Iron Loss of Non-Rare Earth Traction Motor for Electric Vehicle

Masayuki Morimoto
Tokai University,
e-mail morimoto@ieee.org

***Abstract*—In this paper, non-rare earth traction motor for electric vehicles is discussed. Almost all HEV's and EV's use rare earth permanent magnet motor as a traction motor. The authors have proposed novel induction motor made of Soft Magnetic Composite (SMC) for the resource crisis of rare earth materials. Comparison of iron loss characteristics of SMC induction motor and conventional laminated induction motor is shown. As the result, iron loss of SMC motor is lower than that of the conventional laminated motor at high speed operation. An improvement of the production method of SMC core for the test motor will make efficiency high.**

Keywords; induction motor; iron powder; inverter drive; efficiency

I. INTRODUCTION

The resource crisis of rare earth materials has broke out in motor industry in the world. The resource of rare earth material is uneven distributed in the globe. The price of these materials is raising high and high strategically. Nowadays, many of electric motors use rare earth permanent magnet for the source of magnetic field. The efficiency of PM motors is high even in the partial load condition or at the low speed operation. Moreover, the control of PM motors is simple because it is a synchronous motor.

Nd-Fe-B magnet is mainly used for the motor of medium power below 100kW. High efficiency and high power density can be easily realized by using Nd-Fe-B magnet as a field magnet. Almost all hybrid electric vehicles in the market use several kilograms of Nd-Fe-B magnet in their traction motor.

Therefore, car industries and motor industries should consider about how to reduce rare-earth magnet and what is the alternative to the permanent magnet motors. The authors proposed one solution of non-rare-earth motor for traction [1]-[4]. The motor is a novel induction motor. The induction motor uses iron core of Soft Magnetic Composite (SMC). SMC is compressed iron powder which is easy to form by press molding. Recent advances of SMC material realized motors made of SMC [5]-[9]. However, these motors in the literature are all permanent magnet motors.

After 1990th, the developing effort of the motor is mainly on PM motors. New technology of design and manufacturing is applied to PM motors. Therefore, an induction motor is going to be thought as the past technology. The author believes that the improvement of the induction motor can be realized by the application of new technology to the induction motor. The use of SMC to the induction motor opens new aspect of the induction motor.

In this paper, the iron loss of SMC induction motor is discussed. The iron loss of SMC material, the iron loss of the core and the iron loss of the motor are compared experimentally. The result reveals that SMC induction motor has a potential for high performance.

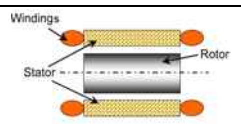
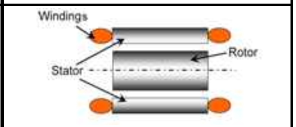
II. EXPERIMENTAL SMC MOTOR

A. Induction motor

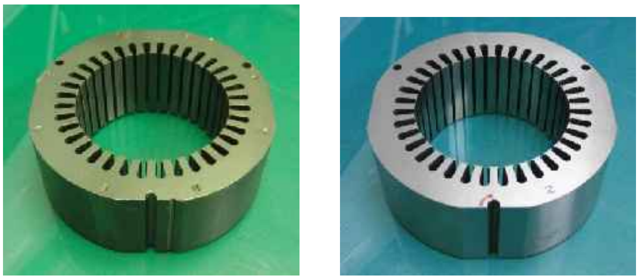
In this study, two induction motors are used. One is the induction motor made of conventional electromagnetic steel laminated core. The other is the induction motor made of SMC core. The SMC material used for the stator core is MBS318 (Mitsubishi Materials Corporation, now, Diamet Corporation).

The specifications of these motors are shown in Table I. The rated output is 750W. Two stators have same dimension of the slot design, and same winding configuration. The cage rotors for both motor use laminated core.

TABLE I. SPECIFICATIONS OF MOTORS

	SMC motor	Conventional motor
Structure		
Stator	SMC core	Electromagnetic steel laminated core
Rotor	Cage and lamination core	
Dimension	Same	
Winding	Same	
Connection	Y-connection	

B. Motor core



(a) laminated core (b) SMC core

Fig. 1. Picture of the stator cores.

Two kinds of stator core without windings are also manufactured. Fig. 1(a) shows conventional electromagnetic steel laminated core. The core material is 50A800. Fig. 1(b) shows the core manufactured by SMC. These two cores have same size and same shape. The difference is only their material.

