Experience with ATOMET Soft Magnetic Composites Properties, Pressing Conditions and Applications

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INTRODUCTION

Insulated iron powders are alternative materials to conventional laminated soft magnetic materials used in electrical machines. Most of the magnetic structures of existing electrical machines with AC excitation were optimized during the 20th century for 2D flux circulation in laminated yokes. Now with the isotropic composite materials, new designs can be used to optimize the materials in terms of technical and economical performances. The design optimization permits to meet the application specifications taking into account the magnetic, thermal and mechanical properties of the materials as well as the cost of the production and assembly process. A design optimization methodology and different SMC applications are presented and illustrated.

DESIGN OF ELECTROMAGNETIC DEVICES

For each application, the electrical machine designer must find an optimal compromise between the specifications, the topological structure, the device dimensions, the properties of the different materials and the cost of the production process (Figure 1). The characteristics of the soft magnetic material technology that is used to realize the magnetic circuit of the device has a strong influence on the optimal solution of the design problem, in terms of topological structure and dimensions. For each soft magnetic material, there is a specific optimal solution because the magnetic, thermal and mechanical properties, the cost of the production and assembly process are different. Consequently, the "direct replacement" technique, where a new material is used without any structural or dimensional modification in a device that was optimized for a conventional material, is generally not interesting in terms of efficiency or power to weight ratio. A systematic research of new topological structures and new compromises between the material properties according to the application specifications is necessary to get an optimal use of a new material in terms of technical and economical performance.

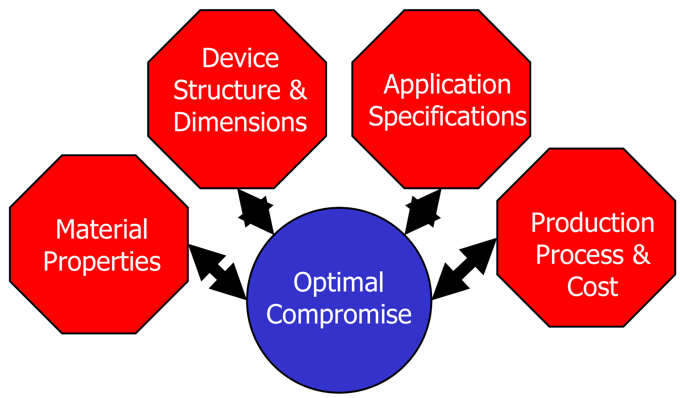

Fig1 Design problem

LAMINATED MATERIALS AND SOFT MAGNETIC COMPOSITES IN ELECTRICAL MACHINES

The steel sheet laminations have been used in AC magnetic applications since the end of the 19th century. This kind of technology takes advantage of high saturation induction and high permeability of iron with limited Eddy current losses. Several grades of laminated materials have been developed in order to be adapted to different specifications and cost-performance compromises for a wide range of applications. Because the laminated technology was the only solution to minimize the Eddy current losses in the yokes of electrical machines with AC excitation, the designers have developed and optimized electromagnetic structures where there is a 2D magnetic flux circulation only. This specific constraint of the laminated material technology has limited the available number of topological structures that can be used to realize electrical machines.

Despite their relatively low values of permeability, the Soft Magnetic Composites (SMC) present a lot of interesting characteristics which can improve the performance of electromagnetic devices, if they are properly used during the design process.

The number of production steps can be reduced and an integrated production process can decrease the cost. The magnetic circuit can be pressed in a single operation or assembled from several pre-pressed parts, by use of different pressing methods. It is also possible to design high performance magnetic structures with complex shapes, which are too difficult or too expensive to realize with laminated materials [1] [2] [4] [6].

The magnetic isotropy can be used to design new electrical machine structures with a 3D circulation of the magnetic flux and higher performance in terms of power or torque to weight ratio. Such 3D structures can be used to reduce the weight of the inactive copper, to simplify the realization of the machine windings and to reduce their production cost [4]. The isotropic SMC materials can be also efficiently used in specific parts of laminated electrical machines that carry a magnetic flux with a strong three-dimensional content to improve their performance [6].

The isotropic thermal properties and the good thermal conductivity improve the heat dissipation of electromagnetic devices. Because the SMC thermal conductivity is isotropic, the heat flux path is 3D and the whole external surface of the device can be used for dissipation [2] [4] [8].

