ANALYSIS AND CHARACTERIZATION OF A SWITCHED RELUCTANCE MACHINE USING SOFT MAGNETIC COMPOSITE MATERIAL

K. Vijayakumar[1] **R. Karthikeyen[2]**
[1]Mailam Engineering College, Mailam, [2]Srivenkateswara College of Engineering, Sriperumbudur
Tamilnadu, India, +91-4422490503, vijipreethi@rediffmail.com, k_vijaymec@yahoo.com

Dr. R. Arumugam
SSN Engineering College, Kalavakkam, Chennai, India
+91-9486521381, arumugamr@ssn.edu.in

Abstract: *Soft magnetic composite (SMC) materials characterized by three dimensional isotropic ferromagnetic behavior and very low eddy current losses find utility in complex geometry electrical machines due to flexible machine design and assembly .The suitability of soft magnetic composite material in switched reluctance motor (SRM) has been investigated through static, dynamic, thermal, vibration and acoustic noise characterization. Extensive Finite Element (FE) and coupled field analysis study has been carried out on three configurations viz (a) SRM made of Sheet Steel (SRM-M19)(b)SRM made of Soft Magnetic Composite material 500 (SRM-SMC500) and (c)SRM made of Soft Magnetic Composite material 1000 (SRM-SMC1000) and few test results are presented.*

Key words: *Soft Magnetic Composite (SMC), Coupled Field Thermal analysis, Vibration and acoustic Noise analysis.*

1. Introduction

The proliferation of power electronics technology with advances in material science has led to the development of special machines for myriad applications in recent times. One of the special machines, the Switched Reluctance Motor (SRM) [1] is gaining recognition in the electric drives market due to its simple and rugged construction. Innovative practices in powder metallurgy technology has led to the development of Soft Magnetic Composite (SMC) materials that have unique properties [2]-[4], which include three dimensional (3D) isotropic ferromagnetic behavior, relatively low iron loss at medium and high frequencies, possibilities for improved thermal and vibration characteristics and a prospect for greatly reduced production cost. This paper investigates the suitability of SOMALOY [4], a soft magnetic composite material (SMC) for use in switched reluctance motor through static, dynamic, thermal, vibration and acoustic noise characterization. Three configurations viz a) SRM made of Sheet Steel (SRM-M19) (b) SRM made of Soft Magnetic Composite material (SRM-SMC500) and (c) (SRM-SMC1000) have been extensively studied.

2. Switched Reluctance Motor

The switched reluctance motor is a doubly salient but singly excited machine [1] wherein the stator carries the winding while the rotor is simply made of stacked silicon steel laminations. A Computer Aided Design (CAD) model of a 6/4 switched reluctance motor is shown in Fig. 1.

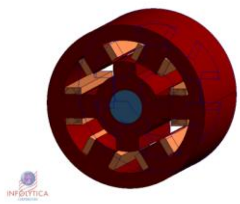


Fig. 1. The CAD model of 6/4 SRM.

3. Soft Magnetic Composites for Electric machines

Electrical steel of the non-oriented type finds application as core lamination material in different kinds of rotating electrical machines. The new soft iron powder metallurgy composite material (Somaloy®1000 3P (0.3P Lube), 800 Mpa) can be considered as an alternative for magnetic core of the electrical machines [24].The research avenues of global research groups working with SMC based electrical machines can broadly be classified into (a) Claw pole machines (b) Permanent Magnet machines and (c) Transverse flux machines. Jansson in early nineties first reported on the product process and properties of SMC materials for AC applications [9].The research group of the Newcastle University (A G Jack et.al), UK, has designed and constructed a prototype claw pole motor with SMC stator core characterized by high frequency complex 3D electromagnetic field [10].The research team at University of Technology, Sydney (UTS) (Y.G. Guo *et al.*) developed a low cost single and three phase claw pole permanent magnet motors using the SMC material SOMALOY™ 500 in late nineties and in early twenty first century [11], [12] and [22]. The use of SMC in transverse flux geometry was first attempted in 1996 by Mecrow *et al.*, who designed a 3-phase 3-stack transverse flux motor (TFM) capable of achieving very high specific torque with a novel structure using SMC core [13]. The team in UTS also developed a three-phase transverse flux permanent magnet SMC motor [14].The research team led by T. A. Lipo at University of Wisconsin-Madison has developed various types of Modular PM and Induction machines with fault tolerant capacity for different application requirements [15]. Cros *et al.* developed an all SMC universal motor with claw pole stator structure [16] while Kim presented a SMC universal motor by combination of SMC pole and silicon steel yoke [17]. Ronghai Qu *et al.* proposed a novel split-phase, claw pole, induction machine (IM) with SMC based stator core [18]. Axial flux SMC based permanent magnet machines had been developed by (i) Zhang *et al.* to achieve an efficiency of 68% for an axial flux PM brushless DC motor using SMC ABM100.32 [19] and (ii) Chen and Pillay presented the potential application of SMC material in low speed, directly driven, axial-flux PM wind generators [20]. Jiabin Wang and David Howe had analyzed the influence of three soft magnetic materials, viz, Transil300, Somaloy 500 and Somaloy 700 on the design and performance of a tubular PM machine to quantify their relative merits [23]. Recently Cvetkovski *et al.* demonstrated the performance improvement of PM synchronous motor by using SMC material [21].The *avant-garde* design, fabrication and development of an all SMC–SRM drive has been attempted by our research group with the objective of developing a low cost, low weight and low vibration switched reluctance drive system.

