Clawpole Transverse-Flux Machine with Hybrid Stator

Maxime R. Dubois, Nicolas Dehlinger, Henk Polinder and Daniel Massicotte

***Abstract*—Recent topological investigations regarding transverse-flux geometries have lead to multiple arrangements with different characteristics. The Clawpole Transverse-Flux Machine (TFM) combines the advantage of high specific torque with ease of manufacturing. But because of 3 dimensional flux path, the topology requires the use of isotropic materials like Soft Magnetic Composite (SMC), with specific losses higher than conventional laminations. Moreover, the TFM shows a dependence of its force density upon its pole pitch and airgap thickness, which leads to high electrical frequencies and thus to high core losses. This paper presents a solution for the reduction iron losses by using a "hybrid stator" built from a combination of Fe-Si laminations and SMC in the stator. A comparison between a Clawpole TFM with hybrid stator and a full-SMC stator based on 3D Finite Element Analysis (FEA) and experimental results are presented.**

***Index Terms*—Clawpole Transverse-Flux Machine, Core losses, Soft Magnetic Composites (SMC), 3D FEA.**

I. Introduction

STUDIES on the topic of Transverse-Flux Permanent Magnet Machines (TFPM) have shown a potential for electrical machines with very high force densities, leading to very compact machines. In [1], a theoretical study based on the double-rotor, double-sided TFPM geometry with flux-concentration shown in fig. 1, indicates that force densities up to 200 kN/m^2 are possible. These force density values are substantially higher than what can be obtained with conventional Permanent Magnet (PM) machines, where values up to 50 kN/m^2 can be expected [2] for standard current density.

The force density of TFPM machines is strongly dependent on pole pitch and air gap thickness [3][4]. In [4], force densities above 200 kN/m^2 are reported as possible if the pole pitch of the TFPM geometry of fig. 1 is kept below 12 mm and if the airgap is kept below 1 mm. Thus, high electrical frequencies will be obtained, making the specific stator core losses higher than with conventional PM machines. For example, a 30-pole TFPM running at 1800 RPM will have an electrical frequency of 450 Hz.

The Clawpole Transverse-Flux Machine (TFM), shown in fig. 2, was proposed by [5]. Compared to the TFPM machine of fig. 1, this machine has the advantages of a single-sided stator and a single row of PMs. These characteristics substantially improve the machine construction and manufacturing, Due to inherent mechanical tolerances, thin and constant airgaps are more likely to be obtained in an electrical machine with a single-sided airgap.

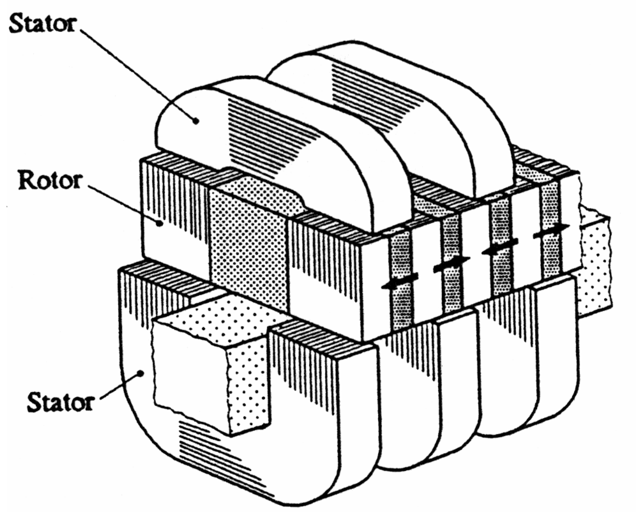

Fig. 1. Double-rotor, double-sided TFPM geometry with flux-concentration, presented by [1].

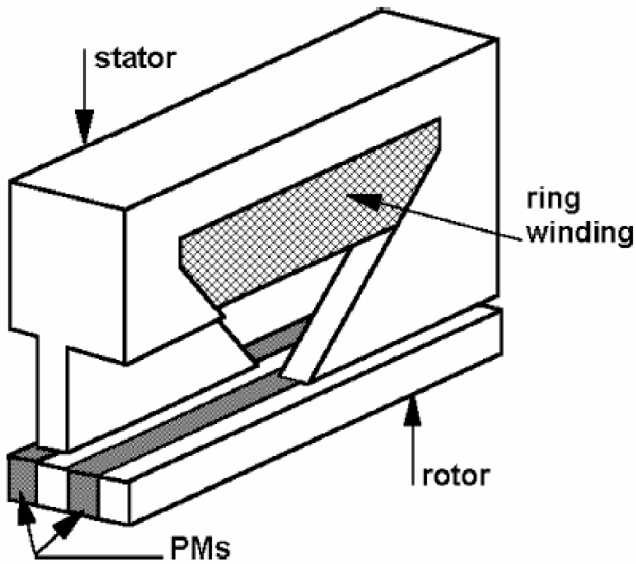

Fig. 2. Clawpole TFM concept, presented by [5].

