Investigation on the Characteristics of a Novel Segmental Switched Reluctance Motor Driven by Asymmetric Converter and Full-Bridge Inverter

Tao Sun[1], Ji-Young Lee[2], and Jung-Pyo Hong[1], *Senior Member, IEEE*

[1]Department of Automotive Engineering, Hanyang University

[2]Industrial Electric Machine Group, Korea Electrotechnology Research Institute

***Abstract*-- The drive of switched reluctance motor usually use the conventional asymmetric converter, which increases the cost of overall system. A novel segmental switched reluctance motor (SSRM) not only can be driven by the conventional converter, but also can be driven by the full-bridge inverter. The use of inverter makes the drive cost reduced. This paper deals with an investigation on the characteristics of a SSRM driven by the converter and inverter. First, the Finite Elements Analysis is employed for the determination of the motor's inductance profiles. And then, the results are used to explain the feasibility of inverter drive using for this SSRM. Depending on the parameters and the terminal voltage equations, the dynamic simulation can be implemented in coupled field circuit method. This series of analysis methods has been verified through examining a conventional toothed-structure switched reluctance motor (CSRM). After dynamic analysis, all the characteristics of the CSRM, the SSRM driven by asymmetric converter and the SSRM driven by full-bridge inverter will be compared to show their merits and demerits.**

I. Introduction

Switched Reluctance Motor (SRM) has been used in various fields for many years, which is due to its some special merits such as simple structure, low cost, extremely high speed, and running under terrible environment. However, the comparatively expensive and complicated drive system, high torque ripple and wind resistance seriously weaken its development and performance [1-5]. For conventional V-type SRM (CSRM), these drawbacks are inherent because of the asymmetric converter and the toothed rotor and stator structure. The authors of [3] introduced a toroidal SRM. The stator coils are wounded around the yokes of the stator make the motor driven by a common full-bridge inverter which is able to consist of the common packaged IGBT or MOSFET. However, as the drive system is decreased, the increased cost in winding manufacture cannot be ignored. [4] and [5] proposed two improved segmental SRM (SSRM). Especially, the SSRM proposed in [5] has a simple structure and winding strategy. It behaves lower torque ripple, lower vertical force, higher average torque and low wind resistance comparing with CSRM of same size. In addition, it has better efficiency and power factor in high speed.

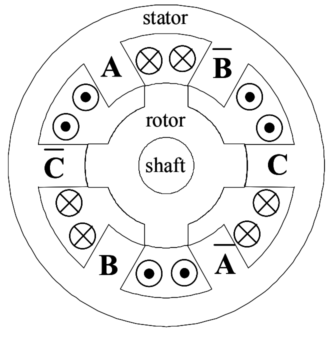
Although the major characteristics of the SSRM have been presented in [5], the studied contents are considered with a 12-IGBT PWM inverter. Because the single phase is switched in any time, this device can be replaced by a conventional asymmetric converter. In fact, owning to the overlap line inductance, this SSRM also can be driven by a full-bridge inverter to excite two phases simultaneity during each 60°. This drive strategy does not only reduce the cost and complexity of the drive system, but also reduce the switching loss, which has a remarkable meaning in high speed operation.

Hence, this paper investigates the characteristics of the SSRM which is driven by asymmetric converter and full-bridge inverter, respectively. Firstly the inductances of the prototype SSRM are calculated by Finite Elements Analysis (FEA). And then, the novel drive strategy is explained by using inductance profiles and flux pattern. The coupled field circuit method is employed for the transient analysis. That is, according to the asymmetric converter circuit and full-bridge inverter circuit, the terminal voltage equations of SSRM are established and solved with corresponding flux equations at the same time. Finally, according to speed variation, the characteristics of current, torque, output power and efficiency are obtained by dynamic simulation. And all the characteristics of the SSRM driven by asymmetric converter and full-bridge inverter will be compared with those of CSRM to show its merits and demerits.