Soft Magnetic Composite (SMC) material is composed of surface-insulated iron powder particles and the powder is coated, pressed into a solid material using a die as depicted in Fig. 2. Finally the solid material blanks are heat-treated to anneal and cure the bond. SMC makes it possible to define a magnetic field in three dimensions, thereby permitting the designer to build an electric motor beyond the restrictions set by the traditional lamination technology. When compared with lamination steel it still posses the following desirable characteristics [4].

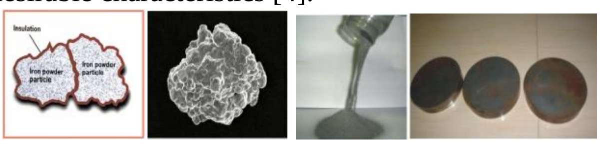


Fig. 2. Iron powder and prototyping solid material blanks for Somaloy1000 (height=20mm and diameter=120mm).

1. Reduced copper volume as a result of increased fill factor and reduced end winding length and reduced copper loss as a result of the reduced copper volume;
2. Reduced high frequency tooth ripple losses since the SMC has essentially very low eddy current losses;
3. Potential for reduced air gap length as a result of the tight tolerances maintained in manufacturing SMC material;
4. Stator is easily recyclable.

The B-H characteristics of M19 steel and SMC material SOMALOY shown in Fig. 3, reveals that the SMC has inferior relative permeability when compared with lamination steel.

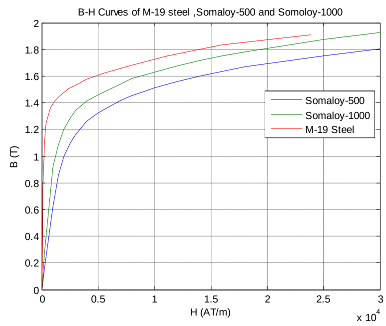


Fig. 3. B-H characteristics of M19 steel, SMC 500 and SMC 1000.

4. Static and Dynamic Characteristics

The static and dynamic electromagnetic characteristics [1,5] has been obtained using Finite Element Analysis (FEA) simulation studies. The finite element mesh along with the flux lines plot at the aligned position obtained through circuit coupled finite element analysis is shown in Fig.4 while the torque profile for SRM-SMC1000 motor is shown in Fig.5.

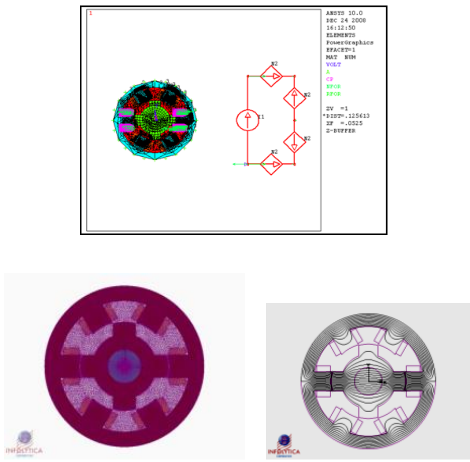


Fig. 4. Finite element mesh and the Flux lines plot for SMC1000-SRM.

