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Improving the Performance of a Synchronous Reluctance Machine through the use of Composite Magnetic Materials

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Abstract

In the present paper, we investigate the improvement of the synchronous reluctance machine performance using a new soft magnetic composite material. This work highlights potential technology applications of the new soft composite magnetic materials in the design of electrical machines. A numerical simulation carried out on the SynRM has shown that the electromagnetic performances such as torque and magnetic losses are better for SMC materials than for laminate materials for a supply frequency beyond f=500 Hz. Subsequently, an optimization of the machine has been performed using the so-called response surface method (SRM) by acting on the most influential geometric parameters of the machine. As a last step, an experimental study is carried out on SynRM in order to validate the finite element results.

Keywords: Synchronous reluctance machine; Soft magnetic composite material; Response surface method; Electromagnetic performances

Introduction

Most of the electromagnetic devices such as transformers, electromagnets, alternators and electrical motors use a magnetic circuit which pipes the flux in order to maximize induction.

The efficiency of electromagnetic devices is strongly affected by losses due to the soft-magnetic material being used. Different structured materials are available. Choosing the most appropriate material for a medium frequency application is not intuitive. Electromagnetic circuits of power transformers or electric motors are usually made of conventional silicon-iron sheets. Higher power densities can be achieved by an increased operational frequency, but the loss density increases with higher frequency as well [1].

At constant magnetic field, losses are low or non-existent. However at variable magnetic field, an induced current appears which causes the heating of the material. As a result, important losses appear, degrading the efficiency of the device and decreasing his performances. One can ask the question "how can we reduce magnetic losses and improve the performance of the electromagnetic devices when working with a variable magnetic field?"

Soft magnetic composite material, frequently designed with their acronym SMC, appear as a promising alternative to the lamination solution. The possibility offered by using moulding by compression and direct tooling on the compressed blocs opens a very wide field for the design of electrical machines with optimization of the used magnetic circuit shape.

In present paper, we highlight the potential offered by this new material in the design of electrical machines. We focus on machines that are used in high-speed applications such as the synchronous reluctance machine (*SynRM*). The paper is subdivided into three parts.

- Soft magnetic composite material
- Synchronous reluctance machine
- Application and validation

Soft Magnetic Composite Materials (SMC)

Soft magnetic composite materials are relatively new. They arise from the latest developments in powder metallurgy. These materials are obtained by mixing particles of iron powder «20 µm to 200 µm» with high purity and coated with a fine electrical insulator as shown in Figure 1 [2]. This choice results in the very good magnetic features.

Soft magnetic composites (SMCs) have been widely used in electromagnetic devices with alternating magnetic fields such as transformers, electric motors, electromagnets, and alternators. This is due to the fact that ferromagnetic metal powders exhibit excellent mechanical ductility, magnetic isotropy, high magnetic saturation, and low hysteresis loss [3].

After the elaboration of the iron powder, the manufacturing of the SMC goes through three phases, which are the mixing phase,

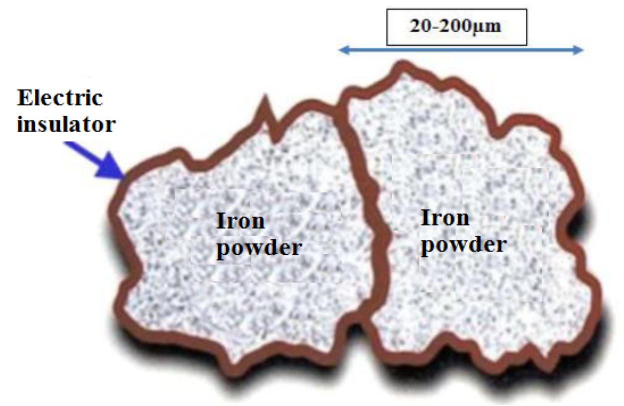

Figure 1: Iron particles coated with a fine electrical insulator.

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the compacting phase, and the thermal treatment phase. In the first phase, the micrometric granules are coated with either an organic or an inorganic insulator film. In the compacting phase the iron powder is put in a matrix which has the desired piece shape and is compressed with a lubricant at pressure of 800 MPA. The last step of the manufacturing process is the phase of the thermal treatment at a temperature near 500°C.

Some properties of SMCs

Induction: Due to the presence of the composite in the SMC, the induction at saturation is lower for SMC than for laminated sheet steel materials. The induction for the materials with organic coating is much lower than for non-organic coated materials. An increase of both the compacting pressure and the SMC material density raises the magnetic induction of the SMC.

