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Noise and Vibration Analysis of Zero Rare-Earth Magnet Integrated Starter-Generator for Military Vehicle Applications

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ABSTRACT

Most hybrid electric vehicle (HEV) applications require the utilization of electric motors that have high torque/power density, high efficiency, a wide speed range and reliability. Interior permanent magnet (IPM) synchronous motors comprised of rare-earth magnet material is the most common electric motor class used for HEVs. However, recent fluctuations in the rare-earth magnet pricing and availability demands the search for zero rare-earth motor topologies as an alternative to IPM for use in HEVs. Switched reluctance machines (SRMs) are rare-earth free alternatives with simple and very robust construction, high efficiency/reliability, high torque at low speed, more thermal capability, and a wide constant power region. Nonetheless, they have several disadvantages which emerge from the nature of the torque production in SRMs, such as high torque ripple, high vibration, and substantial acoustic noise. This paper investigates the acoustic noise mitigation techniques of SRMs with Finite Element Analysis and experimental verifications.

INTRODUCTION

There has been an increasing demand on the engine starting torque and export power generation requirements of military ground vehicles. It is expected that future electric power requirements for ground vehicles will reach or exceed the 100kW limit. The electric machine topologies that typically meet these requirements within *weight, size* and *cost* constraints, frequently require rare-earth materials that usually rely on foreign suppliers. The focus of this work is to continue a previous effort, which was primarily concerned with the investigation of permanent magnet materials that did not include *rare-earth* elements, such as Neodymium (*Nd*), Dysprosium (*Dy),* Terbium (*Tb*), Samarium (*Sm*) or Praseodymium (*Pr*). Additionally, the previous work resulted in an investigation of alternative motor topologies that could be utilized to realize an ISG (*integrated started generator*) capable of producing 100kW of output power with a *continuous/peak* torque of 1200Nm/1800Nm. The previous study resulted in a ZRE (*zero-rare-earth*) materials selection of *Ferrite* and *Alnico 9* due to their high commercial availability, low cost and suitable magnetic properties, such as (*flux density, coercivity, temperature range, etc*.) that were somewhat comparable to that of the *rare-earth* materials. In addition, the previous work's motor topology study found that the SRM (*switched reluctance motor*) to be the favored non-permanent magnet topology and concluded that the SIPM (*spoke interior permanent magnet*) motor was the preferred *zero-rare-earth* permanent magnet topology. The study further established 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. The previous work resulted in the implementation and test of both SIPM and SRM machine classes. From experimentation it was determined that the SRM machine class outperformed the SIPM, and was closest to matching the project requirements.

The switched reluctance machine (SRM) based design has provided superior performance compared to other non- rare-earth machine types in these analyses. Although SRMs are known as having robust, fault tolerant, cost effective, and high performance properties, *torque ripple* and *acoustic noise* are still the main concern for several applications. The ZRE magnet ISG study continues by further pursuing performance improvements of the selected SRM machine class. This paper continues the investigation of alternative motor topologies of the SRM class that can be utilized to realize a 100kW output power ISG, capable of meeting 1200Nm/1800Nm of continuous/peak torque with an acceptable acoustic noise signature.

The focus of this continued effort is to discuss our performance improvement progress, which is centered around noise and vibration reduction of the SRM. Briefly stated, this study provides the noise and vibration analysis of the SRM, including the specific housing designed for military ground vehicles. Detailed Finite Element Analysis results of coupled electromagnetic, mechanical structural and acoustic noise software are provided to predict the noise and vibration of the SRMs for various operating points. Different design alternatives are discussed such as windowing in the stator and rotor poles as well as the rotor and/or stator skewing in mitigating the noise and vibration of the SRM for military combat vehicles.

ELECTRIC MACHINE PERFORMANCE COMPARISON

The motor topologies are analyzed to meet the target specifications of the previous study discussed in [1]. Table 1 presents the performance comparison of the Spoke IPM, Axial Flux PM, Transverse Flux PM, and the SRMs. Based on this study Spoke IPM and the SRM were selected to develop an experimental test ISG.

	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 1: Motor Topology Analysis.

SOURCES OF ACOUSTIC NOISE

The source of the acoustic noise in the electrical machine can be either electromagnetic, mechanical or aerodynamic. The mechanical noise may emanate from the gearbox, bearing or mechanical misalignment and eccentricity. Aerodynamic noise usually appears at high speeds. In [2], it was reported that electromagnetic noise contributed to a majority of the SRM noise.

