Soft Magnetic Composite Core – A New Perspective For Small AC Motors Design

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Abstract. In the paper is presented a new design of a small permanent magnet AC motor, based on the application of the soft magnetic composite (SMC) material, patented under the trade name Somaloy^{TM}500 by Hoganas AB, Sweden. The new possibilities and perspectives of the SMC are analysed.

This experimental work is a step further of the previous authors' research, dealing with a detailed electromagnetic field analysis of a self-starting single-phase permanent magnet synchronous motor. The Finite Element Method (FEM) has been used for evaluation of proposed new designs and estimation of the performance behaviour of the developed models.

A detailed analysis of advantages of the stator core made of SMC, in comparison with laminated steel is presented; the particular emphasis is put on the losses and efficiency of the motor.

Key words

Single-phase Permanent Magnet Motor, Soft Magnetic Composite Materials (SMC), Finite Element Method (FEM), Losses, Efficiency.

1. Introduction

Small electric motors are widely used in many household appliances. Since the alternative voltage is commonly available, these motors are often AC, and in particular they are supplied by a single–phase source. Small electric motors have always been challenging for investigation and research work. Their massive application requests search for more economical production and for more effective performance behaviour.

Continuing advances in materials research has put in reality the ability to produce high quality material with soft magnetic properties, thus competing with steel laminations at a similar production cost, or even cheaper. Hence, since the middle of the 80's in the last century, when the soft magnetic composite (SMC) materials have appeared on the market, the new perspectives in the electric motor design have been opened. These materials are well suited for use in alternating magnetic fields as the eddy currents are significantly restricted. This fact allows one to use soft magnetic composite materials in building cores of AC electrical motors; the output is more compact design of electrical machines.

However, the experiences with soft magnetic powdered materials so far, are mostly limited to the calculation and construction of prototypes [1,2]. This work is also an attempt to exploit SMC benefits when the conventional laminated core is replaced by an equivalent one made of Somaloy^{TM}500.

Knowing the fact that SMCs are isotropic, the special machine topologies such as claw pole machines, transverse flux machines and the like, which have three dimensional flux density patterns have attracted the most attention. This paper proposes new options for design of a small AC non–conventional machine, in which it has been efficiently utilized the SMC material.

2. Benefits of Soft Magnetic Composites (SMC)

Since the SMC (soft magnetic composite) material is magnetically isotropic the majority of investigators, exploring the use of this new material to date, have focused on utilizing it in applications where the lines of magnetic flux have, or it is useful to add, a significant non-planar component [3].

The permeability of SMC is only 10–20% of the permeability of electrical sheets, used for construction of laminated magnetic cores. But their important advantages are isotropic magnetic characteristics, and the possibility to make shapes more complex than with laminated steel.

Another important advantage of SMC could be found in the lower price of small machines, due to the introduction of new more economical manufacturing methods.

The benefits of replacing the conventional laminated core in an electric machine with the powdered iron composites are considerable, and include:

- Essentially unity iron stacking factor, due to the fact that a SMC core is of compact structure.
- Potential for reduced air gap length as a result of the tight tolerances maintained in manufacturing SMC material.
- Increased copper fill factor (up to 66% vs. the typical value of 33%); reduced copper volume as a result of increased fill factor and reduced end winding length.
- Reduced copper loss as a result of the reduced copper volume;
- Reduced high frequency tooth ripple losses since the SMC has essentially no eddy current losses;
- The above two items suggest a potential increase in the overall efficiency;
- Modular construction allows the possibility of easy removal of an individual modular unit for quick repair or replacement;
- Possibility of producing three dimensional flux patterns in the SMC material and thus, to improve the electric machine performance.
- Reduced axial length–over–end–winding dimension as a result of the more compact end winding.
- Absence of the phase insulation as a result of using non–overlapping windings; also, there is an additional potential elimination of the ground wall insulation since the SMC core (stator) itself acts as an insulator.
- There is no need to stress relief, as in the case of the stator lamination after punching and assembling the stack; this is a relatively costly and time consuming task, (stress relief is, however, included in the process of manufacturing the SMC parts).
- Reduced bearing currents in the presence of PWM waveforms, because of the use of SMC which acts as insulation against this type of current flow.
- Stator is easily recyclable since the stator can again be compressed back into powered form with pressure and the copper windings readily removed.
- These advantages are, of course, accompanied by a number of drawbacks. The most significant of these is the relatively low relative permeability of roughly 500 for the most commonly used SOMALOY 500.
- Other concerns include relatively low rupture strength, as well as an important portion of iron losses at lower frequency, due to the increased hysteresis loss, although there is almost no eddy–current loss.

