Performance Analysis of an SMC Transverse Flux Motor with Modified Double-sided Stator and PM Flux Concentrating Rotor

Youguang Guo[1], Jianguo Zhu[1], Haiyan Lu[2], Shuhong Wang[3], Jianxun Jin[4]
[1]Faculty of Engineering, University of Technology, Sydney, NSW 2007, Australia
[2]Faculty of Information Technology, University of Technology, Sydney, NSW 2007, Australia
[3]Faculty of Electrical Engineering, Xi'an Jiaotong University, Xi'an, 710049, China
[4]Center of Applied Superconductivity, University of Electronic Science and Technology of China, Chengdu, China

Abstract-This paper presents the design and performance analysis of a three-phase three-stack transverse flux motor with a modified double-sided stator and a permanent magnet (PM) flux concentrating rotor. Both stator and rotor cores employ SOMALOY™ 500, a new soft magnetic composite (SMC) material specially developed for electrical machine application. By taking advantage of the unique properties of SMC, such as the magnetic isotropy, the motor is designed with three-dimensional (3D) magnetic flux path. To accurately compute the motor parameters and performance, improved formulations are applied in combination with 3D magnetic field finite element analysis. The designed motor shows superior characteristics to laminated machines.

I. Introduction

Permanent magnet (PM) motors with transverse flux configurations have been a strong interest of research since Weh *et al.* proposed two versions of such machines in the 1980's [1-2]. Transverse flux motors (TFMs) employ simple circular coils with a circumferential current, instead of axial current of normal machines. The magnetic flux produced by the rotor PMs is guided to be transversal to the circumferential direction of rotation by C-cores or E-cores, which are separated by two pole pitches and enclose the armature winding. Because every pole sees all of the armature magnetomotive force, TFMs can achieve very high torque-to-volume ratio provided that the number of poles is high. Naturally, these machines are suitable for direct drive applications featuring high torque at low rotational speed.

TFMs have complex magnetic circuit with a large number of magnetic parts, especially for the double-sided structure, so the fabrication of the stator core is quite difficult by using laminated steels. In addition, due to the large flux leakage, which is of three-dimensional (3D) in nature, excessive eddy currents may be generated by the flux component perpendicular to the lamination plane. These problems have limited the wide application of TFMs, but they can be overcome by using a newly developed material: soft magnetic composite (SMC) [3].

SMC materials are specially developed for electromagnetic devices with low and medium operational frequencies, and significant progress has been achieved in the past decade [4]. The unique properties of the material include 3D magnetic and thermal isotropy, very low eddy current loss and relatively low total core loss at low and medium frequencies, near net-shape fabrication process with smooth surface and good finish (without need of further machining), and the prospect of very low cost mass production [5]. The basis of the material is iron powder with high purity and high compressibility. The iron particles are bonded with a coating of an organic material, which produces high electrical resistivity. The coated powder is compressed with high pressure in a die to form the desired solid and then heat treated to cure the bond [6].

The powdered nature of SMC implies isotropic magnetic property and this creates crucial design advantages. Different radical topologies can be exploited for high motor performance as the constraints imposed by the lamination technology can be ignored. For example, the magnetic flux can now be designed with 3D path. Typical examples of SMC application are claw pole and transverse flux motors [7-9].

This paper presents the design and performance analysis of a three-phase three-stack double-sided TFM with SMC core and PM flux-concentrating rotor, aiming to drive swimming pool pumps. Improved design and analysis techniques are applied based on 3D magnetic field finite element analysis (FEA) and our previous experiences on a claw pole SMC motor and a single-sided surface-mounted PM SMC TFM prototype [8-9]. The designed SMC motor shows superior performance when compared to laminated machines.

