A Comparative Study of Switched Reluctance Motors with Conventional and Toroidal Windings

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***Abstract*-- This paper deals with a comparative study of switched reluctance motors (SRMs) with conventional and toroidal windings, which will be called CSRM and TSRM, respectively. In the CSRM there is a complete magnetic decoupling between phases, so that torque is produced entirely due to the rate of change of winding self inductance. If the same machine is wound with toroidal windings then it can be shown that a new configuration produces torque as a result of changing phase inductance, which becomes much smaller due to mutual inductance between phases. This difference of inductance makes the two SRMs have quite different characteristics. Consequently, the CSRM is proper for high voltage and small current and the TSRM is for low voltage and large current. The characteristics comparison is theoretically performed with respect of torque, current, output power, and efficiency according to speed variation.**

I. Introduction

Researches associate with doubly salient reluctance machines are increasing with the development of power conversion drives and control technologies. There are several works to improve torque characteristics and efficiency of the switched reluctance motor (SRM) by changing power drive topologies or switching sequences [1]-[4].

Compared with the other electric motor drives, the SRM needs asymmetric converters to excite the each phase, so that it causes the overall system to be expensive and complicated. Therefore, until now many attempts have been tried to reduce the number of switches of converters for simplification of the converter topology. Among of these attempts, there is an attempt to use 6-switch converters for the SRM, because it is widely used in the other motor drives as well as easy to packing. To use bipolar conduction with 6-switch converters for the SRM, the winding pattern of the SRM should be modified, such as short pitch, full pitch, and toroidal windings. However, in each case, the motor performances become different mainly due to each different inductance profiles. In the short pitch winding, both self and mutual inductances are changed according to rotor positions. On the other hand, in the full pitch winding, only mutual inductance is changed [3],[4].

In the pervious works [5],[6], the authors examined the basic operation of the toroidal winding SRM with delta connection and diodes. However, in [5],[6], the detailed comparison of the motor performances with the conventional SRM has not been performed. Moreover, the toroidal SRM drives with the 6-switch converter and Y-connection has not been handled.

In this paper, a SRM with the Y-connected toroidal winding and a 6-switch converter is introduced and the overall characteristics are examined with respect of magnetic characteristics for motor design, comparing with the conventional winding, which has the same parameters as the toroidal SRM.

In this paper, two different configurations of the SRM are handled; one is a SRM with the conventional winding (CSRM) and the other is a SRM with the Y-connected toroidal winding (TSRM). The CSRM is operated by asymmetric converters and the TSRM is by 6-swtich converters. In the TSRM, two phases should be energized at any times while it is with only one phase in case of the CSRM.

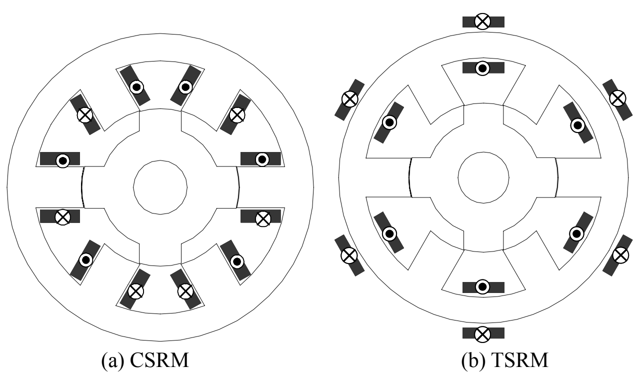
Since highly nonlinear nature of the magnetic circuit makes inductance change unexpectedly, the inductances of each motor should be calculated by finite element analysis (FEA) method according to rotor positions and currents. With the computed inductances, each machine performance is evaluated and compared considering the switching sequence and the electric circuit.

In the CSRM, there is a complete magnetic decoupling between phases, so that torque is produced entirely due to the rate of change of winding self inductance. On the other hand, torque is produced as a result of changing of phase inductance, which becomes much smaller due to the mutual inductance. This difference of inductance makes the two SRMs have quite different characteristics. Consequently, the CSRM is proper for high voltage and small current and the TSRM is for low voltage and large current.