The vibrations and the audible noise of the electromagnetic devices can be reduced, because the stack of laminations has been replaced by a solid and homegeneous SMC yoke [8] [2].

The recycling process of electrical machines armatures is improved because the separation of iron powder and copper is easier than in the case of the laminations [7].

An integrated design approach of electrical machines can be applied: with a soft magnetic material made of metal powder, the thermal, electromagnetic and mechanical functions that are usually performed by different parts of an electrical machine made of laminations can be integrated in a single part to produce. The number of parts and the weight are reduced and the thermal dissipation is improved [4].

SMC materials can be an interesting alternative to conventional laminated materials in electrical machine industry if the designers try to make an optimal compromise between their advantages and their drawbacks in terms of machine structure. Such a topological approach can be performed because the SMC properties bring new degrees of freedom to design structures of Electrical Machines. Because it is a new technology, the expert data derived from one century of industrial experience based on laminated materials cannot be used. It is also necessary to develop specific integrated CAD tools with global optimization methods in order to determine the optimal solution for each application and solve the problem illustrated by Figure 1.

TOPOLOGICAL RESEARCH

Several competitive structures of electromagnetic devices must be selected among multiple electrical machine structures that respect the specifications and maximize the objective function. The authors have investigated specific topological structures which correspond to an optimal compromise between the advantages and drawbacks of the SMC technology. The good isotropic thermal properties of SMC materials have been efficiently used in structures where the dissipation surface is maximized to improve the heat transfer capability (concept of “magnetically active fins” in transformers, inductors and motors [8] [4]). The isotropic magnetic properties allow the use of structures with 3D circulation of magnetic flux that maximize the power or energy to weight ratio (transformers and inductors with cylindrical symmetry [2] [8]). Specific motor structures with 3D circulation of flux have been selected that minimize the copper volume and simplify the winding production (concentrated windings, centralized windings, polyphase claw-pole machines with centralized-concentrated windings [3] [4] [5] [11]). Hybrid machine structures with laminations and SMC flux concentrators have been designed (Hybrid TFPM machine [6]). Several topological solutions that are well adapted to SMC parts production constraints have been also proposed and tested (specific fractional number of slots/poles/phase with regular or irregular distribution of armature teeth to increase the torque to Amp ratio of motors with a low number of big slots easy to press [1] [3] [5] [10] [11]). The specific properties of the SMC technology have been used to design motor structures with a better integration of the electromagnetic, mechanical and thermal functions in a minimal number of parts. With such an approach, that is not applicable with the laminated materials, the number of parts to produce can be reduced and the overall performance can be improved ([4])

DESIGN OPTIMIZATION METHODOLOGY

The authors have developed a specific methodology to design electrical machines with SMC for a wide range of applications. The flowchart of this design environment is illustrated on Figure 2. There are three main steps in the design process.

During the first step, a detailed analysis of the application specifications is performed. There are input and output specifications which can be electrical (power, voltage, current, frequency, power factor, etc.) or mechanical (rated torque, transient torque, rated speed, speed range or torque-speed characteristics in the case of variable speed applications, etc.). There are also dimensional and thermal constraints. All these specifications are formulated like constraint functions of the design variables. Because there is usually a high number of design solutions respecting these specifications and constraints, it is necessary to determine some kind of objective function to maximize or minimize, like energy, power or torque to weight ratio, efficiency, or some other cost-performance ratio taking into account the production constraints. Because the fields of application are very large, a general CAD tool is not used during this important design step: this analysis needs a strong multidisciplinary collaboration with the user and several experts.

The second design step is the topological research illustrated in the previous paragraph. Conventional 2D or 3D structures or original solutions can be chosen among the multiple topological solutions offered by the use of the SMC.

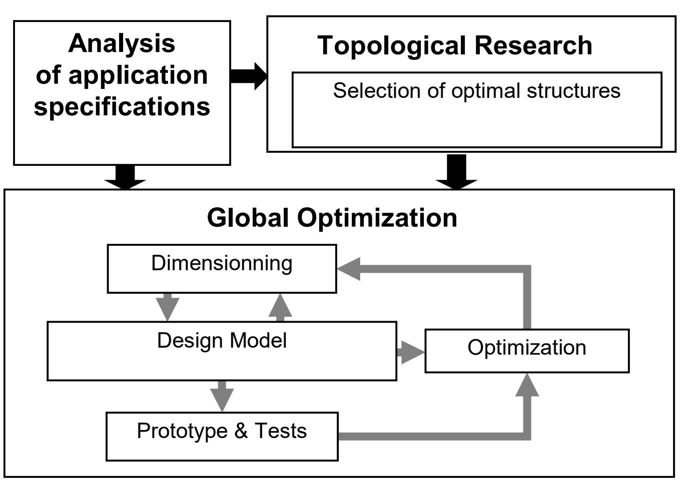

Fig2 Design Optimization Methodology

The third design step is the global optimization process. It is applied to each topological solution selected during the previous design step.

