Design Aspects of SMC Electrical Machines

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***Abstract*—Thanks to their unique properties such as magnetic isotropy and very low eddy current loss, soft magnetic composite (SMC) materials and their applications in electromagnetic devices have attracted strong interest of research in the past decade. This paper presents the key design aspects of SMC electrical machines, based on the previous experiences of the authors and other researchers. To design a high performance SMC motor, the unique properties of the SMC material should be carefully utilized, such as the three-dimensional magnetic flux path, medium and higher operational frequency, and mold fabrication techniques. A number of SMC motor prototypes, particularly a three-phase three-stack claw pole motor with SMC stator and an SMC transverse flux motor, are reviewed to describe the design aspects. The drawbacks of the material are also discussed. Possible further work for commercial success of SMC electrical machines is proposed.**

***Index Terms*—Motor design, Soft magnetic composite (SMC), SMC electrical machine.**

I. Introduction

Soft magnetic composite (SMC) materials are specially developed for application of electromagnetic devices [1]. Compared with the electrical steels commonly used in rotating electrical machines and transformers, SMCs possess a number of advantages such as magnetic and thermal isotropy, very low eddy current loss and relatively low total core loss at medium and higher frequency, net-shape fabrication process with smooth surface and good finish (no need of any further machining), and the prospect of low cost mass production. The basis of SMC is iron powder of high purity and high compressibility. The powder particles are bonded with a thin layer of coating, which produces high electrical resistivity. The coated powder is then pressed in a die to form solid material and finally heat treated to anneal and cure the bond.

Since the early 1990s, extensive work has been carried out on the improvement of the properties of SMC materials and applications of the materials in various electrical machines, and the results appear promising [2, 3]. It is even anticipated that the investigation on the application of SMC in electrical machines would lead to a revolutionary development of electrical machine manufacturing industry [1].

However, SMC has also serious drawbacks such as low magnetic permeability, high total core loss at power frequency, and low mechanical strength. A direct replacement of the electrical steel by SMC would deteriorate the machine performance with little compensating benefit. Therefore, a good design should carefully employ the unique properties of the material while avoiding the drawbacks. Based on this idea, different types of electrical machine using SMC cores have been investigated by various researchers, including axial field motors [4, 5], universal motors [6, 7], permanent magnet (PM) servo motors [8, 9], radial/axial field PM motor [10], claw pole armature machines [11-13], transverse flux machines (TFMs) [14-16], and TFM/claw pole designs [17, 18]. All these designs have been claimed successful with improved motor performance and/or reduced active material cost, compared to their laminated counterparts.

In spite of the success of the laboratory prototypes, a large amount of research work is still required for the SMC machines to achieve commercial success, especially on the mass production process. This paper aims to summarize the key design aspects of SMC electrical machines from both successful experiences and existing difficulties that need to be overcome, based on the study on various types of SMC motor.

II. Design Aspects of SMC Motors

A. *Magnetic Isotropy*

The powdered nature of SMC implies isotropic magnetic properties, and this creates crucial design benefits. Electrical machines can now be designed with three-dimensional (3-D) magnetic flux path and different radical topologies can be exploited to achieve high machine performance. The constraints imposed by electrical steels, such as that the magnetic field must flow within the plane of lamination, can be ignored. Typical examples of SMC application with 3-D flux are claw pole armature motors and TFMs [19]. In such machines, it is almost impossible or very difficult to make the cores by using laminated steels. And solid cores suffer from excessive eddy current loss. Therefore, SMC is an ideal candidate for the core of a 3-D flux machine.

The isotropic magnetic property can be applied to improve the motor performance. In [13], to further increase the specific torque of the claw pole SMC motor, the magnet was designed longer both axially and circumferentially than the claw pole. The flux generated by the rotor PMs enters the stator claw poles from both the front surfaces and side ones. Fig. 1 shows the basic structure and magnetic field finite element analysis (FEA) solution region of one pole of one stack, where *A* is the SMC stator core, *B* the rotor PMs, *C* the mild steel rotor yoke, and *D* the steel shaft. Due to the complex structure and 3-D flux path, 3-D numerical techniques like FEA is necessary for accurate determination of magnetic field distribution and key motor parameters.