Permeability: While the permeability of SMC's is not very sensitive to the frequency the permeability of laminated steel sheets is very sensitive to frequency variations (changes). Indeed when the frequency increases, the permeability of laminated steel sheets and approaches the SMC permeability. Due to the presence of the air gap, laminated steel sheets, behave as SMC's especially for the high field.

Magnetic losses: In a SMC, eddy current losses increase according to the square of the powder diameter while the hysteresis losses decrease. However the total loss tends to increase with powder diameter. On the other hand the denser the material, the smaller the magnetic losses.

Manufacturing process: The manufacturing process strongly affects the magnetic properties of materials. Cutting welding assembling and lining degrade the magnetic properties of classical materials, while the SMC materials holds the same properties issue from the manufacturing, so a best estimation of the magnetic properties of electromagnetic devices.

Isotropy: Isotropy is the main advantage of soft magnetic composite materials. Indeed, the circulation of the flux in classical materials is limited to the plan of the steel sheet, while in the SMC's, it occur in both the axial and radial directions [4].

Thermal and mechanic properties: The mechanical resistance of classical materials is close to 350MPA, while for SMCs it is from 30 to 60MPa smaller. However, this is acceptable for the design of the electrical machines. The thermal conductivity of pure iron is larger than for SMCs, but the thermal conductivity for SMCs is larger than for a steel sheet at 2.4% of silicon. The isotropy of the SMCs increases the dissipation area of the heating, and so results in better cooling.

Environmental recycling cost: After a crash, the separation of copper and iron is easy in SMCs machines. This allows for easy recycling which is not the case for classical machines. Also, the manufacturing of SMCs devices uses exactly required quantity of the material without any wastes.

Synchronous Reluctance Machine (*SynRM*)

The variable reluctance machine is one of the first machines built by man. We can distinguish two types of machines according to the positioning of the salience:

- A double salience machine *DSM* with salience in both the stator and the rotor (Figure 2a).
- A rotor salience machine known as a synchronous reluctance machine (*SynRM*) (Figure 2b).

Compared to the induction motor (IM), the *SynRM* has a larger torque per ampere, smaller rotor loss, easier control, better price and excellent performances. It also exhibits lower price and lower available field weakening control than the permanent magnet synchronous motor (PMSM). In addition, it exhibits easier vector control and topology configuration of inverter as compared to the switched reluctance motor (SRM) [5].

The *SynRM* is a singly excited salient machine in which the rotor employs the principle of reluctance torque to perform electromechanical energy conversion. It represents a possible alternative AC drive to permanent magnet (PM) machines and induction machines. The rotor structure is simple and only made of electrical steel laminations. Therefore, the manufacturing procedure is less expensive as compared to PM machines and induction machines. Moreover, the absence of winding rotor and cage rotor eliminates the rotor copper loss, thus enhancing the efficiency compared to induction machines [6]. Other advantages of the *SynRM* are fast dynamic response, fault tolerance, the capability to operate at higher speed compared to PM machines (making it a suitable choice for many applications like traction and electric vehicles (EVs)), low joules losses (used for high-speed application which corresponds to high frequency), robustness and high rotor temperature acceptance.