III. Experimental Result

A. No load loss of the motor

Two kinds of test motor were driven by VVVF inverter at no load condition. The switching frequency of the inverter is 10 kHz. The comparison of measured iron loss is shown in Fig. 2. Motor loss of PWM waveform is measured by digital power meter (YOKOGAWA WT130). The iron loss is separated from measured loss by;

$$W_i = W_{measured} - 3ri^2 - W_{mech}$$

Where, W_i is iron loss, $W_{measured}$ is measured loss, r is winding resistance per phase, i is line current and W_{mech} is measured mechanical loss of the experimental system.

The iron loss of SMC motor is larger than that of laminated motor below 194 Hz. The iron loss of laminated motor is increasing with square of the running frequency, on the other hand, the iron loss of SMC motor seems to be proportional to the frequency. This implies that the major part of SMC iron loss is hysteresis loss, and that of laminated iron loss is eddy current loss. However, the loss shown in Fig. 2 is RMS loss, which is consists of fundamental frequency loss and switching frequency and harmonic loss.

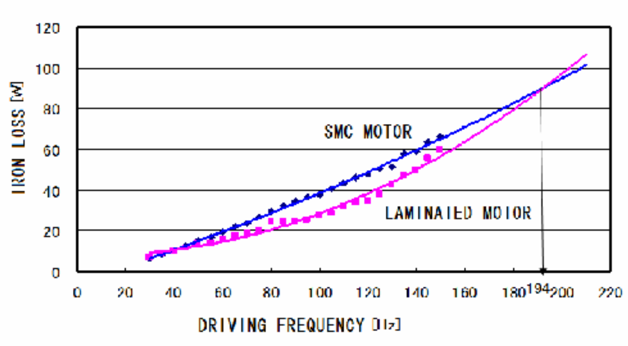


Fig. 2. RMS loss of motors

In order to drive motors by sinusoidal waveform, low pass filter is used as shown in Fig. 3. The effect of the filter

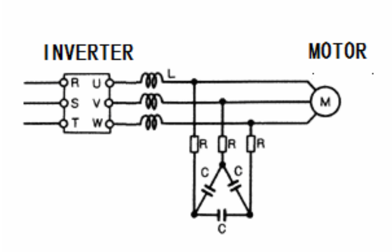
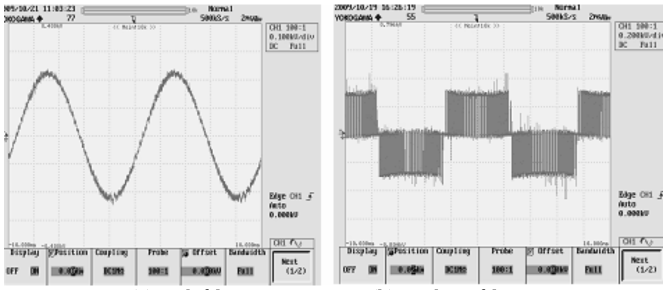


Fig.3. Circuit of low pass filter

on voltage waveform is shown in Fig.4. By the filter, waveform applied to the motor terminal is thought as sinusoidal wave.



(a) with filter (b) without filter

Fig.4. Voltage waveforms

The no-load loss driven by sinusoidal wave is shown in Fig. 5. The cross frequency is the frequency where the loss of both motor is same. The cross frequency decreases to 104 Hz by eliminating harmonics. And the losses of both motors are almost same value below 104 Hz. However, the curve of SMC motor is almost linear, but the curve of laminated motor follows square of the frequency.

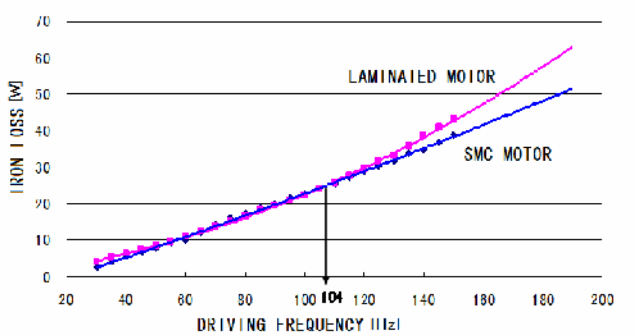


Fig. 5. Loss by fundamental component

B. Loss of the stator Core

The iron loss of stator cores shown in Fig. 1 is measured directly. B-H analyzer with current amplifier (IWATSU SY-8258) is used to measure the iron loss of the manufactured core.

The principle of the measurement is shown in Fig. 6. And, picture of the measurement system is shown in Fig. 7.