3. The Concept

The concept of development the new design of an electric motor starts with a detailed case study of the selected *reference* model. First the motor as is originally produced with magnetic core made of laminated steel is analyzed.

Afterwards, before the new design is developed, the targets to be reached are defined; they are:

- To keep equal or even to get smaller motor size.
- To redesign stator core for Somaloy® application.
- To maintain or improve the motor efficiency;
- To keep the original rotor design.

It has been shown that the direct replacement of electrical sheets with SMC is not reasonable. It has been proved that electrical machines have poorer performance because the SMC material has a lower permeability and a lower saturation flux density. But, the machine manufactured out of powdered iron could offer superior performance despite the inferior magnetic properties [3,5].

The further analysis is performed for the new developed motor model, by simple replacement of the material from which is made the magnetic core; in this case the core is produced from *Somaloy*™500. When using SMC it is important to exploit the advantages which this material offers. In the paper, only the technical advantages and design benefits are studied; the economical as well as manufacturing aspects, which are also very important, are another topic and challenge for further analysis.

Due to the capability of three–dimensional magnetic flux distribution, it is possible to maximize the torque–to–weight ratio and to minimize the total axial length of the motor. In order to achieve more benefits of the SMC, we improve the new proposed construction, and introduce an *optimized* model. These steps are depicted in Fig. 1.

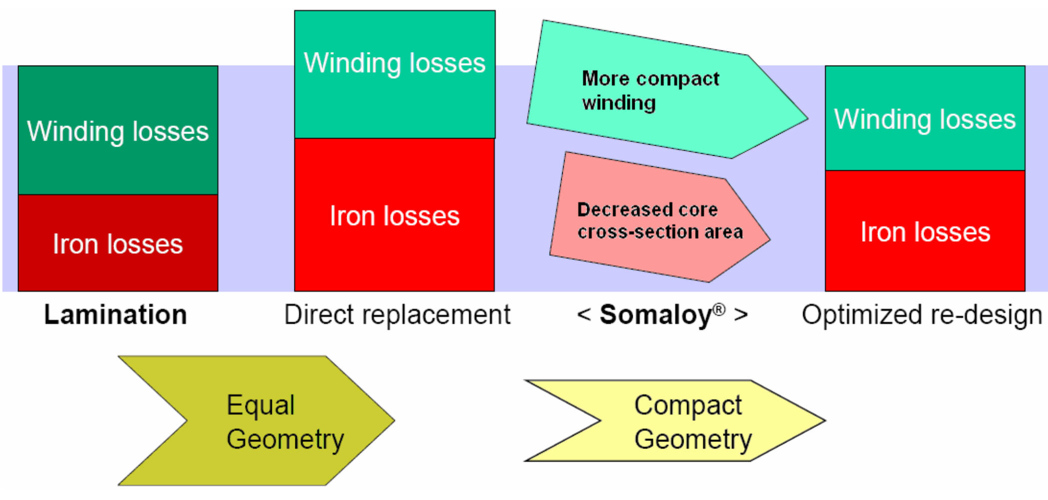


Fig. 1. The concept of a development the motor design

Due to the significant economical and environmental benefits, SMC materials possess great potential for application in electrical machines, particularly those with complex structures. However, because of the outstanding drawbacks of the SMC, as lower magnetic permeability and lower saturation flux density compared with laminated steels, particular efforts to overcome them should be done.