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M. R. Dubois and N. Dehlinger are with the Laboratoire d'Électrotechnique, Électronique de Puissance et Commande Industrielle (LEEPCI), Université Laval, Pav. Pouliot, G1K 7P4, Québec, Canada, (phone: 418-656-2131 ext 2982; fax: 418-656-3159; e-mail: mrdubois@gel.ulaval.ca).

H. Polinder, is with the Laboratory of Electrical Power Processing, Delft University of Technology, The Netherlands, Mekelweg 4, 2628 CD, Delft, The Netherlands, (e-mail: h.polinder@ewi.tudelft.nl).

D. Massicotte is with Eocycle Technologies Inc., 49 Belair, suite 106, G6V 6K9, Lévis, Québec, Canada (e-mail: dmassicotte@eocycle.com).

Like other TFPM machines, the Clawpole TFM demonstrates a dependence of its force density upon its pole pitch and airgap thickness. In the Clawpole TFM, the flux density vector has high components in the 3 dimensions. This isssue is addressed by using isotropic Soft Magnetic Composite (SMC) material for the stator core [5]-[8]. SMCs have been improved substantially in the last years. However, their specific losses are still higher than conventional machine laminations. For example, SMC material Somaloy 550® has specific iron losses of 8 W/kg @ 50 Hz/1.0T [9] and Fe-Si 0.35-mm laminations V330-35A® have specific iron losses of 1.3 W/kg @ 50 Hz/1.0T [10].

As mentioned, the combination of short pole pitches and SMC material will lead to high core losses. In this paper, a solution is proposed for the reduction of iron losses in the Clawpole TFM by using a combination of Fe-Si laminations and Soft Magnetic Composites (SMC) in the stator [11].

II. CLAWPOLE TFM WITH INTERIOR HYBRID STATOR

To reduce iron losses in the stator core of the Clawpole TFM, the stator cores are split in 2 parts: laminated C-cores and SMC stator feet (fig.3-4).

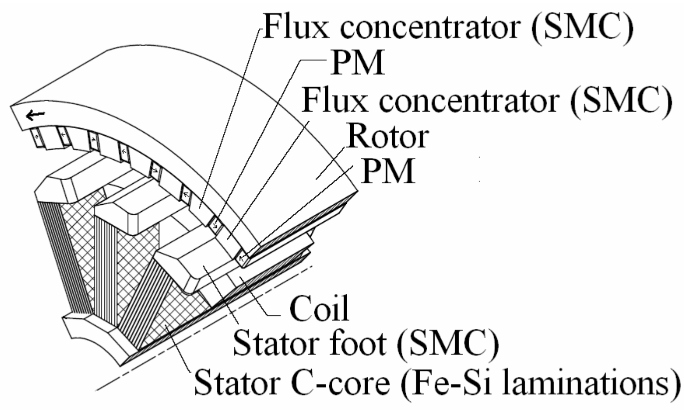

Fig. 3. Clawpole TFM with interior hybrid stator (3 pole pairs of 1 phase).

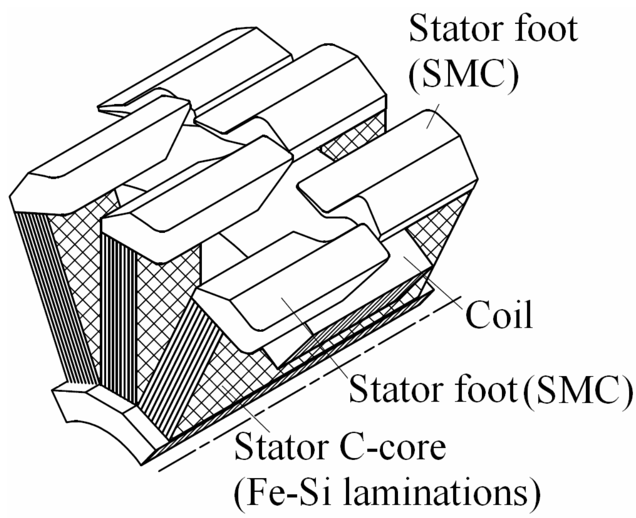

Fig. 4. Clawpole TFM with interior hybrid stator (3 pole pairs of 1 phase, shown without rotor).

