Numerical Investigation and Optimization of Switched Reluctance Machine with Geometrical Parameters Using Ansys

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ABSTRACT

Switched reluctance motors (SRMs) are used in numerous applications due to their simple and robust structure. In addition to being mechanically and thermally robust, features such as high torque density, efficiency, and reliability, coupled with their fault tolerant structure and low manufacturing cost make SRMs quite attractive. SRMs are double salient pole motors. The stator has simple concentrated excitation windings, and there is no winding or magnet on the rotor. Although SRMs have many features and advantages, large torque ripple, vibration, and acoustic noise are the major disadvantages of these machines. The vibration and acoustic noise of SRMs are mainly generated by the radial forces. The radial forces cause deformation on the stator yoke, which results in vibrations and consequently, frame deformation. When these vibrations resonate with the motor body's natural frequencies, the amplitude of the oscillations and the deformations are intensified. Hence, the acoustic noise increases significantly. The vibration and acoustic noise of SRMs have been deeply investigated throughout the years, and various methods are reported based on modifications on the motor structure and motor control for reducing them. Since this thesis is focused on the acoustic noise reduction techniques from the design perspective, the acoustic noise and vibration mitigation techniques based on the motor structure modifications are investigated. Existing methods are focused on the radial force reduction, motor natural frequency manipulation, and stator damping effect improvement. Although, improving one of these factors also improves the others, most previous studies focus on a single factor. In this thesis, a new vibration and acoustic noise mitigation method is proposed. This method combines the radial force reduction and damping improvement on the stator. The radial force is reduced by introducing rectangular windows on the rotor and the stator poles, which result in a reduction on the stator deformation. In addition, damping elements that are diamond shaped air gaps are inserted into the stator back iron. The number, size, the distance between the elements, and the distance from the stator outer surface to the first air gap are adjusted to achieve the minimum stator deformation and consequently, the minimum acoustic noise. Analyses are performed with 2D/3D electromagnetic and mechanical finite element (FEAs) and vibration analyses tools, and the acoustic noise is reduced successfully.

Key Words*— Switched reluctance motor, radial force, acceleration of vibration, acoustic noise, fluctuation voltage, PWM.Ansys MAXWELL.*

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1. INTRODUCTION

1.1 Introduction of Switched Reluctance Motor Drive System

Switched reluctance machine (SRM) offers several advantages including low cost, rugged structure and superior fault tolerance. Due to these features, SRM is
a good candidate for high speed application such as vacuum cleaner [1], starter-generator for aero-engine [2], compressor [3] and automotive traction [4]. However, high levels of acoustic noise and vibration in SRM drive is an impediment for its application in noise sensitive environments/applications.

The conventional Switched Reluctance Motor (SRM) drive system is shown in Fig 1.1. It is composed of an asymmetric half bridge converter and a SRM. By energizing the winding of one stator phase (Phase A in Fig 1.2), the rotor of SRM rotates from unaligned position to aligned position due to the attraction force between stator and rotor. The direction of attraction force between stator and rotor depends on the relative position between stator and rotor in SRM or (derivative of inductance L with respect to rotor positionθ). If the rotor passes the aligned position ($dL/d\theta<0$), the tangential force will prevent the rotor rotating and SRM is operated as generator mode. If the rotor is between unaligned position and aligned position (dL/dθ>0), the force is an attraction force and SRM runs at motor mode. In order to make rotor rotate continuously, the windings of SRM need to be excited in sequence. The current waveform for SRM is shown in Figure 1.3(a). It can be seen that every phase of SRM is excited during the ascending region of inductance which makes SRM run at motor mode.

