Advanced Torque Ripple and Acoustic Noise Correlation in Switched Reluctance Machines

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Abstract **- The switched reluctance machine (SRM) has long been associated with high torque ripple as well as with producing excessive levels of audible noise. The correlation between torque ripple and acoustic noise has been subject to debate over the past decade. While there is no strong consensus, one perspective is that the correlation is weak at best, while the other presumes that a machine with high torque ripple is inherently noisy. This paper neither supports nor refutes these historical perspectives of the SRM. Rather, it presents evidence of multiple factors that affect torque ripple and acoustic noise. This evidence supports both views to varying degrees and has been collected experimentally from an SRM developed for a hybrid vehicle starter-alternator application.**

1 Introduction

Recent emphasis on electric and hybrid-electric vehicle (HEV) technology has motivated the development of high performance machine drives for various applications. One such application is the implementation of an adjustable speed direct-drive, which serves as the starter of the internal combustion engine in the HEV during cranking, and then operates as an alternator to provide electrical power to the vehicle systems. The dual functionality of this type of drive is attractive in reducing the cost and weight of the HEV. The switched reluctance motor (SRM) offers several advantages over the traditional induction machine.

1.1 The Switched Reluctance Motor

Recent advances in power electronic technology have made the switched reluctance machine (SRM) an attractive choice for many applications.

The SRM is a doubly-salient, singly excited synchronous machine. The rotor and stator are comprised of stacked iron laminations with copper windings on the stator, as shown in Fig. 1. The machine is excited with a power electronic converter that energizes appropriate phases based on shaft position. The excitation of a phase creates a magnetic field which attracts the nearest rotor pole to the excited stator pole in an attempt to minimize the reluctance path through the rotor. The excitation is performed in a sequence that steps the rotor around.

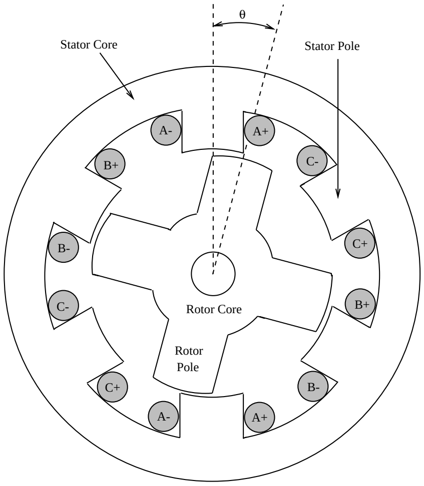

Figure 1: The conventional SRM with windings concentrated around individual poles.

The SRM is similar in structure to the stepping motor, but it is operated in a manner that allows for smooth rotation. Because there are no permanent magnets or windings on the rotor, all of the torque developed in the SRM is reluctance torque. While the SRM is simple in principle, it is rather difficult to design and develop performance predictions. This is due to the nonlinear magnetic characteristics of the machine under normally saturated operation. In [9], a modeling process is outlined for the conventional SRM.

There are several advantages of the conventional SRM over other types of machines. Manufacturing is relatively straightforward as all of the windings are concentrated around the stator poles as opposed to distributed in the induction machine. There are no windings or permanent magnets on the rotor. The simplicity of construction and lack of costly permanent magnets imply that the SRM would be much less expensive to produce in the quantities that DC or induction machines currently enjoy.

1.2 Interest in Torque and Noise

The torque and noise issues are of particular interest in the automotive industry, as is the development of efficient adjustable speed drives and new motor technologies. The motivation behind this research is the need for a clear understanding of the mechanisms that cause torque ripple and/or acoustic noise in an otherwise promising motor technology. The interest is to demonstrate that the SRM can satisfy the torque and noise requirements for industrial and consumer applications.

Previous efforts to decouple the noise and torque performance of the SRM have demonstrated a weak correlation between noise and torque ripple [5]. The casual observer might conclude from this effort that an SRM that has very low torque ripple *m*ight still be noisy. Other efforts have implied that certain SRM structures have high torque ripple, and that ultimately translates into a noisy motor [7]. This paper addresses certain design issues that are believed to be inherently good for acoustic performance. It shows that even a well designed motor (by these standards) can exhibit acoustic noise, suggesting that there are additional causes of acoustic noise in the SRM that have not yet been identified.

2 Acoustic Noise in the SRM

Acoustic noise in the SRM is generally attributed to radial deflections in the stator shell that result from strong radially directed electromagnetic forces. These forces increase as rotor poles move into alignment with excited stator poles. The increase in radial forces as the poles come into alignment is accompanied by a decrease in tangential force. The tangential force is responsible for torque production, and as such, if the rotor is allowed to rotate into alignment with the excited stator, the tangential force will fall to zero and the rotor will reach a stable equilibrium with a strong radial force. This is the principle of stepper motor operation.

