2018 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
POWER & MOBILITY (P&M) TECHNICAL SESSION
AUGUST 7-9, 2018 - NOVI, MICHIGAN

A Demonstration of Noise and Vibration Reduction Techniques For Zero Rare-Earth Magnet Integrated Starter-Generators Used In Military Vehicle Applications

Yilmaz Sozer, Ph.D.
ECE Department
The University of Akron
Akron, Ohio

Joshua Tylenda
Power & Mobility Group
U.S. Army TARDEC
Warren, MI

John Kutz
Ronnie L. Wright, Ph.D.
Systems Engineering Dept.
DCS Corporation
Littleton, MA

ABSTRACT

Due to the recent fluctuations in the rare-earth magnet pricing and availability demands, switched reluctance machines (SRMs) have gained significant interest to be used in automotive and military applications. SRMs are known to have high power density/efficiency, low cost, easy manufacturability, wide constant power region, robust structure and high reliability. On the other hand, high acoustic noise and torque ripple have limited their wide spread usage in the past. This paper investigates the analyses, design and experimental verification of various acoustic noise reduction techniques for SRMs. The prototypes of 100 kW SRMs for military ground vehicles have been built with the implemented acoustic noise reduction techniques and were tested using a dynamometer special for electric and hybrid vehicle testing.

INTRODUCTION

The demand for engine starting torque and power generation have been exceeding the 100 kW limit for military ground vehicles. The design of electric machines to satisfy the performance targets are challenging without using rare earth materials.

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 [1]. Table 1 presents the performance comparison of the Spoke IPM, Axial Flux PM, Transverse Flux PM, and the SRMs. The switched reluctance machine (SRM) -based design has delivered superior performance compared to other non- rare-earth machine types in these analyses.

The torque ripple and acoustic noise remain significant concerns for several applications which utilize the SRM. This paper continues the previous effort by further discussing our performance improvement progress, which is centered around noise and vibration reduction of the SRM.

	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.

There are various studies which have reported on the evaluation of acoustic noise root cause in SRMs. Several solutions for mitigating the acoustic noise have been reported by researchers.

Skewing and the windowing methods are considered to be two of the effective acoustic noise mitigation techniques, as discussed in [2-4]. There is a need to implement multi-physics simulation to obtain globally optimized SRMs which implement these techniques. The challenges in developing SRMs using these techniques, and the correlation between multi-physics simulation and experiments will be explored.

Finite Element Analysis of coupled electromagnetic, mechanical structural and acoustic noise software are used to predict the noise and vibration of the SRMs for various operating points. Likewise, simulation parameters are further tuned to match the experimental noise and vibration results of the respective SRM topologies. Different design alternatives such as windowing in stator and/or rotor as well as the stator and/or rotor skewing techniques are presented as methods to mitigate the noise and vibration associated with SRMs used in ground vehicle applications.

A Baseline SRM along with (*windowed/skewed*) SRMs supporting alternative noise reduction features, were built and tested against various operating conditions. Challenges and solutions surrounding the production process of these SRM technologies are presented in this paper.

SRM OPERATIONS

The SRM is comprised of a laminated stator and rotor with phase windings on the stator. The phase windings are placed around the stator poles while there are no magnets or windings on the rotor. Stator and rotor laminations have saliency through the sequential pole structures which generate a variation in phase inductance with rotor position as shown in Figures 1 and 2. Each of the phases are magnetically independent from each other. When a stator pole is excited, the rotor moves in order to attain the maximum inductance (minimum reluctance) position. The tendency to align the stator and rotor poles to minimize the reluctance produces torque. Torque is produced discretely by the phases.

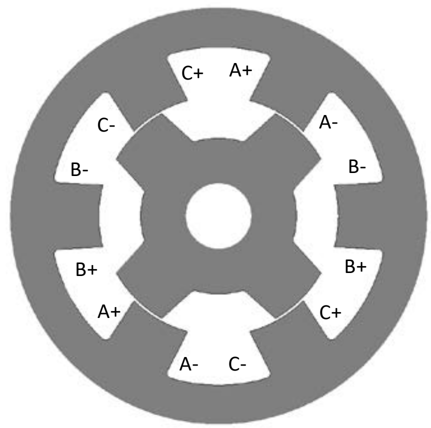

Figure 1: SRM double salient architecture.