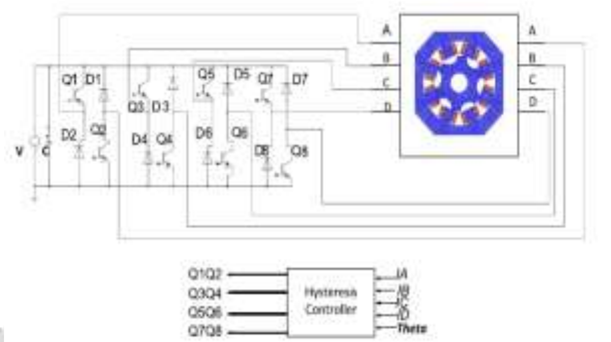


Figure 1.1. Switched reluctance motor drive system

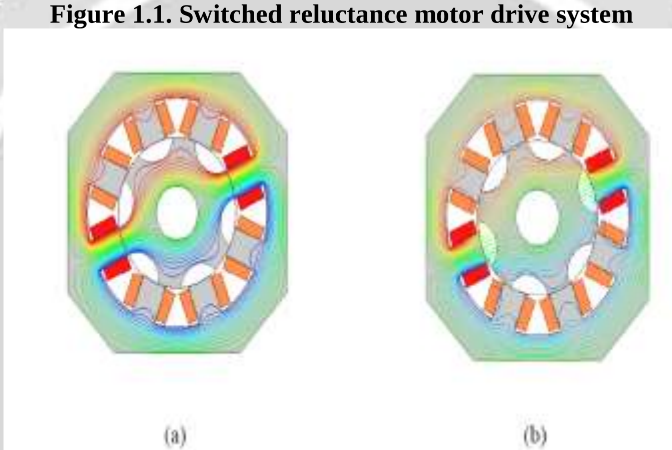
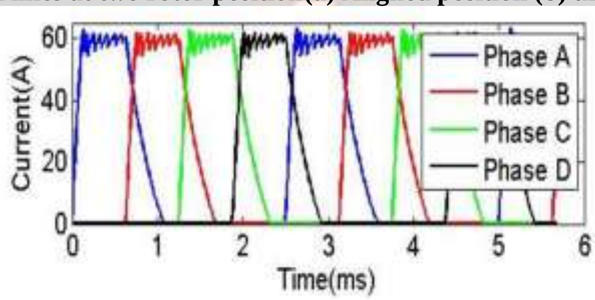
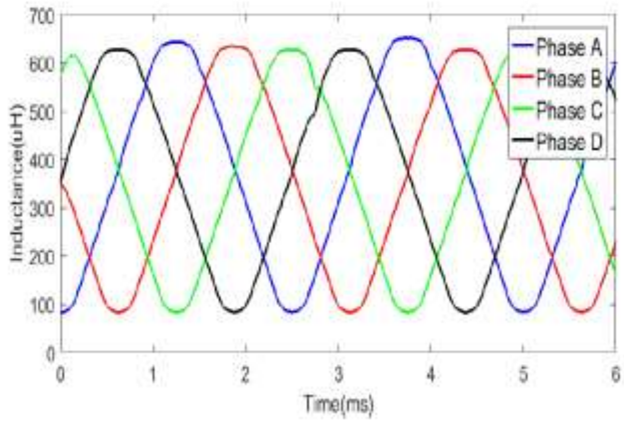


Figure 1.2. Flux lines at two rotor position(a) Aligned position (b) unaligned position



(a) Current waveforms



(b) Inductance profile

Figure 1.3. Current waveform and inductance profile of SRM

1.2 Origin of Electromagnetic Vibration in SRM

- The vibration in SRM drive can be categorized into three types:
- Electromagnetic vibration caused by electromagnetic radial forces and torque ripple
- Mechanical vibration associated with the bearings (defects of bearing), misalignment of shafts and mounting base problem
- Aerodynamic vibration associated with flow of ventilating air through or over the motor

In this research, the electromagnetic vibration caused by radial electromagnetic forces in the SRM is the main focus which is known to be the dominant vibration in SRM drives. Electromagnetic forces distribution on the surfaces of stator and rotor poles when one phase winding is excited is shown in Figure 1.4. As SRM is controlled with hysteresis current control strategy, the electromagnetic forces on the stator and rotor will vary with the current excitation and cause the vibration of stator and rotor. The relationship between current and radial electromagnetic force can be obtained based on virtual work method:

$$F_r = \frac{dW_m}{dx} = \frac{1}{2} i^2 \frac{dL}{dx} \quad \text{........(1)}$$

2. LITERATURE REVIEW

Over the past two decades, SRMs have been intensely developed. The origin of SRMs can be tracked back to 1838, but the SRM concept was not fully implemented due to the lack of the necessary power electronic devices and high power switching techniques [1]–[4], [6], [7]. Over the past decades, the progress made in motor design and high power switching devices made SRMs more attractive to researchers; therefore, SRMs became popular in both academia and industry. Robust and straightforward construction is the most attractive feature of SRMs, which contain no rotor windings, permanent magnets, brushes, or commutators. The rotor is basically made of a piece of steel with laminations which are shaped to form salient poles without any windings. Because of the absence of brushes, SRMs provide a long life. Due to the lack of a permanent magnet and windings, SRMs have a low manufacturing cost, high power to weight ratio, high efficiency over a wide speed range, high speed and acceleration capabilities, and high fault tolerance [8]. The advantages that are mentioned above make SRMs attractive and favorable for researchers and various industrial applications.

