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Influence of Soft Magnetic Materials on the Design and Performance of Tubular Permanent Magnet Machines

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This paper investigates the influence of the choice of soft magnetic material on the performance of a tubular permanent magnet machine, and quantifies the relative merits of silicon iron laminations and soft magnetic composites (SMCs). The machine is equipped with a modular stator winding and employs a quasi-Halbach magnetized moving-magnet armature. It is shown that, despite its poorer space utilization, a machine whose stator is fabricated from silicon iron laminations has the highest force capability, efficiency and power factor. A machine with a SMC stator, on the other hand, has potential advantages in terms of ease of manufacture and lower cost.

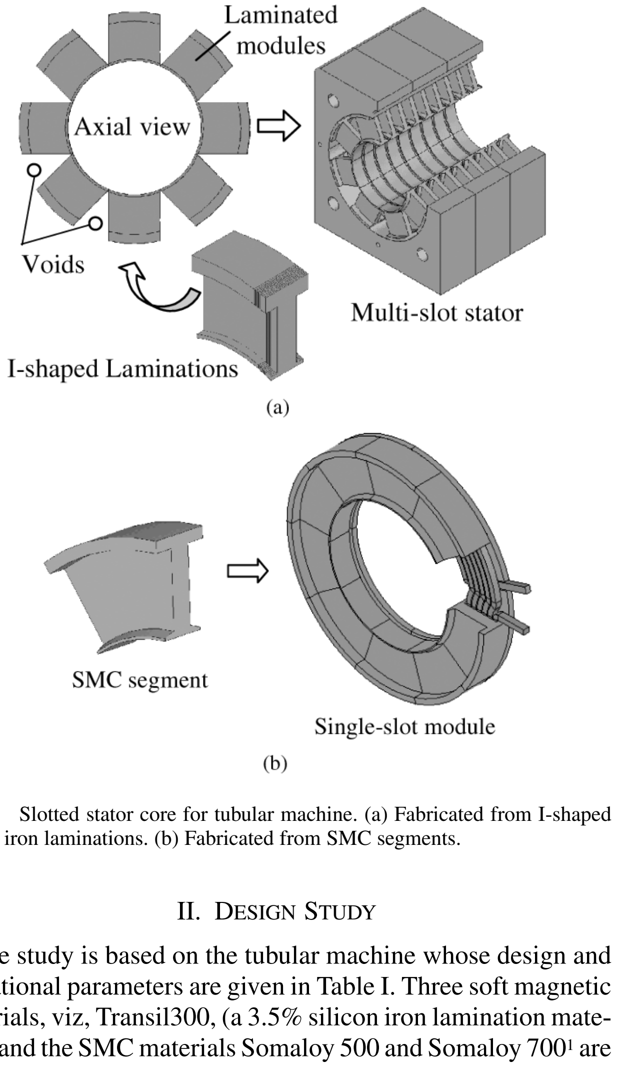
Index Terms—**Linear machine, permanent magnet (PM) machines, tubular machines.**

I. INTRODUCTION

DUE TO their high power density and high efficiency, and the fact that they have no end-windings and zero net attractive force between the stator and armature [1], [2], tubular designs of linear permanent magnet (PM) machine are being used in an ever-increasing variety of applications, ranging from free-piston energy converters [3] to reciprocating compressors [4]. A general framework and comprehensive analysis and design methodologies for both slotless and slotted topologies of tubular PM machine have been reported [2], [5], [6]. It has also been shown that the force capability of a tubular PM machine can be improved significantly by employing a slotted stator, which may be fabricated from either silicon iron laminations or die-pressed soft magnetic composite (SMC) components, as illustrated in Fig. 1.

When silicon iron laminations are used, the flux is effectively constrained to flow in the two-dimensional plane of the laminations, and regardless of how the laminated tubular stator is constructed, the total cross-sectional areas of the teeth and yoke are equal to the circumference of the inner stator bore times the tooth width and yoke thickness, respectively, since voids exist, as highlighted in Fig. 1(a). An SMC material, on the other hand, enables all the available space to be fully utilized, as shown in Fig. 1(b). However, SMCs have a relatively high core loss at typical operational frequencies, as well as a lower permeability and saturation flux density. Although both design and experimental studies on tubular machines which employ silicon iron laminations and SMCs [7], [8] have been reported, to date, no comprehensive comparison has been made as regards their relative merits.

Utilizing the analytical framework established in [2] and [6], that takes account of core saturation, and employing a validated iron loss model [7], this paper investigates the influence of the choice of soft magnetic material on the performance of a tubular PM machine.



(a)

(b)

Fig. 1. Slotted stator core for tubular machine. (a) Fabricated from I-shaped silicon iron laminations. (b) Fabricated from SMC segments.

