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# The Fundamental Characteristics of Novel Switched Reluctance Motor with Segment Core Embedded in Aluminum Rotor Block

**Jun Oyama*, Tsuyoshi Higuchi*, Takashi Abe† and Keisuke Tanaka***

**Abstract** - We proposed a novel segment type switched reluctance motor (SRM) in which the segment core was embedded in aluminum (conductive metal) rotor block in order to increase the mechanical strength and easy manufacturing as well as to improve the performance characteristics and reduce the vibration and acoustic noise. This paper explains the operation principle and the drive system and shows the experimental results in comparison with the VR type SRM.

**Keywords**: Switched reluctance motor, Segment core, Aluminum rotor block

## 1. Introduction

Switched Reluctance Motor (SRM) is expanding it's application area, such as oil pressure pump, washing machine, etc, because of it's simple structure, maintenance free and low cost property. However, following problems still remain; low torque/volume ratio, high level vibration and acoustic noise [1, 2].

It was presented that the segment type SRM had better performance than conventional SRM, because it had twice magnetized poles compared with an usual VR type SRM [3, 4]. Where, the segment cores were arranged on the circumference of the rotor isolated magnetically, for examples, the segment cores were assembled onto a non-magnetic shaft and held by a stainless steel wedging system and it was potted using an epoxy compound. Therefore, it had some problems of complexity for manufacturing and weakness of mechanical strength. Here, we call such segment type SRM as a conventional segment type SRM.

We proposed a novel segment type SRM in which the segment core was embedded in aluminum (conductive metal) rotor block in order to increase the mechanical strength and easy manufacturing as well as to improve the torque performance [5]. The performance characteristics were investigated by the finite element method (FEM). The novel segment type SRM increased in the average torque by 40 % in comparison with the VR type SRM of same size. Where, the vertical force for one pole reduced by 76 %. And the novel segment type SRM increased in the average torque by 2.7 % and reduced in the vertical force for one pole by 4.8 % comparing with the conventional segment type SRM.

This paper explains the operation principle of the novel segment type SRM with aluminum rotor block and the control drive system. The improvement of machine performance in the novel segment type SRM over the VR type SRM is confirmed with experimental results.

## 2. Novel Segment Type SRM

### 2.1 Motor Structure

Fig. 1 shows the construction of our experimental segment type SRM with 6 stator poles and 4 rotor segment cores. The segment cores are embedded in aluminum rotor block and the stator has full pitch windings. The design parameters shown in Table.1 are roughly optimized for average torque using the finite element method (FEM). Fig 2 shows photos of the stator and rotor core of the novel segment type SRM

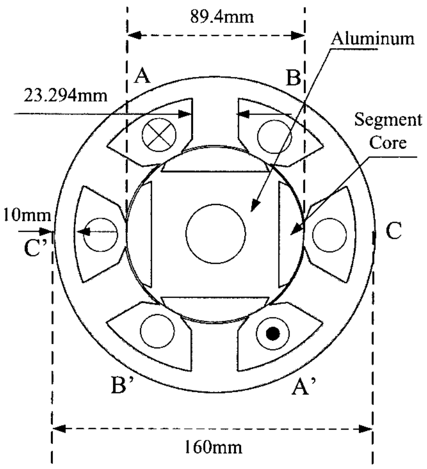

**Fig. 1** Construction of novel segment type SRM

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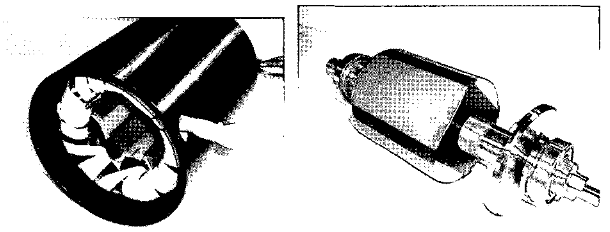
**Table 1** Design Parameters

| | |
|---|---|
| Rated speed | 1,800 rpm |
| Motor length | 100 mm |
| Stator outer diameter | 160 mm |
| Stator back iron depth | 10 mm |
| Stator pole width | 28 mm |
| Rotor outer diameter | 89.4 mm |
| Gap length | 0.3 mm |
| Winding number of turns | 150 |



