A STUDY ON THE EFFECT OF SOFT MAGNETIC COMPOSITE MATERIAL ON THE TORQUE CHARACTERISTICS OF A SWITCHED RELUCTANCE MOTOR

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Abstract—This paper describes applying Soft Magnetic Composite (SMC) material in a Switched Reluctance Motor (SRM). The presented SRM stator uses two materials: classical laminated silicon steel sheet and SMC. Initially, the laminated steel stator core is analyzed. Subsequently, an identical geometry SRM using SOMALOY 500 SMC is analyzed. Comparisons cover the calculated average torque and torque ripple. Means to improve average torque via geometrical modification in the SMC stator core are then presented. Finite element analysis was used to examine magnetic conditions and compute average torque.

Keywords—Finite Element Analysis (FEA), Inductance profile, Soft Magnetic Composite (SMC), Switched Reluctance Motor (SRM), Torque ripple.

I. INTRODUCTION

The advance of power electronics and material technology has driven the development of special-purpose machines. Among these, the Switched Reluctance Motor (SRM) is gaining prominence in electric drives due to its rugged simplicity, low projected cost, fault tolerance, high efficiency, and high torque-to-inertia ratio. Concurrently, innovations in powder metallurgy have produced Soft Magnetic Composite (SMC) materials with unique properties—such as 3D isotropic ferromagnetism, very low eddy-current loss, relatively low total iron loss at medium-high frequencies, potential thermal improvements, flexible design, and lower production costs—that could revolutionize electrical machine design. A promising approach involves substituting traditional laminated silicon-iron cores with SMC or iron powder materials. Using these materials shortens production time, reduces component counts, and minimizes scrap. Employing SOMALOY 500—a soft magnetic composite from Sweden’s Höganäs—for an 8/6 SRM stator offers a cost-effective solution for many low-performance applications. Despite its advantages, the SRM has drawbacks: it requires electronic control and a position sensor, a large DC-link capacitor, and its double-salient structure generates acoustic noise and torque ripple. This paper analyzes the magnetic conditions in an 8/6 SRM, comparing a stator made first from laminated silicon steel and then from soft magnetic composite material [1]. The investigation focuses on how constructional parameters influence the electromagnetic torque of an 8/6 SRM with an SMC stator core.

II.SWITCHED RELUCTANCE MOTOR

A switched reluctance motor produces torque through the rotor's tendency to align with an excited stator phase, thereby minimizing the magnetic path's reluctance. It is a doubly salient, singly excited machine with windings only on the stator; the rotor consists solely of stacked silicon steel laminations[2]. This results in a relatively simple geometry, as illustrated in the two-dimensional (2D) CAD model of an 8/6 switched reluctance motor shown in Fig. 1.

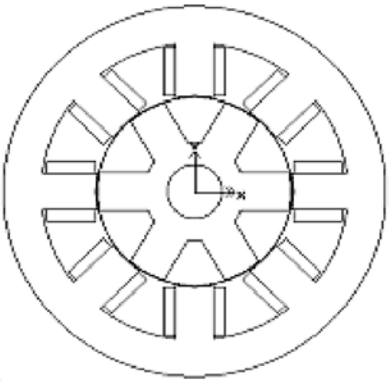

Fig. 1. The Two-Dimensional CAD model of an 8/6 SRM.

III. SOFT MAGNETIC COMPOSITE MATERIALS IN ROTATING ELECTRICAL MACHINES

Electrical steel laminations are the predominant core material in electrical machines. These steels are primarily categorized as grain-oriented, commonly used in power transformers, and non-oriented, widely applied in rotating electrical machines. The electromechanical steels used in manufacturing offer high magnetic saturation induction (BS-~2T), low coercive force (Hc< 100 A/m), and low total losses. For soft iron components in time-varying magnetic fields, electrical sheet steels have long been the standard choice[3]. However, new soft iron powder metallurgy materials present a viable alternative for magnetic cores. The foundation of soft magnetic composites is bonded iron powder, as illustrated in Fig. 2. This powder is coated, pressed into a solid using a die, and then heat-treated to anneal and cure the bonding agent.