SRMs can address unique and varied requirements such as speed-torque relationship and high fault tolerance, which make them an ideal candidate for utility vehicles, golf carts, electric cars, buses, and trains [5], [9], [10]–[13], [14]. Furthermore, SRMs are well suited to the aerospace field due to their high-speed capability and robustness [15].

For a smooth movement, the SRM`s phases need to be excited at certain rotor angles. Conventionally, the position of the rotor is measured using mechanical sensors mounted on the rotor shaft. Aside from increasing the cost and making the drive system more complex, most of the times the mechanical position sensors cause reliability issues. Although sensorless position estimation methods exist in the literature [16], these methods make the control even more complex as they require excessive calculations.

Another disadvantage of an SRM is the high level of torque ripple at low speeds, especially when it is operated in single-pulse voltage control mode that contributes to speed ripple and vibration in the stator. Compared with the sinusoidal AC machines, the torque ripple is higher in SRMs [17]. The torque ripple is mainly due to the nonlinear behavior of the inductance based on the position of the rotor and the excitation current. The existence of the torque ripple causes accuracy problems, especially on the servo systems [18]. There are various known torque ripple reduction methods in the literature. Torque ripple reduction is achieved with different approaches such as improving the motor design, improving the control [19]–[21] strategy, and selecting a higher number of commutation phases [17]. A better design may include optimizing the rotor and stator pole arcs, inserting pole shoes into the rotor poles, etc. Minimizing the torque ripple through the control may cause average torque reduction [18]. Selecting a higher number of phases increases the number of required power electronic components, which raises the cost of the drive system [22]

3. OBJECTIVE OF THE STUDY

Our main objective of the study is to investigate the SRM Model by provide holes in the stator and rotor laminations are introduced to reduce the radial force and mechanical vibration in SRMs. The placement of the holes can be optimized to maximize the benefits. Reducing the radial force is one way to reduce the vibration. However, there is a tradeoff between the radial force reduction and the torque production. A decrease in the radial force leads the tangential force and torque to decrease. Therefore, while reducing the radial force, the reduction in the average torque should be observed, and thus an optimization process needs to be introduced. Other than the radial force reduction, the damping effect of the motor body can be improved to reduce the vibration. In this way, the natural frequencies of the motor can be pushed out of the audible spectrum, or at best the amplitudes of these frequency components can be reduced by adding damping elements to the motor body.

PROPOSED WORK

In this chapter, holes in the stator and rotor laminations are introduced to reduce the radial force and mechanical vibration in SRMs. The placement of the holes can be optimized to maximize the benefits. Reducing the radial force is one way to reduce the vibration. However, there is a tradeoff between the radial force reduction and the torque production. A decrease in the radial force leads the tangential force and torque to decrease. Therefore, while reducing the radial force, the reduction in the average torque should be observed, and thus an optimization process needs to be introduced. Other than the radial force reduction, the damping effect of the motor body can be improved to reduce the vibration. In this way, the natural frequencies of the motor can be pushed out of the audible spectrum, or at best the amplitudes of these frequency components can be reduced by adding damping elements to the motor body.

4. METHODOLOGY

In this chapter, the analysis and optimization procedure are given for determining the size and position of the distributed air gaps on the stator and rotor. A 24/16, 100 kW, 4250 rpm SRM is selected for the analysis. The following section gives the details of the analysis procedure. The natural frequencies are determined through modal analysis of the SRM. The vibration and acoustic noise analysis of hole placements in the rotor and the stator is provided. Placements of the distributed holes are optimized to get the maximum benefit. Results are presented to get a set of guidelines for the design.

4.1. Analysis Procedure

The analysis starts with a modal analysis, which is used for determining the natural frequencies of the motor. These are the frequencies with which the vibrations coming from the radial forces resonate, hence, generating higher vibrations and acoustic noise.