Independently of the type of switched reluctance machine to study,

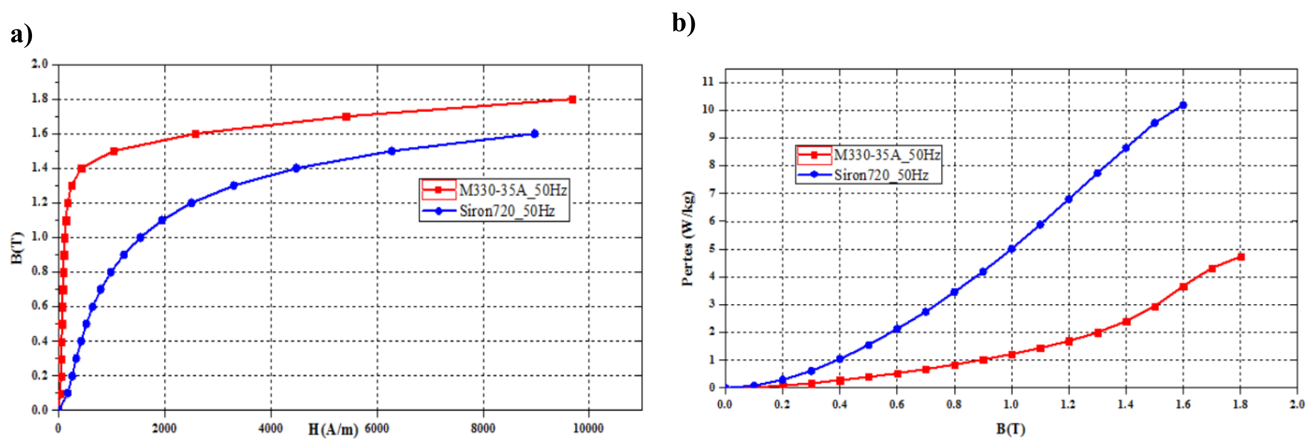

Figure 2: B(H) and P(B) Characteristic of the used materials; **a**) Magnetization curve of M330.35A and Siron720; **b**) Magnetic losses curve of M330.35A and Siron720.

the operating principle is always identical, which can be described by a simple magnetic circuit consisting of a pair of ferromagnetic pieces, one fixed and the other moving around a fixed axis. The torque applied on the moving piece is caused by a variation of the reluctance of the magnetic circuit.

Structurally, the *SynRM* is a synchronous machine with salient pole without excitation. It presents an identical stator as the alternative current machine, and a rotor consisting of a magnetic circuit without any excitation winding. Several structures of rotor had been developed. We can distinguish five mains structures namely massive structure, flux wall structure, laminated axial structure, structure assisted with magnet, structure assisted with supra-conductor.

In references [7-9] we can find the classical electromagnetic equation of the *SynRM* torque, which is given by:

$$C_{em} = \frac{3}{2} p \left(L_d - L_q \right) i_d \, i_q \quad (1)$$

Application and Validation Results

In our study we have chosen four possible configurations for the machine which are shown in Figure 3. The first configuration is all laminated steel sheet *(M330.35A)*. The second and the third configurations are hybrid while the last configuration is all with the SMC material *(Siron720)*. The finite element analysis is performed in nonlinear mode with Ansoft Maxwell by introducing the characteristic induction *B(H)* and losses *P(B)* of the used materials as shown in Figure 4. We use an unstructured triangular grid, which refined the area of interest. The boundary conditions at the external boundary are of the *Dirichlet* type. The coupling of the finite element model with an electrical circuit is carried out with the simulator of the electrical circuit *Ansoft Simplorer*.

As a first step, we investigate both torque and iron losses (magnetic losses) of the machine for a supply current $I_{eff}=8.1A$ at frequency values *f=50, f=500,* and 1000Hz.

Magnetic states of the machine

The analysis of field cards is a good way to check the results. The magnetic states for the various configurations are illustrated in Figure 5. We may notice that:

- Two magnetic poles are present.
- The distribution of the field lines is symmetrical with respect to the direct axis of the machine.
- The induction is maximal in the teeth facing the rotor.

Electromagnetic torque

The torque of the four configurations is shown in Figure 6. At a frequency f=50 Hz, the first configuration exhibits the smallest magnetic losses, while the fourth configuration exhibits the highest of the losses with a difference of 112.43%. However, the magnetic losses for the laminated steel sheet material configuration are larger than for the SMC by 11.96% at f=500Hz and 37.67% at f=1 kHz. This highlights the potential offered by the SMC at medium frequency.

Influence of the machine geometric variables on the torque and magnetic losses

In a second step we study the effect of the machine geometry variables on the electromagnetic torque and the magnetic losses for both the first *(Config1)* and the fourth *(Config4)* configurations. The parameters selected include the air-gap *e* of the machine, the opening angle βr of the rotor and the width and the height of the stator teeth. Two current supply values $I_{eff}=8.1A$ and $I_{eff}=32.4A$ are considered.

The following summarises our findings:

- The torque is inversely proportional to the thickness of the machine air-gap.
- Increasing the machine air-gap results in similar torque values for the two configurations *(all SMC, all laminated steel sheet)*.
- Increasing the current excitation results in a higher torque for the SMC configuration.
- Magnetic losses decrease with an increase of the machine air-gap.
- The maximum torque corresponds to an opening angle value of the rotor βr=66˚. Some authors have obtained a maximum torque for an angle βr near 70˚ [10] and 60˚ [11,12].
- Near an angle βr=66˚, which corresponds to the maximum torque, the magnetic losses remains approximately constant.
- The width of the stator teeth does not affect the torque and the magnetic losses of the machine.
- The torque decreases when increasing the height of the stator teeth.
- The torque is inversely proportional to the thickness of the air-gap.