What is our concept? Simply replacing the laminated steel sheets by an SMC, i.e. keeping the *equal geometry*, will result in poorer machine performance. In this step, the motor will have the same copper loss and increased iron loss, resulting in a lower efficiency. Therefore, it is important to go further and to avoid the disadvantages of SMC, while exploiting the advantages in various stages, such as design, manufacturing, and application. In the next step, we optimise the design developing the *compact geometry* of the machine; now, the magnetic core is with the decreased cross–section area, which results in more compact stator winding. The copper and iron losses, compared to the design of the previous step are lower, and hence, the efficiency of the motor is improved.

In brief, first we employ the SMC opportunities, by using 3D properties and the design freedom; the complex, net shaped parts, with tight tolerances are manufactured. The challenge is how to overcome problems with higher iron loss at lower frequency, the lower permeability, as well as somewhat lower saturation induction than laminations. We propose matching performance by redesigning which philosophy is presented graphically in Fig. 1.

For example, SMC materials would be appropriate for construction of PM motors in which the magnetic circuit is dominated by the magnetic reluctance of the magnets, making such motors insensitive to the permeability of the core. This paper presents an overview of our study on a single–phase self–starting PM motor by using an SMC as the stator core material. The initial design and simulated performance were reported in our previous works [4–7], but this paper adds more updated details and, particularly, the results on the new developed prototype.

4. Practical Application

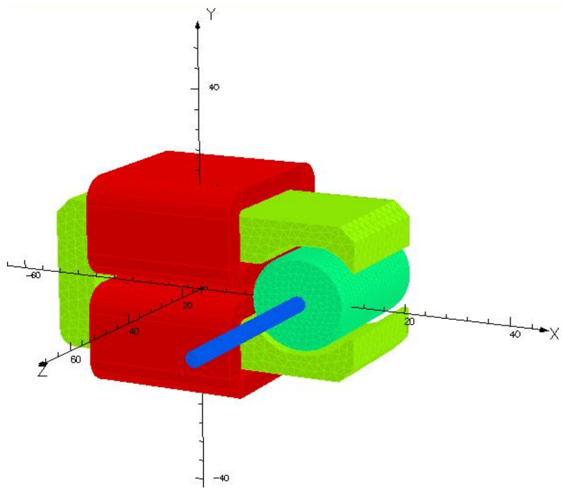
The most significant advantage of SMC materials are the cost effective and environmentally friendly manufacturing, with minimum material waste, by using well developed powder metallurgical techniques. Because the iron cores and electric machine parts can be compacted in a die into the desired net shape and dimensions, further machining is minimized and hence the production cost can be greatly reduced. Furthermore, SMC materials are easy to recycle and possibly reused.

It is clear that most machines constructed of SMC would be the permanent magnet machines. Permanent magnet machines have a relatively wide air gap so that the influence of the lower permeability of SMC in comparison to electrical sheets is not so decisive. The low permeability of this material is most readily overcome with design of permanent magnet machines since the magnetic flux produced by permanent magnets are relatively insensitive to air gap length. New concepts for such a machine will be introduced in this paper.

Single–phase permanent magnet synchronous motors have found growing applications. Their main advantages are the simple design, a low cost production, as well as the higher efficiency than rival motors.

The proposed concept is applied on a single-phase permanent magnet synchronous motor for drain pump with rated data: U_n = 230 V @ 50 Hz; I_n = 0.25 A; P_{1n} = 26 W; n_n = 3000 rpm. The 2 pole permanent magnet rotor is with parallel magnetization, being made as a ferrite cylinder, with characteristics: H_c=–240 kA/m (coercivity) and B_r=0.354 T (remanence). In Fig. 2 there is presented the side view (a) and the 3D motor topology (b). In our study, this motor is adopted to be *reference* model (RM).