II. Fundamental Operating Principles

A. Motor Configurations

Fig. 1 shows the cross-sections of the CSRM and the TSRM and their windings. The winding of CSRM is the basic short pitch winding for the general SRM. However, the coils of the TSRM are wounded around the yokes of the stator. Moreover the winding direction of the TSRM dealt in this paper is different from the TSRM in [5] because of different current conduction scheme, which will be explained in the next section.



(a) CSRM (b) TSRM

Fig. 1. Winding excitation pattern in 6-4 switched reluctance motors with conventional winding (CSRM) and toroidal winding (TSRM) (⊙-go, ⊗-come-directions of winding).

B. Converters and Controls

Fig. 2(a) shows the conventional SRM drives, which use the CSRM, an asymmetric converter, and unipolar switching sequences. Due to the converter configuration, the general 6-switch IGBT module package cannot be used and in addition six external 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 TSRM, due to the unique winding characteristics, the conventional 6-switch converter can be used with bipolar switching sequences as shown in Fig. 2(b). The difference of the previous TSRM study in [5] is the winding connection, such that the previous one is delta connection with diodes and the considered one in this paper is wye connection without diodes. With the each different switching sequence, both the CSRM and TSRM in Fig. 1 rotate in clock-wise direction.

When considering drive and its sequence for each motor, the voltage equation can be expressed as follows. The each inductance is calculated by FEA method according to current and rotor displacement.

- CSRM

In this case, only one voltage equation can be considered. The detail solving method is now very common, and it is introduced in [7]-[9]. 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

$$V = Ri + \left[L(\theta,i) + i\frac{\partial L(\theta,i)}{\partial i} \right]\frac{di}{dt} + i\frac{\partial L(\theta,i)}{\partial \theta}w \qquad (1)$$

- TSRM

The original switching sequence can be referred in [10] for brushless motors. However in case of voltage equations of brushless motors, the variation of inductances does not have to be considered. Therefore, the modified voltage equations should be developed for the TSRM. In the operational modes, the commutation mode 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 (2) to (4) and in steady state mode, (3) and (5).

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

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

$$V_{bld} = V_{12} = V_1 - V_2 = V_s - 2V_q - 2R_q i_1 \qquad (3)$$

$$V_{fwh} = V_{23} = V_2 - V_3 = V_q - R_q i_2 + V_d \qquad (4)$$

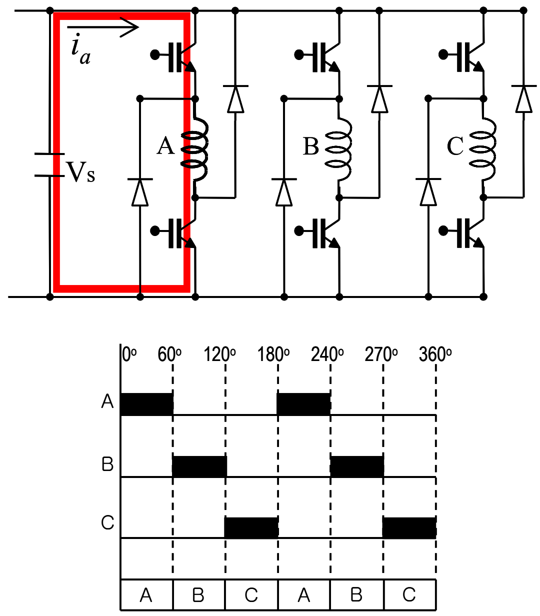
$$V_{fwh} = 0 \qquad (5)$$

where V_{ph} is phase voltage, L_{ph} is phase inductance. L_{ph} is the difference between phase self inductance and phase mutual 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.