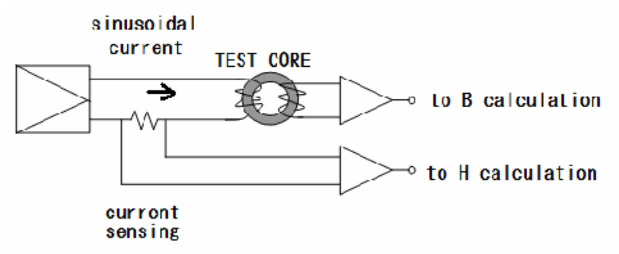


Fig. 6. Principle of B-H measurement

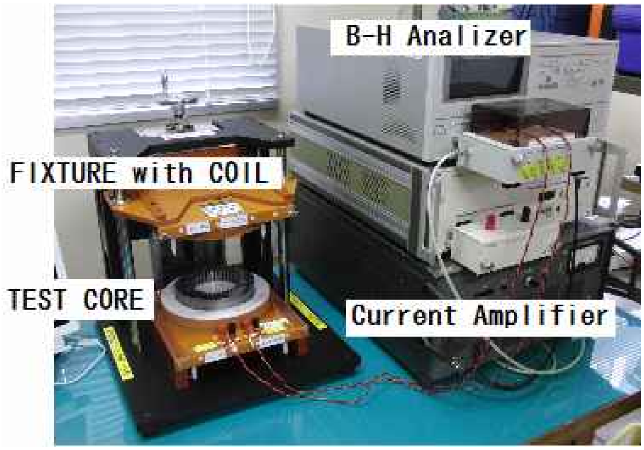


Fig. 7. Measurement system

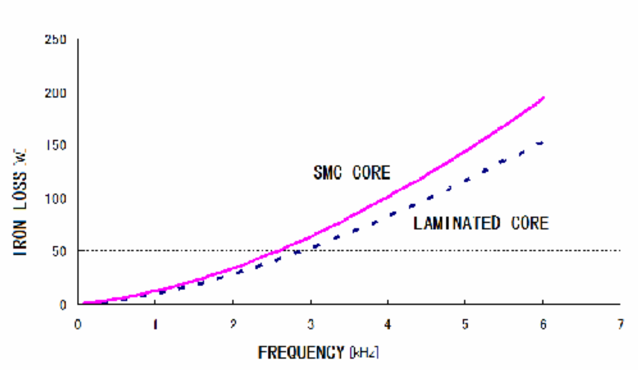


Fig.8. Measured iron loss of the stator core (B=0.1T)

The measured iron loss of the core is shown in Fig. 8. Iron loss of SMC core is larger than that of laminated core for all frequency. Measured iron loss of the motor shown in Fig. 2 and fig. 5 show cross frequency that means the loss of SMC is smaller at high frequency.

This contradiction comes from the mechanism of the generation of the iron loss of the motor. Ref[10] says that there are many causes of the iron loss at the motor operation for laminated motor. They are;

(1) distribution of flux

(2) rotating flux

(3) harmonics of time domain

(4) space harmonics

(5) superposition of flux

(6) mechanical strain and stress

(7) short circuit of the lamination

(8) temperature.

The measured iron loss of the motor is the sum of above causes. On the other hand, the cause of the measured core loss is only "distribution of flux". The causes of the iron loss of SMC motor are some of above. Direct comparison of motor loss and core loss is difficult by the measured data at present.

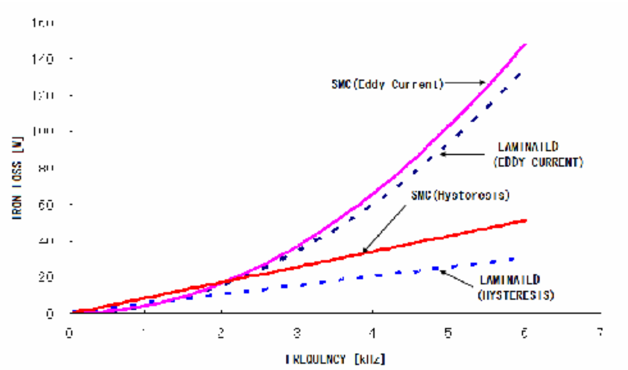


Fig.9. Separation of iron loss

Measured iron loss is separated into hysteresis loss and eddy current loss. The separation was done by following assumption.

$$\frac{W_{measured}}{f} = K_{hys} + K_{eddy} f$$

where, K_{hys} is hysteresis loss factor, and K_{eddy} is eddy current loss factor.

The separated iron loss is shown in Fig. 9. The result shows that there is considerable eddy current loss in SMC iron loss. The eddy current loss is as large as that of laminated core. SMC is small iron powder covered by insulation coating. Therefore, eddy current loss should be very small. The result is opposite to the principle of SMC.

C. The comparison to the material iron loss

The comparison of iron loss of material issued by manufacturer and measured core loss is shown in Fig.10. Major part of the material loss is the hysteresis loss. Eddy current loss of material is lower than hysteresis loss for all frequency. Measured hysteresis loss of the core is almost same as that of material. However, measured eddy current loss of the core is extremely large. Eddy current loss is a major part of the core loss.