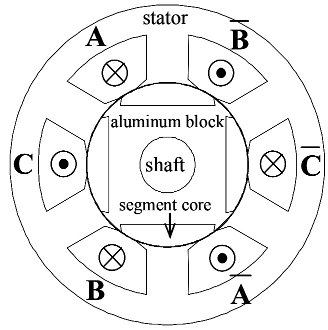
II. Analysis Model and Drive Topology

A. Analysis Model

The cross-section models of the CSRM and SSRM are shown in Fig. 1 (a) and (b), respectively. The CSRM is the same to the conventional toothed-structure design, while the SSRM is designed with distributed winding in stator and the segment cores embedded in rotor. The embedded structure is



(a) Cross-section of CSRM



(b) Cross-section of SSRM

Fig. 1 Cross-section of two models

for simplifying the manufacture process. In order to get wider surface to reduce the torque ripple, the rivet or wedge also can be used for fixing the segment cores. In addition, the block clamping the cores also can be aluminum and stainless steel material alternatively.

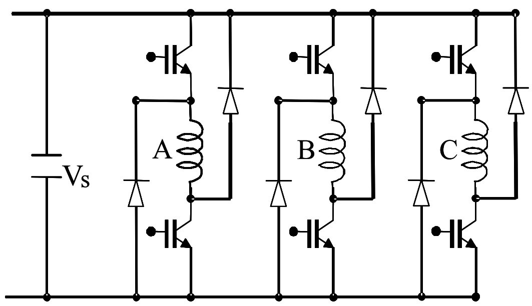
B. Drive Topology

Although it is so different between these kinds of SRM, they can be driven by one asymmetric converter as shown in Fig. 2 (a). Due to the converter configuration, the general 6-switch IGBT module package cannot be used and in addition six external fast recovery diodes are required. In these days, semiconductor device companies developed an IGBT module, which has an IGBT with an external diode in series in a same package. However, even in this case, two models are needed to consist a one phase, so that six models are implemented on a heat sink to drive a three-phase SRM. On the other hand, in case of the 3-phase AC motor, such as the Permanent Magnet Brushless DC Motor (BLDCM) with wye connected or delta connected winding characteristics, the full-bridge inverter shown in Fig. 3 (a) can be used with bipolar switching sequences as shown in Fig. 3 (b). Hence, if the BLDCM drive strategy can be used for driving a SRM, the drive cost will be much decreased. And in the later presentation of this paper, it will be explained that is possible.

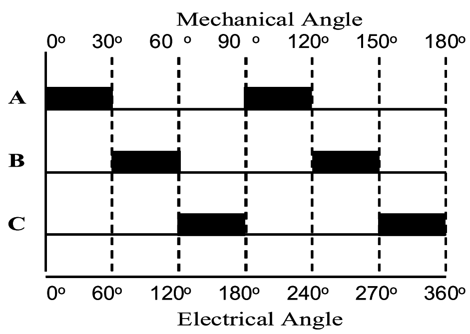
III. INDUCTANCE CALCULATION

It is different to the DC or AC motors, the SRM produces torque by variable reluctance, which can be simply expressed as (1). It is obvious that the rate of change of inductance plays the dominate role for the motor performances. And it is proportional to the square of current magnitude and has no relationship with current polarity