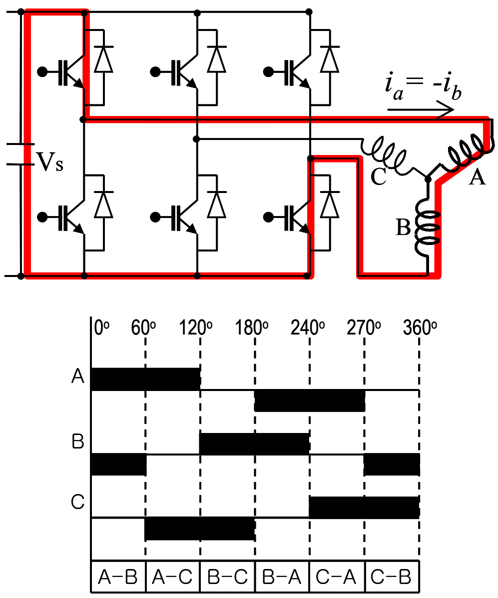
III. Design of CSRM and TSRM

A. Specifications

In order to examine the performance of the TSRM, a conventional CSRM is designed and based on the same design parameters, including the size of stator and rotor and number of winding, are used to design of the TSRM. The design specification of the CSRM is shown in Table I. Only difference of the design parameters are switch turn on angle and dc-link voltage.



(a) Topology and switching sequence of the CSRM



(b) Topology and switching sequence of the TSRM

Fig. 2. Comparison of converters and switching sequences.

TABLE I
DESIGN SPECIFICATIONS OF CSRM

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	30.0	deg.
rotor pole arc	31.0	deg.
switch turn on/off	100/ -150	V
phase voltage and angle	0.0	deg. (unaligned)
rated speed	2000	rpm
rated output power	1	kW

B. Comparison of Inductance Profile

The inductance of the CSRM is shown in Fig. 3. According to current and rotor positions, the phase self inductance is changed. For the inductance profile, the minimum inductance is at the unaligned position is shown in Fig. 3(a) and the maximum inductance at the aligned position is shown in Fig. 3(b) in case that phase A is excited. Fig. 4 shows the comparison of magnetic flux plot when each switching turned on at arbitrary position. While the CSRM has two magnetic poles by one phase excited, the TSRM has four magnetic poles by two phases excited at the same time. As shown in Fig. 4(b), the phase inductance is different according to rotor positions because of the flux quantity due to its different flux path at the same current. The self inductance is relatively very big because the flux flows only through the stator yoke and the mutual inductance is also as same as the self inductance. Therefore, the phase inductance becomes much smaller than that of the CSRM. The self, mutual, phase and line inductances of the TSRM are depicted in Fig. 5. Compared with Fig. 3 and Fig. 5, it is noted that the minimum inductance occurs at the unaligned position in both the CSRM and the TSRM and in case of the maximum inductance, it occurs at aligned position in the CSRM and on the other hand, in the TSRM, it appears at the overlapped position.

In the SRM, torque is proportion to square value of the current and the rate of inductance variation. More increasing inductance period, better torque characteristic can be obtained. In the CSRM, the one switching period is 60^o (electrical angle), and it has almost 90^o of increasing inductance. However, in the TSRM, the inductance increasing period is as much as that of switching period, 60^o. This kind of weak point is rising in any type of winding with bipolar switching sequences with 6-switch converter.

C. Reliability of Expectation

The characteristic comparison is performed by theoretical simulation. Therefore it is necessary to confirm the accuracy of the prediction of performance. Here is one experimental data for predicted and measured current of the CSRM in Fig. 6. With this agreement of the results, the expected values of the CSRM, which are obtained by combination of voltage equations and FEA method, can be acceptable.

For the TSRM, the simulation process can be simplified as below:

- Step 1: Inductance calculation according to rotor positions and current variation by FEA method
- Step 2: Current calculation considering the commutation by voltage equation
- Step 3: Torque calculation with the calculated current in Step 2 by FEA method

The different in the simulation is Step 2. Therefore, if the current is perfectly expected, the torque characteristics can be obtained precisely. As mentioned before, the voltage equations are modified from the ones of brushless motors. Even in worst case, the current shape can not be expected for real case, but the magnitude is similar because it is reconfirmed by the simple relationship of voltage, V, current, I, and impedance Z; $V=IZ$. Therefore, the comparison results of the overall characteristics, such as torque-speed, are acceptable.