The name "Hybrid stator" refers to the use of 2 different magnetic materials in the stator core. Laminations are used to carry the flux around the coil and SMC is used near the air gap to deviate the flux coming from the airgap toward the laminated C-core.

The laminations offer a path with high permeability, high saturation flux density and low iron losses. Moreover, they are easily made with conventional metal stamping methods.

The SMC feet of the hybrid stator of fig. 4 are smaller and simpler to produce than the large SMC stators of fig. 2. In addition, only one type of SMC piece needs to be produced, as both SMC feet are identical.

The use of SMC material contiguous to the airgap on the rotor and stator provides easy machining of rotor and stator, thus leading to very thin airgaps. In the rotor, flux concentrators are also made of SMC. These are larger than the PMs in the radial direction, leaving some excess material (see fig. 5) that will be removed during the machining process. Air gaps of 0.55 mm could be reached experimentally with this method. A resin-based SMC material like ATOMET-EM1 is advisable for good material strength after machining [12].

Concerning the stator winding, the hybrid stator allows easy winding of the coil inside the C-Cores prior to insertion of the SMC stator feet. Thus, the SMC feet can be made to overlap one another in order to catch more flux coming from the rotor. In the proposed Clawpole TFM with hybrid stator, an interior stator is used for easier winding, but the same geometry could be applied to an outer stator.

The rotor can be formed by directly stacking PMs and flux concentrators one next to the other, as proposed in [5]-[8] and as shown in fig. 5. Another possibility is the use of a toothed rotor, proposed in [13], which provides a guiding structure for each rotor pole. Such a toothed rotor has the advantage of accurately positioning each flux concentrator with respect to its mechanical angular position. The resulting rotor layout is shown in fig. 6.

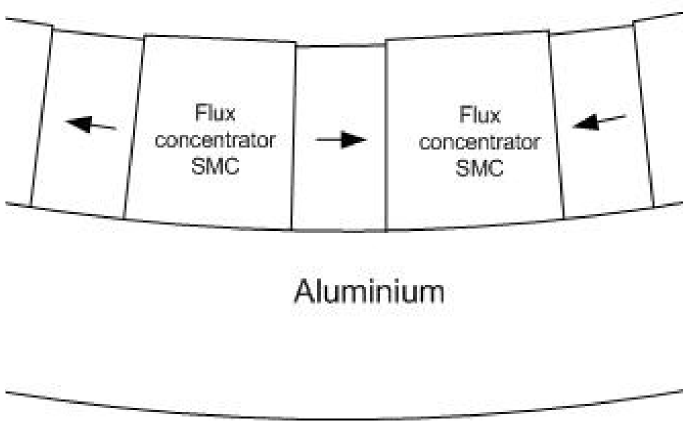

Fig. 5. Detail of rotor layout before rotor machining. Each flux concentrator is made larger than the PMs in the radial direction.

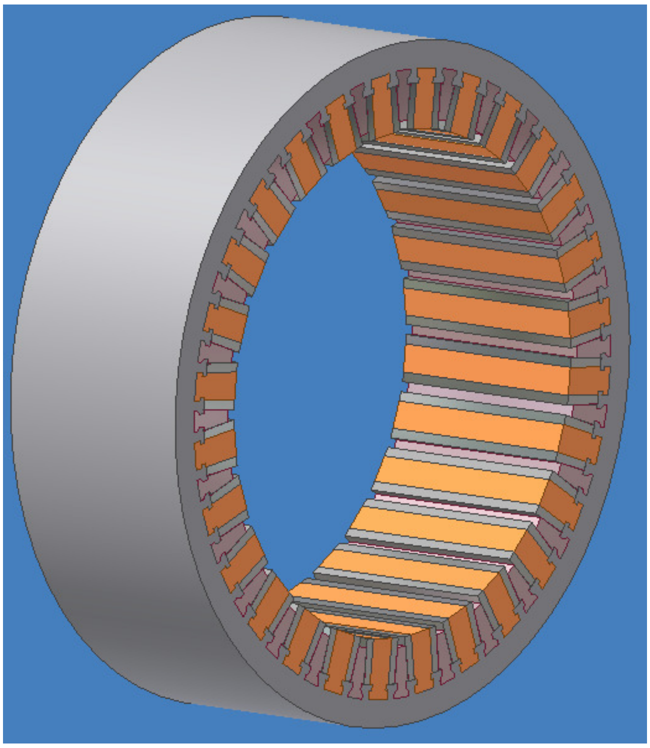

Fig. 6. Rotor of the Clawpole TFM: toothed rotor version.

