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# Advanced SMC Motors and Drive Techniques

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## ABSTRACT

*New technological developments are often generated from breakthroughs of fundamental research, such as novel materials. A new opportunity that electrical machine designers and manufacturers are facing now is the application of another new material – the soft magnetic composite (SMC). The major advantage of using SMC material is to be able to manufacture SMC cores using the highly matured powder metallurgical technology at a cost much lower than that for manufacturing the conventional laminated steel cores. This paper presents the extensive studies on the measurement and modeling of magnetic properties of SMC materials, novel machine topologies of 3D fluxes, and advanced drive techniques, including sensorless brushless DC and direct toque control.*

## 1 INTRODUCTION

New technological developments are often generated from breakthroughs of fundamental research, such as novel materials. The discovery of the NdFeB permanent magnet (PM) is a good example. Because of its high remanence and coercivity, electrical machines made of NdFeB PM can be much smaller, lighter, and more efficient than the conventional ones. Nowadays, PM motors are widely used in various types of drive systems.

A new opportunity that electrical machine designers and manufacturers are facing now is the application of another new material – the soft magnetic composite (SMC). The SMC is made of pure iron powders coated with an inorganic insulation layer. SMC components can be fabricated by compressing the powders into a mould followed by a thermal curing process. The major advantage of using SMC material is to be able to manufacture SMC cores using the highly matured powder metallurgical technology at a cost much lower than that for manufacturing the conventional laminated steel cores.

The magnetic properties of SMC, however, are very different from that of the laminated SiFe, and therefore, non-conventional design method, machine topologies, and drive techniques should be employed for SMC motors. A great amount of research has been conducted along this line, and as shown by the experience a comprehensive understanding and accurate modeling of the magnetic properties is essential for design optimization of SMC motors [1-20]. This paper presents our extensive studies on the measurement and modeling of magnetic properties of SMC materials [3-9], novel machine topologies of 3D fluxes [10-16], and advanced drive techniques, including sensorless brushless DC and direct toque control [17-20].

## 2 MAGNETIC PROPERTIES OF SMC

### 2.1 Microscopic examination

The magneto-optical imaging (MOI) technique was employed to examine the microscopic structure and local magnetization of SMC samples in order to relate the magnetic properties to the magnetization mechanisms [7]. Fig.1 illustrates the MOI images of an SMC sample excited by a 50 Hz AC magnetic field perpendicular to the sample surface. From the MOI images, local magnetic hysteresis loops of the SMC sample can be derived from the brightness profile as shown in Fig.2.