The rest of the analysis is the combination of electromagnetic, structural, harmonic, and acoustic analyses that are performed using ANSYS Electromagnetics Suite, and ANSYS Mechanical coupled through ANSYS Workbench shown in Figure 4.1. The electromagnetic analysis is performed with Maxwell. The outputs of this analysis are the radial and tangential forces on the stator pole tooth tips. The harmonic response analysis takes the results from the electromagnetic analysis and determines the surface deformation, acceleration, and velocity of the stator in the frequency domain to feed this information to the acoustic analysis. The results from the harmonic response are loaded to the acoustic analysis toolbox to determine the sound (acoustic) pressure level. The transient structural analysis is also used to analyze the surface deformation, acceleration, and velocity in time domain. It is also possible to determine the acoustic pressure levels using a one-meter microphone test in the transient structural analysis.

4.2. Modal Frequency Analysis

The modal frequency analysis is required for determining the natural frequencies (modes) of the motor. Generated vibrations on the stator poles that are originated from the radial forces become more dominant when they resonate with the natural frequencies of the stator. Therefore, the total deformation on the stator surface increases, which amplifies the acoustic sound pressure.

5. RESULTS AND DISCUSSION

5.1 Modal Analysis

The modal analysis results of the mentioned 24/16 SRM is performed using the ANSYS tool, and the results are presented in Figure 5.1.

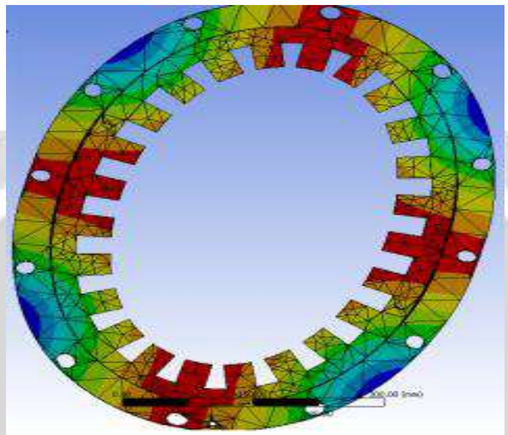


Fig. 5.1 Natural frequency (198 Hz) of 24/16 SRM at mode 1

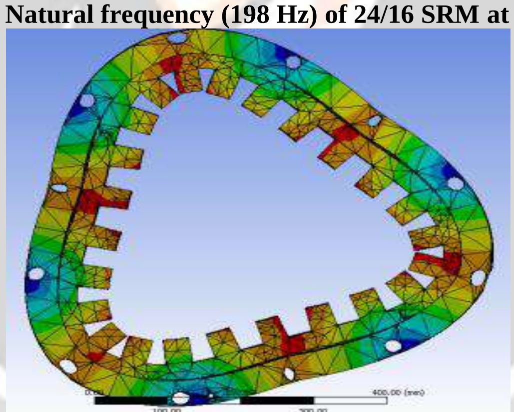


Fig. 5.2 Natural frequency (544Hz) of 24/16 SRM at mode 2

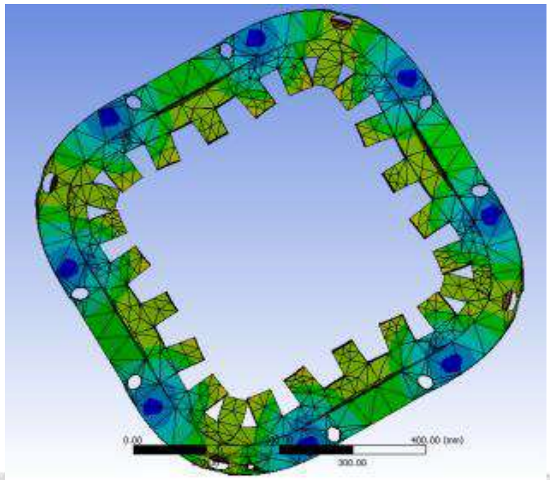


Fig. 5.3 Natural frequency (1009 Hz) of 24/16 SRM at mode 3

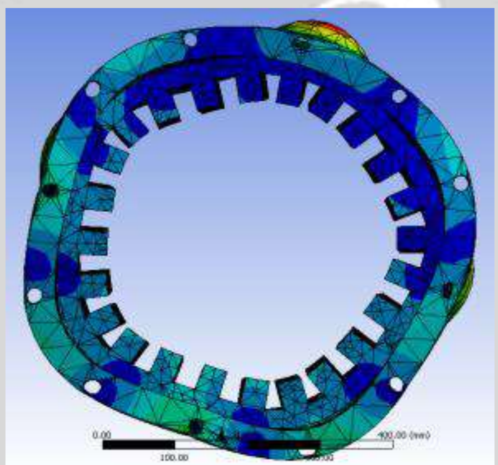


Fig. 5.4 Natural frequency (1568Hz) of 24/16 SRM at mode 4

5.2 Harmonic Response

The second step of the analysis is the harmonic response analysis, which has been performed using ANSYS Mechanical coupled through ANSYS Workbench. The total deformation and the acceleration results have been obtained as an outcome of the mechanical analysis. The total deformation on the stator surface of the conventional machine is found to be 0.27854 µm, while the optimized machine provides 0.17811 µm, as shown in Figure 5.6. These results show that total deformation is reduced by 36 %