III. COMPARISON BETWEEN ALL-SMC AND HYBRID STATORS

In this section, the Clawpole TFM with Hybrid stator is compared with a full-SMC stator. Both are simulated using the 3D Finite Element Analysis (FEA) magnetostatic package MagnetVI® from Infolytica. The geometry used for the comparison is shown in fig. 7.

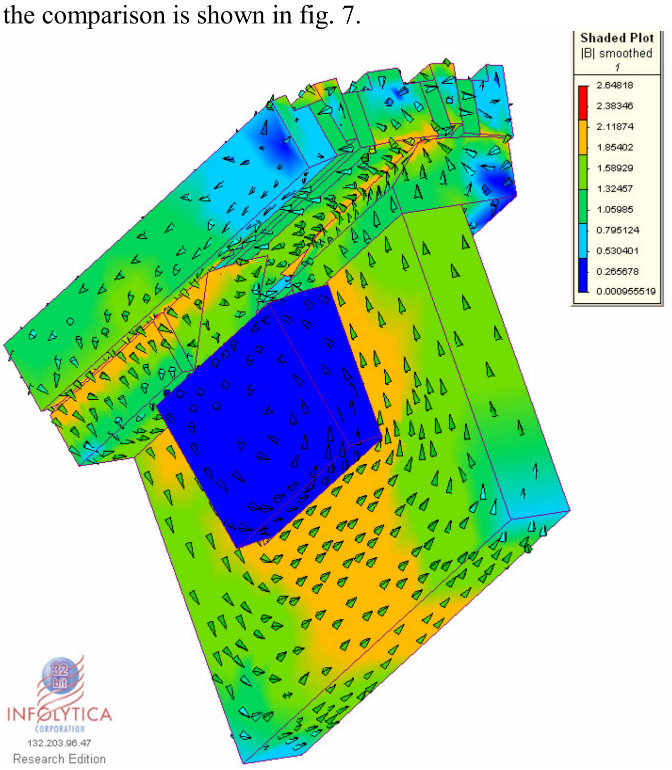

Fig. 7. One pole pair of the clawpole TFM used in the FEA computation.

Symmetrical boundary conditions are imposed in the calculations, such that a single pole pair of the machine needs to be considered. Flux and torque are computed for 24 different positions in a half cycle, that is for every 7.5 electrical degrees. In calculation A, the C-core material chosen is SMC, while in calculation B, the C-core material is the M-19 electrical steel. The *B(H)* curves used in the calculation are plotted in fig. 8. In calculations A and B, the winding carries a sinusoidal magnetomotive force (mmf) of amplitude 3500 A-turns, with a phase shift of 20 degrees with respect to the aligned position. The phasor diagram used for the FEA computations is shown in fig. 9.

The resulting flux and torque values computed with FEA are plotted in fig. 10 and fig.11.

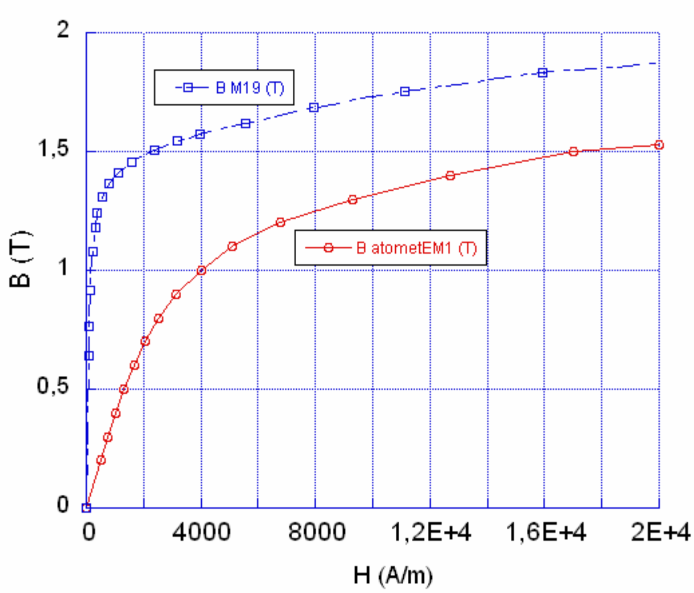

Fig. 8. B-H curves of SMC and laminated steel used in the FEA calculations.

