Development of a Switched Reluctance Motor made of Permendur

Y Hasegawa¹, K Nakamura¹ and O Ichinokura¹
¹Graduate School of Engineering, Tohoku University,
6-6-05 Aoba Aramaki Aoba-ku, Sendai, Japan

E-mail: power15@ec.ecei.tohoku.ac.jp

Abstract. A switched reluctance (SR) motor consists of stator and rotor cores, and windings. Both the stator and rotor have salient poles. The stator has concentrated windings on each salient pole. On the other hand, the rotor has no windings and no permanent magnets. Therefore, the SR motor is a low cost, extremely robust, and wide-range variable-speed motor. The performance of the SR motor greatly depends on magnetic properties of core material since it consists of only iron cores and windings. This paper presents the development of a novel SR motor made of permendur which has extremely high saturation flux density and very low core loss. Two types of SR motors, one is made of conventional non-oriented Si steel, the other is made of permendur, are compared by simulation and experiment. It is demonstrated that the torque of the SR motor made of permendur is greater than that of the conventional Si steel by 20%.

1. Introduction
The demand for electric motors continues to increase in various fields such as home appliances, industries, and transportations. Hence, the improvement of size and weight, torque, and efficiency of the motors is strongly required.

A switched reluctance (SR) motor has a doubly salient pole structure. Concentrated windings are individually coiled around each stator pole, while the rotor is only made of iron core. Therefore, the SR motor is a low cost, extremely robust, wide-range variable-speed motor [1]. The performance of the SR motor depends on magnetic properties of core material since it consists of only iron cores and windings. In previous papers, we have investigated SR motors with divided-core [2] and with C-shaped-core [3], respectively, in order to utilize grain-oriented Si steel. These SR motors exhibited the high power and efficiency, but the productivity is low due to a complicated structure.

This paper presents the development of a novel SR motor made of permendur which has high saturation flux density and low core loss [4]. The permendur is an alloy created by mixing 49% cobalt with iron. The performance of the SR motor made of permendur is investigated by finite element method (FEM) and experiment.

2. Basic configuration and rotating principle of the SR motor
Figure 1 shows a basic configuration of an SR motor drive system. The drive circuit is called asymmetric half bridge converter. Each phase winding is connected to a couple of transistors and free-wheeling diodes. In the motoring mode, electric power from DC battery is supplied to the windings
through the transistors. Contrary to this, in the regenerating mode, stored energy of the SR motor is back to DC battery through the free-wheeling diodes.

Figure 2 illustrates the rotating principle of the SR motor. If the B-phase winding is excited when the A-phase stator pole and the rotor pole of● are aligned as shown in the figure, the rotor pole of □ is attracted to the B-phase stator pole by the electromagnetic force, and the rotor rotates to the position where the B-phase stator pole and the rotor pole of □ are aligned. After that, by switching the excitation phase to the C-phase, the rotor rotates continuously to the position where the C-phase stator pole and the rotor pole of ● are aligned. A continuous rotation can be obtained by switching the excitation phase with the appropriate order and position described above.

Now, let the rotor position angle be \( \theta \), which is 0 deg. when a rotor pole is aligned with the A-phase stator pole as shown in Figure 3(a), while \( \theta = \pm 45 \) deg at the unaligned position. Figure 3(b) illustrates the A-phase inductance \( L_A \), exciting voltage \( v_A \), and current \( i_A \), respectively. In the figure, the excitation beginning angle and the excitation width are \( \theta_b \) and \( \theta_w \), respectively.

If the magnetic nonlinearity is ignored, the A-phase torque \( \tau_A \) of the SR motor is given by,

\[
\tau_A = \frac{1}{2} i_A \frac{dL_A(\theta)}{d\theta}
\]

It is understood from (1) that the positive torque can be obtained when the A-phase winding is excited in Region I of Figure 3(b). On the other hand, the negative torque is generated when the A-phase winding is excited in Region II. Therefore, the SR motor requires the position detection by a rotary encoder or a hole sensor.
3. Trial machines and experimental and analytical conditions

Figure 4 shows the specifications of an SR motor used in the consideration. It has 12 stator and 8 rotor poles, respectively. Three-phase concentrated windings are arranged individually around each stator pole. The number of winding turns per phase is 140 and the winding resistance is 0.37 \( \Omega \) (the average value of three-phases).