IV. COMPARISON OF CHARACTERISTICS

The comparison of current, torque, output power, and efficiency according to voltage and speed variation are shown in from Fig. 7 to 10. In this comparison, the switching turn-on angle is set to 0^o in both cases of the CSRM and the TSRM.

- Current

In Fig. 7, the average input currents are compared. The inductance of the TSRM is about two times lower than that of the CSRM, so that the current of the TSRM is increased about two times as much as that of the CSRM. When current is compared at the rated conditions, 2000rpm and 1kW output power, the current of the CSRM is about 12.7A at 100V and in case of the TSRM is about 22.9A at 55V.

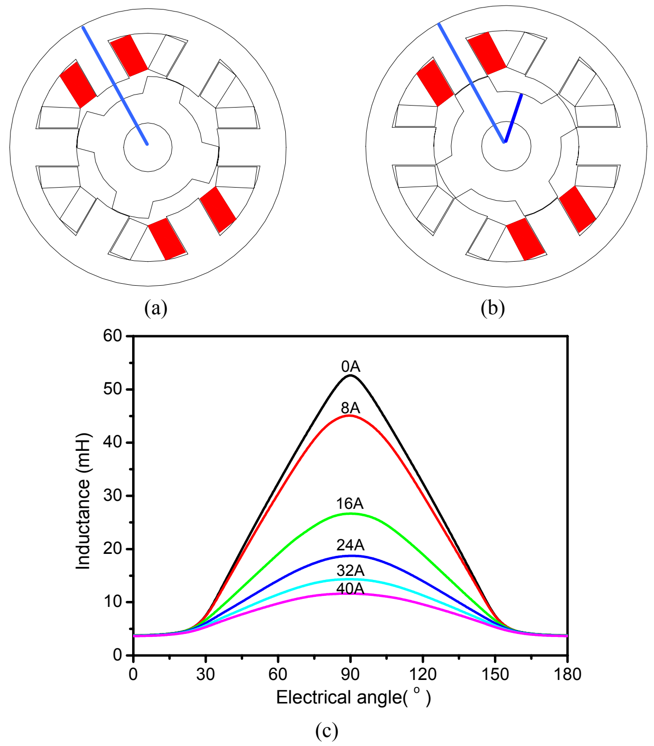
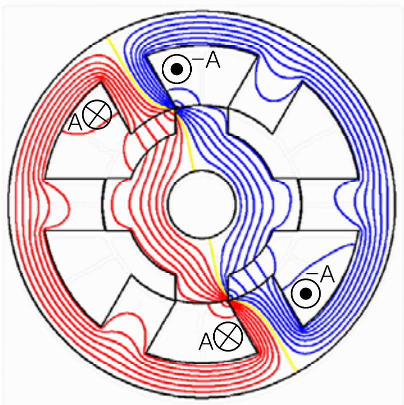
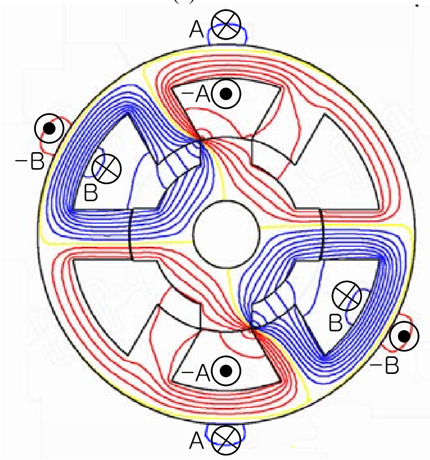


Fig. 3. Inductance profiles of CSRM. (a) Unaligned rotor positions with minimum inductance. (b) Aligned rotor position with maximum inductance. (c) Winding self inductance according to current variation.



(a) CSRM



(b) TSRM

Fig. 4. Magnetic flux plots and the directions of MMF.