$$T = \frac{1}{2} i^2 \frac{\partial L(\theta, i)}{\partial \theta} \qquad (1)$$

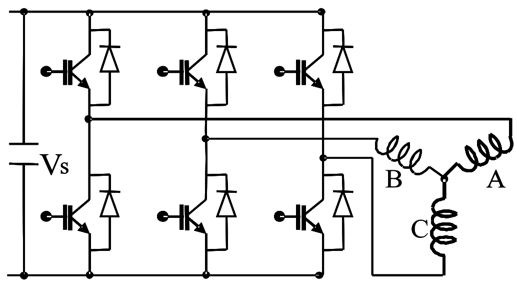


(a) Asymmetric converter

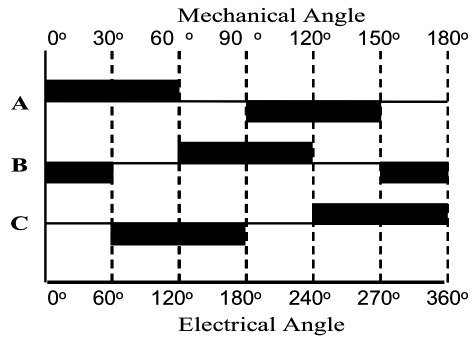


(b) Switching sequence in asymmetric converter

Fig. 2 Asymmetric converter and corresponding switching sequence



(a) Full-bridge inverter



(b) Switching sequence in inverter

Fig.3 Full-bridge inverter and corresponding bipolar switching sequence

The E.M.F, which is a commercial Finite Elements Analysis (FEA) software in Korea, is used to obtain the inductance profiles according to current and rotor position. When inductance is classified into three kinds such as apparent, effective, and incremental inductances as introduced in [6], the self and mutual inductances are calculated by the same method as apparent inductance calculation. And the detailed process of calculating self or mutual inductance by FEA is listed as follows.

-step 1: The permeability of each element is obtained and saved at operating point for current variation by nonlinear analysis

-step 2: Linear analysis is performed with the permeability obtained in step 1 after setting the magneto-motive force of another phase to zero

-step 3: Since the three inductances, incremental, apparent, and effective inductances are identical in linear system, the inductance is calculated by the effective inductance equation [6]. (The effective inductance is defined as twice the energy stored in the magnetic filed divided by the square of the current in the device winding.)

Table I lists the specifications of the prototype SSRM. And according to them, the solved flux pattern and inductance profiles are shown in Fig. 4.

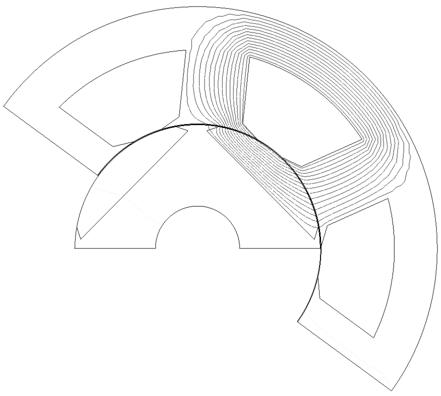
TABLE I
DESIGN SPECIFICATIONS OF SSRM

Parameters	Values	
number of poles	stator : 6, rotor : 4	
stator outer diameter	140.0	mm
rotor outer diameter	71.6	mm
rotor stack length	97.0	mm
air gap length	0.3	mm
stator pole arc	46.0	deg.
rotor pole arc	70.0	deg.
dc link voltage	100	V
rated speed	2000	rpm
rated output power	1	kW
number of turns per phase	120	turn

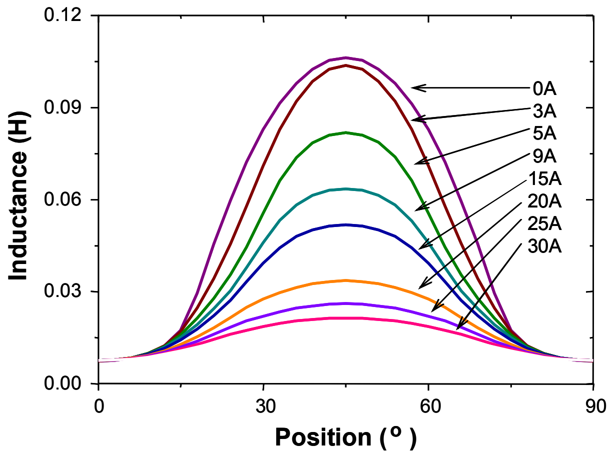
Fig. 4 (a) shows the flux pattern in an arbitrary position when single phase is turned on. By means of the same calculation process, the line inductance is obtained and shown in Fig. 5 (b). In Fig. 5 (c), it is observed that there are two successive rising inductances during 60^o mechanical angle. And as mentioned before, the reluctance torque is produced by the positive slope of inductance. Therefore, for this 4-pole motor, the each phase current can keep flowing during 120^o electrical angle, which is the same as the drive strategy of BLDCM.