a) **b)**

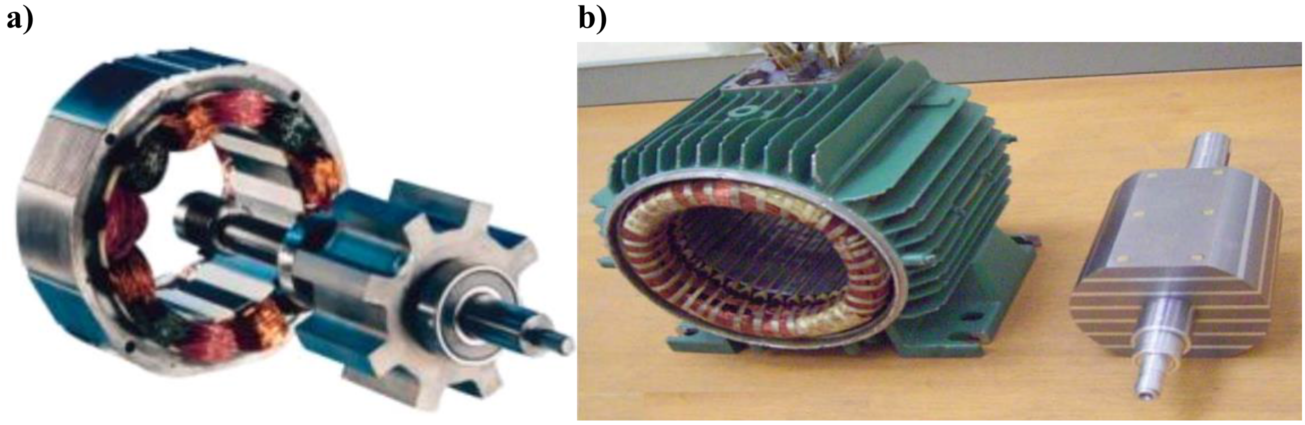

Figure 3: Types of variable reluctance machines; **a):** Switched Reluctance Machine (SRM); **b):** Synchronous Reluctance Machine (SynRM).

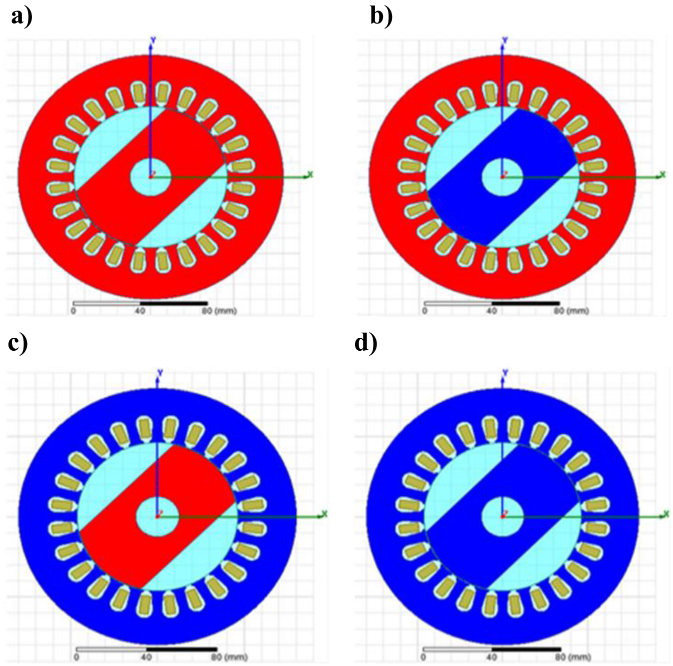

Figure 4: The four possible Machine configurations; **a)** Config1 all laminated steel sheet; **b)** Config2 (Stator/laminated sheet) (Rotor/SMC); **c)** Config3 (Stator/SMC) (Rotor/laminated sheet); **d)** Config4 all SMC.