**(a)** Photo of the Stator **(b)** Photo of the Rotor

**Fig. 2** Photo of novel segment type SRM

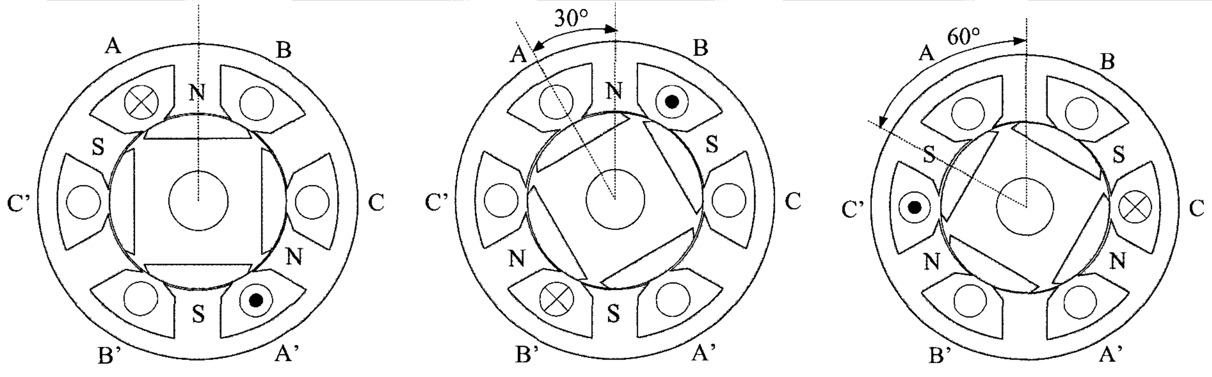
## 2.2 Operation Principle

Fig. 3 facilitates the understanding of the motor operation. When the A and A' phase windings are excited, both side stator poles of the A and A' windings are magnetized and the rotor rotates counterclockwise by 30 degree. Then rotor rotates continuously with switching the excitation to B and B', and then C and C'.

## 2.3 Special Merits

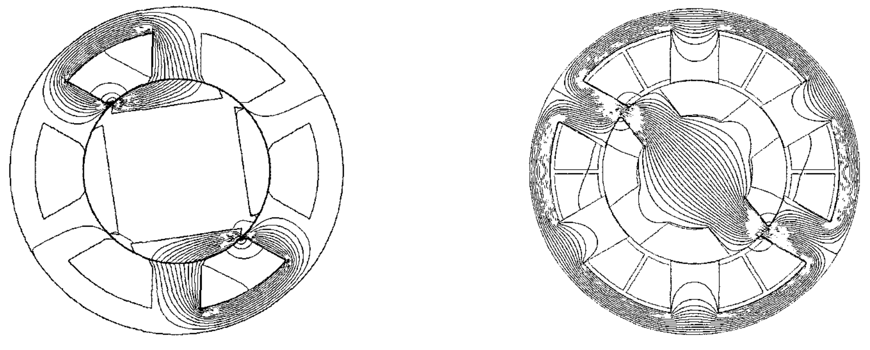
Fig. 4 shows the flux distributions of the segment type SRM and the VR type SRM at 8 degrees. It is confirmed that the novel segment type SRM has two small flux loops through two stator poles and one segment core while the VR type SRM has two large flux loops through two stator poles and two rotor poles.

Therefore, the novel segment type SRM is expected to have following special merits. (a) The vibration and acoustic noise are reduced rather than the VR type SRM, because the four stator poles are always excited among the six poles and the radial attractive force is dispersed electromagnetically. (b) The torque/volume ratio increases because of the twice magnetized stator poles in comparison with the VR type SRM. The additional copper loss in the long coil end and the eddy current loss in the aluminum block affect motor efficiency. But the flux distributes comparatively in parallel with the circumference of the rotor owing to the eddy current induced in the aluminum block, therefore, the torque characteristics are improved. (c) The novel segment type SRM has a simple and



**(a)** Starting phase A excitation **(b)** Starting phase B excitation **(c)** Starting phase C excitation

**Fig. 3** Construction of novel segment type SRM



**(a)** Novel segment type SRM **(b)** VR type SRM

**Fig. 4** Flux distributions (8 degrees) robust rotor structure suitable for high speed applications and easy manufacturing, since the segment cores are secured in the aluminum block structurally.

## 3. Experimental System

### 3.1 Drive System Hardware

Fig.5 shows an overview of the drive system hardware. This system consists of the novel segment type SRM, the bipolar type driver using IGBT-based voltage source inverter and the controller using the floating point 32 bit DSP TMS320C31. The following events are processed in the DSP, such as rotor speed calculation using rotor position information from the rotary encoder, selection of the phase to apply current command from the table corresponding with position information, decision of current command to output through D/A converter. The sampling period of the all events is 100μs. The gate pattern for IGBTs is generated by comparing the current command with a measured armature current. The PWM inverter has 12 IGBT devices and is used not only for bipolar drive test but also for unipolar drive test.