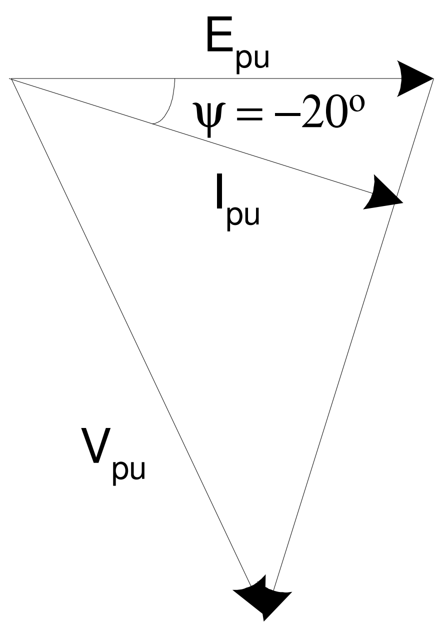

Fig. 9. Phasor diagram used for the FEA simulation.

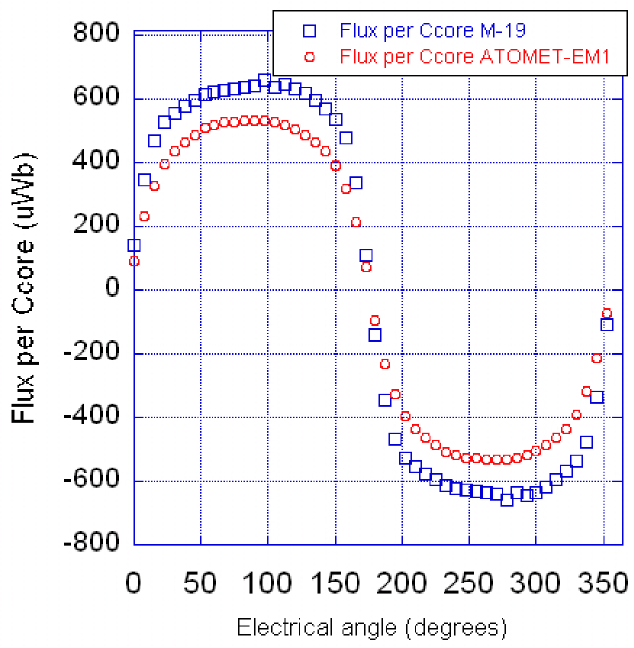

Fig. 10. Flux waveform computed with FEA, as a function of electrical angle.

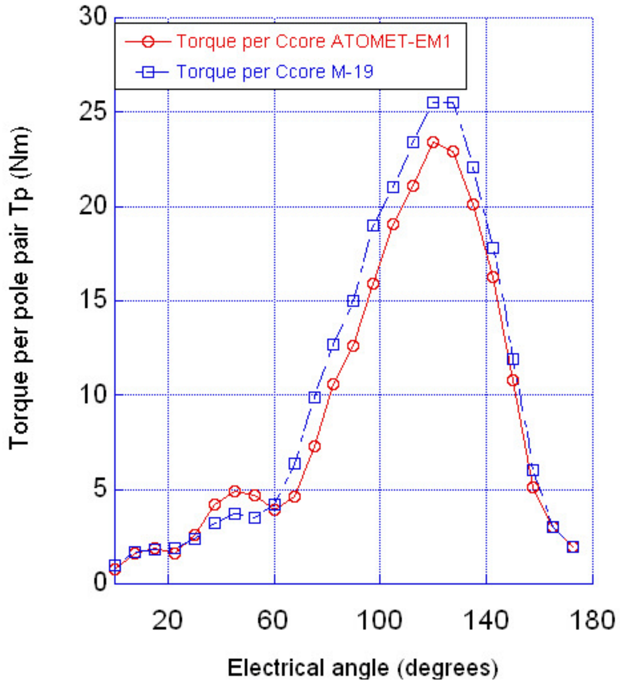

Fig. 11. Torque waveform computed with FEA, as a function of electrical angle.