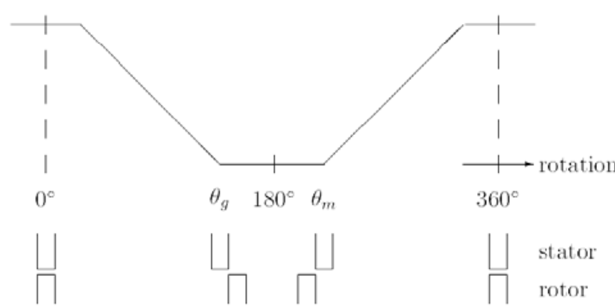

Figure 2: Inductance variation of SRM phase with rotor position.

ACOUSTIC NOISE IN SRMs

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 3 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 tooth 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 salient structure, the variation of the radial force is very high in SRM, causing much higher vibration and noise than in the smooth air gap machines.

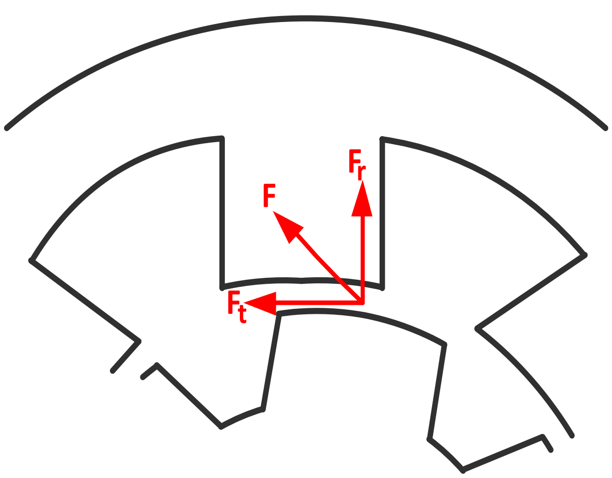

Figure 3: Magnetic force and its component.

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 4 presents the parameters for the window dimensions in the stator and the rotor poles. The method is quite helpful for noise reduction if the 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.

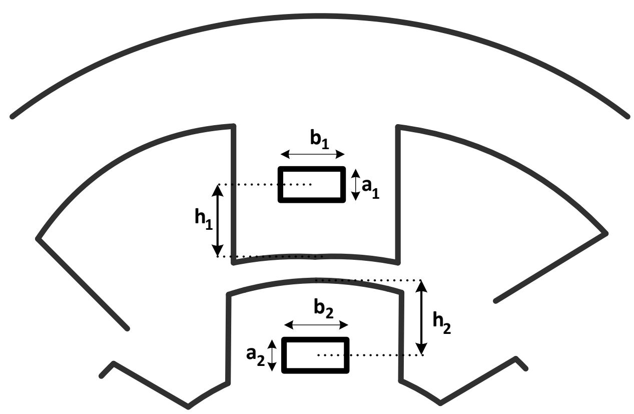

Figure 4: Stator/Rotor poles windowing of the SRM.

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 5 presents the skewing topologies for the stator and the rotor stacks.

Radial force in the airgap 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, generated force differences between the yoke segments are reduced.

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

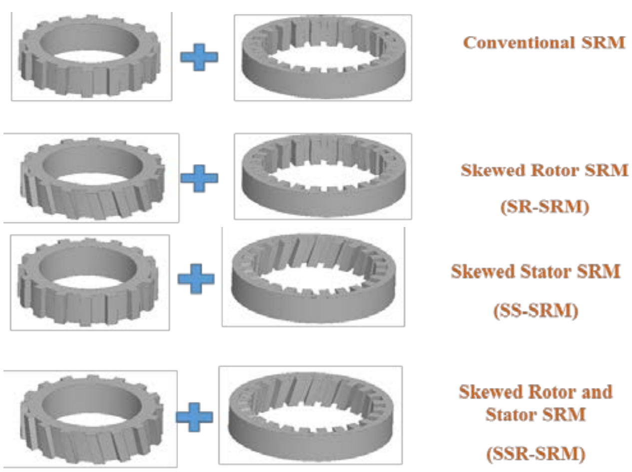

Figure 5: Definition of different skewing methods.