This efficient CAD tool is used to determine the optimal values of the design variables of each topological structure (dimensions, current and magnetic flux densities, etc.) which are respecting the constraints and are maximizing or minimizing the objective function.

This search is performed by a non linear constrained optimization routine. At each step of this iterative process, the constraints and the objective functions are evaluated by use of a global design model of the electromagnetic device, its materials and its production process.

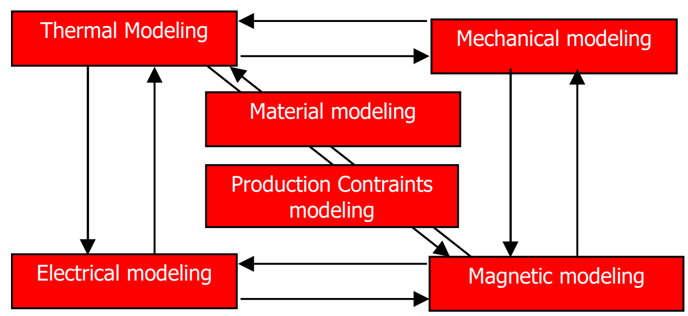

Fig3 Global design model of electromagnetic devices

Several modeling tools are coupled together (Figure 3). For example the magnetic modeling tool is coupled to the material modeling tool that delivers the SMC B(H) magnetic characteristic and used to evaluate the torque output of the device when it is supplied by a specific electrical power source. This torque output is used to derive the mechanical performance of the device. The magnetic and copper losses can be derived from the electrical and magnetic modeling tools to evaluate the thermal constraints. All these different modeling tools are analytical or based on internal FE analysis. One can notice that the production constraints modeling is included in this global design model. With such an approach it is possible to take account of the pressing constraints of the SMC parts during the early steps of design. This global optimization methodology has been successfully used in a wide range of SMC applications.

APPLICATIONS EXAMPLES

Different potential applications of composite powders in several sectors such as lighting, electro-domestic, and automotive industry have been investigated.

SMC INDUCTORS

The first application example is an inductor used in the passive power factor correction (PFC) of a low-cost fluorescent lamp ballast system illustrated in Figure 4. The inductor L is used to smooth the 60Hz line current and to correct the power factor that is lowered by the harmonic distortion created by the electronic ballast. For such an application, the magnetic core of the inductor is usually made of laminations with C-I, E-I or E-E shapes. The optimal solution for the SMC structure is a pot-core geometry with integrated cooling fins on the external surface that greatly improve the thermal dissipation and the efficiency. The absence of eddy currents in the SMC cores is also a very interesting feature for the lighting applications with high current harmonic distortion. The total losses are then lower than in the case of the laminated materials. The hum and the EMI of the lighting magnetic components can also be reduced in great proportions, because the windings are totally enclosed by the magnetic circuit and shielded. This structure is simple and easy to press in two parts. The winding can be realized separately and inserted in the magnetic circuit during the assembly process. The magnetic circuit is equipped with integrated SMC cooling fins on the external surface to improve the heat transfer and the thermal dissipation (Fig. 4). The magnetic flux circulates in the fins that are “magnetically active”. With such an approach, the external surface can be maximized without increasing the weight. The stored magnetic energy to weight ratio or the efficiency are improved because the temperature rise of the copper and the corresponding increase of winding resistance are reduced. A comparative performance analysis of the SMC inductor and the commercial laminated inductor has showed that several improvements have been performed: with the SMC inductor a 30% reduction of the total losses, a 25% reduction of the total occupied volume, a 10% weight reduction and a 25% reduction in Temp rise have been obtained [8].