(a) side view of the studied motor



(b) the 3D topology of the motor

Fig. 2. The reference PM synchronous motor

In our previous work, we have published detailed study of the steady–state and dynamic performance analysis [6]; also the reference (original) PM motor has been investigated in the laboratory, and relevant measured data are obtained. Some of these results are valid while carrying out the new design developments.

5. Methodology

In accordance with the proposed concept, presented with a flowchart in Fig. 1, the applied methodology comes out naturally; it is consisted of the following procedures:

- We start with the existing motor – the original model, which is used as *Reference – RM*. It has been analysed in details by using various methods; the results are proved by experimental measurements and published [4–7]. Thus, the methodology has been confirmed as reliable and accurate; hence, it is applicable in the further steps.

- Afterwards, we develop a new model *Somaloy – SM*; the model is obtained at a direct and simple replacement of the stator laminations with SMC material, while the rotor is kept the same. Thus, the original geometry of the motor is not changed. Applying the same methodology as in the previous step, the full and thorough analysis of the motor is carried out. Observing the results, we studied the weak points of this structure, although it should be pointed out that some gain was obtained, too.

- This is the crucial step in the concept. Keeping the equal rotor geometry, but optimising the structure of the stator and its winding, we develop the *Optimised – OM* model; in this motor the stator core is made of SMC too, but with a new design and optimization involved, making it more compact. The stator winding is improved too, and is changed in accordance with the new stator core design. The target is to increase, or at least to keep the same efficiency, at the same output torque on the motor shaft. The optimised motor model *OM* is analysed by the same methodology, and all results are presented comparatively, in figures, charts and tables.

From our experience, the Finite Element Method (FEM) is proved to be the powerful method for full magnetic field analyses, as well as for the numerical calculation of electrical machine characteristics. The FEM is applied in this study, too. Having in mind that the studied motor is of the synchronous type, it is possible to simplify the field computations, and to apply the magnetostatic FEM approach. However, in order to numerically calculate the iron loss in the stator core, and to compare efficiency in the three motor models, the time–harmonic FEM at a frequency of 50 Hz is employed [8–11]. From the bulk of calculation results, here are presented the most interesting characteristics. In a separate heading, the obtained results are compared and the full performance analysis is carried out. Finally, the conclusions are proposed.

A. FEM Calculations

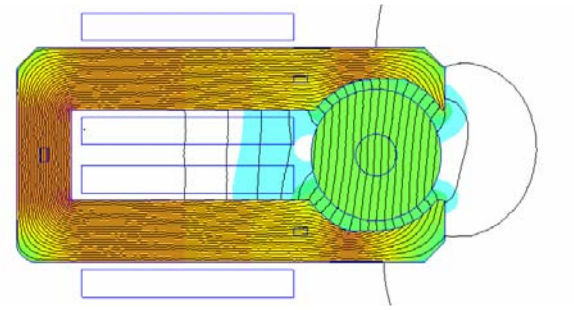
The FEM calculations are carried out at various loads of the motor, by changing the excitation current in the stator winding; the rotor is freely rotating and is continuously changing position θ along one revolution (360^o). For the starting rotor position and definition of the initial angle $\theta=0^o$, it is adopted the position when the stator and the rotor fields are aligned and in the same direction. Series of FEM simulations are carried out. For an assessment of the motor performance, the most important is operation at *rated load* with I_n,θ_n, and the *rest position* δ_o at $I=0$ [7,8].

In the FEM solver numerical nonlinear field calculations are performed. The stator winding current is varied, while the PM rotor is freely rotating in a *clock–wise* (CW) direction. The output is the magnetic field distribution in the cross-section of the motor.