Considering the structural symmetry and almost independent magnetic circuit between stacks, only one pole region of one stack is required for FEA solutions, as shown in Fig. 1.

The three phases are stacked axially with a circumferential shift of 120^o electrical to each other. The major dimensions and parameters include: outer diameter of the inside stator: 80 mm; main airgap length: 1 mm; effective axial length of each stack: 31 mm; number of turns of one phase winding: 75; and number of poles: 20. Each phase has a single coil winding (not shown for clarity) around an SMC core, which is molded in two halves.

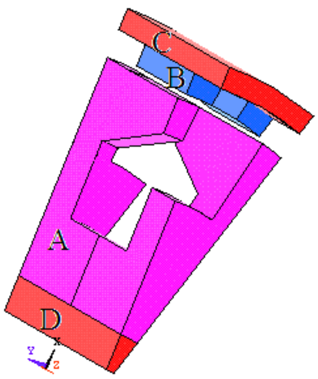
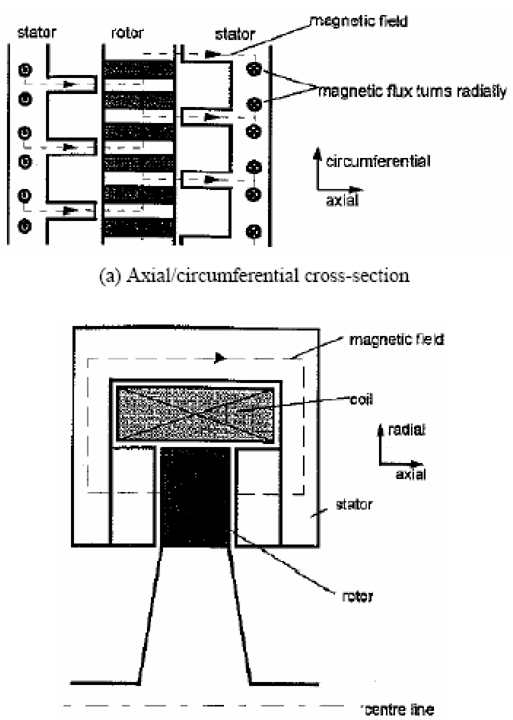


Fig. 1. Magnetically relevant parts and magnetic field FEA solution region of a PM claw pole SMC motor [13].

Another typical example is a TFM prototype developed by the University of Newcastle upon Tyne, UK, as illustrated in Fig. 2. SMC was used for the stator iron parts for the 3D magnetic fields in the TFM prototype.



(a) Axial/circumferential cross-section

(b) Axial/radial cross-section

Fig. 2. Newcastle's SMC TFM prototype of one phase [14]

The machine employs PM flux concentration rotor and the magnets are magnetized circumferentially in alternating directions. The magnetic fluxes from two successive magnets aid each other in the soft iron part between them and then flow out of the axial surface to the stator pole via the axial air gap. The flux then turns radially into the stator sidewall, passes axially the stator yoke, turns radially into the other sidewall, passes axially through the stator pole, the air gap, the flux concentration iron, and finally returns to PMs to form a closed loop. The main magnetic flux flows in all the three coordinate directions in the core. The TFM structures have also a large amount of flux leakage. Therefore, laminated steels are not suited for this complex magnetic circuit and SMC is an ideal substitute. In addition, the paper highlighted that SMC allows the armature core to be made much larger than laminations. By SMC, the available space on the flanks and core back can be used, while the overall machine volume does not increase.

Besides the claw pole machine and TFM, other types of motors can also benefit from the isotropic magnetic property of SMC. For example, in an axial-field machine, the key issue is to form the armature core with slots and teeth. If the electrical steel is used the lamination has to be wound spirally, which is tedious and costly [4, 5, 20]. By SMC, the core can be easily formed.