II. DESIGN STUDY

The study is based on the tubular machine whose design and operational parameters are given in Table I. Three soft magnetic materials, viz, Transil300, (a 3.5% silicon iron lamination material), and the SMC materials Somaloy 500 and Somaloy 700[1] are considered. Fig. 2 and Table II compare their BH (flux density B, field stength H) curves and iron loss constants [7], respectively. Clearly, the silicon iron lamination material has a significantly higher permeability and saturation flux density, while its

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TABLE I
DESIGN AND OPERATIONAL PARAMETERS FOR COMPARATIVE STUDY

Outer stator radius (m)	0.05
Pole-pitch (m)	0.01
Number of pole-pairs	5
Magnet thickness (m)	0.005
Air-gap length (m)	0.001
Magnet remanence (T)	1.049
Ambient temperature (^{0}C)	40
Temperature rise (^{0}C)	100
Surface convection coefficient (W/^{0}C/m^2)	20
Rated velocity (m/s)	4.0

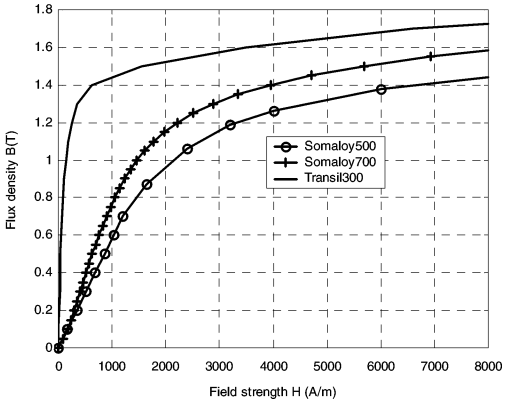

Fig. 2. Comparison of BH curves.

TABLE II
COMPARISON OF IRON LOSS CONSTANTS

	Somaloy500	Somaloy700	Transil300
K_h	0.1236	0.08	$1.55\mathrm{x}10^{-2}$
α	1.84	1.75	2.45
K_e	$1.88\mathrm{x}10^{-4}$	$1.60\mathrm{x}10^{-4}$	$1.0\mathrm{x}10^{-4}$
σ (1/mΩ)	0	0	$1.33\mathrm{x}10^{6}$

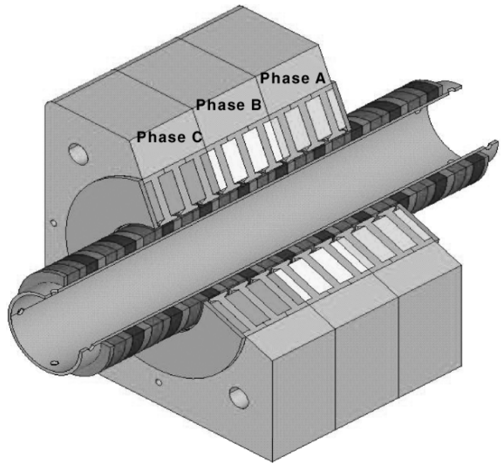

Fig. 3. Schematic of nine-slot/ten-pole tubular modular PM machine.

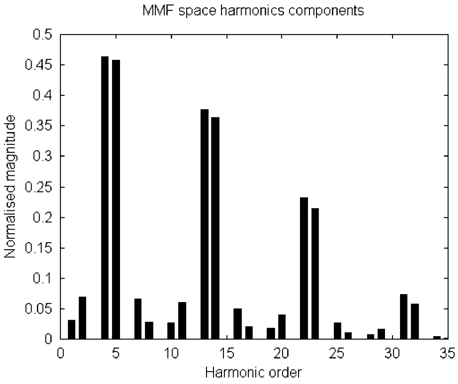

Fig. 4. Normalized space harmonic mmf distribution for three-phase, nine-slot/ten-pole modular tubular PM machine.

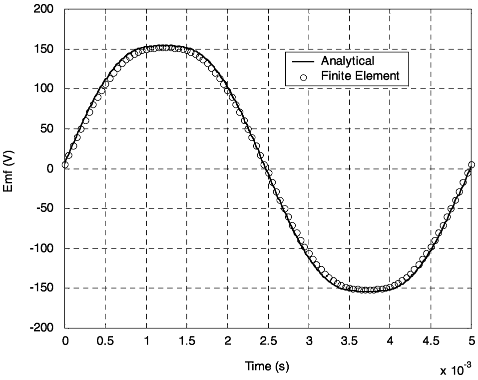

Fig. 5. Comparison of analytically and finite element predicted phase emf waveforms.

specific iron loss at low frequencies is much lower than that of the SMC materials.

The tubular PM machine under consideration has a modular stator winding and employs a quasi-Halbach magnetized moving-magnet armature which comprises one radially magnetized magnet and one axially magnetized magnet per pole (Fig. 3). It has a number of advantages over conventional tubular PM machines in terms of ease of manufacture, a higher force capability, a lower mass armature, and a lower force ripple. The performance of the modular tubular machine can be predicted either analytically or by finite element analysis. By way of example, Fig. 4 shows the stator magneto-motive force (mmf) distribution of the nine-slot/ten-pole modular machine normalized to the Ampere-turns per slot divided by the width of the stator slot openings. When the stator winding is excited with balanced three-phase currents, it produces forward travelling mmf harmonics of order $n = 1, 4, 7, \ldots$, backward travelling mmf harmonics for $n = 2, 5, 8, \ldots$, and zero triplen harmonics. The thrust force is developed by the interaction of the fifth space harmonic mmf with the ten-pole PM field. The lower and higher order mmf harmonics travel at different speeds to the armature, and will induce eddy current losses in both the PMs and the support tube (if it is electrically conducting), and may cause other undesirable effects, such as localized core saturation and noise and vibration.