ELECTROMAGNETIC PERFORMANCE

Electromagnetic analysis was performed for the baseline, skewed and the windowed SRMs. Figure 6 presents the torque speed curve of the different ISGs.

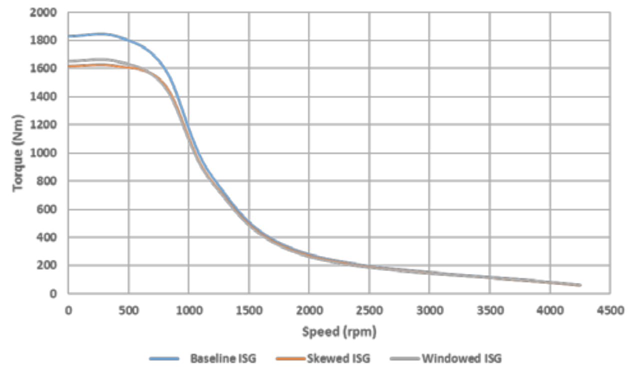

Figure 6: Torque –speed curves of different ISGs.

SRM DEVELOPMENT

The ISG assembly components were designed and built for the baseline, skewed and windowed SRM structures. The cross section of the major internal mechanical components is illustrated in Figure 7. The critical part of the design is the lamination material which was selected as the Hiperco50 iron-cobalt alloy from Carpenter Technology. The selected lamination material is the enabling technology as the magnetic saturations happens at 2.2 T compared with 1.5 T for nominal electrical steel.

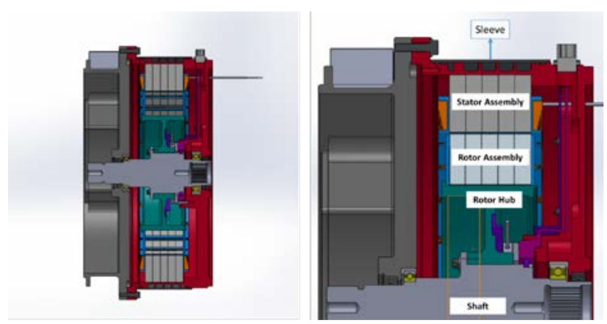

Figure 7: Cross section of mechanical components for the ISG.

The stator and the rotor laminations are bonded to form a stack. Each lamination was coated with 3M Scotchcast 265 mixture containing 20% of the material with 80% acetone. Individual laminations were placed onto the fixture with each one rotated by one rotor pole to increase structural integrity. The assembled unit was cured at 350° F to activate

UNCLASSIFIED: Distribution Statement A. Approved for public release; distribution is unlimited.

the adhesive material. The rotor and the stator stacks for the skewed ISG are shown in Figure 8.

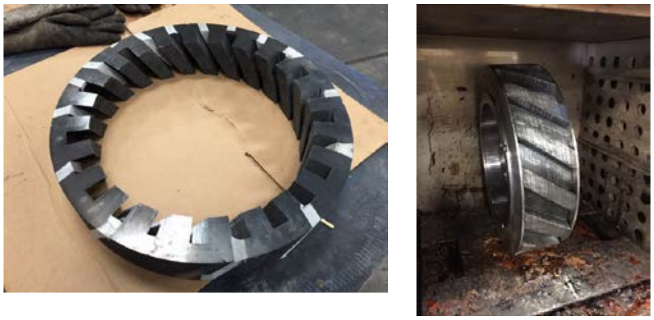

Figure 8: Stator and rotor development of the ISG.