The decrease in torque production associated with the increase in radial force implies some correlation between noise, plausibly caused by radial deflection, and torque. From a design perspective, efforts to stiffen the stator structure, or make it more resistant to deflection will reduce acoustic noise without improving torque ripple.

2.1 Stiff Stator Design

There are dimensional design criteria that are required in the SRM for adequate magnetic performance. Since the motor is typically operated with some degree of saturation in the steel, the region of saturation should be limited for efficiency purposes. This is accomplished by designing the motor such that magnetic saturation occurs in the stator poles as opposed to the stator back iron. A cursory analysis of the flux paths in the motor will show that the pole flux generally splits in the back iron to take two paths around the machine to other poles of the same phase. To ensure that the flux density in the stator back iron is less than the flux density in the stator pole, the following relationship must be followed:

$$A_{yoke} \geq \frac{A_{pole}}{2} \quad . \tag{1}$$

In the above expression, A_{yoke} represents the cross-sectional area of the stator back iron, and A_{pole} represents the cross-sectional area of the stator pole. Following this relationship blindly may lead to some complications from a mechanical perspective. As the number of stator poles is increased, A_{pole} decreases and the related A_{yoke} decreases as well. As the back iron thickness is reduced (the prevailing assumption is that the motor length is remaining constant), the stiffness of the structure is reduced.

Given the trade-off in shell stiffness as pole count increases, our experience has demonstrated that the above relationship is far too liberal. In an effort to reduce radial deflection, the a better relationship has been followed. This relationship represents a well-designed motor from both a magnetic *and* a mechanical point of view:

$$A_{yoke} \geq A_{pole} \quad . \tag{2}$$

Realize that taking this relationship to an extreme will not produce a motor that is well-designed from an electrical perspective. Increasing back iron thickness will reduce available winding space assuming that the overall motor diameter is a design constraint.

The efforts put forth to reduce the radial deflections may not be effective in reducing noise if rotor and stator concentricity is not guaranteed. In the SRM, if an airgap imbalance is present, the forces will not distribute symmetrically for a series phase coils. It is possible to balance these forces in the presence of air gap imbalance if the coils of each phase are connected in parallel [6].

3 SRM Noise Measurements and Torque Ripple

The acoustic performance of the starter-alternator was considered in the design stages. Efforts to develop a stiff stator structure include maximizing the stator back iron to reduce radial deflection according to the relationships of the previous section. In addition, stator poles are tapered and coils are vacuum impregnated to minimize pole "wiggle" and pagination of the steel laminations. As a result, extraneous sources of noise, with the exception of rotor eccentricity, have been minimized.

A series of tests have been performed to demonstrate the acoustic performance of the machine. Measurements have been taken by incorporating accelerometers onto the stator housing to observe radial and tangential motion. Excitation of the system was altered to cause variations in the torque ripple and the resulting variations in acoustic performance were observed. A sample of these results is shown in Fig. 2.

The top trace in Fig. 2 is associated with an operating condition where phase turn-on is close to the unaligned

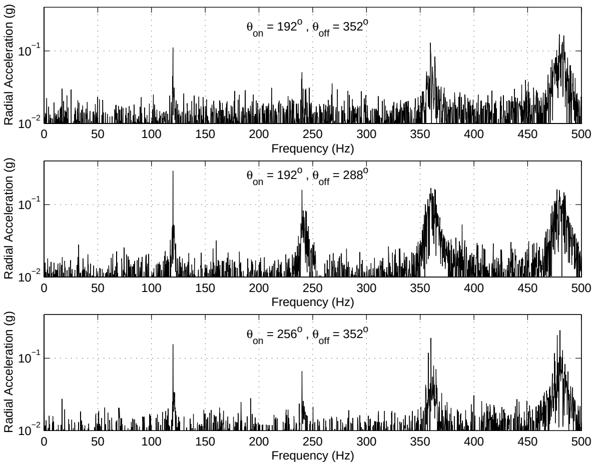

Figure 2: Fourier transform of radial acceleration for one of the stator poles

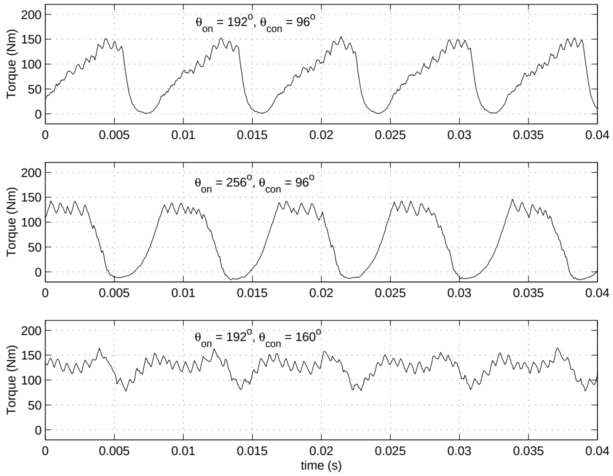

Figure 3: The conventional SRM with windings concentrated around individual poles.