The average torque value is T_p = 11.0 Nm/pole pair for the Hybrid stator and T_p = 9.9 Nm/pole pair for the SMC stator. A lower average torque is obtained with SMC as a result of lower permeability and lower saturation flux density.

For the loss calculation, we consider a uniform flux density over the C-core cross-section (337 mm^2). The flux waveform shown in fig. 10 is expanded in Fourier series giving the flux density harmonic content plotted in fig. 12. The loss curve shown in fig. 13 is used for the SMC material ATOMET-EM1 and laminated steel M-19 of thickness 0.35 mm.

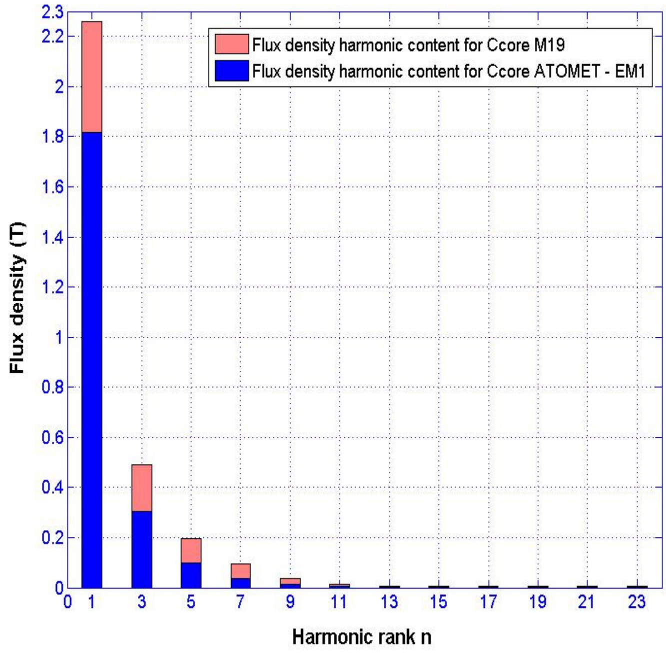

Fig. 12. Flux density harmonic content in the C-core at full-load.

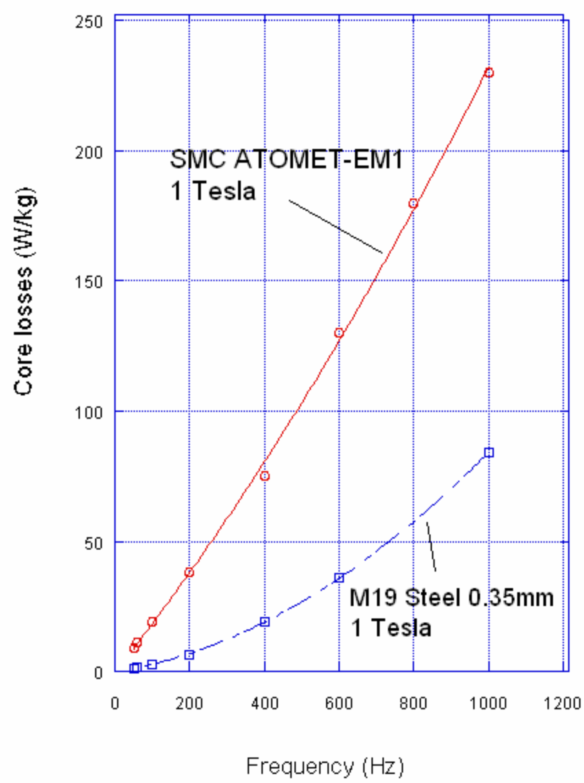

Fig. 13. Core losses for the SMC material ATOMET EM-1 and Fe-Si laminated steel M19 of thickness 0.35 mm.

For a sinusoidal flux density, the specific losses can be mathematically modeled with eq. (1) for the SMC material ATOMET-EM1 and with eq. (2) for the laminated steel M19.

$$\frac{P_{Ccore}(f,B)}{m} = 0.18B^{1.7} f + 5x10^{-5} B^2 f^2 \qquad (1)$$

$$\frac{P_{Ccore}(f,B)}{m} = 0.024B^{1.7} f + 6x10^{-5} B^2 f^2 \qquad (2)$$

where P_{Ccore}/m is the specific core losses in W/kg.