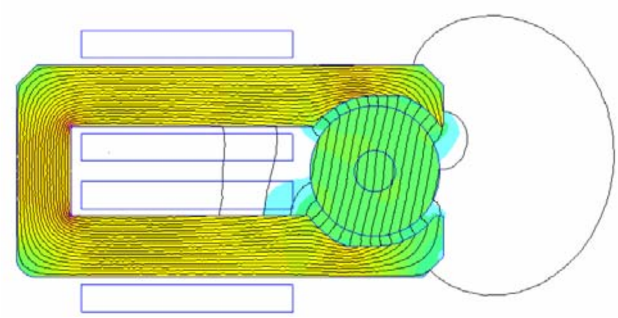
It is usually started with no–load operating regime, when the magnetic field is excited by permanent magnets only; in this state, the rotor is in its *rest position*. The angle δ_o, defining this position, is not the same in the three motor models; it is determined by using the particular procedure [7], and the values are presented in Table I. The next operating mode relevant for the analysis is the rated load (δ_n), and the peak–torque ($\delta_{max}=90^o$) regime.

B. Magnetic Field Distribution

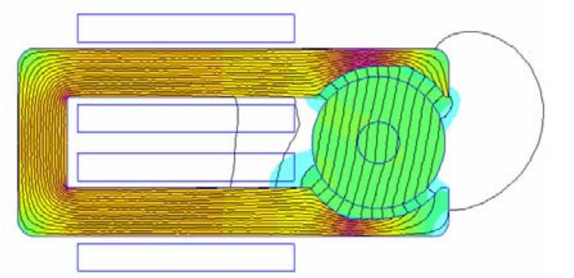
When the winding current is with the rated value, the output torque should be the same in the three analyzed models of the motor. This fact defines different rated load angles δ_n; their values are also presented in the Table I. The magnetic field distribution at a rated operating mode is shown in Fig. 3. (a), (b) and (c), for all three studied motor models *RM*, *SM* and *OM*, respectively. The regime at a peak–torque, is presented in Fig. 4, in the same way.



(a) *RM*: $\delta_n=10^o$

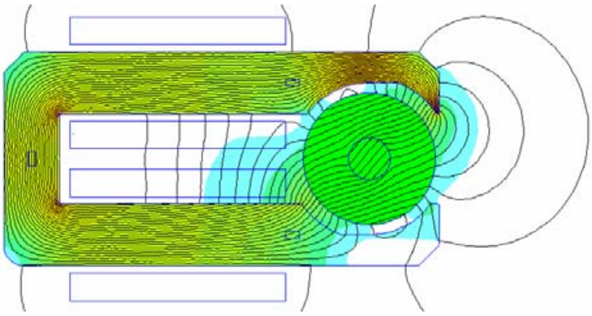


(b) *SM*: $\delta_n=18^o$

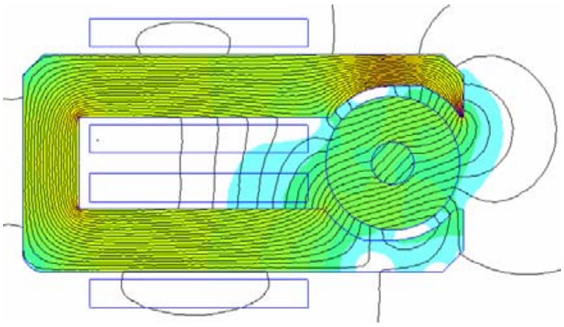


(c) *OM*: $\delta_n=17.5^o$

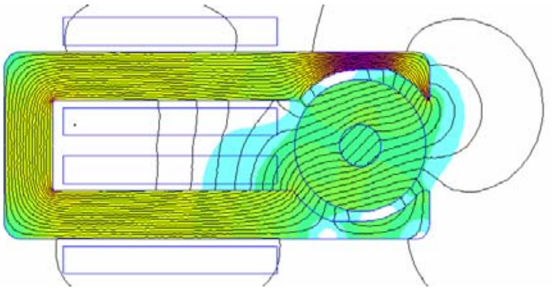
Fig. 3. Magnetic flux distribution at rated current $I_n=0.25$A