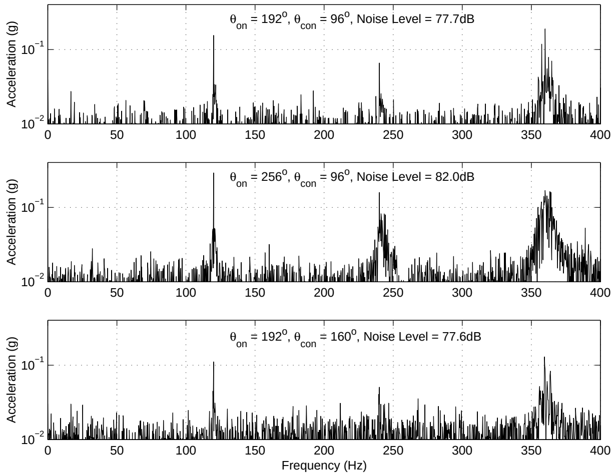

Figure 4: The conventional SRM with windings concentrated around individual poles.

position and turn-off is at the aligned position. The measured noise level was $77dB$ for this point. Torque ripple for this case was 60%.

In the second trace, turn-on was again close to the unaligned position but turn-off was far away from aligned position. For this short conduction interval, noise level was was measured at $82dB$. Torque ripple for this case was 90%.

In the last trace, turn-on was near the intermediate position and turn-off was close to the aligned position. This was another example of a short conduction interval but it demonstrated a noise level of $77dB$ again. Torque ripple for this case was more than 100%.

We have observed that the location of the torque ripple relative to the inductance profile is very important. Torque ripple coinciding with the aligned position is not contributing to the noise as much as the ripple coinciding to the intermediate positions. The figures demonstrate that excitation changes that cause marked changes in the torque ripple can in fact reduce the radial deflection in the motor. The figures also demonstrate that there are other mechanisms for noise production that are not dependent on radial deflection. This is noted by observing that a decrease in torque ripple may not cause a corresponding reduction in acoustic noise even though there is a clear reduction in radial acceleration.

4 Analysis of Results

The information presented here suggests that the noise in the SRM is caused by at least two sources. One of these is of course the radial deflection of the stator. As mentioned, structural design considerations can be implemented to minimize this component of noise. As witnessed with the experimental SRM starter-alternator, this approach can be very effective.

The second source of noise does not appear to be related to radial deflection. In contrast, this noise component *is* related to torque ripple. This is concluded by the reduction of radial deflections without corresponding reduction in acoustic noise.

This paper will discuss the nature of these noise components. The current investigation considers the possibility that the torque ripple component of noise is secondary to the radial deflection component. In machines that are not designed with acoustic performance in mind (i.e. motors that do not have stiff stator structures), the radial component of torque is dominant in all excitation modes. This results in dramatic noise reducion as the excitation angles are adjusted. In this case, the stator deformations are reduced, but remain severe in the best operating conditions. Said another way, even when the radially-driven component of noise is minimized, it still exceeds the noise component driven by torque ripple or tangential vibrations.

If the machine is designed with a stiff stator, it is possible that the tangential component of noise is dominant over even the worst-case radial noise. In this instance, all efforts to reduce radial deflection appear to have little or no effect on acoustic noise. This is because the mechanism for noise production in this mode is different than has been previously considered. This paper investigates this mode of noise production and presents a discussion of possible solutions to the problem.

5 Contributions and Conclusions

This paper investigates noise production in the SRM and treats it as a multi-sourced problem. The previously accepted views are reviewed, but the thrust of the work is to present evidence that SRM noise has components that are dependent on torque ripple and some that are not. Minimizing acoustic noise requires addressing first, the structural design of the motor to minimize radial deflections and pole movement. The second step to minimizing noise is the reduction of torque ripple. In summary, the paper will show that a SRM that is not structurally stiff will be noise regardless of torque ripple. At the next level, even a motor that is structurally stiff may be noisy if torque ripple is not addressed.

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