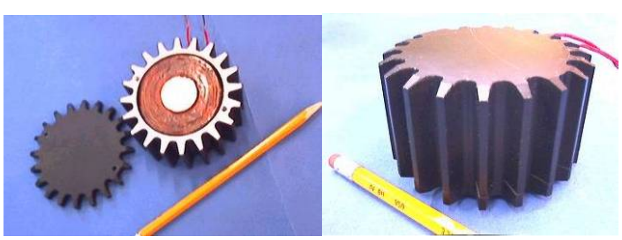

Fig4 SMC Pot-core inductor with “magnetically active” cooling fins

SMC UNIVERSAL MOTOR FOR AN ELECTRODOMESTIC APPLICATION

A lot of chorded hand tools or domestic appliances are using the universal motor or AC commutator motor. The usual version of these motors has a 2 poles stator with a concentrated field winding and an armature with conventional distributed windings. With such interlocked coil elements, the end windings are important. These bulky end windings are illustrated on the laminated commercial motor on the left part of Figure 5. A new SMC universal motor with a claw structure of stator and a concentrated winding armature has been developed. It is illustrated by the 2 motors on the right part of Figure 5. The stator of the universal motor has a claw structure, because its assembly process is very simple, and because such an arrangement can minimize the total stator weight if the number of poles is increased. However, in this kind of AC motor, the stator magnetic flux is alternative and the iron losses can be important in the yoke and claws. Soft Magnetic Composite materials like Atomet-EM1 that are isotropic magnetic materials with relatively low magnetic losses, are then very well adapted to such an application. The motor armature has a concentrated winding structure [5], where the coils are wound around the rotor teeth. This technique facilitates the realization and reduces the number of slots, the copper volume and total axial length of the motor without decreasing the motor performance [5] [3]. This new universal motor structure has been designed in order to meet the specifications of an existing laminated universal motor structure presented on the left part of Figure 5. A reduction of the total motor volume by a ratio equal to 200% has been obtained.

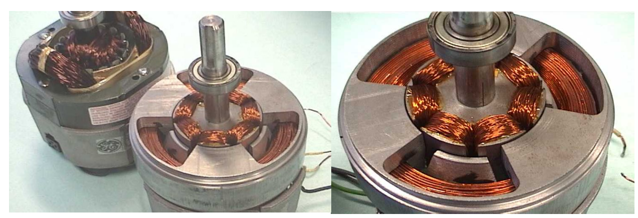

Fig5 SMC Universal motor for an electrodomestic application (Commercial laminated universal motor on the left, SMC motors on the right)

SMC BRUSH DC MOTORS

The Figure 6 illustrates a 180W SMC brush DC motor for an automotive fan. The armature magnetic circuit of a conventional brush DC motor is generally realized with a laminated material and distributed windings with bulky end windings. The inactive copper of the end windings is lowering the motor efficiency and increasing the total axial length of the motor and its production cost. New design approaches have been proposed by the authors for the realization of such brush DC motors with SMC [11]. These structural solutions are using new multi-layer concentrated windings with a small number of big slots easy to press to improve the performance and to minimize the production cost.

Fig 6 180W SMC brush DC motor for an automotive fan

The total axial length of the motor and the copper volume are then reduced without decreasing the motor performance. They are well adapted to the production process of metal powder parts. The Figure 6 presents a SMC brush-DC prototype that has been designed. A comparative analysis with a classical laminated motor used for an automotive 180W motor fan application has demonstrated that a 50% gain on the copper volume is obtained for the same specifications and performance [10] [11].

SMC BRUSHLESS MOTORS

The Figure 7 is presenting a structure of SMC brushless motor with a 16 poles rotor made of surface-mounted NdFeB permanent magnets [9]. Its stator structure has an irregular distribution of slots and 6 coils concentrated around some teeth only. This structure with a fractional number of slots/pole/phase and an irregular distribution of slots has a high torque to Amp ratio and a low cogging torque that is very interesting for the direct drive (gearless) traction applications. The volume of the inactive copper of the end-windings is minimized. One can notice on Figure 7 the sidewall made of the same SMC material which is fixed on the external stator yoke. The cooling water circulates in the skirt and is in contact with the soft magnetic material that presents a good and isotropic thermal conductivity. With this integrated cooling system, the traction motor has a very high transient over-torque capability.