(a) Reference model – *RM*



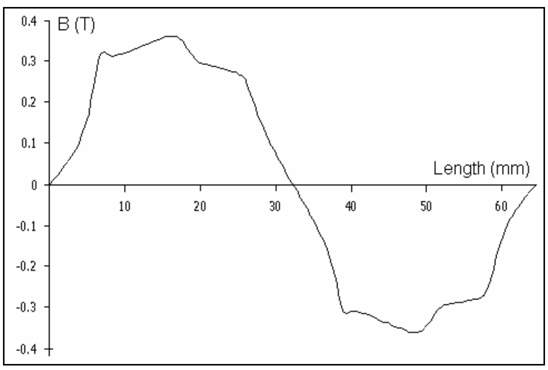
(b) Somaloy model – *SM*



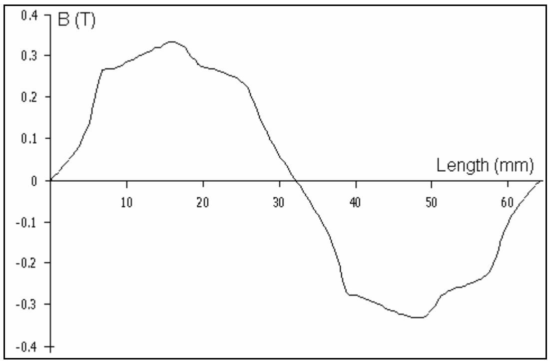
(c) Optimized model – *OM*

Fig. 4. Magnetic flux plot at peak–torque regime δ_{max}=90°

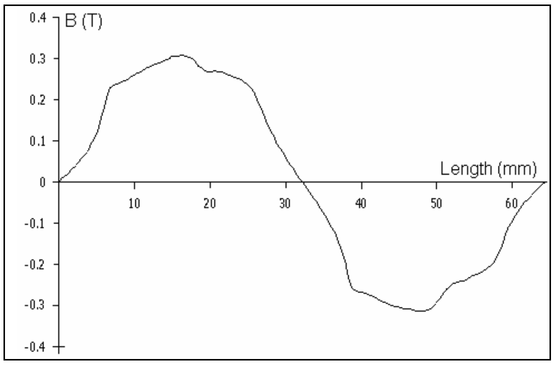
In order to compare the magnetic field properties of the original reference motor *RM* (iron stator core), the first derived design of the motor *SM* (SOMALOY®500 same stator core), and the proposed solution *OM* (optimised stator SOMALOY®500 core), it is analysed the state at the maxim air–gap flux. In fact it is not working regime; in this case winding current is set to the rated value I_n=0.25A, while the rotor position is adopted to be θ=0°. The spatial distribution of magnetic flux density along the air-gap mid-line is presented in Fig. 5 (a), (b) and (c).



(a) Reference model – *RM*



(b) Somaloy model – *SM*



(c) Optimized model – *OM*

Fig. 5. Spatial distribution of the magnetic flux density along the mid-gap line

C. *Characteristics*

In our previous works, the methods and the results of the numerical calculations of electromagnetic and electromechanical characteristics of the reference motor model are intensively studied and published. [4, 6-7]. Here, we are going to present directly the characteristics of the most interest, i.e. the air–gap flux and the electromagnetic torque for the three studied motor models, obtained by the same methodology. Thus, in Fig. 6, the characteristics of the air-gap flux are presented comparatively; in Fig. 7, are shown the torque characteristics. The numerical calculations are done in the FEM postprocessor; the stator winding current is with rated value, while the rotor displacement starts from the defined initial position and is spanned along one full revolution, i.e. a pair of poles.