• Torque

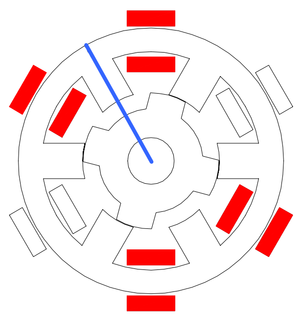
The aspect of torque variation has similar tendency to the case of the current. It is because that the switching turn-on angle is set to 0^o. If the angle is advanced, the torque is oppositely proportion to the current because the current rising and falling times are getting shorter within inductance increasing period in low speed. If the angle is moved to backward, the torque is sharply decreased in proportion to current due to reverse torque in high speed. Fig. 11 shows the rated torques at the rated speed. The difference of inductance increasing periods causes the torque profile to be different and it is note that zero torque regions are existed in the TSRM.

• Output power

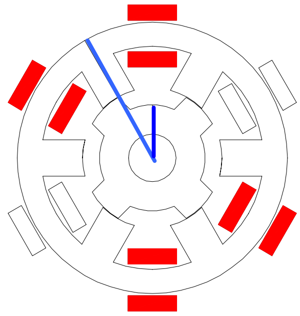
In case of output power, the rate of power change of the TSRM is lower than that of the CSRM. The lower ratio of inductance variation causes small variation of the current and output power is slightly changed according to the current variation. If the maximum output power is compared at 100V, the output power of the CSRM is 2.43kW at 700rpm and the TSRM is 2.6kW at 1,500rpm. This phenomenon comes from that quantity of input current due to the inductance.

• Efficiency

At the rated speed and output power, the efficiency is about 84.9% in the CSRM (100V), and 80.75% in the TSRM (55V). Even though the efficiency of the TSRM is lower at the rated conditions due to bigger copper loss, in the higher speed the TSRM has higher efficiency than the CSRM.



(a)



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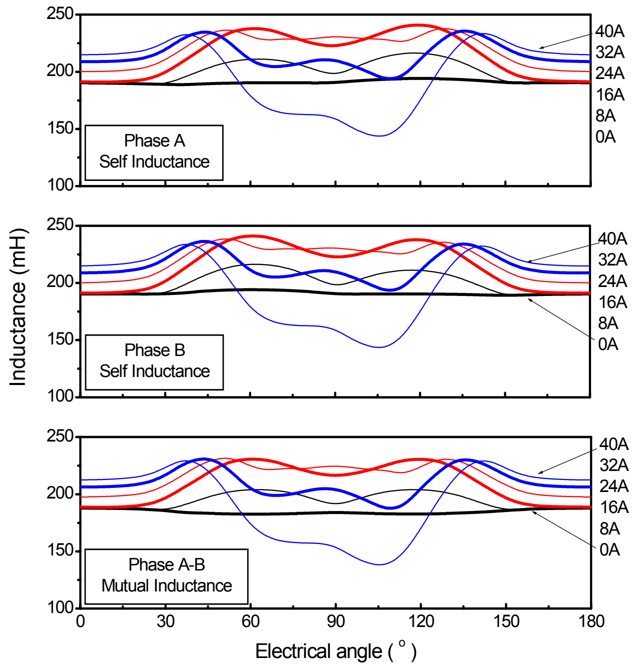
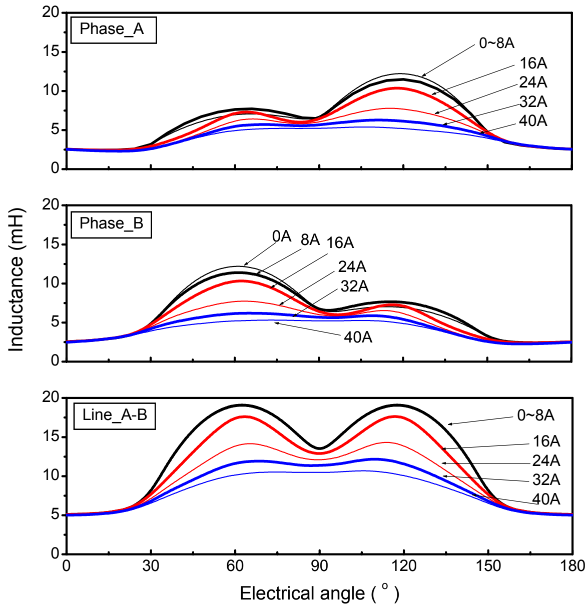
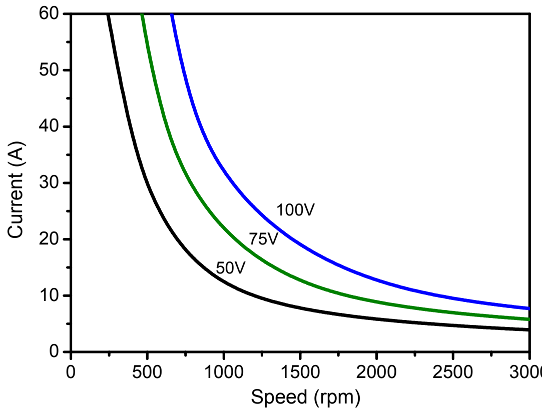