### 3.2 Control method

Fig.6 shows the measured inductance profile for one phase of the novel segment type SRM. Output torque of the SRM is in proportion to the slope of motor inductance and excitation current. If the excitation current is supplied during the rising slope of the inductance, the positive torque is produced, and if the excitation current is supplied during the falling slope of the inductance, negative torque is produced. Therefore, the turn-on and turn-off angles of stator currents should be dependent upon the rotor position and are important control parameters. The control method, in which the current command is supplied in advance before the inductance begins to increase, is called 'advanced firing angle control' and is illustrated in Fig.7(a). The optimal value of the advanced firing angle is dependent upon motor speed, load current and inverter DC voltage. The another control method, in which the IGBT is turned off earlier before the inductance begins to decrease, is called 'cut-off angle control' and illustrated in Fig.7(b).

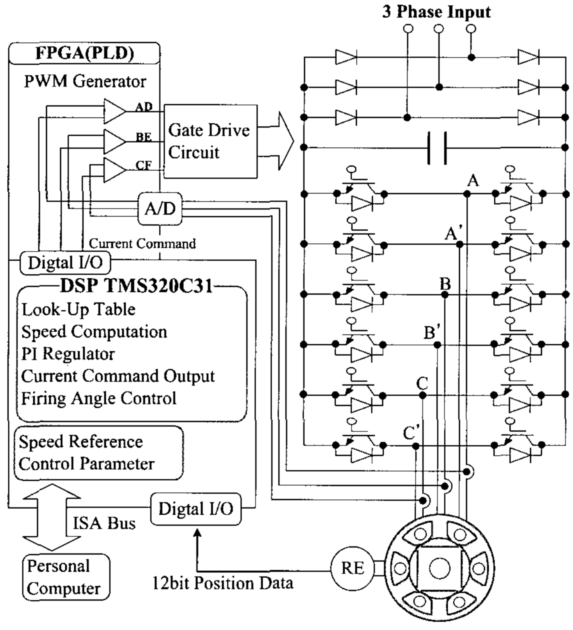


**Fig. 5** The overview of drive system hardware

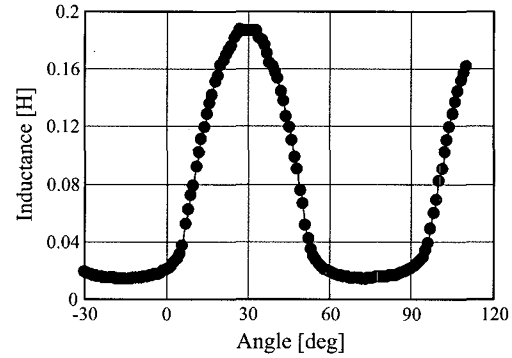
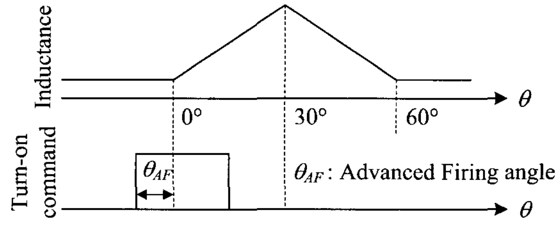
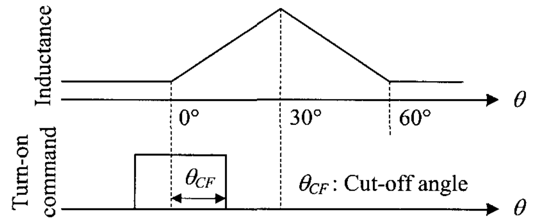


**Fig. 6** The measured inductance profile



**(a)** Advanced firing angle control



**(b)** Cut-off angle control

**Fig. 7** Firing Angle Control

### 3.3 Measuring Equipment

Fig.8 shows a photo of the measuring equipment for the load test. The load is a servo motor that is connected to the motor axis through a torque detector. Motor output is calculated from the torque and the motor speed. Also, input effective (RMS) value is measured using WT-130 made by YOKOGAWA ELECTRIC.