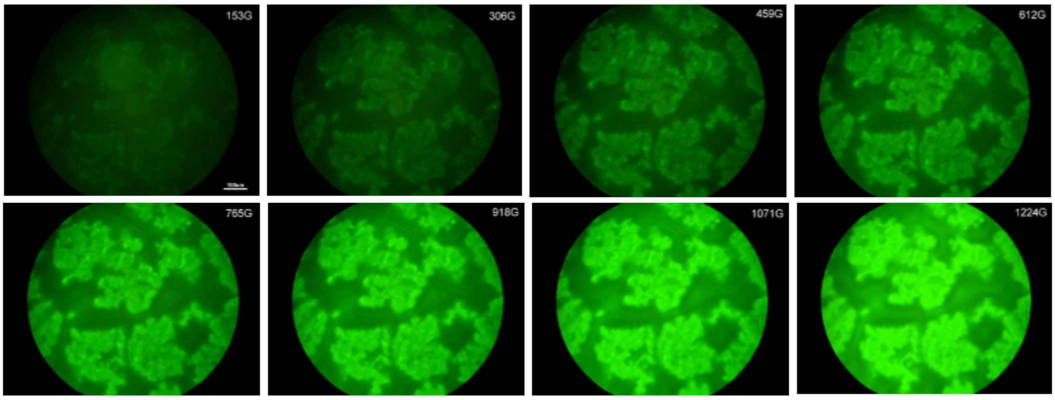


Fig.1 – MOI images of SMC sample under sinusoidal excitation

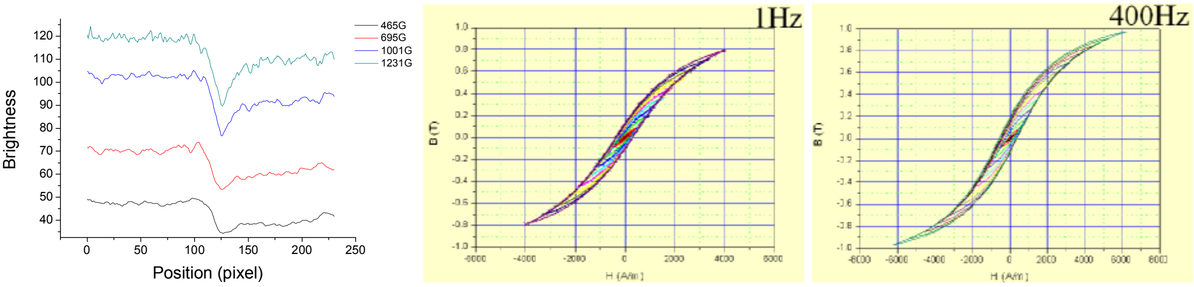


Fig.2 – Brightness profile and hysteresis loops of SMC sample

### 2.2 Vector characterization

Vector magnetic properties like B-H loci and core losses of SMC samples under various types of magnetic excitations, such as alternating and rotational with circular and elliptical fluxes, were measured with 2D and 3D magnetic testers [3-6]. Fig.3 presents an example of circular B-H loci in the XOY, YOZ, and ZOX planes, and Fig.4 the alternating and rotational core losses at different frequencies, where the core loss is calculated by

$$P_t = \frac{1}{T}\int_0^T \left(\mathbf{H} \bullet \frac{d\mathbf{B}}{dt}\right) dt \tag{1}$$

### 2.3 Vector magnetic property models

A vector reluctivity tensor model and core loss models were developed and employed in SMC motor design optimization [8-9]. When there is a phase difference between **B** and **H**, e.g. **B** lags **H** by an angle, the constitutive equation can be expressed as

$$H_i = \sum_j \nu_{ij} B_j \tag{2}$$

where $\nu_{ij}$ is the reluctivity tensor. Fig.5 illustrates the reluctivity tensor obtained from the vector characterization of the SMC sample.

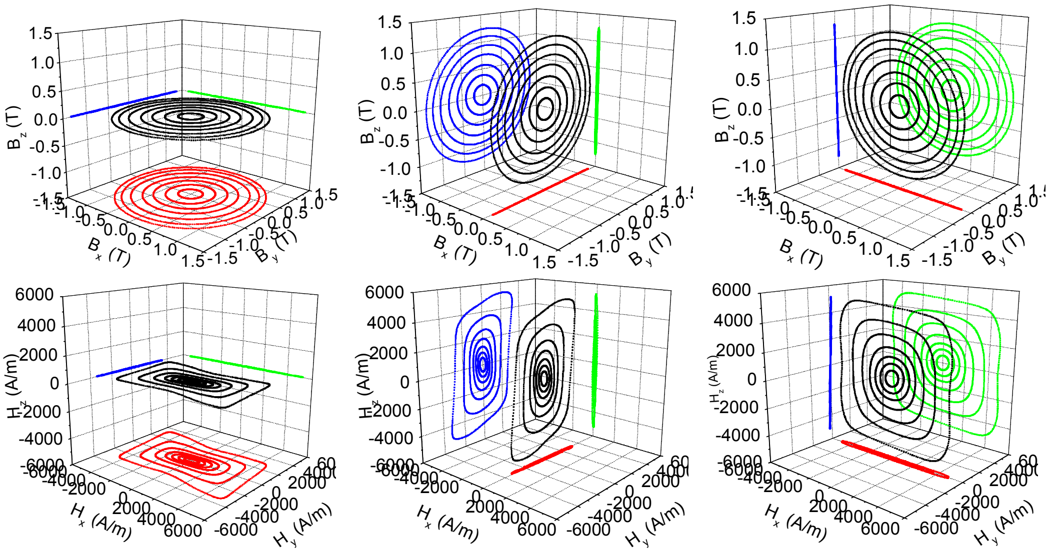
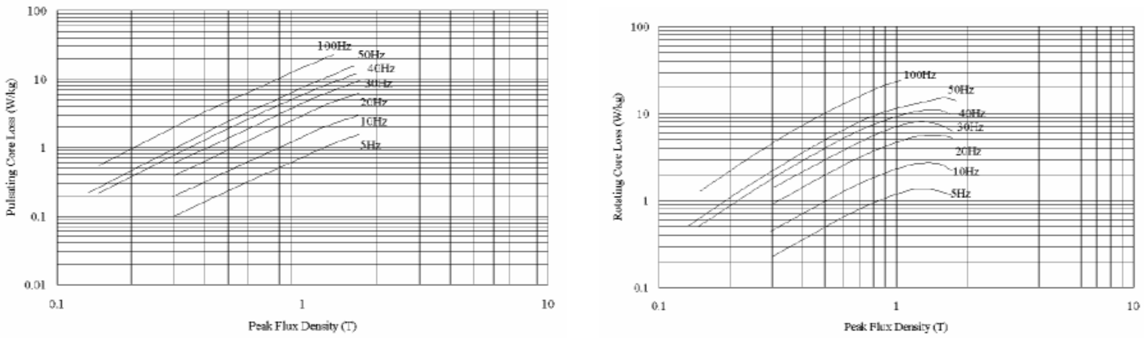
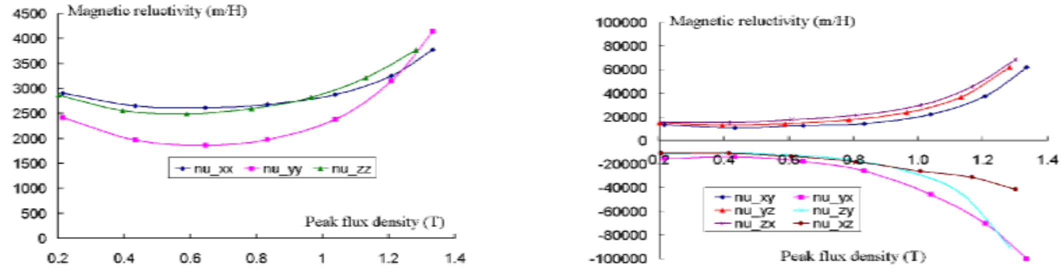