The torque is generated by the tendency of the rotor to align with the excited stator pole to minimize the reluctance of the magnetic path in SRMs. Figure 1 shows the magnetic force *F* that pulls the rotor to the excited stator pole. The magnetic force *F* consists of two components: the tangential component F_t and the radial component F_r. The tangential component acts on the rotor teeth surface generating the torque. The radial force acting on the stator pole tips excites one or more of the circumferential mode shapes of the stator structure at their natural frequencies. When the radial force decreases during commutation of the phases, the stator will oscillate with its natural frequency and it will create a pressure in the surrounding air causing airborne acoustic noise. Due to its saliency structure, the variation of the radial force is very high in SRM, causing much higher vibration and noise than the smooth air-gap machines. Figure 2 presents the first five circumferential mode shapes of the stator yoke, the mode shapes with *m*=0, 2, 4 are the most dominant and they are responsible for a majority of the vibration and acoustic noise [5].

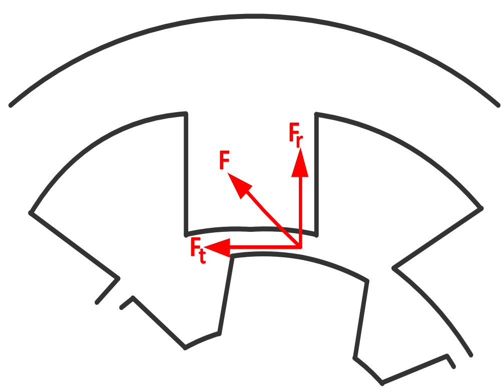

Figure 1: Magnetic force and its component.

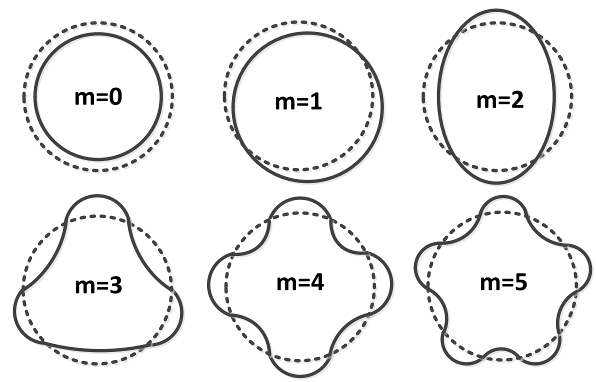

Figure 2: Dominant circumferential mode shapes.

ELECTROMAGNETIC AND MECHANICAL ANALYSIS

Electromagnetic FEA Simulations

The Baseline ISG is built with an SRM having 24 stator poles and 16 rotor poles as presented in Figure 3. The Finite Element Analysis (FEA) simulations were performed for the Baseline SRM with a 300 Amp peak current at 800 rpm, producing 1125 Nm, such that the peak of the radial force was 4215 N.

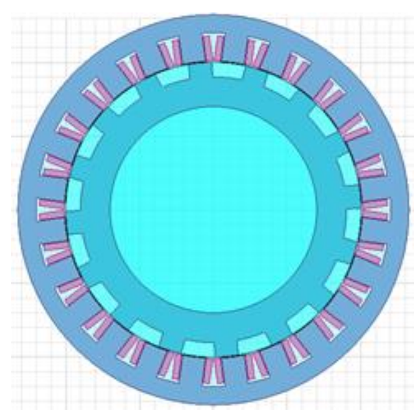

Figure 3: FEA model of the 24/16 SRM.

Mechanical and Acoustic Simulations

Mechanical FEA was performed to predict and compare the vibration and acoustic noise of the windowed stator, windowed rotor, and the conventional SRMs. The flow diagram of the simulation work is shown in Figure 4. After the radial forces were determined by electromagnetic FEA, the frequency spectrum of the radial force was calculated and loaded as an input to the mechanical FEA. The deformation, acceleration, and velocity are calculated by means of harmonic response analysis, which determines the steady state response of a structure to loads that vary sinusoidally in time for each harmonic of the frequency spectrum. Finally, the velocity of the outer surface is transferred to the acoustic analyzer to determine the sound pressure level (SPL) around the motor.

The SRM model used in the mechanical FEA is shown in Figure 5. The outer frame of the machine and the screwing point are fixed support and incorporated into the analysis as they affect the mode shapes, natural frequencies, and damping of the system.