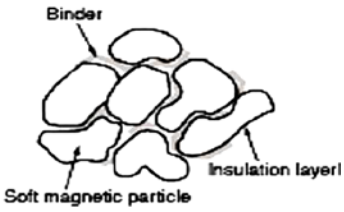

Fig. 2. Schematic picture of a SMC material

A comparison of the B-H characteristics of M19 silicon steel and the SMC material SOMALOY 500, shown in Fig. 3, indicates that while SMC has a lower relative permeability than laminated steel[4], it retains several advantageous features:

a. A smaller copper volume due to an improved fill factor and shorter end-windings, leading to lower copper loss.

b. Greatly reduced high-frequency tooth ripple losses, as SMC materials exhibit negligible eddy current losses.

c. The potential for a smaller air gap, enabled by the tight manufacturing tolerances achievable with SMC.

d. A modular construction that allows for the easy removal and replacement of individual units for quick repair.

e. Simplified recyclability, as the stator can be compressed back into powder form for recovery, with copper windings easily removed.

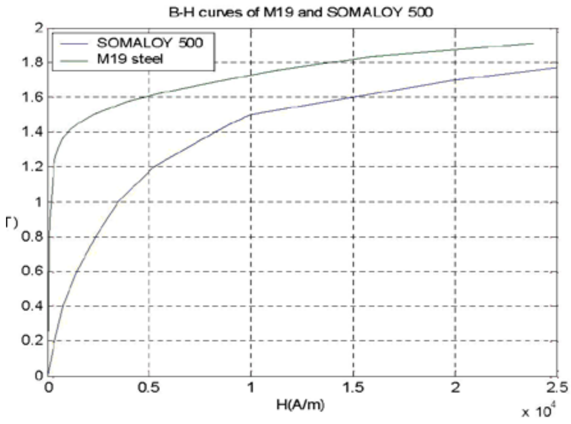

Fig. 3. B-H characteristics of laminated steel and SMC

IV.THE TWO-DIMENSIONAL NUMERICAL FINITE ELEMENT ANALYSIS

Time-stepped Finite Element Analysis (FEA) is the most precise method for determining the magnetic characteristics of an electromagnetic device [5]. This paper employs a two-dimensional FEA on the two machine configurations listed in Table I, utilizing the FEA-based Computer Aided Design (CAD) software package MAGNET 6.22.1.

TABLEI
STUDIED STRUCTURES

Structure I	Structure II
Laminated steel stator (Ml9)	Soft Magnetic Composite (SMC) stator
Laminated steel rotor (Ml9)	Laminated steel rotor

The model of the machine when the stator core is the SMC material SOMOLOY 500[6] is shown in Fig. 4.

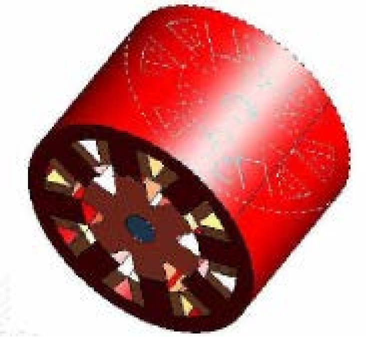

Fig. 4. 8/6 SRM - Projected Model

The flux linkage characteristics as well as the inductance profile [7] of SMC cored SRM has been obtained as shown in Fig. 5 and 6.

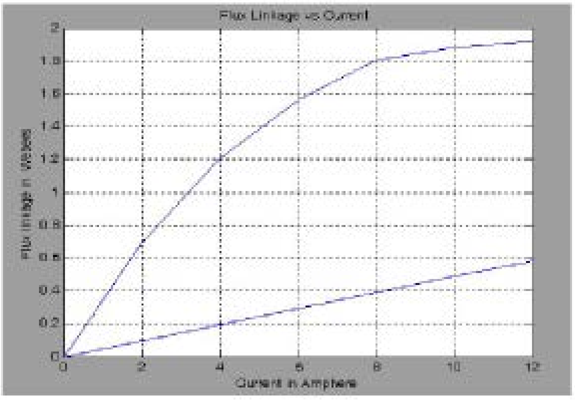

Fig. 5. Flux linkage characteristics

The inductance profile obtained at the operating current indicates that the electromagnetic torque in SRM is a function of variation of excited phase inductance with the rotor position and is expressed mathematically as