For a non-sinusoidal excitation, the loss in the C-core is given by eq. (3) for the ATOMET-EM1 and with eq. (4) for the laminated steel M19.

$$P_{Ccore\_SMC} = P_{Ccore}(f_1, B_1) + \sum_{n=2}^{\infty} 5x10^{-5} m B_n^2 f_n^2 \qquad (3)$$

$$P_{Ccore\_M19} = P_{Ccore}(f_1, B_1) + \sum_{n=2}^{\infty} 6x10^{-5} m B_n^2 f_n^2 \qquad (4)$$

where n is the rank of the harmonic considered, f_n and B_n are the frequency and amplitude of the flux density for each harmonic contained in the flux waveform. The hysteresis losses are only considered for the fundamental component of the flux waveform and the amplitude of B used for the hysteresis losses is 1.8 T for laminated steel and 1.5 T for SMCs. The losses associated with the harmonics are eddy current losses only.

Considering the machine of fig. 7 with 30 poles (p = 15), the C-core mass for the 15 pole pairs is m = 6.1 kg. The C-core losses are plotted as a function of the rotational speed in fig.14.

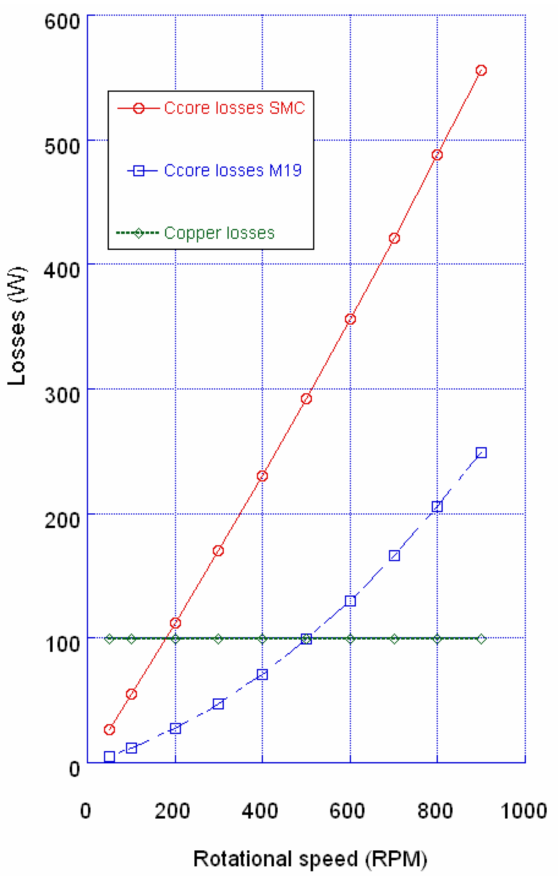

Fig. 14. Losses in the C-core for Clawpole TFM with p=15 and m_{Ccore} = 6.1 kg.

For the SMC material, the C-core losses are 560 W at 900 rpm, while laminated C-cores dissipate 249 W at the same speed. The copper losses are 99 W for this mode of operation.

From the theoretical analysis performed in this section, we conclude that a Clawpole TFM with Hybrid Stator will substantially decrease the machine losses. This reduction of losses is critical for the temperature management of the machine. In this example, the machine volume is 7000 cm^3 per phase and its outer rotating surface is 0.09 m^2 per phase. The same machine was experimentally tested with a hybrid stator at 240 RPM, with a forced dissipation of 200 W which lead to an internal temperature rise of 100 °C above ambient. According to fig. 14, such a 200 W dissipation will be reached at about 180 RPM for SMC C-cores and at about 500 rpm with laminated C-cores.

IV. Experimental Results

A 3-phase Clawpole TFM with interior Hybrid stator was built. Dimensions are: p= 15 pole pairs/phase, pole pitch= 19 mm, length= 100 mm/phase, outside diameter = 30 cm, air gap = 0.55 mm, airgap diameter = 18 cm. The design was not optimized for high force density. The design was intended to produce 60 Hz from a 240 rpm rotating shaft. Therefore, the number of poles was set to 30. The rotor was built with a toothed rotor, as pictured in fig. 15. The whole machine is shown in fig. 16.

Fig. 15. Inside view of the three-phase rotor.