Fig.3 – B and H loci of SMC sample excited by rotating fields in different orientations



(a) (b)

Fig.4 – (a) Alternating and (b) rotational core losses



(a) (b)

Fig.5 – Magnetic reluctivity tensor: (a) diagonal terms, and (b) off-diagonal terms

With an alternating flux, the core loss can be calculated by

$$P_a = C_{ha} f B^h + C_{ea}(fB)^2 + C_{aa}(fB)^{1.5} \tag{3}$$

where $C_{ha}$=0.1402, h=1.548, $C_{ea}$=1.233x$10^{-6}$ and $C_{aa}$=0.3645x$10^{-3}$ for the SMC sample.

With a circular rotating flux, the core loss can be calculated by

$$P_r = P_{hr} + C_{er}(fB)^2 + C_{ar}(fB)^{1.5} \tag{4}$$

where

$$\frac{P_{hr}}{f} = a_1\left[\frac{1/s}{(a_2+1/s)^2+a_3^2} - \frac{1/(2-s)}{[a_2+1/(2-s)]^2+a_3^2}\right]$$

and $C_{er}$=2.3x$10^{-4}$, $C_{ar}$=0, $a_1$=6.814, $a_2$=1.054, $a_3$=1.445, and $B_s$=2.13 T for the SMC sample.

With an elliptical rotating flux, the core loss can be calculated by

$$P_{er} = R_B P_r + (1-R_B)^2 P_a \tag{5}$$

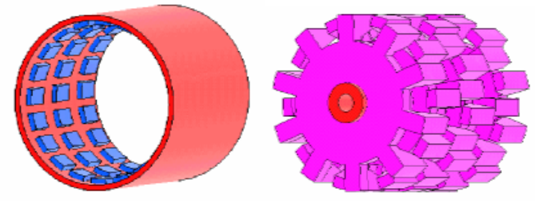
where $R_B=B_{min}/B_{maj}$.

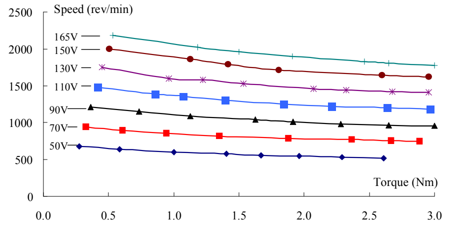
## 3 SMC MOTORS

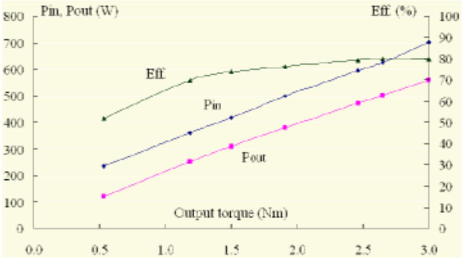
In order to develop low cost SMC motors with performance comparable to the conventional motor made of silicon steel sheets, various motor topologies were investigated [10-16]. Table 1 presents the parameters, topologies, and measured performance of a three phase claw pole SMC motor and a three phase transverse flux SMC motor driven by the brushless DC (BLDC) scheme (section 4) [10-14]. Fig.6 shows the photos of a high speed three phase claw pole motor operated at 20,000 rev/min [15-16]. We also developed a linear SMC motor. Restricted by our industry partner, we cannot present the topology in this paper.