$$T = (i^2 / 2)\frac{dL(\theta)}{d\theta}$$

i= constant

The average electromagnetic torque is given by

$$T_{avg} = \frac{1}{n}\sum_{i=1}^{n} T_i$$

Tr- Instantaneous torque
n - Number of rotor positions

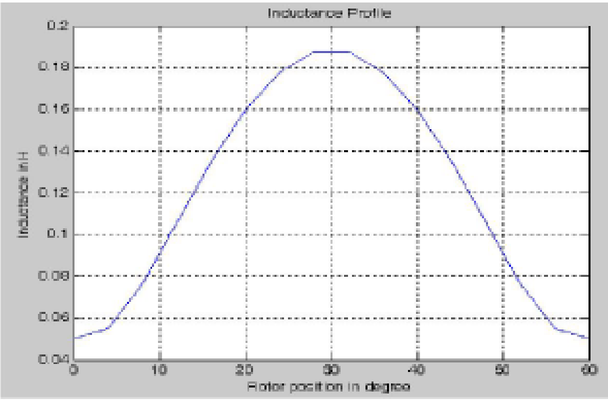

Fig. 6. Inductance profile.

V. TORQUE-RIPPLE OF SWITCHED-RELUCTANCE MOTOR

A key inherent problem in SRMs is torque ripple, caused by the switched nature of torque production. Torque ripple can be determined from variations in output torque. To predict its magnitude, static torque characteristics must be analyzed. The "torque dip"—defined as the difference between the peak torque and the common overlap point of two consecutive SRM phases, as shown in Fig. 7—is critical. By denoting the maximum static torque as Tmax and the minimum torque at the intersection point as Tint, the percentage torque ripple can be defined using the following equation.

$$\%TorqueRipple = \frac{T_{max} - T_{int}}{T_{max}} \times 100$$

The torque dip is an indirect indicator of torque ripple in the machine, the lesser the value of the torque dip, the lesser will be the torque ripple[9].

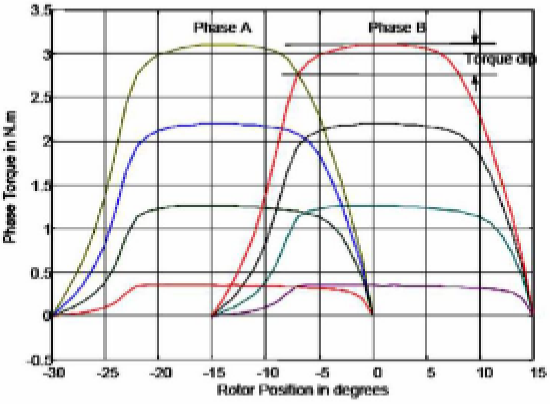

Fig. 7. Torque angle characteristics showing torque dip.

The toque dip of both the machines has been computed by FEA and the results are shown in Fig. 8 and 9 for laminated steel cored machine as well as for SMC cored SRM.

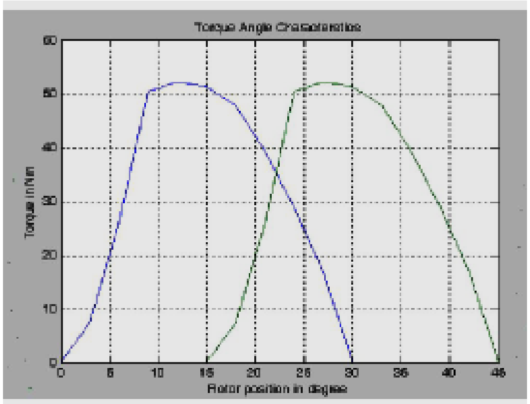

Fig. 8. Torque angle characteristics of laminated steel core SRM.

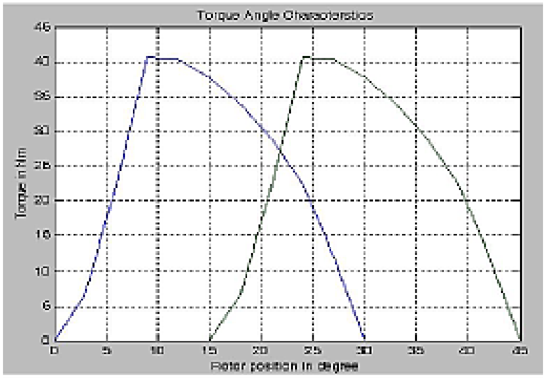

Fig. 9. Torque angle characteristics of SMC core SRM.