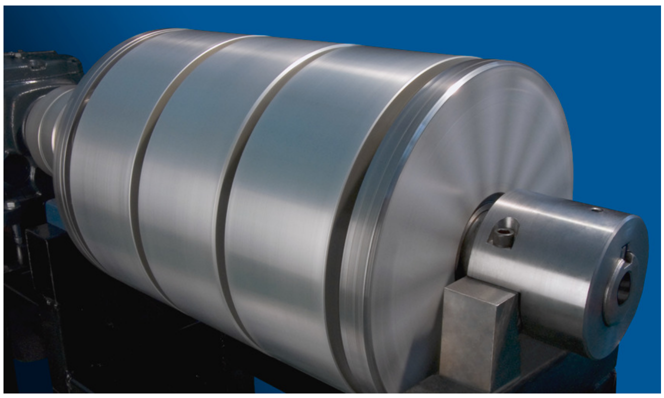

Fig. 16. Prototype of Clawpole TFM with Hybrid stator.

The machine was driven as a generator at a rotational speed of 240 rpm. Its output leads were connected to a resistor in series with a capacitor, to compensate for the large machine inductance. Since the RC load is linear, non-sinusoidal flux waveform as the one achieved with FEA could not be obtained. Therefore, a phase angle of ψ = -55 degrees was chosen. The mmf was set to 4400 A-turns, with an rms current I_{rms} = 13 A and a stator of 240 turns. The phasor diagram used in the experiment is shown in fig. 17. The length of the vector V_{pu} is much lower with ψ = -55 degrees, which prevents deep saturation and allows a more sinusoidal flux waveform. Higher power could be obtained with an active rectifier connected to the machine leads instead of the linear RC load. The active rectifier would allow creating a non-sinusoidal voltage waveform. However, such an active rectifier was not available for the experiment.

The torque was measured with a strain gauge. The value recorded was 134 Nm per phase At 240 rpm, the total losses (Cu Losses, Fe losses and mechanical losses) measured were 236 W per phase, for a total efficiency of 93%. The copper losses are estimated to 89 W/phase and the iron losses in the 15 C-cores are estimated to 28 W/phase. They are lower than the graph of fig. 14, due to the lower harmonic content in the experiment. The experimental results are shown in Table I.

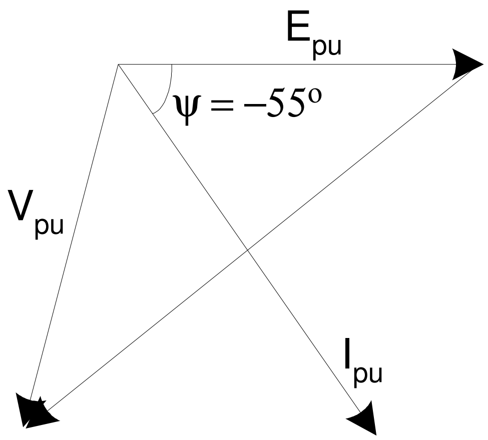

Fig. 17. Phasor diagram used in the experiment.

TABLE I EFFICIENCY OF CLAWPOLE TFM WITH HYBRID STATOR. (MACHINE USED AS GENERATOR, LINEAR RC LOAD)

(Rotational speed = 240 rpm f = 60 Hz, I = 13 A)	Prototype Hybrid (measured per phase)
Torque (Nm)	*134*
Mechanical power (W)	*3373*
Cu losses (W)	*87*
C-core losses (W)	*28*
Mechanical losses and other Magnetic losses (W)	*108*
Efficiency (%)	*93*

V. CONCLUSION

Despite the improvements of SMC made in the last years, their use in Clawpole TFM strongly limits the latter to low rotational speeds to avoid cooling difficulties. The solution of a hybrid stator provided in this paper enables the machine to reach higher rotational speeds by the important decrease of iron losses in the stator C-cores. Moreover, this new geometry further improves the ease of manufacturing of the machine thanks to the use of SMC material contiguous to the airgap both on the rotor and stator.

As predicted by a 3D FEA, the use of a combination of Fe-Si laminated steel M19 C-cores and SMC ATOMET EM-1 stator feet leads to a machine with a higher specific torque and much lower iron losses than one with full-SMC stator. Results have shown that for a Clawpole TFM with 30 poles (p = 15), SMC C-cores dissipate 560 W at 900 rpm, while laminated C-cores dissipate 249 W at the same speed. A prototype was built with the same dimensions, and an efficiency of 93% could be obtained at 240 rpm with an electrical frequency of 60 Hz.

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