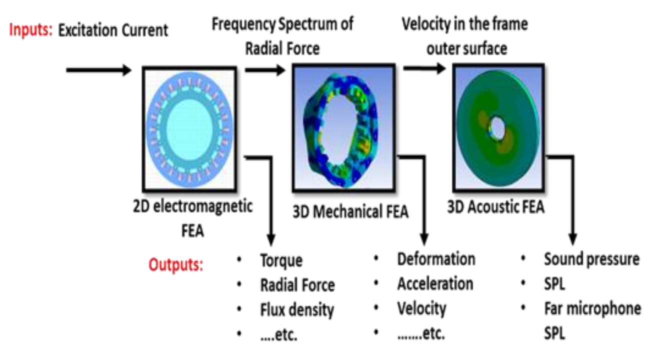

Figure 4: Structural simulation flow diagram.

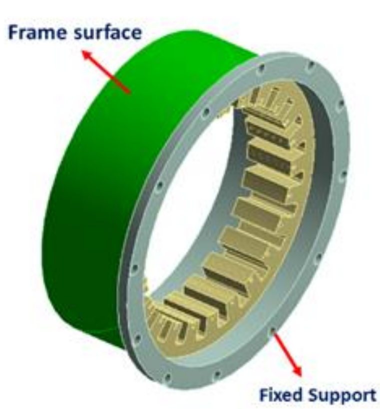

Figure 5: FEA SRM model for mechanical analysis.

Modal analysis was initially done to calculate the mode shapes and their natural frequencies of the SRM stator/housing assembly. When any of the harmonic components of radial force coincides with one of the natural frequencies of the mode shapes, resonance will occur. The resonance causes vibration and thus the acoustic noise will occur at that natural frequency. The velocity and acceleration of the frame surface creates pressure in the surrounding air, which causes acoustic noise.

ACOUSTIC NOISE REDUCTION METHODS

Windowing in Stator/Rotor Poles

According to studies about windowing methods [3], the radial component of the magnetic field density is reduced by adding a window in the rotor poles. In this research the effect of adding a window in either the stator or the rotor, or both is studied. Figure 6 presents the parameters for the window dimensions in the stator and the rotor poles. The method is quite helpful for noise reduction if the machine designer successfully optimizes the position and the sizes of the window. However, there is a trade-off between generated electromagnetic torque and the radial force. Given that the radial force component is reduced by increasing the reluctance, the tangential force component, which is used to produce torque, is also reduced. Therefore, optimization is performed to yield maximum reduction in radial force and acoustic noise with minimum impact on the torque production.

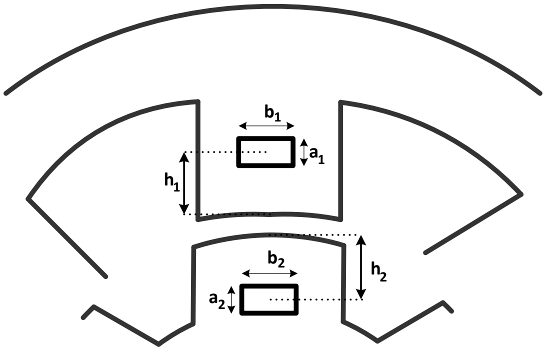

Figure 6: Stator/Rotor poles windowing of the SRM.

Skewing of Stator/Rotor Laminations

The skewing method is considered to be one of the most effective acoustic noise mitigation methods, as discussed in [4]. Figure 7 presents the skewing topologies for the stator and the rotor stacks.

Radial force in the air-gap of the skewed SRM will be concentrated on the stator pole surfaces. These forces are transferred to the frame through the stator pole and the yoke. In conventional SRMs, the radial force on the stator surface is directly transferred to the rear yoke parts behind the teeth. In the case of stator skewing, this force will be distributed to the yoke along the *z-axis*. The acoustic noise arises due to force differences between each yoke segment which cause deformation in the yoke. When the skewing angle is applied to the stator, emerged force differences between the yoke segments are reduced.

A comparison of different skewing methods and parameters is reached by analyzing the SRM at the same torque level. To reach the same torque level, phase currents and the switching angles are modified and optimized in each skewing angle. An interactive closed-loop design optimization process, including electromagnetic and mechanical studies, was performed.

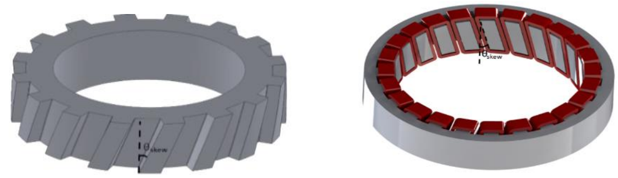

Figure 7: Skewing of SRM stator/rotor stacks.