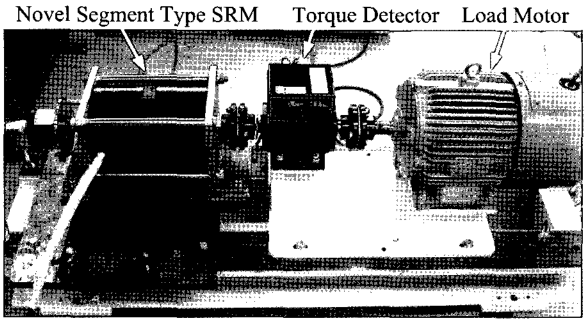
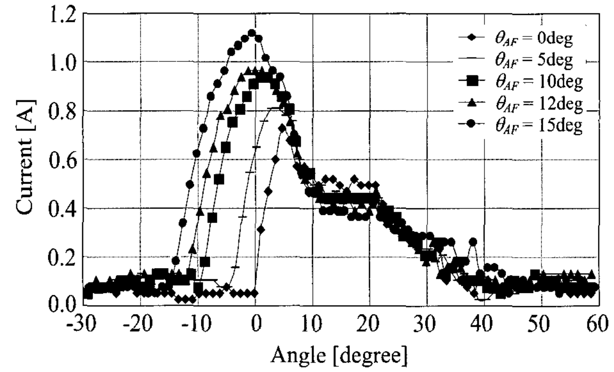


**Fig. 8** Photo of Measuring Equipment

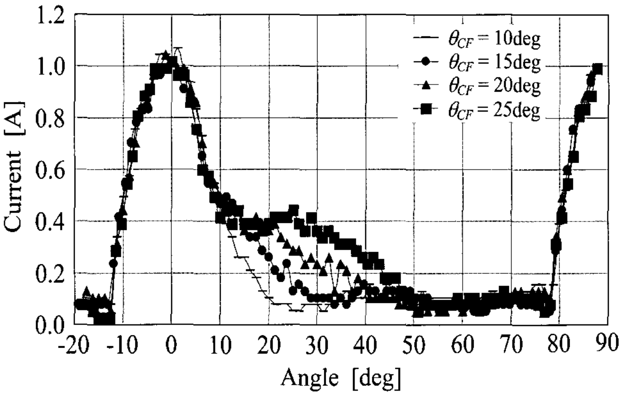
## 4. Experimental Results

### 4.1 Current Wave-forms

Fig.9 shows the measured current wave-forms for one phase under advanced firing angle $\theta_{AF}$ control and cut-off angle $\theta_{CF}$ control. Fig.9(a) shows the effect of the varying the advanced firing angle $\theta_{AF}$, when the cut-off angle $\theta_{CF}$ = 20 degrees and rotor speed $\omega$ = 1,000rpm. The peak current increases with increasing advanced firing angle. However, the too large current before the rising slope of the inductance reduces the efficiency. Fig.9(b) shows the effect of the varying the cut-off angle $\theta_{CF}$, when the advanced firing angle $\theta_{AF}$ = 12 degrees and rotor speed $\omega$ = 1,000rpm. The remaining current increases with increasing cut-off angle $\theta_{CF}$. The remaining current generates the braking torque when the inductance slope is negative.



**(a)** The measured current wave-forms
($\theta_{CF}$ = 20 degrees and $\omega$ = 1,000rpm)



**(b)** The measured current wave-forms
($\theta_{AF}$ = 12 degrees and $\omega$ = 1,000rpm)

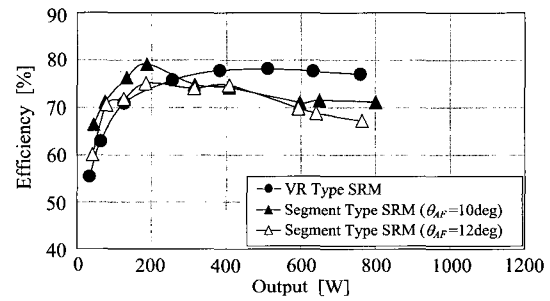
**Fig. 9** Firing Angle Control

### 4.2 Efficiency and power factor

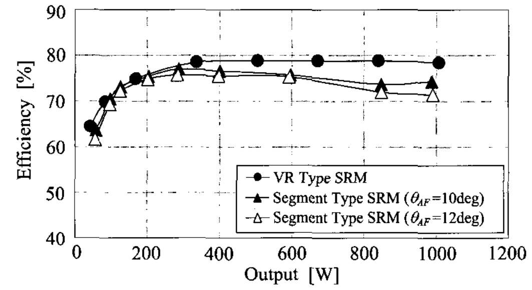
The comparison of output characteristics of segment type SRM and VR type SRM are given in Fig.10 to Fig.13. In these experimental results, the control parameters for VR type SRM are decided using the optimized approximate equations of the advanced firing angle for high efficiency. But the control parameters for segment type SRM are roughly selected from the results Fig.9. In Fig.10, the segment type SRM has better efficiency characteristics in comparison with the VR type SRM in low output region. The power factor of the segment type SRM are improved several percents as compared with the VR SRM as shown in Fig.11. At the high speed region of Fig.12 and Fig.13, the maximum output of the segment type SRM increases considerably, as it requires less input current for the same output and speed as shown in Fig.13.