II. Motor Design

A. Previous Study of SMC TFMs

The first attempt to apply SMC in transverse flux geometry was conducted by Mecrow *et al.* in 1996 [10]. SMC was used for the stator iron parts of a TFM prototype with a PM flux-concentrating rotor, double axial air gaps and a modified double-sided stator topology. Since the main magnetic flux in the stator core flows in all the three directions, laminated steels are not suitable for the complex magnetic circuit and SMC is an ideal substitute. The authors also highlighted that SMC allows the armature core to be made much larger than laminations, as the available space on the flanks and core back can be used by SMC without increasing the overall machine volume. Considering that each stack forms a phase and is magnetically independent from the others, a single-phase prototype was constructed. Some results have been obtained from the test on the prototype, such as electromotive force (*emf*) and torque. However, the actual performance as a motor, which is normally of multi-phases, cannot be obtained directly.

Another investigation was reported by Henneberger *et al.* in 2000 [11]. The paper described a TFM prototype with three phases magnetically coupled in the laminated stator in order to reduce the motor volume. The external rotor comprises PMs and flux concentrating iron parts, which are made by SMC as "the guidance of the flux in three dimensions is impossible with laminated steel". However, 3D magnetic field FEA has shown that the flux in the stator core, particularly in the poles, has significant components in all the three directions and high eddy current losses may be produced by the varying field perpendicular to the direction of lamination [12]. Therefore, the authors further developed the prototype by using SMC in both stator and rotor cores [12].

Since 1998, the authors of this paper have been actively involved in the research on measurement and modelling of the magnetic properties of SMC materials, and development of SMC motors with different topologies, including a single-sided SMC TFM [9]. The prototype has successfully operated with a brushless DC drive scheme.

Based on the previous experiences with TFM geometries and design and analysis approaches, this paper studies a three-phase three-stack TFM with a modified double-sided stator and a PM flux-concentrating rotor, in which both the stator and rotor cores employ SOMALOY™ 500 [13], an SMC material specially developed for application in electrical machines. Improved formulations, in combination with 3D magnetic field FEA, are applied for effective computation of the motor parameters and performance.

B. Structure and Major Dimensions

Fig. 1 illustrates the magnetically relevant parts of the motor and magnetic field FEA solution region of one pole-pair of one stack, and Table I lists the major dimensions and parameters. Each stack forms a phase, consisting of a PM flux-concentrating rotor, a modified stator with double active sides facing the rotor via two axial air gaps, and one circular coil between the stator and rotor (not shown in the figure for clarity). Three phases are stacked axially with an angular shift of 120 electrical degrees to each other. To avoid flux leakage between phases, magnetic insulation sheets are inserted between stacks. The rotor is supported by cantilevers on the shaft.

Each stack of the rotor has 12 NdFeB permanent magnets, which are magnetised circumferentially in alternating directions. In between the magnets are flux-concentrating SMC core whose axial end-surfaces act as the active surfaces of the rotor. The fluxes produced by two adjacent PMs flow circumferentially into the flux-concentrating iron between them. The strengthened flux flows axially into the air gap, the stator pole, and then radially into the stator side and back core. The flux returns in a similar manner via the other half of the stack, enclosing the stator phase winding.