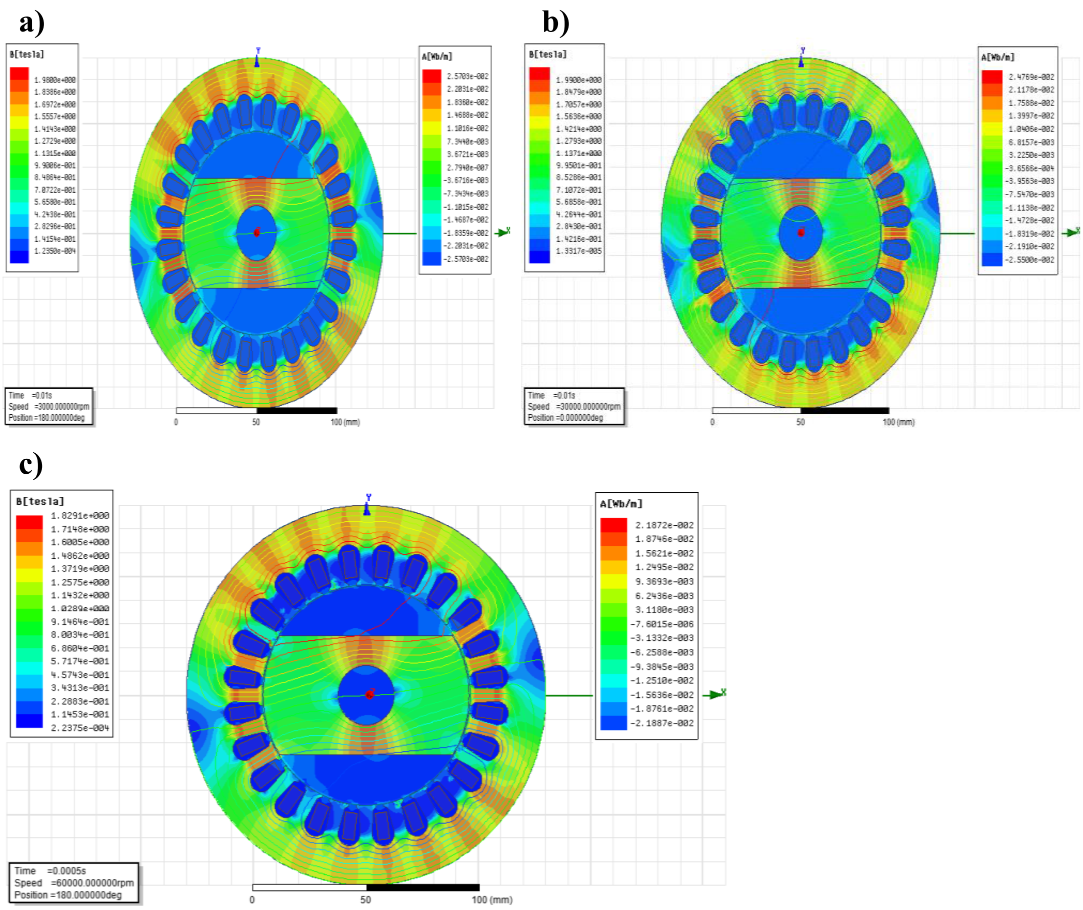

Figure 5: The Induction and the field lines (I=8.1A); **a)** f=50 Hz; **b)** f=500Hz; **c)** f=1 kHz.