HARDWARE DEVELOPMENT

The stator development of the Windowed ISG machine is shown in Figure 8. The Baseline and Windowed ISG development platforms were debugged and tested using a dynamometer test bench, illustrated in Figure 9.

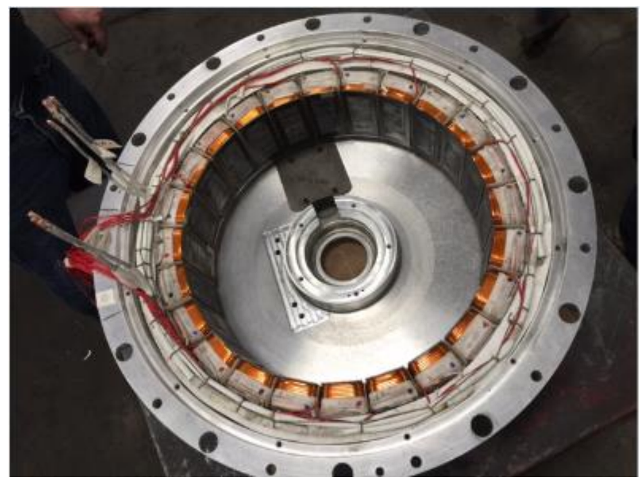

Figure 8: Stator development of the Windowed ISG.

Figure 9: Test setup on the dynamometer.

Preliminary acoustic noise tests were conducted at a speed of 800 rpm. An acoustic noise comparison between the Baseline and Windowed ISG builds is shown in Table 2.

Baseline ISG		Windowed ISG	
Torque (Nm)	Noise Level (dbA)	Torque (Nm)	Noise Level (dbA)
296	88.4	250	82.9
600	88.8	567	86.2
975	92.2	921	89.4

Table 2: Acoustic noise level tests of experimental ISGs.

RESULTS

The acoustic noise performances of the Baseline, Windowed and Skewed SRMs are compared using integrated Electromagnetic, Mechanical and Acoustic Noise software for the same operating conditions. Figure 10 presents the acoustic noise performances of the three SRMs over the frequency range. The weighted acoustic noise performance is presented in Figure 11, which shows acoustic noise performances of the Skewed, Windowed and Baseline SRMs over the frequency range.

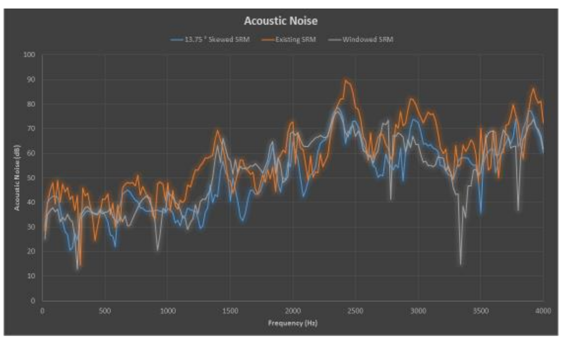

Figure 10: Acoustic noise performances.

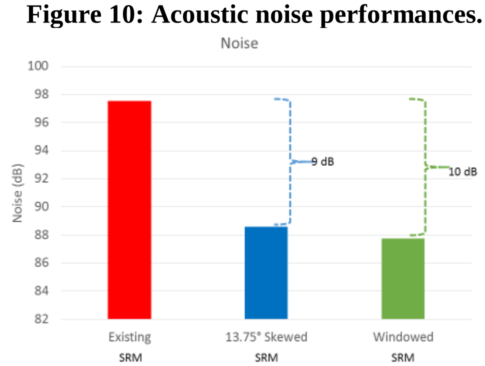

Figure 11: Weighted acoustic noise measures of the skewed, Windowed and the Baseline.

CONCLUSION

This paper presented noise and vibration analysis for *integrated starter generators,* which use *switched reluctance* electric machine technology. Various noise reduction techniques have been explored and analyzed using coupled electromagnetic, mechanical, and acoustic noise simulations. During the project's period of performance, Baseline and Windowed ISG machines were designed and fabricated. Experimental results of the respective machine types were provided, and they demonstrated that both the *Windowing* and *Skewing* techniques offer a good reduction in overall acoustic noise for the ISG. Preliminary tests confirmed that use of the Windowed ISG resulted in a ~(10*dB*) acoustic noise reduction, relative to the Baseline ISG. A build of the *Skewing* ISG machine along with a detailed experimental comparison will be provided in future work.

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