Analysis of the two graphs confirms a reduction in torque ripple for the SMC-cored SRM. However, this is accompanied by a decrease in average torque, and the torque characteristic is more peaked rather than flat, as seen in structure 1. To enhance the electromagnetic torque characteristics of structure 2, modifications to several constructional parameters have been explored, as detailed in references [8]-[11].

1. Stepped air gap structure with the step introduced inthe rotor.
2. Stepped air gap with the tapered rotor model.
3. Tapered stator pole model.

The various studied structures with magnified view of stepped airgap have been shown in Fig. 10, 11, 12 and 13.

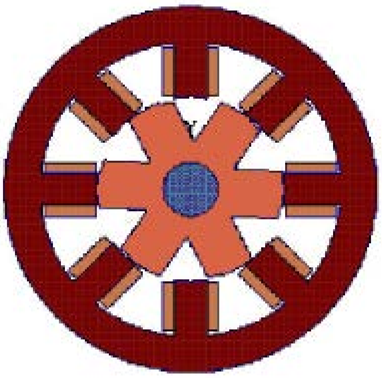

Fig. 10. Stepped air gap-SMC cored SRM.

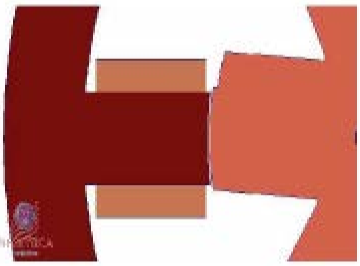

Fig. 11. Magnified view of the stepped air gap.

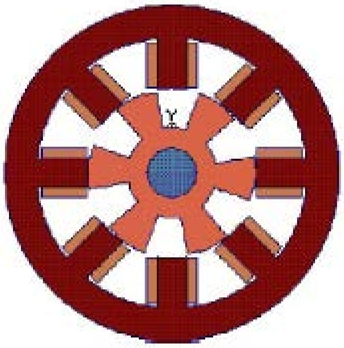

Fig. 12. Tapered rotor with stepped air gap SMC cored SRM.

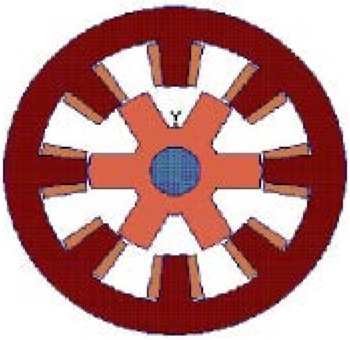

Fig. 13. Tapered stator pole model.

A comparison of the static characteristics from time-stepped FEA for the three modified SMC stator designs reveals that the stepped air gap with a tapered rotor yields the best average torque and smoother performance. In contrast, the tapered stator pole offers the least desirable characteristics. The stepped air gap model alone provides flat torque characteristics but with reduced average torque. Torque ripple, estimated from the static torque overlap of two consecutive phases, is illustrated for these three modified SMC stator models in Figures 15, 16, and 17.

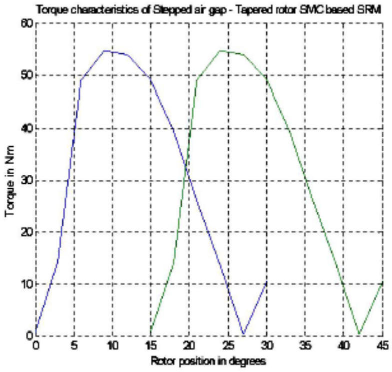

Fig. 15. Torque angle characteristics of stepped airgap, tapered rotor SMCstator cored switched reluctance motor.

The results obtained have been summarized in Table II and also displayed in the bar chart that follows in Fig. 18.