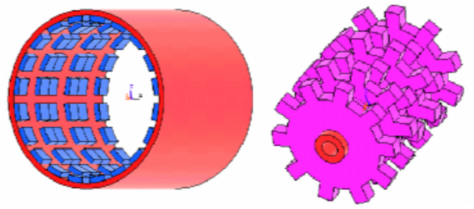
Table 1. Three phase claw pole and transverse flux SMC motors

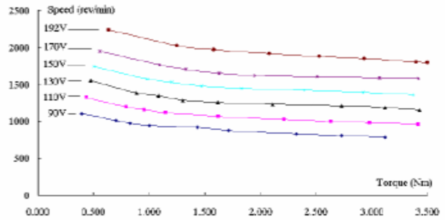
| **Three Phase Claw Pole BLDC Motor** | | **Three Phase Transverse Flux BLDC Motor** | |
|---|---|---|---|
| Rated frequency | 300 Hz | Rated frequency | 300 Hz |
| Number of poles | 20 | Number of poles | 20 |
| Rated power | 560 W | Rated power | 640 W |
| Rated voltage | 50 V | Rated voltage | 80 V |
| Rated current | 5.5 A | Rated current | 5.5 A |
| Rated efficiency | 80% | Rated efficiency | 80% |
| Permanent magnet | NdFeB | Permanent magnet | NdFeB |
| Stator core material | SOMALOY$^{TM}$ 500 | Stator core material | SOMALOY$^{TM}$ 500 |

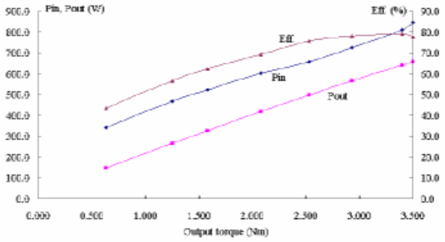












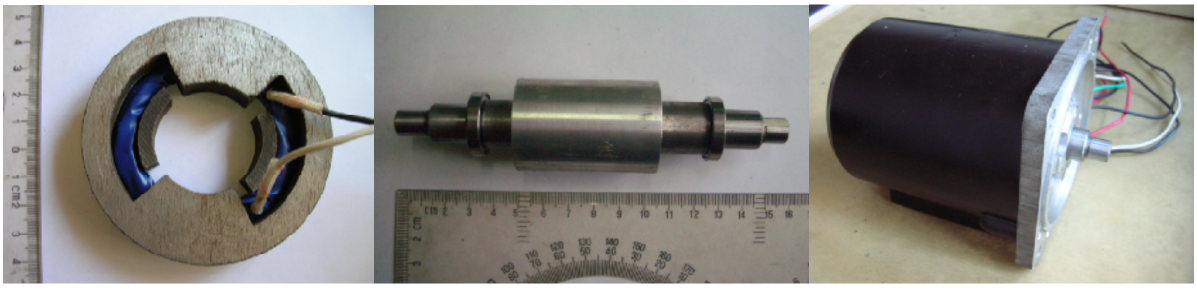


Fig.6 – High speed SMC motor

## 4 DRIVE TECHNIQUES

### 4.1 Brushless DC drive

The SMC motors presented in section 3 are drive by a sensorless brushless DC drive scheme. Fig.7 shows the block diagram and a photo of the controller prototype. The rotor position is obtained from the back emf signal. A special issue with the SMC motors is the high inductance of the stator windings. If the conventional back emf zero crossing switching technique is employed, the overall motor performance would be affected. In order to maintain the performance, the voltage drop across the stator winding inductance should be compensated. Low cost is a major objective for SMC motor drives. To achieve this goal, the PWM inverter has been dramatically simplified and a special switching algorithm is composed to avoid the performance deterioration [18].