The ISG stator winding bobbins were made from electrically isolated and thermally conductive material. A mold was designed and the bobbins are made through an injection molding process. The stator lamination stack assembly is thermally fit into the housing and the coils are inserted into the stator slots. After insertion, the coil leads were welded to the routing phase wire. Phase leads are routed about the end-turns, with each phase isolated from the others using Nomex paper. A Teflon tube was inserted into the center of the stator assembly while an epoxy mixture was poured around the windings. Figure 9 presents the stator assembly in the ISG housing.

Figure 9: Stator assembly placed in the housing.

SRM DRIVE DEVELOPMENT

SRM drive is developed using 3 H-bridge modules. The unit takes PWM signals from the controller and generates gating signals for the IGBTs. The current measurements are provided to the controller to achieve current regulations. The inverter was fed by the battery simulator of the dynamometer system. Figure 10 presents the block diagram of the ISG drive components. The actual hardware for the inverter and the ISG is presented in Figure 11.

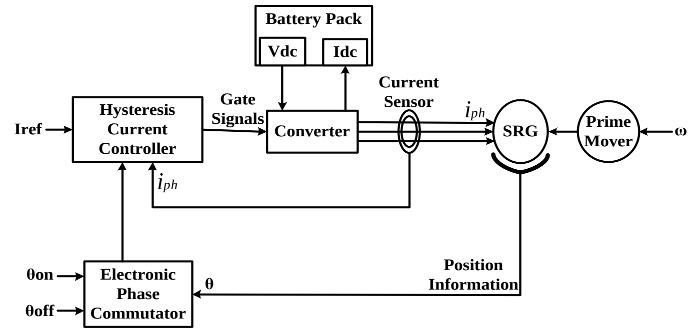

Figure 10: Block diagram of the ISG drive component.

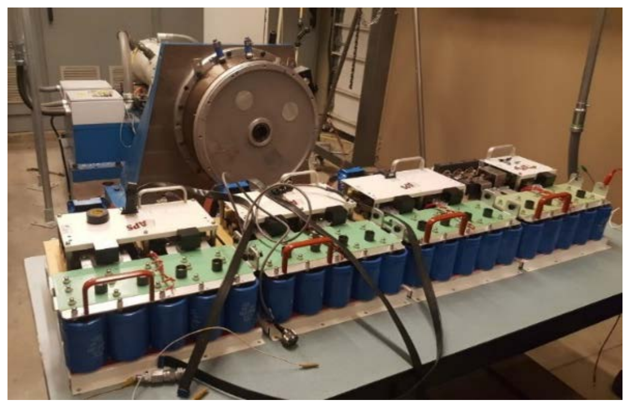

Figure 11: ISG Drive hardware placed on a dynamometer.

DYNAMOMETER TESTING

The testing was performed at the Center for Advanced Vehicles and Energy Systems (CAVES) at University of Akron utilizing a 150 kW Dynamometer. CAN communication was developed to send the control commands from the dyno's STARS software to the ESI controller. The torque and speed from the torque sensor attached to the shaft, and the current and voltage readings from the power connections were recorded by WT 3000 Yokogawa power analyzer and sent through CAN communication to the STARS software. Thermocouples were used to monitor the temperature of the ISG (particularly windings) and sent through STARS software also. The vibration reading was done by PCB Piezotronics High Sensitivity Tri axial Accelerometer that attached to the motor behind the center of one of the stator poles. For sound level measurement, a free field standard microphone was utilized. The microphone was set 1 meter away from the center of the ISG. The placement of the microphone and the accelerometer is shown in Figure 12.

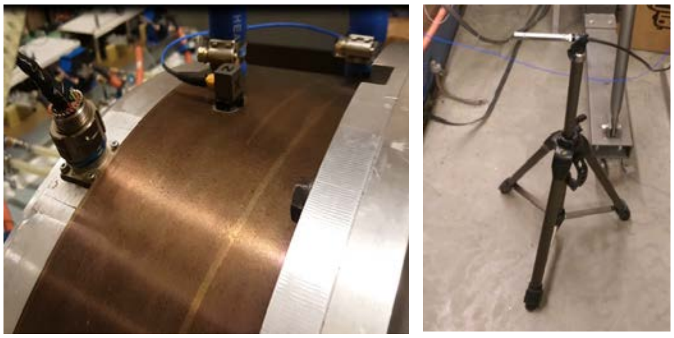

Figure 12: Noise and vibration test units.