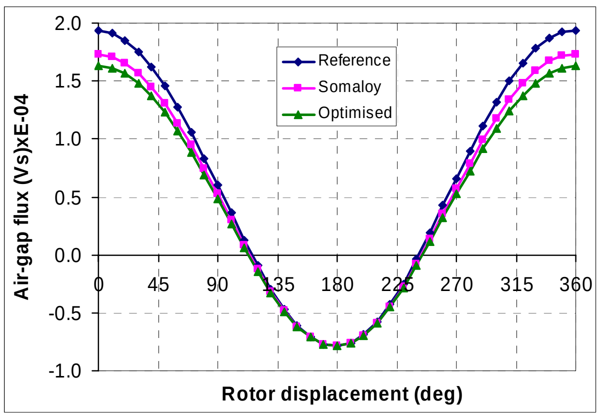


Fig. 6. Air–gap flux characteristics

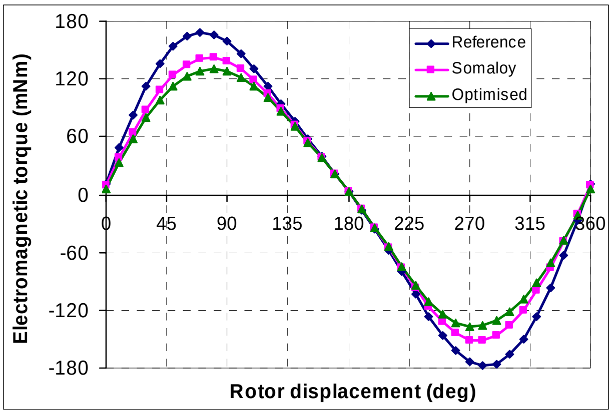


Fig. 7. Electromagnetic torque characteristics

From the first glance at the previously given Fig. 6 as well as Fig. 7, one can notice that the differences in the presented characteristics are of 15–20 % maximum. However, it is worth to emphasize that "behind" these simple figures are hidden more complex phenomena and more interesting results; they are the object of our investigations and analyses in the following heading.

6. Analysis of Results

The analysis of the results is carried out at the specified operating conditions, described as follows: • the winding current is kept at the rated value I_n; • the output (shaft) torque is kept the same as in the reference motor T_n. The calculated quantities by FEM, under these circumstances, are given comparatively in Table I.

First, the observations are focussed on the values of: • the angle of rest position δ_o; • the rated load angle δ_n; • the rated electromagnetic torque T_{em}; • the pull–out (peak) torque T_{max}; • the flux per pole Φ.

TABLE I. – Comparison of FEM results

	RM	SM	OM
Rest position δ_o	7.1°	8.5°	8.0°
PM flux Φ_{PM}	1.35×10^{-04} Vs	1.28×10^{-04} Vs	1.25×10^{-04} Vs
Rated load δ_n	10°	18°	17.5°
Rated torque T_{em}	48.23 mNm	59.35 mNm	52.07 mNm
Rated flux Φ_n	1.91×10^{-04} Vs	1.67×10^{-04} Vs	1.58×10^{-04} Vs
Pull–out δ_{max}	90°	90°	90°
Peak torque T_{max}	158.63 mNm	138.35 mNm	127.79 mNm
Flux per pole Φ	6.01×10^{-05} Vs	5.23×10^{-05} Vs	4.83×10^{-05} Vs

The rest position in the new developed models is slightly changed due to the involvement of a new material (SMC) in the motor structure. From an aspect of the shaft torque, as the studied motor is of synchronous type, when it is driving a load the lesser developed torque will be compensated with increased load angle. More precisely, if the prescribed constraint is to keep the rated torque T_n the same, the statement would be that the rated load angle δ_n, is increased in the new *SM* and *OM* motor models. Consequently, the peak–torque is changed accordingly. The Fig. 7 is apparently showing these conclusions.

In order to analyze the efficiency, particular procedures for calculating the losses have been carried out. Results are recorded in Table II. Regarding the iron loss, the SMC are definitely loosing the competition. However, one could easy realize that due to the lesser copper loss the total losses in the optimised model are improved; this is grace to the more compact design of *OM*. The input power of the motor is changed respective to the change of losses, thus determining the value of motor efficiency.