IV. COUPLED FIELD CIRCUIT ANALYSIS

SRM is a position sensitive machine which causes the partial saturation and nonlinear magnetization. Usually the coupled field circuit analysis is effective for this case. In the previous, the inductance profiles have been obtained. Thus, the flux linkage profiles can be easily calculated using them. And then, making use of the cubic-spline and interpolation, the slope of the flux linkage in corresponding position and current may be known. According to iterative method and terminal voltage equations, the current can be solved. The terminal voltage equations under two different drive conditions will be

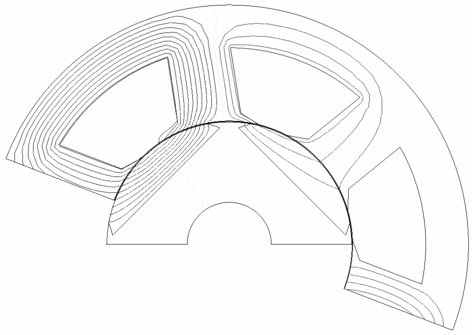


(a) The flux pattern of the SSRM driven by converter

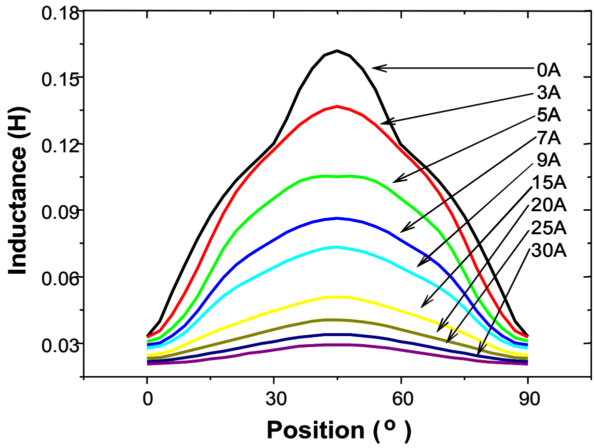


(b) Phase inductance profile of the SSRM driven by converter

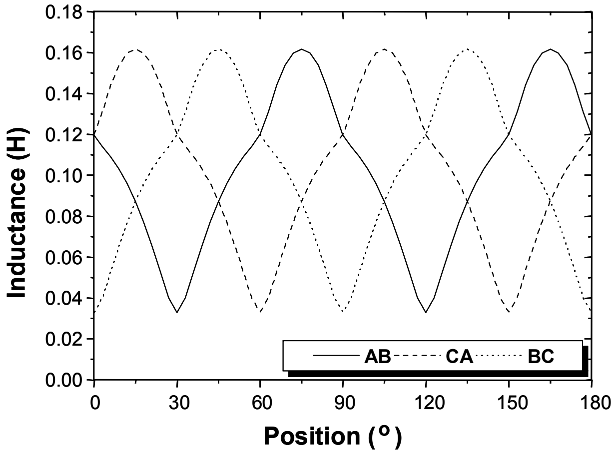
Fig. 4 Flux pattern and inductance profiles of the SSRM driven by



(a) Flux pattern of the SSRM driven by inverter;



(b) inductance profile of the SSRM driven by inverter



(c) The inductance in half mechanical cycle when the current is 0 A

Fig. 5 Flux pattern and inductance profiles of the SSRM driven by inverter introduced in the following. This method has a drawback, that is, it is hard to analyze mutual affection between two phases or two lines. However, the flux linkages generated by two phases are decoupled by the segmental core structure, which lead the mutual inductance can be ignored. This set of methods has been verified through examining a CSRM. The comparison of experimental and analyzed current is shown in Fig. 6.