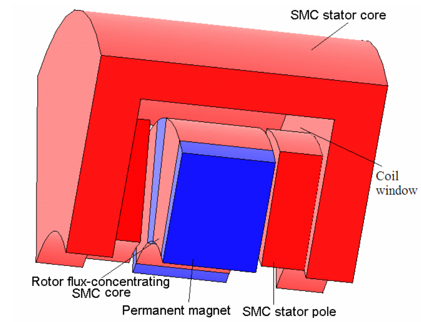

Fig. 1. Motor structure and FEA solution region of one pole-pair of one stack

TABLE I
MAJOR DIMENSIONS AND PARAMETERS

Dimensions and parameters	Quantities
Rated frequency (Hz)	300
Number of phases	3
Rated power (kW)	2.25
Rated line-to-neutral voltage (V)	85
Rated phase current (A)	12.1
Rated speed (rpm)	3000
Rated torque (Nm)	7.2
Rated efficiency (%)	90
Rated temperature rise (^oC)	100
Number of poles	12
Stator core material	SOMALOY™ 500
Stator outer diameter (mm)	115
Effective axial length of stator of one stack (mm)	40
Rotor outer diameter (mm)	88
Rotor inner diameter (mm)	54
Permanent magnets	NdFeB, Grade N30M
Number of magnets	36
Magnet dimensions	OD88 x ID54 x 13 mm arc 10.5^o
Magnetization direction	Circumferential
Main axial air gap length (mm)	1 + 1
Radial air gap clearance (mm)	1.5
Number of coils	3
Coil window dimension (mm^2)	27 x 6
Number of turns	52
Diameter of copper wire (mm)	1.40
Resistance per phase at 150^oC (Ω)	0.221

III. MAGNETIC FIELD FEA AND PARAMETER CALCULATION

Because of the almost independent magnetic circuit between phases and the structural symmetry, only one pole-pair of one stack is required for field analysis, as shown in Fig. 1. At the two radial boundary surfaces, magnetic scalar potentials should obey the so-called periodical conditions:

$$\varphi_m(r, \Delta\theta/2, z) = \varphi_m(r, -\Delta\theta/2, z) \tag{1}$$

where $\Delta\theta = 60^o$ is the angle of one pole-pair.

Fig. 2 illustrates the plot of flux density vectors at no-load at $\theta = 0^o$ position, where the rotor flux-concentrating core faces the stator pole. It can be seen that the magnetic flux path is really complicated and 3D FEA is necessary to accurately determine the magnetic field distribution and then the motor parameters and performance. There is also a significant amount of leakage flux, which is 3D in nature.

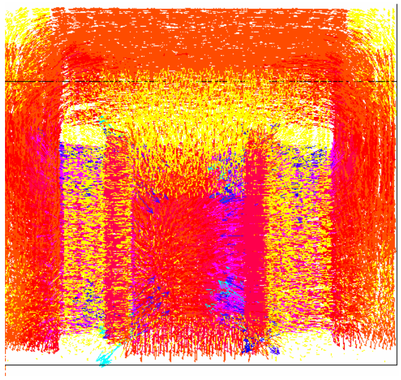

Fig. 2. Plot of flux density vectors at no-load

Some key motor parameters can be obtained from the no-load magnetic field distribution, such as the PM flux, defined as the flux of the stator phase winding produced by the rotor PMs, back electromotive force (*emf*), cogging torque, and core losses at no-load. For example, the curve of the PM flux versus rotor angle can be obtained from a series of no-load field calculation with different rotor positions. The peak value of the fundamental of the flux curve is calculated as ϕ_1=0.957 mWb, so the back *emf* and torque constants, K_E and K_T, can be determined to be 0.211 Vs/rad and 0.633 Nm/A, respectively, by

$$K_E = \frac{p}{2} N_s \frac{\phi_1}{\sqrt{2}} \tag{2}$$

$$K_T = mK_E \tag{3}$$

where p is the number of poles, N_s the number of turns of a stator phase winding, and m the number of phases.

As the magnetic circuit of each stack is almost independent, the mutual inductance between phase windings can be considered as zero. The self-inductance of the phase winding is calculated to be 2.18 mH by a modified incremental energy method (MIEM) in the following steps [14]: (I) Perform a non-linear magnetic field analysis with the excitation of the rotor PMs to determine the operational point; (II) Compute and save the differential permeability in each element; (III) Conduct a linear analysis with the saved differential permeabilities and a perturbed current Δi only (from zero current); (IV) Calculate the co-energy increment ΔW_c and then the incremental inductance by

$$L_{inc} \approx \frac{2\Delta W_c}{(\Delta i)^2} \tag{4}$$

Core loss is an important factor in SMC motor design. In the FEA, the total core loss of the motor is computed by summing up the core loss of each element, and in each element the core loss is attributed to hysteresis, eddy current and anomalous losses. For accurate prediction of core losses, the locus of the rotating magnetic flux density vector is calculated by rotating the rotor for one pole-pair, and the Fourier series is used to consider the effect of harmonics. The method for accurate prediction of core losses in SMC motors with 3D magnetic fluxes has been presented in detail in the previous publications [15-16]. The core loss of this SMC TFM is calculated as 79.7 W.