(c)

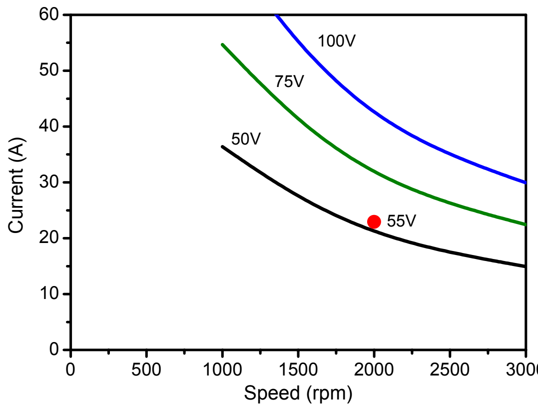


(d)

Fig. 5. Inductance profiles of TSRM. (a) Unaligned rotor positions with minimum inductance. (b) Overlapped rotor position with maximum inductance. (c) Winding self and mutual inductances according to current variation. (d) Winding phase and line inductances according to current variation.

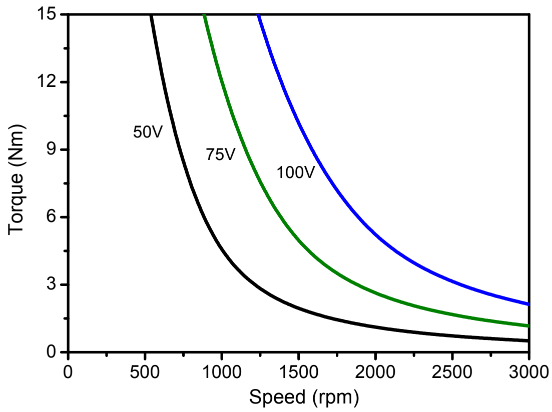


(a) CSRM

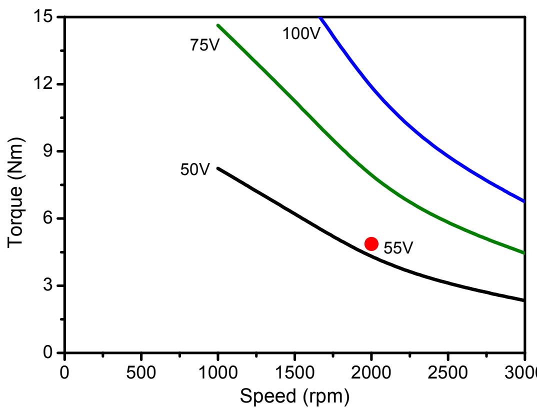


(b) TSRM

Fig. 7. Comparison of speed-current curves for input voltage and speed.