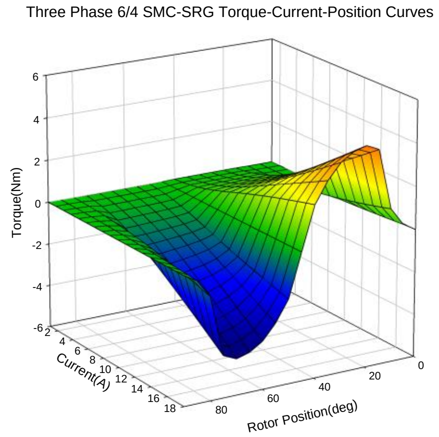


Fig. 5. T-i-θ characteristics of SMC 1000-SRM.

The self inductance profile of SMC1000-SRM for various current levels is shown in figure 6.

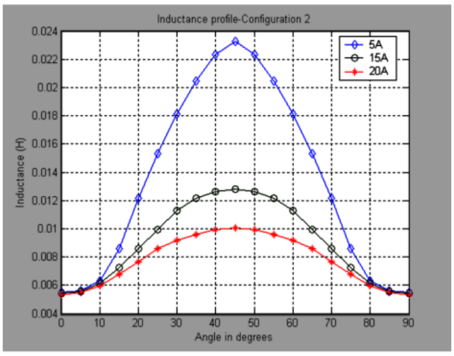


Fig. 6. Inductance profile of SMC 1000-SRM.

The torque characteristics for the two machine types has been illustrated in figure 7.

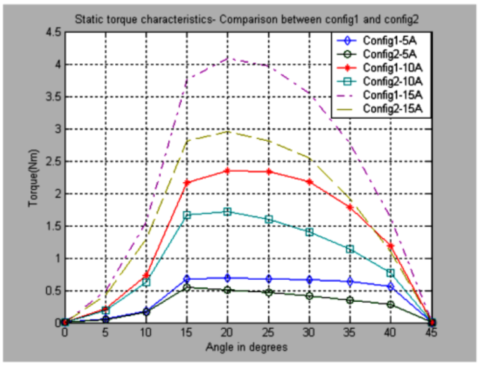
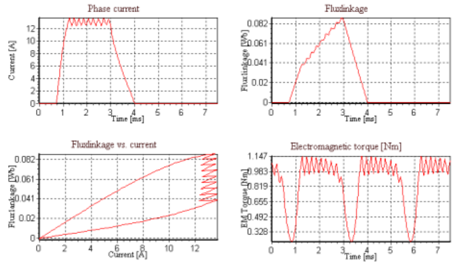


Fig. 7. Torque characteristics of the two motors.

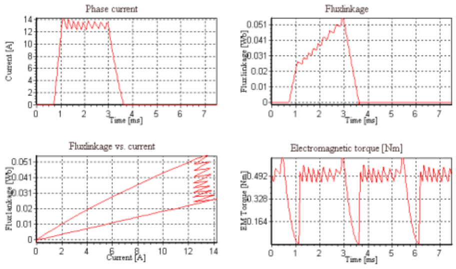
The comparative study results of torque and phase winding inductance for the three motors given in Table 1 reveal that the SRM-SMC motor suffers from poor effective torque owing to poor relative permeability of SMC material which is also evident from dynamic characteristics of the motors shown in Fig.8.

Table 1. Comparison of static torques and inductances

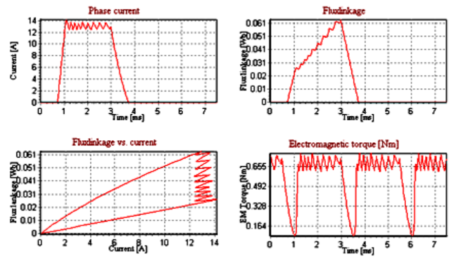
Type	Inductance (H)		Torque (N.m)		
			Effective Torque		
	L_a	L_{ua}	5A	10A	15A
SRM-M19	0.016	0.005	0.41	1.29	2.18
SRM-SMC 500	0.012	0.005	0.27	0.91	1.59
SRM-SMC 1000	0.014	0.005	0.31	0.95	1.64



(a)



(b)



(c)

Fig. 8. The dynamic characteristics of a) SRM -M19 b) SRM-SMC500 c) SRM-SMC1000 at a speed of 2000 r/min.