Figure 5 shows the appearance of the trial SR motors, which have the same shape and dimensions shown in Figure 4 but have different core materials. One is made of conventional non-oriented Si steel with a thickness of 0.35 mm and the other is made of permendur with a thickness of 0.2 mm. Figure 6 shows the \( B-H \) curves of core material. The figure indicates that the saturation flux density of permendur is larger than that of conventional non-oriented Si steel by 40% or more.

Figure 7(a) shows a three-dimensional FEM model of the SR motor. Since the SR motor used in the study has a relatively flat body that the motor diameter is about three times as large as the stack length, the influence of the leakage flux in the axial direction cannot be neglected. Hence the three-dimensional electromagnetic field analysis is necessary. Figure 7(b) indicates an electric circuit model of the drive circuit, which is coupled with the FEM model. The transistors are approximately expressed as the ideal switches as shown in the figure.

In the experiment and FEM simulation, the DC battery voltage of the SR motor made of non-oriented Si steel is \( V_{DC} = 60 \text{ V} \). On the other hand, \( V_{DC} = 84 \text{ V} \) in the case of permendur since it has 1.4 times high saturation flux density as shown in Figure 6. The excitation beginning angle and the excitation width are \( \theta_b = 22.5 \text{ deg.} \) and \( \theta_w = 15 \text{ deg.} \), respectively.

---

**Figure 4.** Specifications of the 12/8-pole SR motor.

| Specification         | Value     |
|-----------------------|-----------|
| Stack length          | 40 mm     |
| Stator diameters      | 136 mm    |
| Rotor diameters       | 83.2 mm   |
| Gap                   | 0.2 mm    |
| Number of windings/phase | 140 turns |
| Winding resistance/phase | 0.37 \( \Omega \) |

**Figure 5.** Appearance of the trial SR motors.

**Figure 6.** Comparison of the \( B-H \) curves of core material.
Figure 7. Specifications of the 12/8-pole SR motor. (a) Three-dimensional FEM model of the 12/8-pole SR motor. (b) Drive circuit model.

4. Calculation and experimental Results

Figure 8 (a) and (b) indicate the observed and calculated voltage and current waveforms of the SR motors made of non-oriented Si steel and permendur. The measured rotational speed is conformed to calculate ones. These figures clearly indicate that both waveforms are in good agreement.

Figure 9 shows the comparison of the current density versus torque characteristics. It is understood that the torque of permendur at a current density of 10 A/mm$^2$ is 1.2 times larger than that of non-oriented Si steel, and that the measured and calculated values are in good agreement.

Figure 10 indicates the rotational speed versus torque characteristics. The SR motor made of permendur has wider speed and torque range.

Figure 11 shows the efficiency characteristics of the both motors. The efficiency of the SR motor made of permendur is improved from the conventional SR motor, especially under heavy load region.

Figure 8. Current and volt waveforms. (a) Non-oriented Si steel at a speed of 2000 rpm. (b) Permendur at a speed of 2500 rpm.
5. Conclusions

This paper presented the development of a novel SR motor made of permendur which has extremely high saturation flux density and very low core loss. The performance of the new developed SR motor was compared with the conventional SR motor by the FEM simulation and experiment. As a result, it was demonstrated that the torque of the SR motor made of permendur is greater than that of non-oriented Si steel by 20%, and that the speed range is wider and the efficiency is also improved.

6. References

[1] Becerra C R, Ehsani M, and Miller E J T 1993 Commutation of SR motors IEEE Trans. Power Electron. 8 257–263

[2] Nakamura K, Ono T, Goto H, Watanabe T, and Ichinokura O 2005 A Novel Switched Reluctance Motor With Wound-Cores Put on Stator and Rotor Poles IEEE Trans. Magn. 41 919-3921

[3] Murota K, Nakamura K, and Ichinokura O 2006 Calculation of Characteristics of an SR Motor with Divided Stator Core made of Grain-Oriented Silicon Steel 17th International Conference on Electrical Machines (ICEM 2006) OTA2-2

[4] Ish-Shalom J 1995 Composite Magnetic Structure for Planar Motors IEEE Trans. Magn. 31 4077-4079