A. Voltage Equation under the Converter Drive Condition

In this case, only one voltage equation need be considered. The terminal voltage is V, resistance, inductance, current and angular velocity are R, L, i, and w respectively. Each phase voltage equation can be expressed as

$$V = Ri + \left[L(\theta,i) + i\frac{\partial L(\theta,i)}{\partial i} \right] \frac{di}{dt} + i\frac{\partial L(\theta,i)}{\partial \theta} w \qquad (2)$$

B. Voltage Equations under the Inverter Drive Condition

As mentioned before, the drive strategy is the same as the one of BLDCM if the SSRM is driven by an inverter. Therefore, the voltage equations could be modified from those of BLDCM. Being the voltage equations of SRM, the original constant inductance in BLDCM equations is valid no more, and the nonlinear and saturated inductance must be considered. In addition, the BLDCM drive has a special commutation mode during operation, which should be differently considered to the steady state mode. In the commutation mode, all three-phase currents are conducted. And in the steady state mode, only two excited phases are conducted. In case of commutation mode, the voltage equations can be expressed by (3) to (5) and in steady state mode, (4) and (6).

$$V_{ph} = Ri_{ph} + \{L_{ph}(\theta,i_{ph}) + i_{ph}\frac{\partial L_{ph}(\theta,i_{ph})}{\partial i_{ph}}\}\frac{di_{ph}}{dt} + i_{ph}\frac{\partial L_{ph}(\theta,i_{ph})}{\partial \theta} w$$

where $ph = 1, 2, 3$ (3)

$$V_{bld} = V_{12} = V_1 - V_2 = V_s - 2V_q - 2R_q i_1 \qquad (4)$$

$$V_{fwh} = V_{23} = V_2 - V_3 = V_q - R_q i_2 + V_d \qquad (5)$$

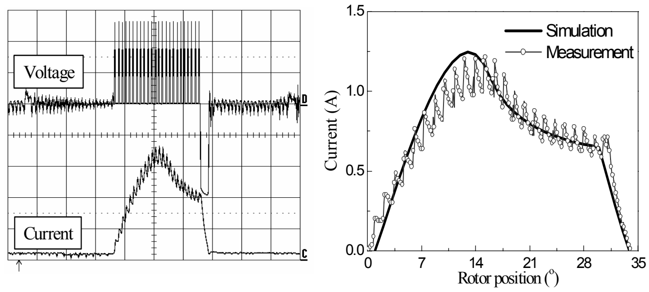
$$V_{fwh} = 0 \qquad (6)$$

where V_{ph} is phase voltage, and L_{ph} is phase inductance. The number 1, 2, and 3 means phase A, B, and C, and V_s is the dc-link voltage and V_q, V_d and R_q are the voltages of IGBT and diode, and resistance of IGBT, respectively.

Depending on these equations, at 4000 rpm, the current is calculated and shown in Fig. 7.

V. Comparison of Characteristics

The dynamic simulations have been implemented for a CSRM model, the SSRM model driven by converter, and the same SSRM model driven by inverter. The CSRM has same size, the same number of winding turns per phase, and the same dc link voltage with the proposed SSRM. The torque, current,



(a) The current shape from experiment (b) Current comparison

Fig. 6 Comparison of measured and calculated current of CSRM

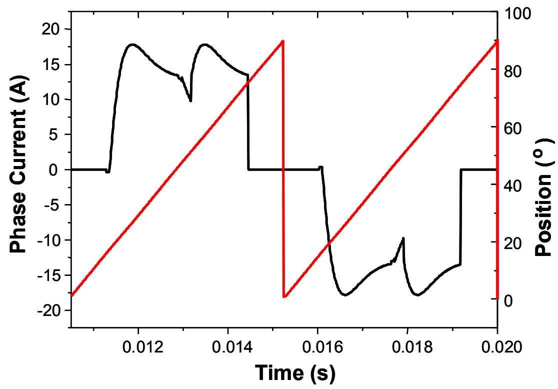


Fig. 7 Current shape of proposed SSRM driven by inverter

output power, and efficiency will be compared according to speed variation. In addition, although the CSRM has the same dimension as SSRM, the different winding strategy and rotor structure seriously impact the results of comparison, which can not present which one is better or worse. For different requirement, the better one may be different.

