High torque on rotor ID causing structural instability
Reduced axial length	Complex stator core geometry
Simple winding pattern	Low inductance and field weakening capabilities
Can utilize alnico magnets	3D flux paths
SRM	
Low cost, simple construction	High acoustic noise and vibration
Suitable for high temperature applications	High torque ripple
Suitable for high speed applications	Low efficiency
No requirement for magnets, but can be used to boost performance	No neutral connection, 2x more terminals and wiring harness mass compared to sine-wave drive
No secondary winding in rotor	Complex control strategy
Proven in industry applications	
TFPM	
Short axial length	Low power factor
No end turn windings	Potential for high torque ripple
High torque density for low speed applications	Must overcome potential for unbalanced phase inductance in 3-phase applications
Can utilize ferrite magnets	Requires high pole count
	Complex construction
	Requires use of soft magnetic composite

Table 4: Comparison of Selected Topologies.

COMPARATIVE DOWN-SELECTION PROCESS

Down-selection Design Problem

The analysis and preliminary down-selection from the initial trade study was completed on a purely qualitative basis. In order to complete the final down-selection to two topologies, further design, validation and quantitative analysis was completed.

The qualitative analysis allowed for comparison between topologies on a general level and primarily used motor topology characteristics and analysis from previously completed design studies or testing.

In most cases, these comparisons cannot be completed with respect to the same technical baseline. As such, a quantitative design study has been designed to ensure that the best possible motor topologies for the given technical targets are selected. This quantitative design study was an electromagnetic and basic structural analysis completed based upon the motor performance requirements shown in Table 1.

Motor Topology Analysis & Results

Based upon this study, it is unlikely that any of the permanent magnet topologies will fully meet design specifications using commercially available zero rare-earth magnets. Of the PM topologies considered, *Spoke IPM* offers the best performance potential. Table 5 summarizes the performance of the preliminary design simulations for the four topologies considered.

AFPM was removed from consideration because of the inability to fully isolate the rotor alnico magnets from demagnetizing currents from the stator. Additionally, AFPM provides significant structural challenges to maintain a consistent air-gap across the wide machine diameter.

TFPM machines require a high pole count to reach the desired performance. Analysis showed that a fifty pole count design produced the highest torque within the specified packaging size, but is uncontrollable without specially designed inverters for the high machine fundamental frequency. Additionally, the limited axial length of the TFPM machine allows for stator tooth area. However, this feature limits the maximum achievable torque.

While the *Spoke IPM* machine is unable to meet the specified peak torque and power requirements, it offers the best performance for a ZRE permanent magnet machine within the package size constraints. Additional optimization can be completed to improve performance through advanced pole shaping and winding optimization.

	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

Table 5: Motor Topology Analysis.

SWITCHED RELUCTANCE offers the best potential for meeting the output torque and power requirements of the design specifications. SR does have disadvantages with regards to torque ripple and acoustic noise; it is expected that optimization to minimize those effects will have a negative effect on overall machine performance. Care must be taken in the optimization process to balance the minimization of negative performance effects without overly compromising the overall machine performance.

FUTURE WORK

The *SWITCHED RELUCTANCE* and *SPOKE IPM* topology selections have progressed to the detailed design phase and will continue with prototype development of the two motor topologies. Upon completion of the prototype hardware, testing and validation will be undertaken to compare the final designs to the original specification shown in Table 1. It is anticipated that validation will be completed by October 2014. Upon completion of the prototyping and validation phases, the ZRE ISG effort will consider areas for performance improvement that include but are not limited to reducing torque ripple and reducing motor noise.

CONCLUSION

As vehicle export power generation demands and ground vehicle electrification increase so does the U.S. dependence on rare-earth earth elements, such as *Neodymium* (Nd), *Samarium* (Sm), *Dysprosium* (Dy) and *Terbium* (Tb). These rare-earth elements are primarily harvested outside of the U.S. and frequently experience availability shortages as well as price volatility. Because of those factors along with diminished rare-earth material reserves, continued use of rare-earth permanent magnet materials for high-performance (100kW and beyond) military vehicle power systems may not be viable. To address this issue, work has been undertaken to find alternative motor/machine topologies that are rare-earth material independent and meet significant export power generation demands, which was the focus of this paper. Additionally, this paper presented the performance design criteria and the motor topology down-selection process used for the design/development of a ***zero-rare-earth*** (ZRE) magnet 100kW *integrated-starter-generator* (ISG), targeted for military vehicle applications. The zero-rare-earth materials study resulted in the selection of Ferrite and Alnico 9 due to their high commercial availability, low cost and suitable magnetic properties (flux density, coercivity, temperature range, *etc.*) that were somewhat comparable to that of the rare-earth materials. The motor topology study found the *SWITCHED RELUCTANCE* (SR) motor to be the favored non-permanent magnet topology and concluded that the *SPOKE IPM* (*Interior Permanent Magnet*) motor was the preferred zero-rare-earth permanent magnet topology. The study concluded that the two candidate motor topologies, along with their accompanied magnet materials, would have a high probability of meeting the ZRE-ISG design performance specifications.

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