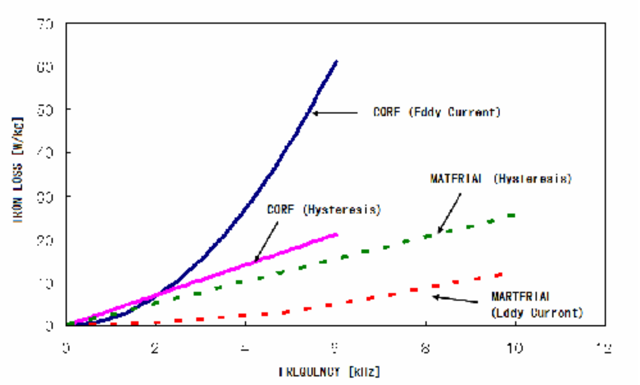


Fig. 10. Comparison of material and core

The cause of the increase of the eddy current loss is thought to be from manufacturing process of the core for the test motor. SMC is to be produced by press molding in a mass production process. But, in this case, the motor is trial design and trial manufacturing. So, the discharge machining and the grinding are used to form the shape of the core.

The heat by the friction at the machining degrades the insulation coating on layer near surface. As the result, the conductivity of the surface is high. The entire surface of the core is conductive. The conductive surface forms a circuit for the eddy current loop.

SMC should be molded even if the production is trial. At least, grinded surface should be covered by an insulation layer. An oxidation treatment after grinding makes insulation layer on the surface. That will make iron loss low and SMC core will show its specific characteristics.

IV. CONCLUSION

In this paper, iron loss of the motor, iron loss of the stator core and the iron loss of SMC material have compared experimentally. Iron loss of SMC motor by sinusoidal drive was almost same as that of the laminated motor even in degraded condition of SMC. The iron loss of SMC motor is lower than that of laminated. The grinding process of bulk SMC material to form trial production makes iron loss large.

Low iron loss at the motor operation can be expected if the molding is used for test machine.

ACKNOWLEDGMENT

Part of this work is supported by New Energy and Industrial Technology Development Organization (NEDO), Japan.

REFERENCES

[1] T. Fukuda, M. Morimoto, "Load characteristics of Induction Motor Made of SMC", The 11th International Conference on Electric Machines and Systems, CMP-02 (2008.)

[2] M.Morimoto, "Rare Earth less Traction Motor for Electric Vehicle", EVS24, The 24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition(2009)

[3] M.Morimoto, "Induction motor made of Iron Powder Core", EPE 2009, European Power Electronics Conference, DS2.11, No.0074(2009).

[4] Y.Sasaki, M.Morimoto, ""The Inverter Drive loss of Induction Motor Made by Soft Magnetic Composite", PEDS 2009, Power Electronics and Drive Systems, No. 453 (2009)

[5] A. Jack, B. Mecrow, P. Dickinson, D. Stephenson, J. Burdess, N. Fawcett and J. Evans, "Permanent-Magnet Machines with Powdered Iron Cores and Prepressed Windings", *IEEE Transactions on Industry Applications*, Vol. 36, No. 4, July / August, 2000.

[6] Y. G. Guo, J. G. Zhu, P. A. Watterson and W. Wu, "Comparative Study of 3-D Flux Electrical Machines With Soft Magnetic Composite Cores", *IEEE Transactions on Industry Applications*, Vol. 39, No. 6, November / December, 2003.

[7] Y. Alhassoun, C. Henaux, B. Nogarede, €Potential of Soft Magnetic Powders for Switched Reluctance Machines in Comparison with the Laminations Solution" , Proc. of ICEM 2004 ,p188(2004).

[8] F. Marignetti, V. C. Delli, R. D. Stefano, A. Cavagnino, "Design Issues Of A Fractional-Slot Windings Axial Flux PM Machine With Soft Magnetic Compound Stator€, 35Annu. Conf IEEE Ind. Electron Soc, Vol.33rd Vol.1 Page.187-192 (2007).

[9] H. Amano, Y. Enomoto, M. Ito, R. Masaki, M. Matsuzawa and M. Mita, "Characteristics of a Permanent-Magnet Synchronous Motor with a Dual-Molding Permanent-Magnet Rotor", *IEEE Power Engineering Society General Meeting*, 2007.

[10] C. Kaido, H. Mogi, T. Kawachi, M. Yabumoto and N. Suzuki, " The Effect of Manufacturing of Core Materials on the Performance of Rotating Machines", Technical Rep. of IEEJ, RM-02-09, pp11-16 (2002). (*In Japanese)*