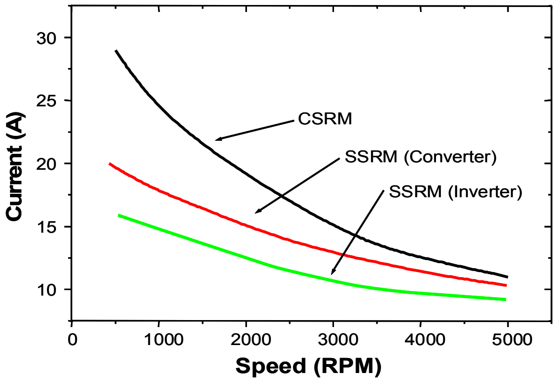
• Current

In Fig. 8 (a), the mean values of input currents are compared. When both of the CSRM and SSRM are driven by converter, the SSRM has much lower current comparing with CSRM because of its higher inductance. In the case of SSRM driven by inverter, the same one dc link voltage source is parallel connected with two phase winding, i.e. line winding. Thus, double inductances and resistances lead to almost half current value of the one of SSRM driven by converter. When the resistance is small enough, lower current results in lower copper loss. The effect on efficiency will be presented later.

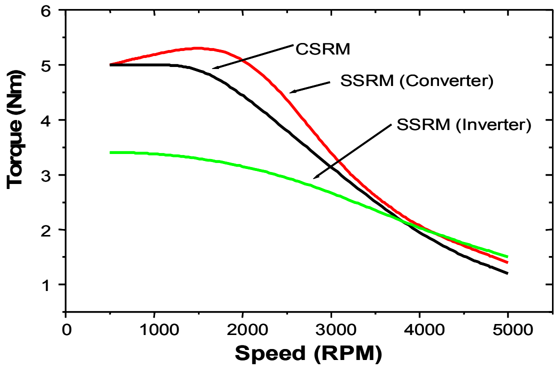
• Torque

Usually, each SRM has own optimized switch on/off angles to obtain maximum torque or minimum torque ripple. However, in this paper, for comparison, the optimized switch on/off angle is not employed for any model. The switch on angle is 0° and switch off angle is 30° for converter drive, while the 15° and 75° are used for the inverter drive.

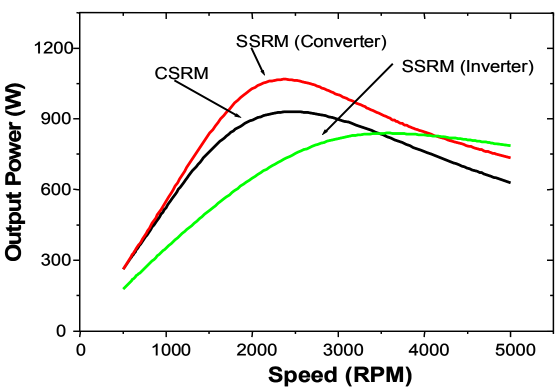
In Fig. 8 (b), the SSRM driven by converter has greater torque at rated speed. However, as the speed increasing, the leading vanishes. After 4000rpm, the SSRM driven by inverter goes to the top from the bottom. Due to low current, the SSRM driven by inverter is not saturated, which means the slope of inductance does not change too much from high relative current



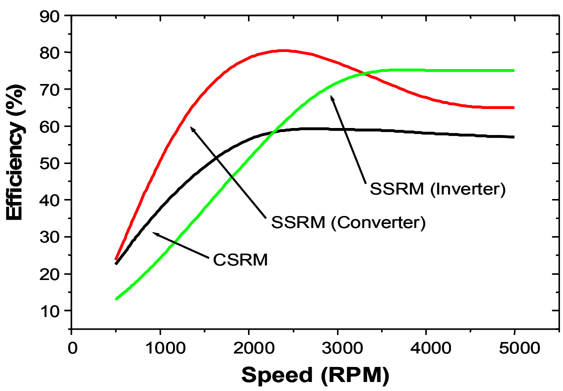
(a) Characteristic of current vs. speed



(b) Characteristic of torque vs. speed



(c) Characteristic of output power vs. speed



(d) Characteristic of effieciency vs. speed

Fig. 8 Comparison of characteristics

to low current. On the other hand, the low current can not generate great difference from low speed to high speed. Comparing with the small current, the main contribution for generated torque is from the high slope of the line inductance. Hence, the SSRM driven by inverter may keep the torque value in a longer speed range. This characteristic makes the SSRM driven by inverter more suitable in high speed operation.