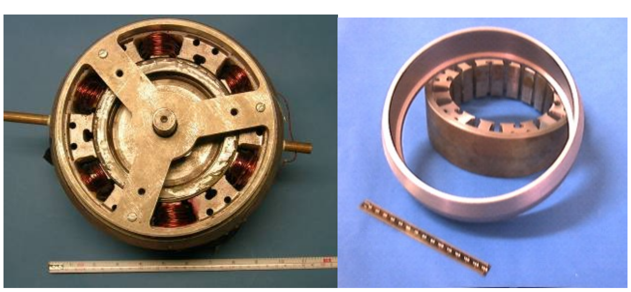

Fig7 SMC Brushless PM Motor for light traction application: Concentrated winding structure with an irregular distribution of slots and an Integrated liquid-cooling system (Sidewall & Skirt)

The Figure 8 is presenting a SMC brushless motor used for the motorization of an assisted electric bicycle. There are 24 stator slots and 22 rotor poles made of sintered NdFeB permanent magnets. The stator structure has a specific 3-phase concentrated winding with coils directly wound around the teeth. This winding configuration is easier to realize than a lap winding and reduces the copper volume of the end-windings, the copper losses and the total axial length of the motor. The small number of slots with relatively large dimensions is well adapted to the realization of the magnetic circuit with a SMC material. Three identical sectors are pressed and assembled to realize the stator. With such an approach, the mechanical constraints on the molding device are reduced and the pressing process is easier.

Fig8 Assisted electric bicycle with SMC Brushless PM motor mounted in the rear wheel & realized in 3 sectors

The Figure 9 is presenting an original 3-phase claw pole structure of SMC brushless motor. All parts of the magnetic circuit are made with the Soft Magnetic Composite Atomet-EM1. This stator is associated a 22 poles NdFeB PM rotor. The claw-pole magnetic stator structure divided in three SMC parts to press. The two lateral parts equipped with 9 claws with irregular dimensions are identical and there are 9 claws on the central part. This motor is using a centralized-concentrated winding structure that drastically simplifies the winding production process. There are only three individual phase coils wound on the central part of the magnetic circuit. The two lateral parts are easily assembled to the central part to finalize the stator. One can notice the absence of end-windings and the flat parts of the stator that simplify the assembly with the flanges supporting the bearing housings and improve the heat dissipation by conduction

Fig9 Polyphase Claw-pole structure of SMC Brushless PM motor with a centralized-concentrated winding (22 poles)

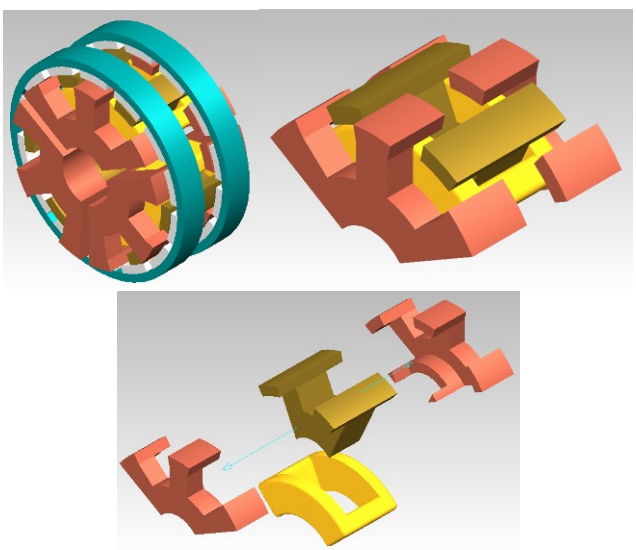

Fig10 Three phase claw pole structure with centralized-concentrated windings, and an outer 14 poles rotor

The Figure 10 is presenting an original structure of permanent magnet SMC brushless motor for another traction application. This structure is a three phase claw pole machines with centralized-concentrated winding and surface mounted permanent magnet rotor. It is using an outer permanent magnet rotor with two rings that can be directly implemented in the vehicle wheel. The inner magnetic stator circuit is split in three parts and the magnetic flux flows in the 3 dimensions inside them [4]. The armature magnetic circuit is divided in several parts equipped with claws, which encircle the coils. There is a 3D magnetic flux circulation in the yoke that must be made with an isotropic magnetic material like SMC. There is only one common yoke for the flux return. There are no end-windings. There is only one coil per phase and the winding is totally embedded in the stator yoke. The axis of each phase coil is perpendicular to the air-gap surface and the coils are wound directly on the base of the claws (Fig.10).