5. Coupled Field Electro Thermal Analysis

Thermal characterization of the SRM is performed considering the copper loss in the stator winding as heat source [7]. The thermal characterization through coupled field interaction enables the most accurate computation of the nodal temperature and the thermal gradient stresses [6]. The finite element formulation of coupled field analysis which treats single phenomenon uses matrix algebra and is represented by equation (1):

$$[K]\{X\}=\{F\} \quad (1)$$

Where $[K]$ is the coefficient matrix

$\{X\}$ is the vector of the nodal unknowns

$\{F\}$ is the known load vector

For direct matrix coupling is described by equation (2)

$$\begin{bmatrix}[K_{11}][K_{12}]\\ [K_{21}][K_{22}]\end{bmatrix}\begin{Bmatrix}[X_1]\\ [X_2]\end{Bmatrix}=\begin{Bmatrix}[F_1]\\ [F_2]\end{Bmatrix} \quad (2)$$

Coupled effects are accounted for by off-diagonal coefficient terms $K_{12}$and K_{21} provides for coupled response in solution after one iteration. The diagonal algebraic equation (3) for direct load vector coupling is

$$\begin{bmatrix}[K_{11}][0]\\ [0][K_{22}]\end{bmatrix}\begin{Bmatrix}[X_1]\\ [X_2]\end{Bmatrix}=\begin{Bmatrix}[F_1]\\ [F_2]\end{Bmatrix} \quad (3)$$

Coupled effects are accounted for by load terms $F1$and $F2$ provides for coupled response in solution after two iterations. The coupled field interaction combines two [6] physics fields: direct-coupled and indirect fields whose process chart is depicted in Fig.9. The nodal temperature distribution for SRM-SMC1000 is presented in Fig. 10.The nodal temperature distribution shown in Table 2 exhibit mediocre heat transfer capability for SRM-SMC1000.

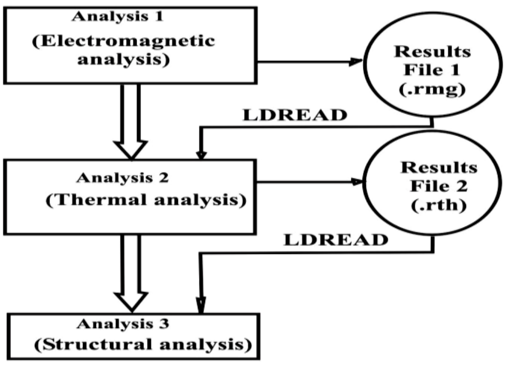


Fig.9. Data flow for coupled field analysis.

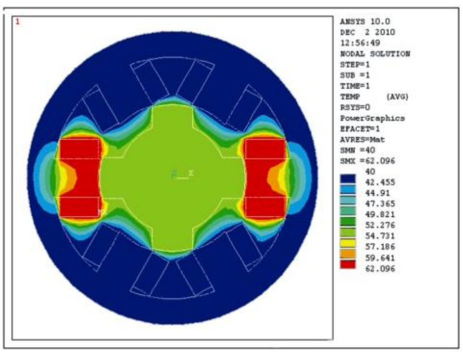


Fig.10.Nodal temperature distribution SRM-SMC1000.

Table 2. Nodal temperature distribution

Configuration	Coupled filed analysis
	Max. temp(°C)
SRM-M19	56
SRM-SMC 500	73.6
SRM-SMC 1000	62.1

6. Vibration and Acoustic Noise Prediction

The circumferential mode shape of the stator (m = 2) for SRM-SMC1000 is shown Fig. 11. The Fast Fourier Transform (FFT) of the acoustic noise level for SRM-SMC1000 shown in Fig. 12 gives the proportional intensity level of radial force [8] at each excitation frequency. Critical analysis of the Table 3 which shows the comparison of mode shape frequencies and acoustic noise level reveals that SRM-SMC1000 configuration is characterized by less acoustic noise level to the tune of 8% than SRM-M19.

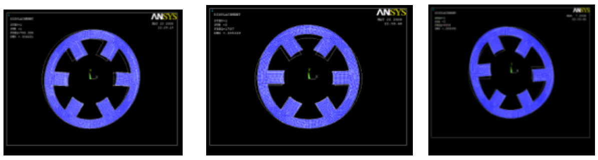


Fig.11.Circumferential vibration modes of SRM-SMC1000.