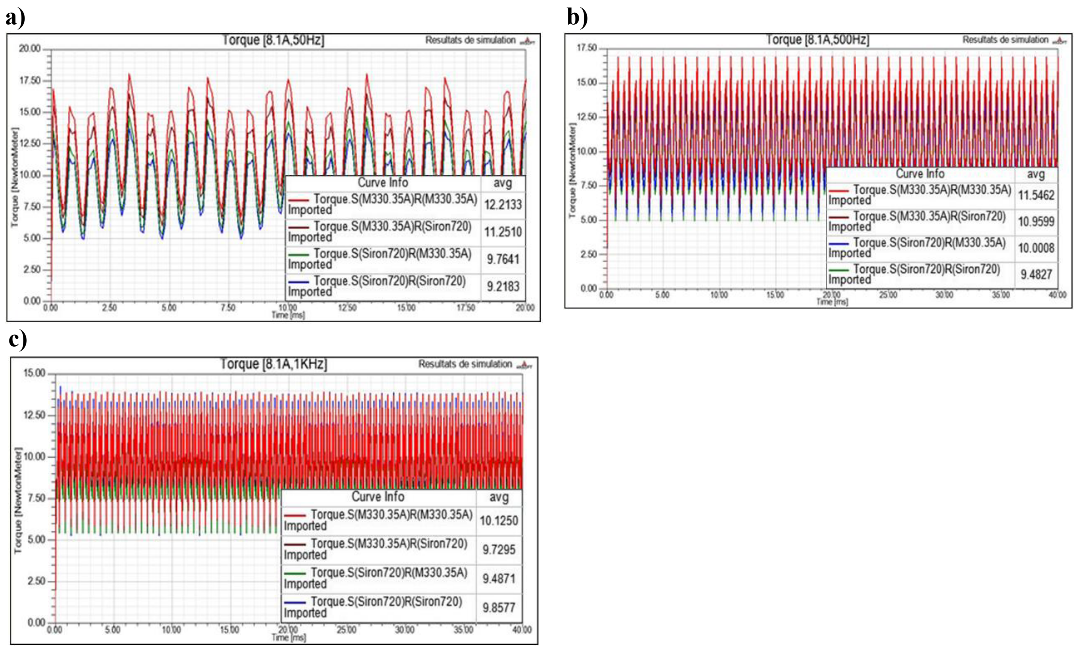

Figure 6: The torque wave form (I=8.1A); **a)** f=50 Hz; **b**) f=500 Hz; **c)** f=1 kHz.

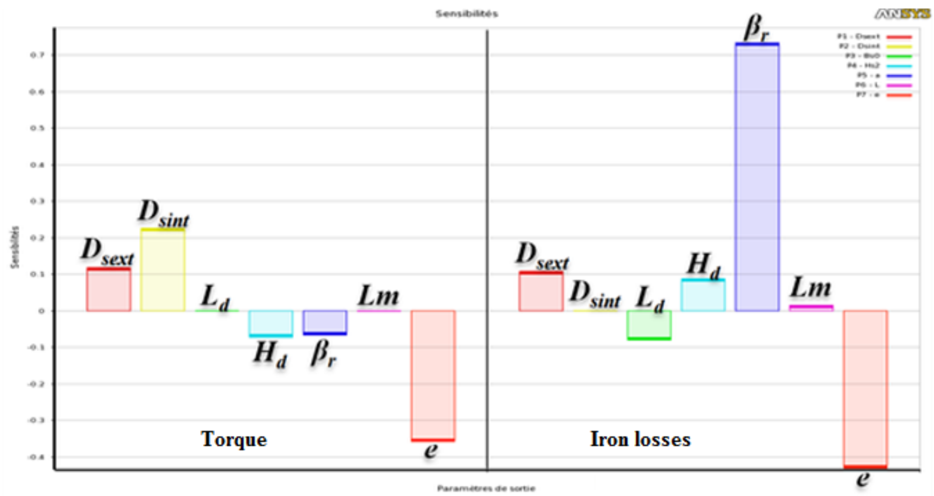

Figure 7: Sensitivity of the electromagnetic torque and the iron losses (config4, f=50 Hz)

- Increasing the current excitation to f=1 kHz, results in the torque of all SMC configuration being larger for the case of lamination steel sheet configuration.

Machine optimization by using the response surfaces method (RSM)

In our optimization we apply the technique of the response surface implemented under the environment of ANSYS workbench. Seven parameters are selected for the optimization (the air gap of the machine, the width and the height of the stator teeth, the inner and outer diameters of the stator and the length of the machine) for the configuration4, at frequency values f=50 Hz and f=500 Hz.

Optimization results (*config*4, *f*=50 *Hz*): The sensitivity of the torque and the magnetic losses on each optimization parameter is shown in Figure 7. We note that the parameters which strongly affect the torque and the magnetic losses are D_{sint}, D_{sext}, the opening angular βr of the rotor, and the air-gap e of the machine. On the other hand, the width L_d of the stator teeth and the length L_m of the machine seem to have no influence on torque and the magnetic losses.

Let us note that, within the bounds of this optimization we have decreased the losses by 23.63% and improved the electromagnetic torque by 1.29% (Tables 1-3).

Optimization results (*config*4, *f*=500 *Hz*): Figure 8 shows both torque and magnetic losses in 3D.

The present optimization, results in a torque value equal to the torque of the all laminated steel sheet configuration (11.54 Nm) with an improvement of 21.72% while reducing the losses by 15.83%.

Experimental study

The experimental study is performed to validate the simulation results. Two test benches have been built at the Electromagnetic Laboratory of the Research and Teaching Unit of the Electrical engineering Department.

Parameters	Value
Number of stator slots	24
Number of poles	2
Length of machine	100 mm
Stator Outer diameter	160 mm
Stator inner diameter	92.7 mm
Height of stator pole	16.85 mm
Rotor diameter	91.7 mm
Shaft diameter	25 mm
Air-gap length	0.5 mm
Opening angle of the rotor	66°
Number of turns per phase	120

Table 1: Parameters of the studied SynRM.