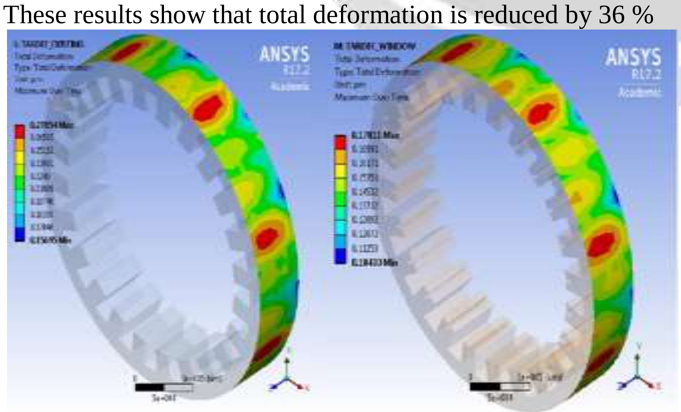


Figure 5.6. Total Deformation of the conventional and windowed motors.

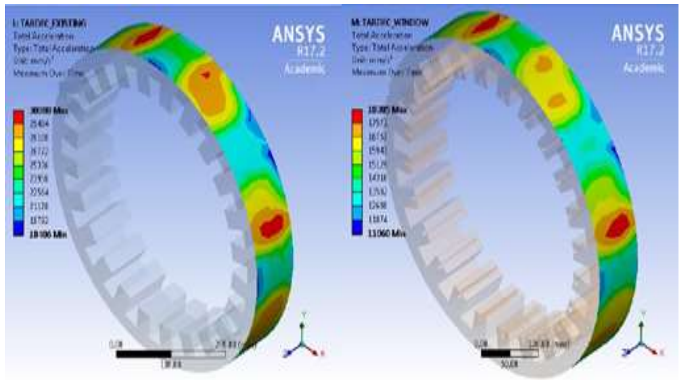


Figure 5.7 Total acceleration of the conventional and windowed motors.

The total acceleration on the stator surface is 30880 mm/s2 for the conventional machine, and 18385 mm/s2 for the optimized design. Thus, the total acceleration is improved by 40.46 %.

5.3 Analysis of the Distributed Air Gaps

The effect of the distributed air gaps on the stator for various configurations of the air gap patterns and locations are investigated in this section. First, the distributed air gaps that have the same total area, number, and the size are placed on the stator teeth and back iron separately. For a fair comparison, simulations are performed by adjusting the peak current for a similar average torque production. Table 5.1 compares the FEA results of the motors that have distributed air gaps on the stator teeth and back iron with the conventional SRM.

CASE	Without Airgap	Airgap in teeth	Airgap in Back Iron
Tavg [Nm]	1136	1142	1132
Peak Current [A]	300	500	300
Frad, p-p [N]	1927	994	1678
Total Deformation [µm]	0.27854	0.25672	0.23867
Total Acceleration [mm/s2]	30880	28653	25581

Table 5.1. Comparison of the distributed air gap locations.

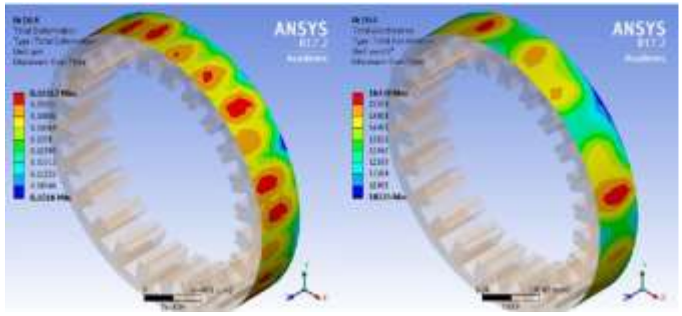


Figure 5.8 Total deformation an acceleration of the optimized SRM.