IV. Motor Performance

Fig. 3 illustrates the per-phase equivalent electrical circuit, where E_1, R_1, and X_1 are the back *emf*, stator winding resistance, and synchronous reactance, and V_1 and I_1 are the stator terminal voltage and phase current, respectively. The optimum brushless DC operating mode, i.e. I_1 is in phase E_1, is assumed for this SMC TFM motor.

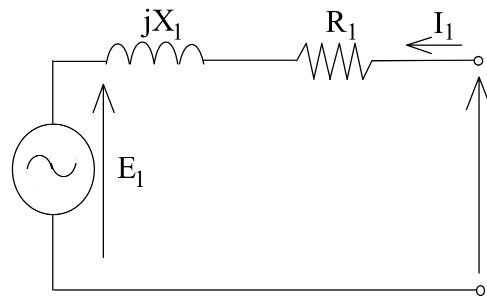

Fig. 3. Per-phase equivalent electrical circuit

Figs. 4 and 5 plots the torque/speed curves with different values of terminal voltage and the curves of the input and output powers and efficiency versus the rotor speed when the terminal voltage is 85 V (rms). In the optimum brushless DC operating mode, this motor can output 2250 W with an efficiency of 90% at 3000 rpm when the terminal voltage is 85.0 V, or when its q-axis component is 69.0 V.

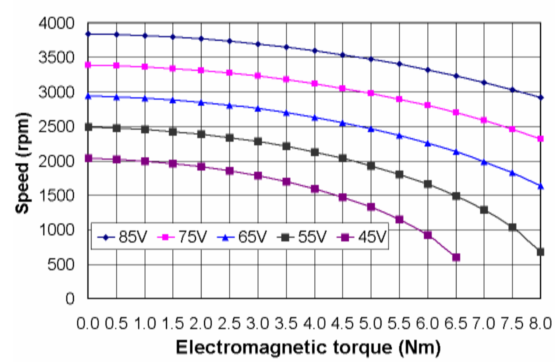

Fig. 4. Mechanical characteristics with different terminal voltages

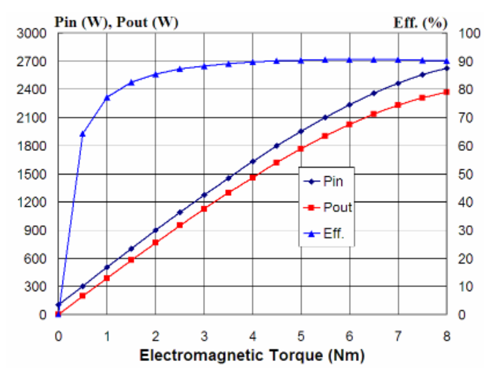

Fig. 5. Input and output powers and efficiency versus electromagnetic torque when the terminal voltage is 85 V

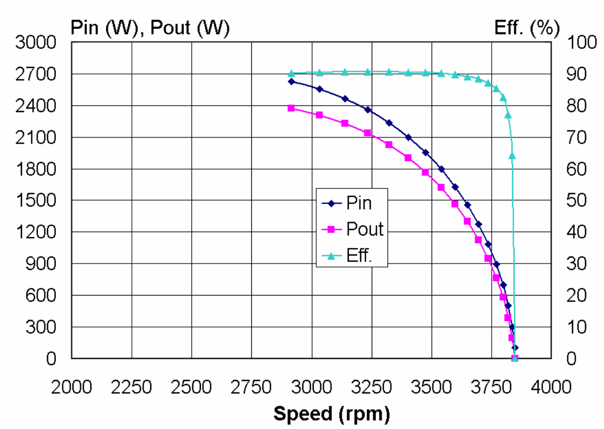

Fig. 6. Input and output powers and efficiency versus rotor speed when the terminal voltage is 85 V