Except the low current, there is the other reason why the SSRM driven by inverter has small torque. As shown in Fig. 5 (c), the drive strategy is as the order of AB-CA-BC-AB. After AB, the line current CA still flow through phase A. This produces a negative torque value. Because that phase A inductance is near to saturation and phase C inductance is highest positive rate of change, the total torque is positive value. This negative torque only reduces the starting torque of each stroke, and hence, the torque ripple is reduced.

- Output Power

The prototype SSRM driven by converter is designed as 1 KW motor as shown in Table I. In Fig. 8 (c), the output power of CSRM get 900 W, while the SSRM driven by inverter reaches about 800W. It is obvious that the rated speed of CSRM also is 2000rpm, but the rated speed of SSRM driven by inverter is about 3000rpm. The SSRM driven by inverter keep the output power after its rated speed, and beyond the CSRM and SSRM driven by converter after 4000rpm. This phenomenon is easy to be explained by their torque characteristics.

- Efficiency

Fig. 8 (d) shows the comparison of efficiencies of three analysis models. The SSRM driven by converter is much better than the other two before 3000rpm. This may be comprehended with its low current and high output power. However, as the speed increasing, the SSRM driven by inverter gets higher.

The low current of SSRM driven by inverter lead to low copper loss as mentioned before. Although the resistance is two times of the other models, but the difference of current is squared. In addition, due to the segmental rotor structure, the flux path is short, which results into lower magnetic resistance. It is also the reason why the SSRM driven by converter has much higher efficiency comparing with CSRM.

VI. CONCLUSIONS

This paper presents the comparisons on characteristics of CSRM and SSRM. Specially, the SSRM is analyzed in two drive strategy, asymmetric converter and full-bridge inverter. The main reason of using inverter is for reducing the drive cost. In this analysis process, the feasibility of novel drive method is proved first. Then, FEA is employed to calculate the inductance. The generated inductance profile is used in the couple field circuit analysis to calculate the current and torque. Finally, by means of the results of the dynamic simulation, the characteristics of three analysis models are obtained.

According to the comparisons, the SSRM driven by converter has better performance around rated speed, while the SSRM driven by inverter is recommend using in high speed operation due to its high efficiency. But, the low torque and output power is the weak points of the SSRM driven by inverter, which makes it away from the heavy works.

In addition, the analysis method presented in this paper does not consider the eddy current loss in the aluminum rotor. But in practice, this is a dominate loss in overall system. Although the SSRM structure behaves higher efficiency in this paper, the real efficiency can not be determined. It depends on the specified dimensions, rated variables, materials and so on.

REFERENCES

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

[2] C. Pollock, B. W. Williams, "Power Converter Circuits for Switched Reluctance Motors with the Minimum Switches", IEE Proc., Vol. 128, pp. 373-284, November 1990

[3] Kim, K. B., "Toroidal switched reluctance motor part I, Fundamentals," Proc. Korea-Germany Symp., pp. 135-141, 11, 1998.

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

[5] Oyama. J.; Higuchi. T.; Abe. T.; Tanaka. K. "The fundamental characteristics of novel switched reluctance motor with segment core embedded in aluminum rotor block". Electrical Machines and Systems, 2005. ICEMS. Volume 1, Issue , 27-29 Sept. 2005.

[6] Ji-Young Lee, Jung-Pyo Hong, and Do Hyun Kang, "A Study of Inductance Computation for Transverse Flux Linear Motor Considering Nonlinearity of Magnetic Material," Key Engineering Materials, vols. 277-279, pp391-396, 2005

IEEE

INTERNATIONAL ELECTRIC MACHINES AND DRIVES CONFERENCE

IEMDC'07

May 3-5, **2007**

Antalya, TURKEY

- Sponsors
- Conference Program
- Technical Program
- Author Index
- Search

IEEE Catalog Number : 07EX1597C
ISBN : 1-4244-0743-5
Library of Congress : 2006935481