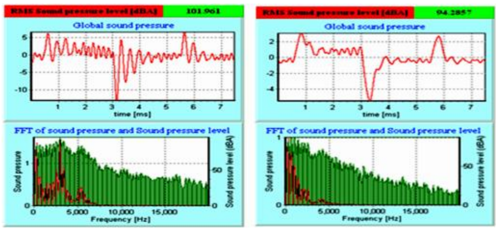


Fig. 12. FFT plots of acoustic noise level (sound pressure in dB) for SRM-SMC1000.

Table 3. Comparison of Mode shape frequencies and Acoustic noise level.

Type	SRM-M19	SRM-SMC500	SRM-SMC1000
Mode shape frequencies (Hz)	901 2298 3052 8632	700 1786 2338 6612	850 1910 2386 6748
Acoustic noise level (dB)	102	98.8	94.3

7. SRM-SMC1000 Drive Development

To validate the simulation study findings a prototype

SRM-SMC drive is under development which makes use of three blocks of prototyping material (SOMALOY-1000) which has been bonded by Loctite-638 epoxy glue. The bonded stator and rotor block has been subjected to precision machining to yield the stator and rotor of design dimensions. A glimpse of the fabrication process is illustrated in Fig.13.

Fig. 13.Fabrication process of SMC based SRM a) Bonded material blanks b) Machining process c) Stator and Rotor component of SMC switched reluctance motor.

The assembled stator and rotor with shaft ,windings along with rotor position sensor fixation scheme implementation is illustrated in Fig. 14.

Fig.14. The entire assembly process displaying the windings on the stator, slotted disk fixed to shaft,fixing photo sensors for position sensing and the associated wiring.

An asymmetric half bridge converter (AHBC) with three phase legs have been designed along with the necessary gate drivers as shown in figure 15.

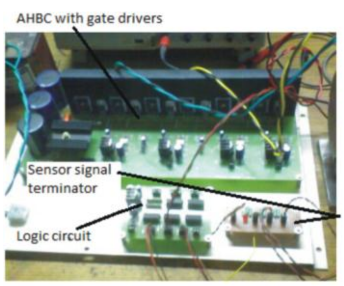


Fig.15.Power Electronic Converter and Controller.

The experimental setup for the impulse hammers excitation - free vibration test of the SMC-SRM using RT pro Photon data acquisition system is shown in figure 16.

(a) (b) (c)

Fig.16. Impulse hammer excitation-Free vibration test (a) accelerometer fixed to stator (b) Stator under test (c) Rotor under test.

A modal hammer is used to supply an impulse force signal (broad band force excitation). The setup is the same as that of the shaker excitation experiment, except that the hammer is used to supply the excitation source instead of shaker. With one hit, information for all the frequencies within interest can be recorded and ready for analysis. The test results depicted in figure 17 shows the impulse force and the measured vibration displacement in the frequency domain in the free vibration condition.

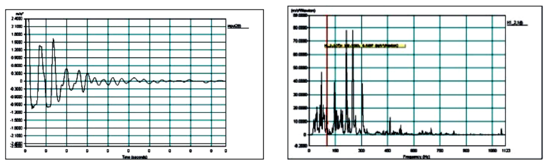


Fig .17. (a) Vibration test result of stator.

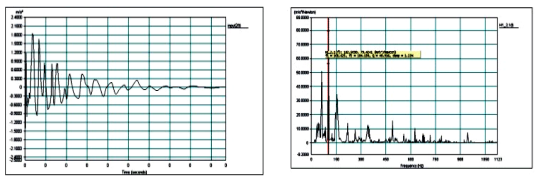


Fig .17. (b) Vibration test result of rotor.

The compliance of the stator structure at the normal operating condition is such that no special vibration mitigation effort is warranted in SMC1000-SRM drive shown in figure 18.

Fig.18. The SMC1000-SRM Drive System.

8. Conclusion

The study concludes that SRM-SMC motor albeit its poor average torque in comparison with conventional SRM-M19 motor, promises to possess acceptable heat evacuation capability. The overall vibration mode shape frequencies and acoustic noise level show that the structural capability of SRM-SMC is better when compared with SRM-M19 configuration.