The stator is divided in three independent phase sectors. The magnetic circuit of each sector has been also divided in several parts to simplify the motor assembly and the winding realization (see Fig 10). One can notice that each phase coil can be realized separately and inserted in the magnetic circuit during the last steps of the assembly process. This kind of original structure is an example of the research of topological structures that take the best advantage of the SMC materials, and that represent an optimal compromise between the motor performance and the production cost of both the magnetic circuit and windings.

The size of the additional parts that are necessary for the bearing housings and the mechanical fixing of the rotor, can be reduced in great proportions. There are specific structures of polyphase claw pole machines with centralized concentrated windings where the bearing housings can be integrated in the lateral parts of the stator magnetic circuit (if a composite powder material with an adequate mechanical resistance is used). This integration must avoid any undesirable magnetic short circuit of the machine air-gap, but it has been demonstrated that there are existing structures where two different claws which present the same value of magnetic potential can be connected without any modification of the flux paths [4]. Fig. 11 show an example of such a 3-phase stator structure of permanent magnet brushless motor where the rotor mechanical fixing is integrated in a single part to press. Two diametrically opposed claws of the lateral part present the same value of magnetic potential. They can be connected by a bridge of SMC magnetic material without any modification of the flux paths, in order to support the bearing housing. The cooling system can be also integrated in the magnetic circuit stator SMC parts of such structures, without using another kind of material. For example, the cooling fins of the structure of Fig.11 are distributed around the outer surface of the stator yoke to increase the heat dissipation of the external surface. Because these fins are oriented along the axial length of the machine, the magnetic flux can also circulate in them: they are “magnetically active”. With such an arrangement the total size and weight of the motor is still minimized and the torque to weight ratio of the machine is increased.

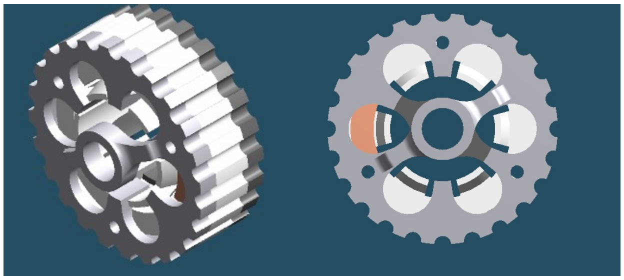

Fig11 Integration of the bearing housings and the cooling system (magnetically active fins) in the magnetic circuit

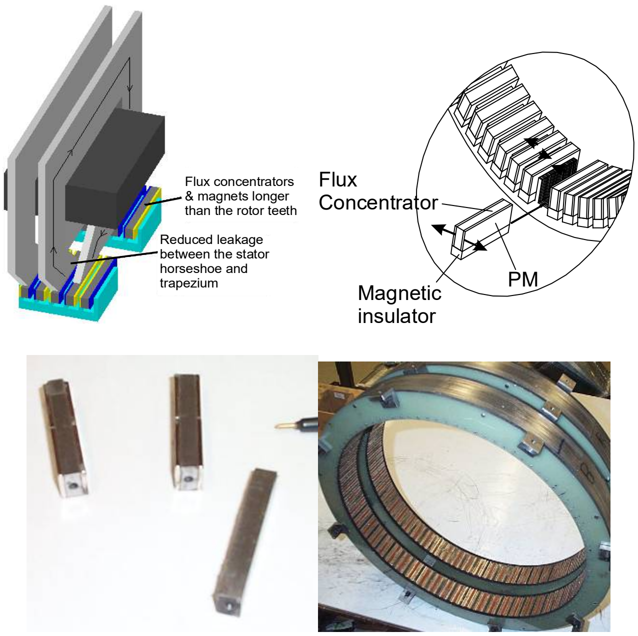

Fig12 Prototype of TFPM machine with toothed rotor equipped with Flux concentrators made of SMC material

The Figure 12 illustrates the use of Soft Magnetic Composites in a Transverse-Flux Permanent Magnet (TFPM) machine with toothed rotor made of Fe-Si laminated and SMC materials [6]. Fe-Si laminations have been used to minimize iron losses in the stator. The rotor flux concentrators where a three-dimensional magnetic flux is circulating, are made of SMC material. This hybrid solution is the most efficient in terms of cost-performance ratio.

CONCLUSION

A systematic research of new topological structures and a systematic design optimization methodology is necessary to get an optimal use of a new material like the SMC in terms of technical and economical performance. This design approach has been successfully adopted by the authors in a wide range of industrial applications.

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