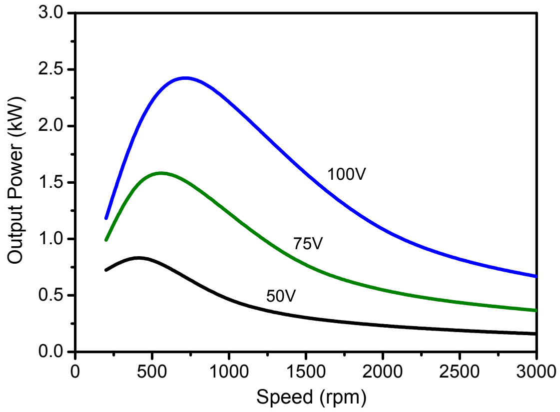


(a) CSRM

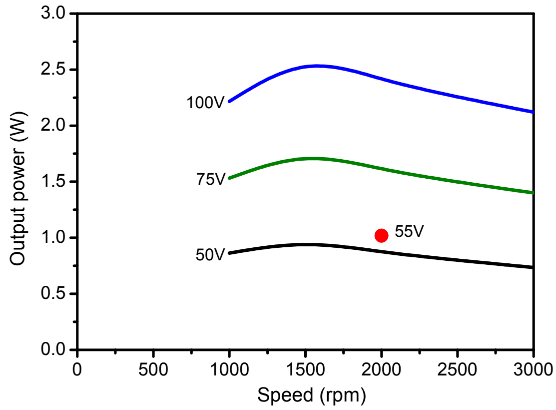


(b) TSRM

Fig. 8. Comparison of speed-torque curves for input voltage and speed.

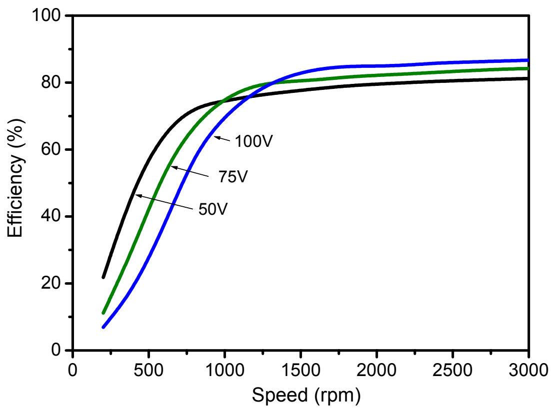


(a) CSRM

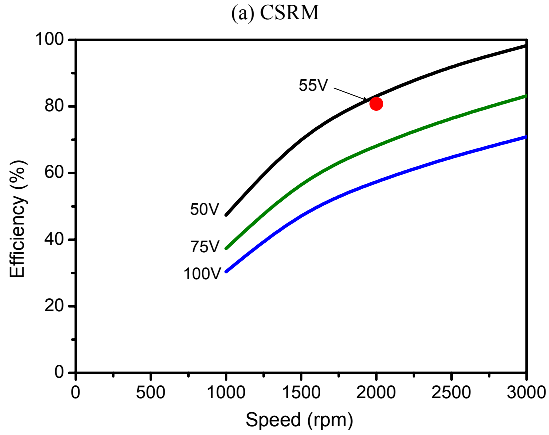


(b) TSRM

Fig. 9. Comparison of speed-output power curves for input voltage and speed.

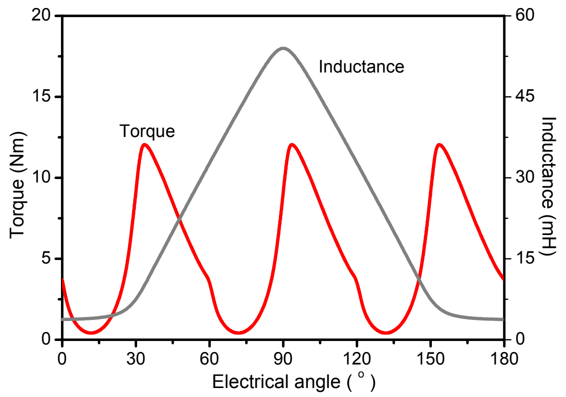


(a) CSRM

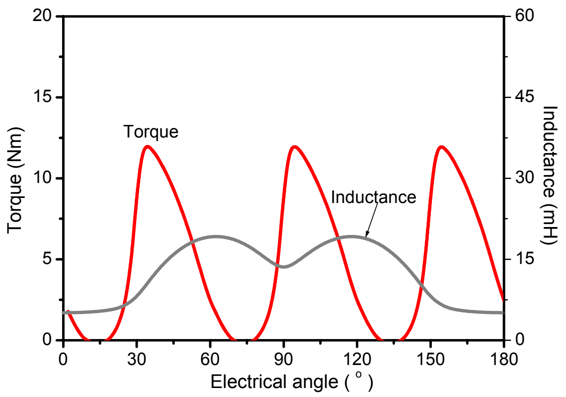


(b) TSRM

Fig. 10. Comparison of speed-current curves for input voltage and speed.