5.4 Summary

In this chapter, placement of the distributed air gaps on the stator back iron in combination with the single holes in the stator and rotor poles is proposed and analyzed. Distributed air gaps have diamond shapes. These diamond shaped air gaps act like series-parallel connected springs and damp the oscillations. Therefore, the total deformation and acceleration of the stator outer surface are reduced. The conventional and proposed SRMs are tabulated for comparison purposes in Table 5.3. The total deformation is reduced 36% with the optimized windowed machine and 41.4% with the optimized windowed and distributed air gap machine. The total acceleration is reduced 40% with the optimized windowed machine and 47% with the optimized windowed and distributed air gap machine.

	T_{avg} (Nm)	Peak to Peak Frad (N)		Total Deformation (µm)	Total Acceleration (mm/s²)
Conventional SRM	1136	1927.33	0.5890	0.27854	30880
Windowed SRM	878.7	613.77	1.4316	0.17811	18385
Windowed SRM with Distributed Air Gaps	872.6	692.12	1.2607	0.16317	16338

Table 5.2. Comparison of conventional, windowed, and distributed air gap SRMs.

6. CONCLUSION

This thesis proposes an acoustic noise and vibration mitigation technique for switched reluctance machines (SRM). SRMs are favored in many applications due to their simple, reliable, and robust structures. However, these machines generate high torque ripples, vibrations, and consequently, high acoustic noise. SRMs have a doubly salient pole structure where the operation relies on exciting stator phases in a switching pattern. Every excitation attracts the appropriate rotor pole, and the rotor rotates through the attraction direction. The force pulling the rotor through the excited pole has two components called tangential and radial forces. The tangential force produces torque while the radial force pulls the stator pole through the center of the motor. During the commutation between the phases, the current that excites the phase suddenly goes to zero, which causes the radial force to decrease abruptly. The potential energy stored on the stator pole when it is pulled is suddenly released, and the stator pole and the stator back iron start to move in the opposite direction and oscillate just like releasing an elastic tape after it is stretched. These oscillations have frequency components that resonate with the motor's natural frequencies and thus amplify the oscillations at certain frequencies. As a result, acoustic noise is generated. Therefore, the source of the acoustic noise can be considered as the radial force and the motor's natural frequencies that are on the audible spectrum.

Many researchers investigated the mitigation of the acoustic noise and vibration, and numerous methods are reported based on modifications on the motor structure and motor control. This thesis is focused on acoustic noise reduction techniques from the design perspective. Therefore, a detailed literature survey on design considerations to reduce the acoustic noise and vibration is provided in Chapter II. In this chapter, the basic principles, classification, and the operation of SRMs are explained. Then, existing methods, which include modifications on stator and rotor poles, modifications on the stator back iron, optimal pole arc design, stator/rotor pole number optimization, skewing, etc. are investigated. The advantages, disadvantages, manufacturing, and structural issues of these methods are discussed. In general, existing methods focus on one aspect, which can be the radial force reduction, or motor natural frequency adjustment, or introduce damping elements on the stator.

In Chapter III, the proposed acoustic noise and vibration reduction method is introduced. The proposed method combines the radial force reduction and the introducing damping elements on the stator. A damping element is a group of diamond shaped holes distributed on the stator back iron. The reason for diamond shape selection is that it generates zigzag shaped bridges along the stator back iron and these zigzag shaped bridges can be considered as a spring network. The variation in the diamond shape sizes, positions, and the distance between the elements affect the spring constants. Consequently, the damping and the motor's natural frequencies are affected. Thereby, diamond shape sizes, positions, and the distance between the elements are optimized for minimum total deformation and total acceleration on the stator outer surface while having less than 20% average torque reduction.

The proposed method is applied to a 100 kW, 24/16 SRM using coupled electromagnetic and structural finite element analysis (FEA) software packages from ANSYS.

The combination of distributed air gap with the hole placement in the stator and rotor is proposed and analyzed. The dimensions and the placement of the holes are optimized to reduce the vibration and deformation without significantly impacting the torque production. The performance index developed as average torque over peak-to-peak radial force variation ($N = T_{avg} / F_{rad.pp}$) is , improved from 0.589 to 1.26.7 with the optimized design, and consequently, the total deformation on the stator surface is reduced by 47 %.

In conclusion, the proposed method provides satisfactory acoustic noise and vibration reduction without having an intolerable effect on the torque production. Moreover, the method does not require a complicated manufacturing process, as it only requires the insertion of rectangular and diamond-shaped holes into the stator and rotor laminations.

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