Fig. 5 compares analytically and finite element predicted phase emfs at an armature speed of 4 m/s when the machine employs I-shaped silicon iron laminations for the stator core. It will be noted that, at the rated speed of 4 m/s, the fundamental electrical frequency is 200 Hz.

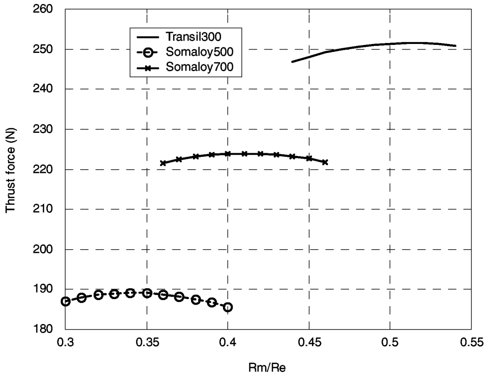

Fig. 6. Variation of thrust force as a function of R_m/R_e.

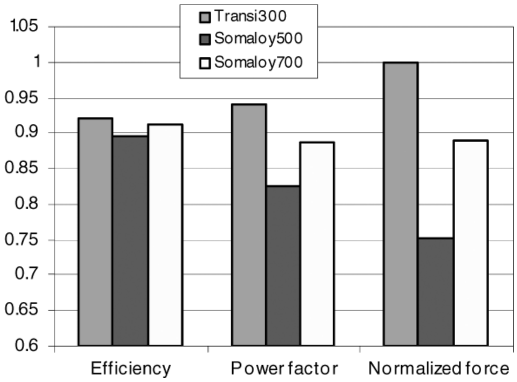

Fig. 7. Comparison of force capability (normalized to 250 N), efficiency, and power factor.

III. Results and Discussion

Machine designs based on the three different soft magnetic materials whose loss constants are specified in Table II were optimized with respect to two dimensional ratios: viz. the ratio of the outer magnet radius R_m to the outer stator radius R_e, and the ratio of the axial length of the radially magnetized PMs τ_{mr} to the pole-pitch τ_p, subject to the design conditions specified in Table I. It can be shown that, irrespective of which soft magnetic material is employed, an optimal ratio of $\tau_{\mathrm{mr}}/\tau_p = 0.60$ exists for minimum force ripple and maximum force capability. Fig. 6 shows the variation of the thrust force as a function of R_m/R_e for the three materials. As will be seen, each material has a different optimal R_m/R_e ratio for maximum thrust force. The optimal ratio is lower for the machines equipped with the lower permeability SMC stators. It should be noted that this ratio represents an optimal balance between the electric and magnetic loadings of the machine, and that the magnetic loading will be lower when the permeability of the magnetic material is reduced. Hence, a higher electric loading and a larger stator volume are required, which leads to a lower optimal R_m/R_e ratio.

Fig. 7 shows the influence of the soft magnetic material on the force capability, efficiency, and power factor of the optimal machine designs in which the full load peak flux density is set to 1.3, 0.9, and 1.0 T for Transil300, Somaloy 500, and Somaloy 700, respectively. As can be seen, the machine design which employs silicon iron laminations has the highest force capability and the best performance, despite its poorer space utilization. As is evident from Fig. 2, the permeability of Transil300 at 0.8T is at least 2.5 times greater than that of the SMC materials, while the space utilization of the laminated tubular stator, due to the voids, is only ~33% lower. Hence, overall, the laminated stator provides a more permeable magnetic path while incurring a lower iron loss. Further, for a given volume and magnetic loading, a higher permeability stator core allows for a greater coil area and a higher electric loading, which leads to a higher force capability and a higher efficiency. In addition, since, for a given allowable temperature rise, the total losses of a machine are limited by its thermal dissipation capability, a lower iron loss also permits a higher current density, and, hence, a higher force capability and efficiency. Table III compares the loss components of the three machine designs normalized to their rated output power of 1 kW. It should be noted, however, that, although having an inferior performance, the SMC machine designs may be easier to manufacture, and, therefore, potentially be lower cost.

TABLE III
Comparison of Loss Components of the Three Machine Designs

	Somaloy500	Somaloy700	Transil300
Iron loss	0.043	0.039	0.021
Copper loss	0.045	0.049	0.067

IV. Conclusion

The influence of three soft magnetic materials, viz, Transil300, Somaloy 500, and Somaloy 700, on the design and performance of a tubular PMic machine has been analyzed, and their relative merits have been quantified. It has been shown that a design which employs silicon iron laminations (Transil300) has the highest force capability, efficiency, and power factor, despite its stator having a poorer space utilization. The SMC machine designs, on the other hand, offer the potential for lower cost manufacture.

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