B. Eddy Current and Operational Frequency

Among the unique properties of SMC is the low eddy current. Because the iron particles are coated by a thin layer of electrical insulation, the eddy current loss is much lower than that in laminated steels, especially at higher frequencies. The total loss is dominated by the hysteresis loss, which is higher than that of laminated steels due to the particle deformation during compaction. For example, at the power frequency of 50 Hz and the peak flux density of 1.5 T, the total core loss in SOMALOY™ 500 (with 0.5% Kenolube), an SMC material developed by Höganäs AB, Sweden, is 14 W/kg, double that of even the low grade Kawasaki 65RM800 (0.65 mm thick, 28×10^{-8} Ωm) [21, 22]. When the excitation frequency increases, however, the increment of core loss in SMC is smaller than that in electrical steels due to the much smaller eddy currents.

Therefore, SMC materials are more likely to be better used for motors operating at higher excitation frequencies, e.g. 300 Hz is chosen for the UTS prototypes [13, 16].

C. Magnetic Permeability

The permeability of SMC material is significantly lower than that of electrical steels because it contains non-ferromagnetic coating, whose permeability is approximately equal to that of air. Best figures of maximum relative permeability for SMCs are in the range of 500 or 550 [21, 23]. It is expected that this material would be appropriate for construction of PM motors, in which the magnet reluctance dominates the magnetic circuit, making such motors less sensitive to the permeability of the core than armature magnetized machines such as induction and reluctance machines. In spite of the lower value, the permeability of SMC is much more stable with respect to the frequency than that of electrical steels. SMC can maintain nearly a constant magnetic permeability up to a quite high frequency. This is a favorable property for motors operating at higher frequencies.

D. Power Loss

Unlike conventional machines in which the copper loss is generally much higher than the core loss, SMC motors have comparable core and copper losses. It can be an interesting design point that the two losses are chosen the same value for high motor efficiency [24].

E. Production Technique

The production by powder metallurgy technique may be the aspect of the greatest benefit as it creates the prospect of large volume manufacturing of low cost motors. The iron cores and parts can be pressed in a die into the desired shape and dimensions, further machining is minimized and hence the production cost can be greatly reduced. In addition, the SMC parts by molding are much stronger than those cut from preforms.

From the view of production efficiency and material utilization, SMC and the powder metallurgical process offer major advantages over the conventional lamination technique, which is commonly used in electromagnetic devices. It can be up to 50% more cost-effective than convention production [1]. Furthermore, it is an environment friendly technique with minimum material waste. The SMC core is recyclable as it can be easily smashed back to iron powder.

Since the production techniques and facilities of laminated machines have been well established, manufacturers are usually reluctant to make such as a big change. Further work should be focused on the production aspect in close collaboration with industry.

F. Summary of SMC Motor Design

In summary, successful experiences about the SMC motor development have been achieved with 3-D magnetic flux design, novel motor topology, machines like PM motors with low sensitivity to the magnetic permeability, higher operational frequency, and molding fabrication technique.

III. Conclusion and Further Work

To investigate the application potential of SMC materials in electrical machines, different types of motor have been studied by various researchers. The performance of SMC prototypes is comparable to or even better than that of similar laminated motors with the prospect of greatly reduced mass production cost. It is even anticipated that SMC machines may lead to a revolutionary development of electrical machine manufacturing industry.

In spite of the encouraging progress, a large amount of research work is still required for commercial success of SMC electrical machines. The further work may include the following aspects:

(1) The material: The properties of SMC materials can be further improved by choosing the best material composition, compaction pressure, annealing temperature, etc.

(2) Motor structure and advanced analysis: Research should be conducted to find novel motor topology to best use the unique properties of SMC. Considering the complex structure and magnetic field distribution, advanced techniques like numerical magnetic field analysis and design optimization should be used. System level integrated design would be helpful since modern motor drives are closely combined with power electronics and control schemes.

(3) Modeling of magnetic properties: SMC is particularly suitable for application in rotating electrical machines with complex structure and 3-D flux. In such a machine, when the rotor rotates, the flux density vector at a location can be very complicated, e.g. alternating (1-D) with or without harmonics, two-dimensional (2-D) or even 3-D rotating with purely circular or elliptical patterns [24-26]. Therefore, the magnetic properties of SMC, such as B-H curves and core losses, under different vector magnetizations should be investigated and properly modeled and applied in the motor design [27-29].