The anechoic chamber used to suppress the unwanted noise coming from outside and absorb the noise from inside minimizing reflection effects. The anechoic chamber design and materials is shown in Figure 13.

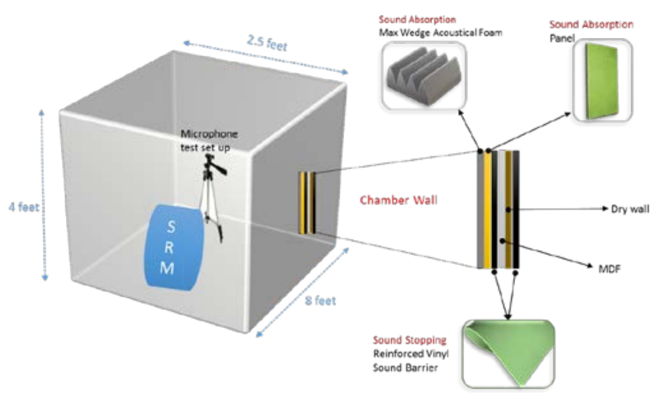

Figure 13: Anechoic chamber design.

TEST RESULTS

The tests were conducted for the baseline, windowed, and skewed ISGs for various operating conditions. Figure 14 presents the current waveforms at 500 rpm 975 Nm motoring for the baseline ISG. Current waveforms at 2000 rpm - 297 Nm Generating for the skewed ISG is shown in Figure 15.

The simulated and experimental acoustic noise performance results of the machines were compared. The comparison of different machine acoustic noise with simulations at the rated condition is illustrated by Figure 16. The comparison indicates that peak noise is reduced from 89.7 dB for the *baseline ISG* to 78.02 dB for the *skewed* and 76.9 dB for *windowed ISG*.

A comparison of the experiment noise data of the different machines is presented in Figure 17. Both the skewed and windowed ISGs provide good noise reduction. At 800 rpm, the peak noise coming from the SRM is reduced to 81.3 dB with the *windowed SRM* and 74.2 dB with the *skewed SRM*, compared to 87.2 dB with the *baseline ISG*.

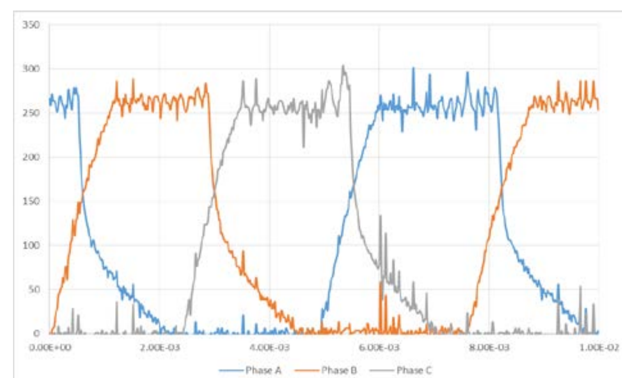

Figure 14: Current waveforms at 500 rpm and 975 Nm Motoring for the baseline ISG.

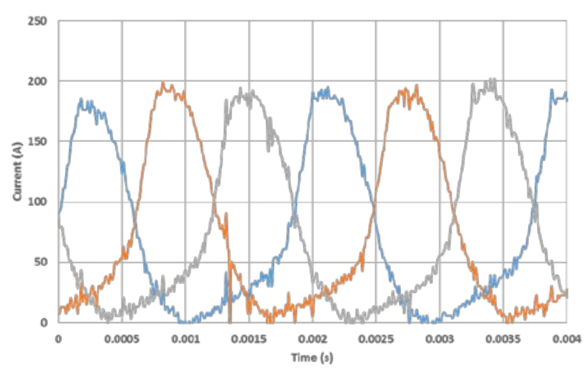

Figure 15: Current waveforms at 2000 rpm and 297 Nm Generating for the skewed ISG.