Parameters	Before Optimization	After Optimization
βr	66°	60.34°
e	0.5 mm	0.792 mm
Hd	16.85 mm	15.99 mm
Ld	8.62 mm	8.65 mm
Dsext	160 mm	163.22 mm
Dsint	92.7 mm	96.10 mm
Lm	100 mm	102.07 mm
Torque	9.21 Nm	9.32Nm (+1.29%)
Losses	103.50 W	79.03W (-23.63%)

Table 2: Optimization Results (config 4, f=50 Hz).

Parameters	Before Optimization	After Optimization
βr	66°	67.46°
e	0.5 mm	0.546 mm
Hd	16.85 mm	16.58 mm
Ld	8.62mm	8.32 mm
Dsext	160 mm	173.94 mm
Dsint	92.7 mm	101.08 mm
Lm	100 mm	91.43 mm
Torque	9.48 Nm	11.54 Nm (+21.72%)
Magnetic losses	1309.02 W	1251.1 W (-4.42/*Conf4*) (-15.83%/*Conf1*)

Table 3: Optimization Results (config4, f=500 Hz).

As shown in Figure 9 the benches contains mainly:

- A continuous power supply
- An oscilloscope
- A measure unit
- An ammeter
- A tachometer
- A synchronous reluctance machine (*SynRM*)
- A continuous current machine (CCM)
- A control unit
- An alternative power supply
- An electromagnetic brake

Inductance measurements: The inductance can be defined as flux-linkage per ampere. Applying that definition to an electrical motor, the inductance is calculated by dividing the magnetic flux through a coil by the excitation intensity [13].

We use the voltage echelon method which consists of applying an echelon of the constant voltage at the stator winding terminal, and turn the rotor at low speed, then save the values for current and voltage of the corresponding phase.

The inductance can be calculated by using the following expression [14]:

$$L_1 = \frac{\int_0^\infty V_1 dt - R_s \int_0^\infty I_1 dt}{I_{1\infty}} \tag{2}$$

The synchronous inductance of the machine, which is obtained by simulation and measurements, is shown in Figure 10. Clearly the two curves coincide and we can measure the inductance values L_d and L_q.

Magnetic losses measurements: We have built the test bench as shown in Figure 9b. The magnetic losses of the machine can be determined using Expression (3).

$$P_{mag(SynRM)} = P_{abs(SynRM)} - \left(P_{u(SynRM)} + P_{joul(SynRM)} + P_{mec(SynRM)}\right) \tag{3}$$

The mechanical losses are obtained through two tests. In the first test, the *CCM* and the *SynRM* are coupled, whereas they are decoupled in the second test. The mechanical losses of the *SynRM* are deduced from Expression (4):

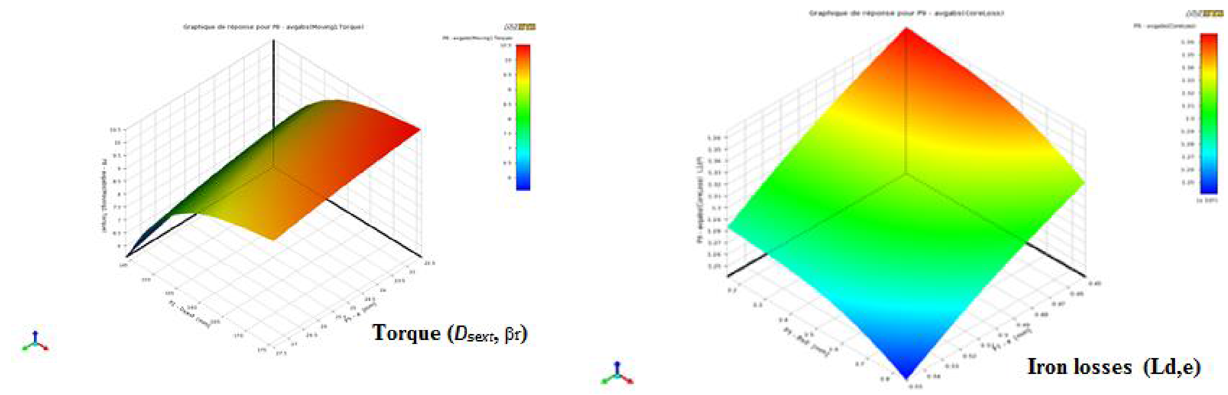

Figure 8: The electromagnetic torque and the magnetic losses in 3D (config4, f=500 Hz)