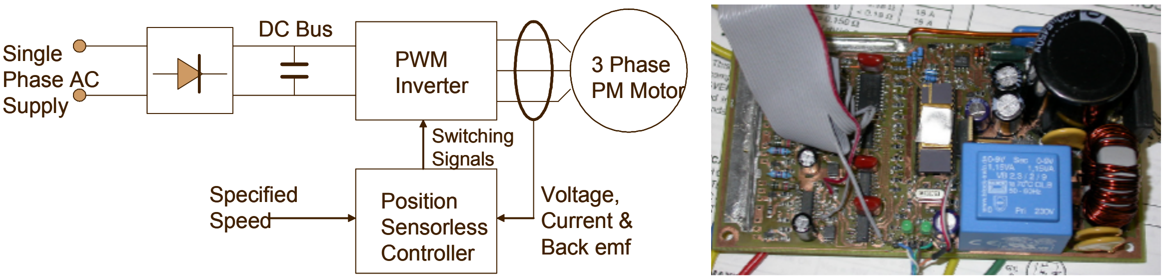
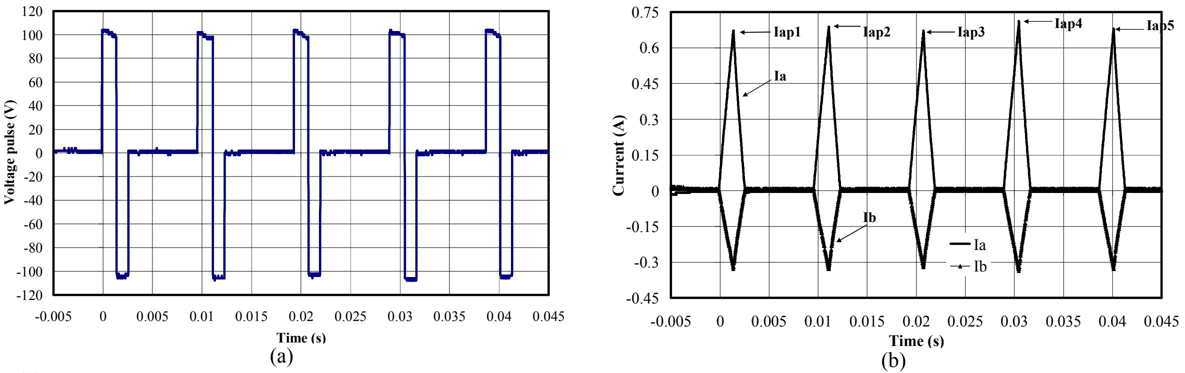


Fig.7 – Sensorless brushless DC drive

### 4.2 Direct torque control

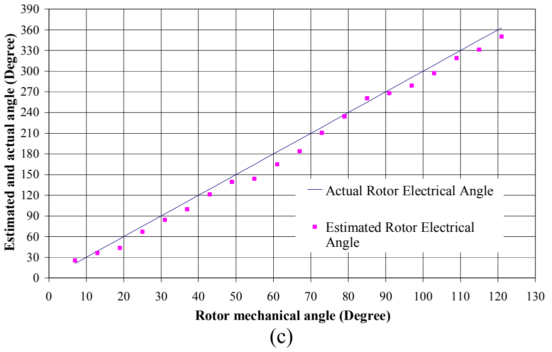
Direct torque control (DTC) can yield excellent steady state and dynamic performance. Two typical problems that are currently in the way of commercial application of the DTC scheme are large torque ripples and requirement of initial rotor position for starting with load. To solve the former problem, a refined switching table by the fuzzy logic and a space vector modulation techniques were investigated [17]. Both the simulation and experimental test show satisfactory results.

The latter is much more difficult for the SMC motors as they have far smaller structural saliency than those made of conventional silicon steels. To effectively study possible techniques for initial rotor position detection, a special permanent magnet motor model incorporating both structural and saturation saliencies was developed. Because of the very small structural saliency, the initial rotor position detection mainly relies on the saturation detection, which requires high current excitation. Fig.8 illustrates a method for detection initial rotor position using high voltage pulses, and the results of the estimated rotor positions versus the actual rotor position. In order to avoid the rotation of the rotor caused by the high currents, a negative voltage pulse is applied right after the application of the positive voltage pulse [19-20].



(a)

(b)



(c)

Fig.8 – (a) High voltage pulses, (b) peak current versus rotor position with high voltage pulses, and (c) Estimated and actual initial rotor positions.

## 5 CONCLUSION

As presented above, a comprehensive understanding and accurate modeling of the material is crucial for SMC motor design optimization, and the goal for low cost high performance can only be achieved through joint efforts on novel motor design, simplified power electronic converter hardware, and advanced control algorithms. Through the past years of hard work on the SMC material characterization and modeling, SMC motor design optimization, high performance drive techniques suitable for SMC motors, the technology development has finally reached the stage for commercial applications.

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