V. CONCLUSION AND DISCUSSION

This paper presents the design and performance analysis of a three-phase three-stack transverse flux motor by using SMC cores. The motor has a modified double-sided structure and a PM flux-concentrating rotor. As the structure is really complicated with 3D flux, only SMC is suitable for construction of the motor. The design is successful according to the predicted performances. The methods for designing the SMC motor and computing the parameters and performance were validated by two previous SMC motor prototypes [8-9].

This motor was initially designed to replace an existing induction motor driving swimming pool pumps. It is a single-phase capacitor-run induction motor with a rated output power of 2.25 kW, or a torque of 7.7 Nm at 2800 rpm. As the TFM has no end-windings, the space for the stator winding overhangs of the induction motor can be used as the effective volume. The designed SMC TFM has a better specific torque of 5.746 x 10^3 Nm/m^3 when compared to 3.301 x 10^3 Nm/m^3 of the laminated induction motor. Furthermore, the TFM can operate with variable speed, a very important factor for saving energy.

The key issue for commercial success of SMC motors relies on the fabrication, which requires close collaboration with industry. The greatest benefit is also with the manufacturing with greatly reduced cost, which may lead to a revolutionary development of electrical machine manufacturing industry.

REFERENCES

[1] H. Weh and H. May, "Achievable force densities for permanent magnet excited machines in new configuration," in *Proc. Int. Conf. on Electrical Machines*, Munich, Germany, Sept. 1986, pp. 1107-1111.

[2] H. Weh, H. Hoffmann, and J. Landrath, "New permanent magnet excited synchronous machine with high efficiency at low speed," in *Proc. Int. Conf. on Electrical Machines*, Pisa, Italy, Sept. 1988, pp. 35-40.

[3] Y. G. Guo and J. G. Zhu, "Application of soft magnetic composite materials in electrical machines, a review," *Australian Journal of Electrical & Electronics Engineering*, Vol. 3, No. 1, pp. 37-46, 2006.

[4] "The latest development in soft magnetic composite technology," SMC Update, Reports of Höganäs AB, Sweden, 1997-2007. Available at http://www.hoganas.com/, see News then SMC Update.

[5] 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.

[6] 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, UK, Sept. 1995, pp. 242-246.

[7] 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*, Vol. 39, No. 6, , pp. 1696-1703 Nov./Dec. 2003.

[8] 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 Journal of Electrical & Electronic Engineering,* Vol. 2, No. 1, pp. 21-30, 2005.

[9] 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. 426-434, June 2006.

[10] B. C. Mecrow, 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.

[11] G. Henneberger and M. Bork, "Development of a transverse flux traction motor in a direct drive system," in *Proc. Int. Conf. on Electrical Machines*, Helsinki, Finland, Aug. 2000, pp. 1457-1460.

[12] R. Blissenbach and G. Henneberger, "New design of a soft magnetic composite transverse flux machine with special attention on the loss mechanisms," in Proc. Int. Symposium on Advanced Electro-mechanical Motion Syst. (Electromotion), Bologna, Italy, June 2001, paper D-6/88.

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

[14] Y. G. Guo, J. G. Zhu, H. W. Lu, R. Chandru, S. H. Wang, and J. X. Jin, "Determination of winding inductance in a claw pole permanent magnet motor with soft magnetic composite core," in *Proc. Australasian Uni. Power Eng. Conf.*, Hobart, Australia, Sept. 2005, pp. 491-496.

[15] 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 Trans. Magn.*, Vol. 39, No. 5, pp. 3199-3201, Sept. 2003.

[16] 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, pp. 3925-3927, Oct. 2005.