(a) CSRM



(b) TSRM

Fig. 11. Comparison of torque (speed: 2000rpm, output power: about 1kW).

The comparison results are summarized in Table II. In rated speed and output power, it is difficult to claim that the TSRM has advantages over the CSRM. However, as shown in Fig. 7 to 10, the characteristics of the TSRM in high speed are better than the CSRM, especially in efficiency point of view. If the torque ripple can be reduced, it is expected that the TSRM can be useful for an application, which requires low input voltage and high efficiency.

V. Conclusions

In this paper, a comparative study of two different winding types' switched reluctance motors has been performed to provide informative data for practical industry applications. From this study, it is noted that one needs to consider the criteria to decide the types of converters and the SRM according to each application, considering torque, speed, size, cost, and etc. The toroidal SRM has advantage over the conventional SRM on using the 6-switch converter, so that it makes overall system cost be minimize. However, the entire electric performance of the TSRM needs to be compared in prior to apply to a specific application. Consequently, it is expected that the comparative design process and data, which are performed in this paper, can be utilized in various applications.

Table II
Characteristics Comparison of CSRM and TSRM

		CSRM	TSRM
At rated speed and rated output power point (2000 rpm, 1kW)	Input voltage	100V	55V
	Input current	12.7A	22.9A
	Input power	1270.0W	1259.5W
	Torque	5.15Nm	4.86Nm
	Efficiency	84.90%	80.75%
Maximum power (at 100V)		2.43kW	2.60kW

Acknowledgment

This work was partially supported by KEMCO and MOCIE through IERC and K-MEM R&D Cluster in Korea.

References

[1] Yasser G, Dessouky, Barry W. Williams, and John Edward Fletcher, "A Novel Power Converter with Voltage-Boosting Capacitors for a Four-phase SRM Drive," *IEEE Trans. on Industrial Electroics*, vol. 45, no. 5, pp. 815-823, 1998

[2] Barrie C. Mecrow, "New Winding Configurations for Doubly Salient Reluctance Machines," *IEEE Trans. on Industry Applications*, vol. 32, no. 6, November/December, 1996

[3] Yifan Tang, "Switched Reluctance Motor with Fractionally Pitched Windings and Bipolar Current," *Industry Applications Conference*, vol. 1, pp. 351-358, 1998

[4] Jin-Woo Ahn, Seok-Gyu Oh, Jae-Won Moon, and Young-Moon Hwang, "A Three Phase Switched Reluctance Motor with Two-Phase Excitation," *IEEE Trans. on Industry applications*, vol. 3, no. 5, pp.1067-1075, 1999

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

[6] H.Y.Yang, J.G.Kim, Y.C.Lim, S.K.Jeong, and Y.G.Jung, "Position detection and drive of a totoidal switched reluctance motor (TSRM) using search coils," *IEE Proc. Electr. Power Appl*. vol. 151, no. 4, July 2004

[7] Ji-Young Lee, Ki-Yong Nam, Jung-Pyo Hong, and Jin Hur, "Magnetic Barrier Effect on Operating Performances of Switched Reluctance Motor," *ICEM2004, 2004*

[8] Ji-Young Lee, Geun-Ho Lee, Young-Kyoun Kim, Jung-Pyo Hong, Jin Hur, "Coupled Field-Circuit Analysis for Characteristic Comparison in Barrier Type Switched Reluctance Motor" *IEEE Conference on Electromagnetic Field Computation*, pp 71, 6, 2004

[9] Longya Xu and Eric Ruckstadter, "Direct Modeling of Switched Reluctance Machine by Coupled Field-Circuit Method," *IEEE Trans. on Energy Conversion*, vol. 10, no. 3, pp446-454, September, 1995

[10] Hendershot Jr., and TJE Miller, *Design of Brushless Permanent-Magnet Motors*, Magna Physics Publishing and Clarendon Press, Oxford, 1994