UNCLASSIFIED: Distribution Statement A. Approved for public release; distribution is unlimited.

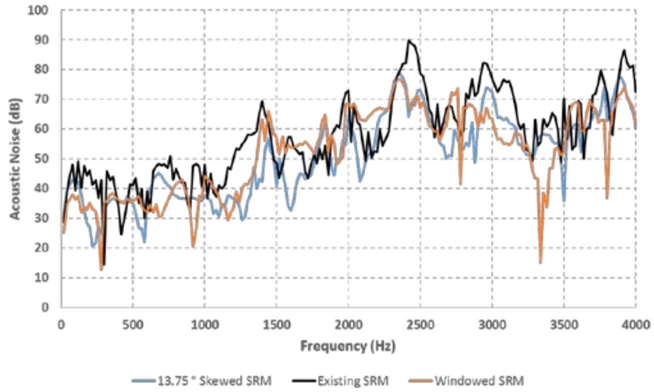

Figure 16: Comparison of acoustic simulation results for different machines at rated condition.

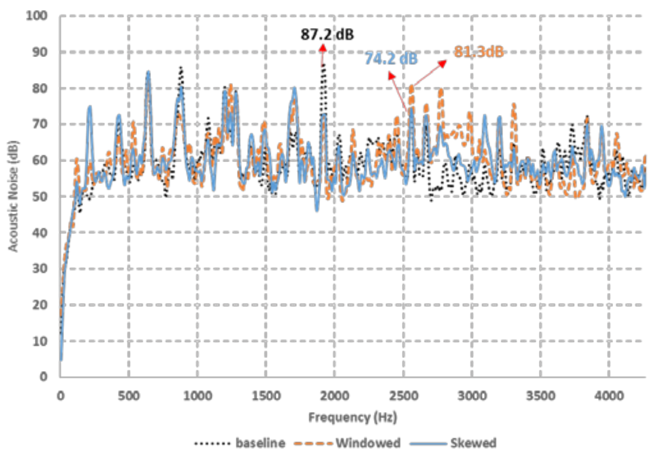

Figure 17: Comparison of experiment noise results for different machines at 800 rpm 600 Nm.

CONCLUSIONS

This paper presented the performance of the noise and vibration reduction techniques of SRMs designed and built for integrated stator/generators. *Windowing* and *Skewing* techniques have been explored and analyzed using coupled electromagnetic, mechanical, and acoustic noise simulations. Baseline, windowed, and skewed machines were built and experimental results are provided. The experimental results demonstrated that both the *windowing* and *skewing* techniques provided good reduction in overall acoustic noise of the ISG compared to the baseline machine. Experimental results indicate that the *windowing* and *skewing –based ISGs* produced 5.9 dB and 13.0 dB less acoustic noise when compared to the *baseline ISG*.

REFERENCES

[1]K. Riley et al., "Zero rare-earth magnet integrated starter-generator development for military vehicle applications" 2013 NDIA Ground Vehicle Systems Engineering and Technology Symposium, Troy, MI, August 2013.

[2]C. Y. Wu and C. Pollock, "Analysis and reduction of vibration and acoustic noise in the switched reluctance drive," *IEEE Trans. Ind. Appl.*, vol. 31, no. 1, pp. 91–98, Jan./Feb. 1995.

[3] K. Nakata, K. Hiramoto, M. Sanada, S. Morimoto, and Y. Takeda, "Noise reduction for switched reluctance motor with a hole," *Proceedings of the Power Conversion Conference, 2002. PCC-Osaka 2002*, vol. 3, pp. 971-976, 2002.

[4]C. Gan, J. Wu, M. Shen, S. Yang, Y. Hu, and W. Cao, "Investigation of skewing effects on the vibration reduction of three-phase switched reluctance motors," *IEEE Trans. Magn.*, vol. 51, no. 9, 2015.