TABLE II. – Comparison of losses and power

	RM	SM	OM
Iron loss P_{Fe}	3.72 W	6.78 W	4.57 W
Copper loss P_{Cu}	10.62 W	10.62 W	10.09 W
Friction loss P_{fr}	1 W	1 W	1 W
Total loss ΣP_{loss}	15.34 W	18.4 W	15.66 W
Rated power P_n	10.66 W	10.66 W	10.66 W
Shaft torque T_n	34 mNm	34 mNm	34 mNm
Input power	26 W	29.06 W	26.32 W
Efficiency η	41 %	37%	40.5 %

Here below, in the Fig. 8, the results of loss calculations are presented; the figure itself is enough illustrating the features of the three analyzed motor models.

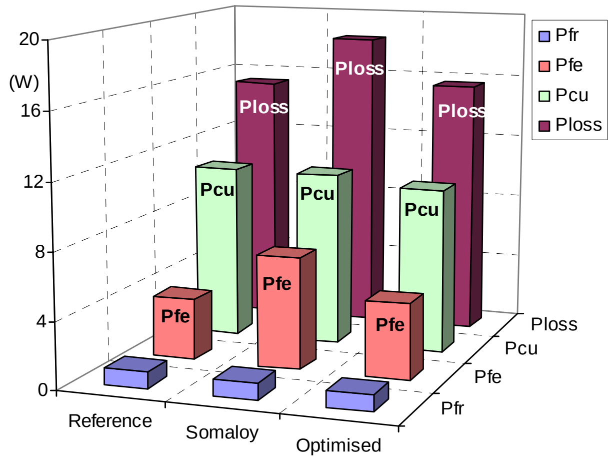


Fig. 8. Comparison of the losses

Finally, what is the gain? Obviously, the second model is the least applicable, and consequently is not a subject of our conclusions. If the emphasis is put on the efficiency, then there exists small discrepancy between the reference and optimal model, in favour of the initial motor *RM*; but, the more compact design of the optimized model, as well as the simpler manufacturing of the motor, are in favour of the *OM*. As the performance characteristics are kept very close to the initial values, the obtained result could be qualified as a new motor, with an improved and more compact design, while its performance is still good.

7. Conclusions

This paper has presented an overview of attractive research directions for the application of soft magnetic composites in the design of AC machines, applied on the conventional small AC motor of a synchronous type.

The benefits of replacing the conventional laminated cores in the electrical motors with the powdered iron composites are considerable, resulting in a compact design. In brief they include: • greatly reduced production costs, due to the simplified design; • essentially unity iron stacking factor; • simple production of the stator core and windings; • a reduced axial length–over–end–winding dimension; • the reduced both copper volume and end winding length, i.e. reduced copper loss; • lower eddy current loss; • lower hysteresis loss at medium and high frequencies; • a suggested potential increase in overall efficiency; • finally, due to the decreased volume, an increased torque–to–weight ratio.

These advantages are, of course, accompanied by a number of drawbacks: The most significant of these is the relatively low relative permeability for the most commonly used SMC materials; in Somaloy^{TM}500 it is roughly 500. The low permeability of this material is most readily overcome with design of permanent magnet machines since the magnetic flux produced by permanent magnets are relatively insensitive to the air–gap length. The total iron losses are higher at lower frequency, due to the greater increase of hysteresis loss, compared to the lower eddy-current loss. The other manufacturing and design concerns include relatively low rupture strength.

In summary of our work, it appears that the use of SMC materials in machine design will remain an interesting and challenging research area for the foreseeable future. In order to investigate completely the potential of SMC materials and the perspectives of their application in the design of electrical machines, a lot of research works have to be conducted; it is expected the improvements both in materials and their applications to be achieved.

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