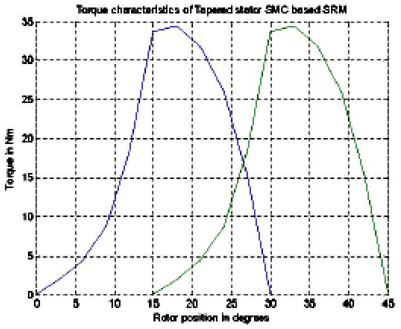

Fig. 16. Torque angle characteristics of tapered stator SMC stator cored Switched reluctance motor.

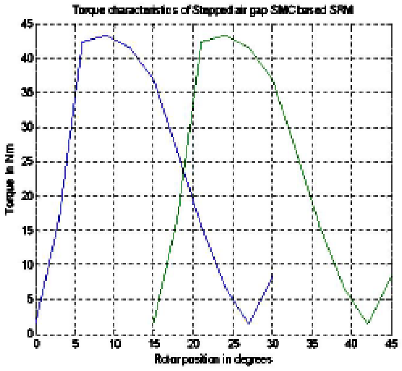

Fig. 17. Torque angle characteristics of stepped airgap rotor SMC stator cored Switched reluctance motor.

The flux lines plot for the stepped air gap-tapered rotor SMC-cored SRM model, shown in Fig. 19, demonstrates that tapering the poles magnetically unloads them. This results in higher flux linkage for a given magnetomotive force (mmf) and produces smoother torque. This inherent torque shaping reduces the demand on both the torque smoothing and current controllers. Consequently, for many low-performance applications, additional torque smoothing beyond this geometric modification may not be required.

TABLE II
SUMMARIZED RESULTS OF CONSTRUCTION PARAMETERS MODIFIED SMC CORED SRM

Geometry modifiedSMC statorcored SRM structure	**% Torque ripple**	**Tavg (Nm)**
Stepped air gap	45.82	21.79
Tapered rotor pole with stepped air gap	40.68	28.29
Tapered stator pole	50.94	15.88

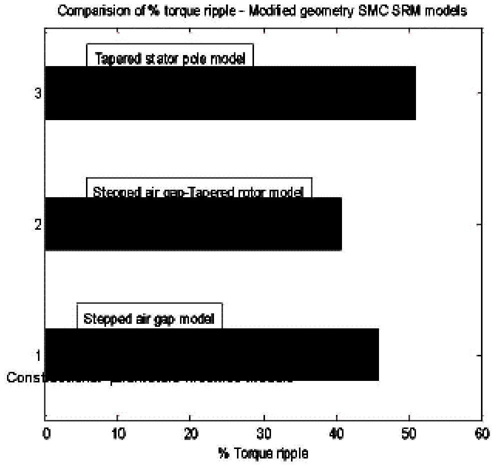

Fig. 18. Torque ripple comparison of modified geometry SMC stator coredswitched reluctance motor

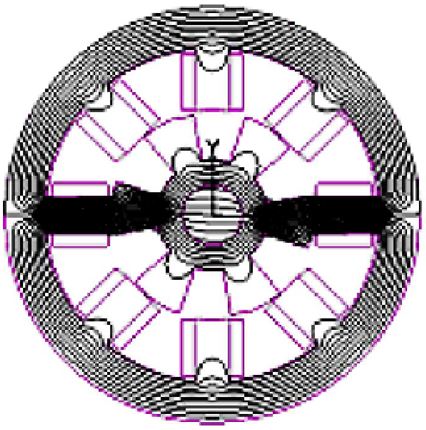

Fig. 19. Flux lines in the stepped air gap-tapered SMC stator cored SRM.

VI. CONCLUSIONS

This paper investigated the impact of using Soft Magnetic Composite (SMC) material for the stator core of an 8/6 SRM on its electromagnetic performance. A time-stepped two-dimensional finite element analysis (FEA) was conducted using the CAD package MAGNET 6.22.1 to obtain static torque characteristics. Replacing a conventional stator core with SMC material (SOMALOY 500) reduced torque ripple but also decreased the average torque. Further FEA on three modified SMC stator designs revealed that a stepped air gap with a tapered rotor geometry provides superior electromagnetic characteristics and a cost-effective solution for SMC-cored SRMs. Future research should explore the machine's dynamic performance, thermal behaviour, and vibrationcharacteristics.

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