(4) Production technique: Effective and cheap SMC core manufacturing techniques should be developed using mold compaction/injection, in close collaboration with industry. Non-uniform mass density may be considered, which can significantly reduce the product cost. Attention should be paid to the motor performance and mechanical strength, which depend upon the mass density and fabrication approach.

References

[1] "The latest development in soft magnetic composite technology," *SMC Update, Höganäs AB*, Sweden, 1997-2005. Available at http://www.hoganas.com, see News then SMC Update.

[2] A.G. Jack, "Experience with the use of soft magnetic composites in electrical machines," in *Proc. Int. Conf. on Electrical Machines*, Istanbul, Turkey, Sept. 1998, pp. 1441-1448.

[3] J.G. Zhu and Y.G. Guo, "Study with magnetic property measurement of soft magnetic composite material and its application in electrical machines," in *Proc. IEEE Industry Application Society Annual Meeting*, Seattle, USA, Oct. 2004, pp. 373-380.

[4] M. Persson, P. Jansson, A.G. Jack, and B.C. Mecrow, "Soft magnetic composite materials – use for electrical machines," in *Proc. 7th IEE Conf. on Electrical Machines and Drives*, Durham, England, Sept. 1995, pp. 242-246.

[5] Z. Zhang, F. Profumo, A. Tenconi, and M. Santamaria, "Analysis and experimental validation of performance for an axial flux permanent magnet brushless DC motor with powder iron metallurgy cores," *IEEE Trans. Magn.*, vol. 33, no. 5, pp. 4194-4196, Sept. 1997.

[6] A.G. Jack, B.C. Mecrow, P.G. Dickson, P. Jansson, and L. Hultman, "Design and testing of a universal motor using a soft magnetic composite stator," in *Proc. 35th IEEE*

Industry Applications Society Annual Meeting, Rome, Italy, Oct. 2000, pp. 46-50.

[7] J. Cros, P. Viarouge, Y. Chalifour, and J. Figueroa, "A new structure of universal motor using soft magnetic composites," *IEEE Trans. Industry Applications*, vol. 40, no. 2, pp. 550-557, Mar./Apr. 2004.

[8] A.G. Jack, B.C. Mecrow, P.G. Dickison, D. Stephenson, J.S. Burdess, N. Fawcett, and J.T. Evans, "Permanent magnet machines with powdered iron cores and pre-pressed winding," in *Proc. 34th IEEE Industry Applications Society Annual Meeting*, Phoenix, USA, Oct. 1999, pp. 97-103.

[9] J. Cros, P. Viarouge, and A. Halila, "Brush DC motors with concentrated windings and soft magnetic composites armatures," *in Proc. IEEE 36th Industry Application Society Annual Meeting*, Chicago, USA, Sept. 2001, pp. 2549-2556.

[10] A.G. Jack, B.C. Mecrow, C.P. Maddison, "Combined radial and axial permanent magnet motors using soft magnetic composites," in *Proc. 9th Int. Conf. on Electrical Machines and Drives*, Canterbury, UK, Sept. 1999, pp. 25-29.

[11] C.P. Maddison, B.C. Mecrow, and A.G. Jack, "Claw pole geometries for high performance transverse flux machines," in *Proc. Int. Conf. on Electrical Machines*, Istanbul, Turkey, 1998, pp. 340-345.

[12] J. Cros and P. Viarouge, "New structure of polyphase claw-pole machines," *IEEE Trans. Industry Applications*, vol. 40, no. 1, pp. 113-120, Jan./Feb. 2004.

[13] Y.G. Guo, J.G. Zhu, P.A. Watterson, and W. Wu, "Development of a claw pole permanent magnet motor with soft magnetic composite stator," *Australian J. of Electrical & Electronic Eng.*, vol. 2, no. 1, pp. 21-30, 2005.