## 5. Conclusion

The operation principle, control method and drive system for a novel segment type SRM with aluminum rotor block are presented. It is shown from the experimental results that the segment type SRM has better performance than the VR type SRM.

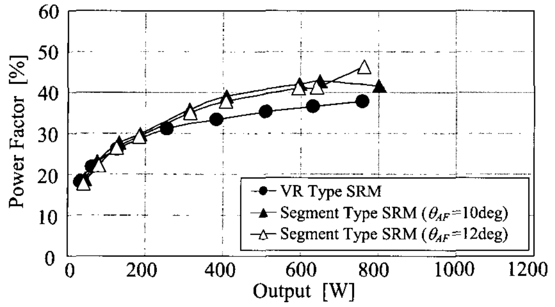


**(a)** 600rpm

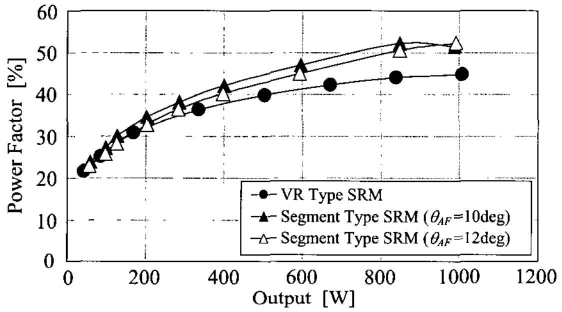


**(b)** 800rpm

**Fig. 10** Efficiency-Output characteristics



(a) 600rpm



(b) 800rpm

**Fig.11** Power Factor-Output characteristics

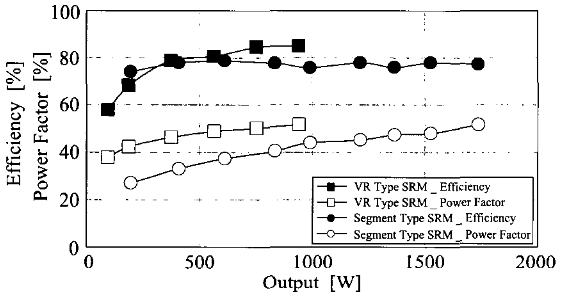


**Fig. 12** Efficiency, power factor - output characteristics (1,800 rpm)

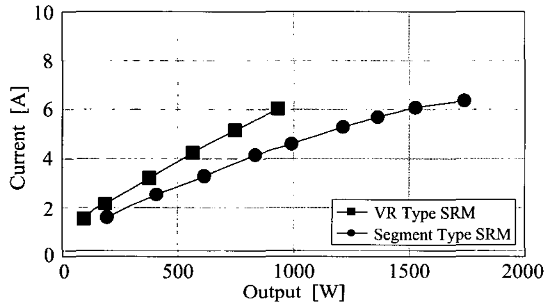


**Fig. 13** Current - output characteristics (1,800 rpm)

## References

[1] J. M. Stephenson, Switched Reluctance Motors, *IEEE/IAS Tutorial Course*, held in Seattle, USA, October 12, 1990, pp.4-35

[2] T. J. E. Miller, Ed., "Switched Reluctance Motors and their Control", Lebanon, OH:Magna Physics/Oxford University Press (1993)

[3] T. J. E. Miller, Ed., "Electronic Control of Switched Reluctance Motors", ser. Newnes Power Engineering Series. Oxford, U.K.:Newnes (2001)

[4] B. C. Mecrow, J. W. Finch, E. A. El-Kharashi and A. G. Jack: "The Design of Switched Reluctance Motors with Segmental Rotors" Conference Record of ICEM 2002 No. 336 (2002)

[5] B. C. Mecrow, J. W. Finch, E. A. El-Kharashi and A. G. Jack: "Switched Reluctance Motors with Segmental Rotors" IEE Proc. of Electr. Power Appl., Vol. 149, No. 4, pp. 245-254 (2002)

[6] Jun Oyama, Tsuyoshi Higuchi, Takashi Abe and Nobuyuki Kifuji: "Novel Switched Reluctance Motor with Segment Core Embedded in Aluminum Rotor Block", IPEC-Niigata, No.S35-5, pp.1260-1265 (2005)

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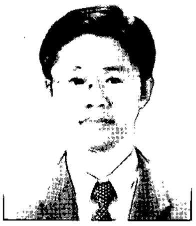

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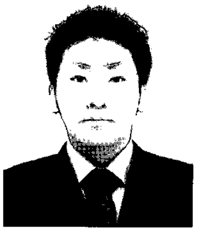

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