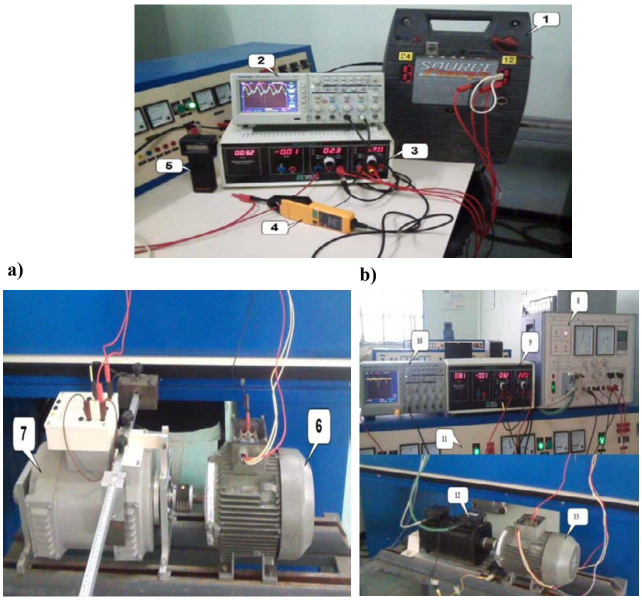

Figure 9: Tests benches; **a)** Inductance measurement; **b)** Magnetic losses measurement.

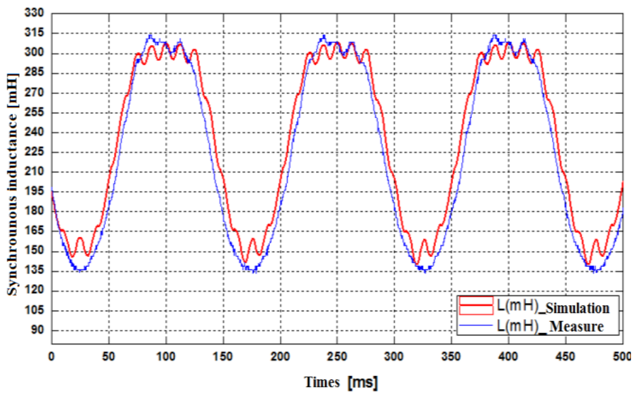

Figure 10: The Synchronous inductance of the machine.

$$P_{mec(SynRM)} = P_{abs(CCM)} - P_{abs2(CCM)} \quad (4)$$

For the other power values, we use the control unit and the electromagnetic brake to apply a resistant torque (3.2Nm) to the *SynRM* and we record the current and the total power absorbed. The obtained results, for several tests and simulations, are shown in Table 4.

In the table, R_s is the stator resistance, L_q the direct axis inductance, L_q the quadrature axis inductance, I_{eff} the effective current supply, $P_{mag(SynRM)}$ the magnetic losses, $P_{abs(SynRM)}$ the absorbed power, $P_{u(SynRM)}$ the useful power, $P_{joul(SynRM)}$ the Joule losses and $P_{mec(SynRM)}$ the mechanic losses of the *SynRM*.

An analysing of the obtained results shows the agreement between the values obtained from both the simulation and the experimental measurements. Hence, one can conclude that the FEM results are validated.

Conclusion

From the study carried out in the present work, we conclude that:

Parameters	Numeric values	Unit
R_s	3.2	Ω
L_d (Experience)	472.5	mH
L_d (Simulation)	462.33 (-2.15%)	mH
L_q (Experience)	210.22	mH
L_q (Simulation)	202.5 (-3.67%)	mH
$P_{abs(SynRM)}$	1143	W
$P_{abs1(CCM)}$	205	W
$P_{abs2(CCM)}$	192	W
$P_{mec(SynRM)}$	13	W
I_{eff}	3.2	A
$P_{joul(SynRM)}$	98.30	W
$C_{u(SynRM)}$ (Experience)	3.20	Nm
$C_{u(SynRM)}$ (Simulation)	3.31 (+3.43%)	Nm
$P_{u(SynRM)}$	1005.3	W
$P_{mag(SynRM)}$ (Experience)	26.39	W
$P_{mag(SynRM)}$ (Simulation)	28.70 (+8.75%)	W

Table 4: The obtained results (tests and simulations).

The performance of the *SynRM* using SMC materials is best over f=500 Hz. This clearly demonstrates the advantages offered by SMC materials in medium frequencies.

The use of SMC materials has allowed us to reduce the magnetic losses of the machine from 11.96% at f=500 Hz and 37.67% at f=1 kHz.

The use of the response surface technique allowed us to contribute to the optimization of the machine operating at f=50Hz and f=500 Hz.

The Optimization of the entire SMC configuration allowed us to reduce the magnetic losses by 23.63% and increase the electromagnetic torque by 1.29%.

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