[14] B.C. Mecrow BC, A.G. Jack, and C.P. Maddison, "Permanent magnet machines for high torque, low speed applications," in *Proc. Int. Conf. on Electrical Machines*, Vigo, Spain, Sept. 1996, pp. 461-466.

[15] R. Blissenbach, G. Henneberger G, U. Schafer, and W. Hackmann, "Development of a transverse flux traction motor in a direct drive system," in *Proc. Int. Conf. on Electrical Machines*, Helsinki, Finland, 2000, pp. 1457-1460.

[16] Y.G. Guo, J.G. Zhu, P.A. Watterson, and W. Wu, "Development of a permanent magnet transverse flux motor with soft magnetic composite core," *IEEE Trans. Energy Conversion*, vol. 21, no. 2, pp. 429-437, June 2006.

[17] C.P. Maddison, B.C. Mecrow, and A.G. Jack, "Claw pole geometries for high performance transverse flux machines," in *Proc. Int. Conf. on Electrical Machines*, Istanbul, Turkey, 1998, pp. 340-345.

[18] Y.G. Guo, J.G. Zhu, and H.W. Lu, "Design and analysis of a permanent magnet claw pole/transverse flux motor with soft magnetic composite core," in *Proc. 6th IEEE Int. Conf. on Power Electronics and Drive Systems*, Kuala Lumpur, Malaysia, Nov. 28 – Dec. 1, 2005, pp. 1413-1418.

[19] Y.G. Guo, J.G. Zhu, P.A. Watterson, and W. Wu, "Comparative study of 3-D flux electrical machines with soft magnetic composite core," *IEEE Trans. Industry Applications*, USA, vol. 39, no. 6, pp. 1696-1703, Nov./Dec. 2003.

[20] Y. Chen and P. Pillay, "Axial-flux PM wind generator with a soft magnetic composite core," in *Proc. 40th IEEE Industry Applications Society Annual Meeting*, Hong Kong, China, Oct. 2005, pp. 231-237.

[21] "Soft magnetic composites from Höganäs Metal Powders - SOMALOY™ 500," *Höganäs Product Manual*, 1997.

[22] "RM-core non-oriented magnetic steel sheet and strip," *Kawasaki Steel Catalogue*, March 1999.

[23] "Soft magnetic composites from Höganäs Metal Powders - SOMALOY™ 550," *Höganäs Product Manual*, 1999.

[24] Y.G. Guo, J.G. Zhu, Z.W. Lin, and J.J. Zhong, "Measurement and modeling of core losses of soft magnetic composites under 3D magnetic excitations in rotating motors," *IEEE Trans. Magn.* vol. 41, no. 10, Oct. 2005, pp. 3925-3927.

[25] J.G. Zhu and V.S. Ramsden, "Improved formulations for rotational core losses in rotating electrical machines," *IEEE Trans. Magn.*, vol. 34, no. 4, pp. 2234-2242, July 1998.

[26] Y.G. Guo, J.G. Zhu, J.J. Zhong, and W. Wu, "Core losses in claw pole permanent magnet machines with soft magnetic composite stators," *IEEE Tran. Magn*, vol. 39, no. 5, pp. 3199-3201, Sept. 2003.

[27] Y.G. Guo, J.G. Zhu, and J.J. Zhong, "Measurement and modeling of magnetic properties of soft magnetic composite materials under 2D vector magnetizations," *Journal of Magnetism and Magnetic Materials*, vol. 302, no. 1, pp. 14-19, July 2006.

[28] J.G. Zhu, J.J. Zhong, Z.W. Lin, and J.D. Sievert, "Measurement of magnetic properties under 3-D magnetic excitations," *IEEE Trans. Magn.*, vol. 39, no. 5, Sept. 2003, pp. 3429-3431.

[29] Y.G. Guo, J.G. Zhu, Z.W. Lin, and J.J. Zhong, "3D vector magnetic properties of soft magnetic composite material," *Journal of Magnetism and Magnetic Materials*, vol. 302, no. 2, pp. 511-516, July 2006.