9. References

[1] R. Arumugam, D. A. Lowther, R. Krishnan and J. F. Lindsay, "Magnetic field analysis of a switched reluctance motor using a two dimensional finite element model," *IEEE Trans. Magn*., vol. MAG-21, no. 5, pp. 1883-1885, Sep. 1985.

[2] M. Persson, P. Jansson, A. G. Jack, B. C. Mecrow, "Soft Magnetic Composite Materials – Use for Electrical Machines," *7th International Conference on Electrical Machines and Drive* at Durham, England, Sep. 1995.

[3] A.G. Jack, "Experience with the Use of Soft Magnetic Composites in Electrical Machines," *International Conference on Electrical Machines*, Istanbul, Turkey, 1998, pp. 1441-1448.

[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] K. N. Srinivas and R. Arumugam, "Analysis and characterization of switched reluctance motors: Part I—Dynamic, static, and frequency spectrum analysis," *IEEE Trans. Magn.*, vol. 41, no. 4, pp. 1306–1320, Apr. 2005.

[6] J.Driesen, H.De Gersem, R.Belmans and K.Hameyer, "Coupled thermal-magnetic analysis of a saturated permanent magnet motor," *Symposium on Power electronics and electrical drives advanced machines power quality*, pp. 1.1-6.

[7] K. N. Srinivas and R. Arumugam, "Analysis and characterization of switched reluctance motors: Part II—Flow, thermal, and vibration analysis," *IEEE Trans. Magn.*, vol. 41, no. 4, pp. 1321–1332, Apr. 2005.

[8] M. N. Anwar and Iqbal Husain, "Radial force calculation and acoustic noise prediction in switched reluctance motor," *IEEE Trans. Ind. Applicat.*, vol. 36, pp. 1589–1597, Nov./Dec. 2000.

[9] P. Jansson, "Soft magnetic materials for AC applications," *Powder Metallurgy*, Vol. 35, No. 1, pp. 63-66, 1992.

[10] A. G. Jack, B. C. Mecrow, C. P. Maddison, and N. A. Wahab, "Claw pole armature permanent magnet machines exploiting soft iron powder metallurgy," in *Proc IEEE Int. Conf. on Electric Machines and Drives,* Milwaukee, USA, May 1997, pp. MA1/5.1-5.3.

[11] 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.

[12] 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, 2005.

[13] 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.

[14] Y. G. Guo, J. G. Zhu, P. A. Watterson, and W. Wu, "Development of a PM transverse flux motor with soft magnetic composite core," *IEEE Trans. Energy Conversion*, Vol. 21, No. 2, pp. 426-434, June 2006.

[15] T.A. Lipo, S.M. Madani and R. White, "Soft Magnetic Composites for AC Machines -A Fresh Perspective," Research report, 2004-26.

[16] 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.

[17] B.T. Kim, "Design of new type universal motor using soft magnetic composites," *Journal of Electrical Engineering & Technology*, Vol. 1, No.2, pp. 211-215, 2006.

[18] R. Qu, G. B. Kliman, and R. Carl, "Split-phase claw-pole induction machines with soft magnetic composite cores," *in Proc. IEEE Industry Applications Society Annual Meeting*, Vol. 4, Oct. 2004, pp. 2514-2519.

[19] 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.

[20] Y. Chen and P. Pillay, "Axial-flux PM wind generator with a soft magnetic composite core," in *Proc. IEEE Industry Applications Society Annual Meeting*, Hong Kong, China, Oct. 2005, Vol. 1, pp. 231-237.

[21] G. Cvetkovski and L. Petkovska, "Performance improvement of PM synchronous motor by using soft magnetic composite material," *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 3812–3815, Nov. 2008.

[22] Youguang Guo, Jianguo Zhu, and D. G. Dorrell, "Design and analysis of a claw pole permanent magnet motor," *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 4582–4585, Oct. 2009.

[23] Jiabin Wang and David Howe, "Influence of soft magnetic materials on the design and performance of tubular permanent magnet machines," *IEEE Trans. Magn.*, vol. 41, no. 10, pp. 4057-4059, Oct. 2005.

[24] Ola Anderson and Paul Hofecker, "Advances in soft magnetic composites – materials and applications," resented at PowderMet2009, Las Vegas, USA, July. 2009.