

# Design and Optimization of High Torque, Low Ripple Switched Reluctance Motor with Flux Barrier for Direct Drive

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**Abstract**—While Switched Reluctance Motors (SRM) have good performances, such as high torque, high speed, and high reliability, SRM has serious disadvantage of large torque ripple. In order to reduce the torque ripple and improve the average torque of the motor, this paper proposes a new type of SRM with inserted flux barriers into the rotor. The proposed type SRM is simulated for various configurations of the flux barriers and a shape optimization of the barrier has been carried out additionally. The performances of proposed type of SRM were confirmed by finite element analysis and experimentation and advantages and limitations of using flux barriers in SRM design for high torque are discussed. From the analysis results, it must be noted that the proposed type has great advantage over the conventional type toward trend of higher torque per a volume. Calculated and experimental results are presented, to validate the inserting the flux barriers and the resulting improvements.

**Keywords**—Flux barrier type Switched Reluctance Motor, Shape optimization, Reduction of torque ripple, High torque, Direct drive.

## I. INTRODUCTION

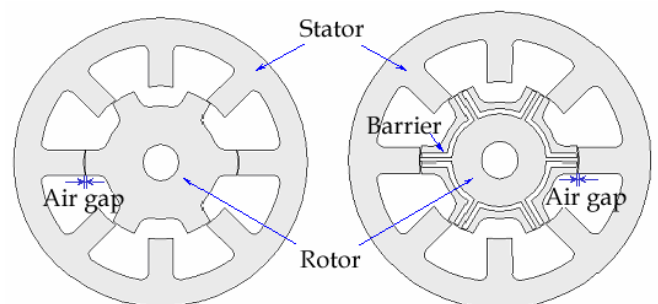
The Switched Reluctance Motor (SRM) is a doubly-salient singly-excited reluctance motor, which has salient poles on both rotor and stator sides. Even the rotor has no windings, magnets, or cage winding, it is built up with a stack of salient-pole laminations and the rotating motion is generated due to the difference of variable reluctance in the air gap between rotor and stator. Although SRM has been recognized to offer high efficient, reliable, robust, easy to manufacture, and inexpensive characteristics, it requires expensive position sensors and suffer from producing vibrations and acoustic noise as well as high torque ripple [1]-[3].

In recent, these disadvantages of SRM have been improved with the help of rapid development of power electronics circuits, so that its applications have been continually expanded according to the requirements of high speed, variable speed, and high reliability. Therefore, it is highly expected that SRM will have a more growing application in near future. Until now, many efforts in terms of design and

control have been tried in order to improve the performance of SRM, however, most of the results are based on handling pole arcs of stator and rotor to reduce the torque ripple [4]-[6]. However, handling the pole arcs has severe problems, such as decreasing average torque and increasing weight of the motor.

In this paper, a new type of SRM with inserted flux barriers into the rotor pole is proposed and the geometric diagram is shown in Fig. 1. The inserted flux barriers make radial components of magnetic flux be changed into tangential components, so that the total tangential component becomes increased and it results in reducing torque ripple and increasing average torque, even in the overlapped condition of stator and rotor poles. These characteristics are appealing for a variety of machine and actuator design such as Synchronous reluctance motor and Spoke type brushless DC motor etc. That is, much wider design boundary by the barriers can be introduced at the rotor geometry without the accompanying disadvantages of low average torque and high weight of the motor.

So, the purpose of this paper is to explore the benefits and limitations of this type SRM and optimize the inserted barriers of rotor in SRM. In the rest of this paper, the detail theoretical analysis of the proposed SRM with barriers is explained and the performance is verified with informative simulation and experimental results, along with the various comparisons.



(a) Conventional SRM (b) Proposed SRM with barriers.  
Fig. 1 Rotor Structure of proposed SRM inserted a flux barrier.

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## II. THE CHARACTERISTICS OF SRM WITH A FLUX BARRIER

The operation of SRMs is strongly influenced by the nonlinear magnetic characteristics with high levels of saturation, which are periodically occurred as the rotor continuously moves from unaligned to aligned positions with reference to the energized stator phase as shown in Fig. 2, which shows the linkage flux due to the current at the several rotor positions.

As shown in Fig. 2, this poses a difficult task on exact calculation of the magnetic distribution and the torque characteristics at the several rotor positions and also the mathematical representation of the motor for the analysis and design purposes.

The nonlinear relationship between the flux linkages and the currents has made it much difficult to analytically represent the phase inductance or the phase flux linkages as a function of current and position for the entire ranges of operation. Therefore, the calculation of related machine variables are typically performed using a numerical analysis method, such as Finite Element (FE) Method. In this paper, to compare the conventional SRM with the proposed SRM, a FE analysis considering magnetic saturation has been carried out.

In order to get exactly nonlinear characteristics of the inductance according to the current as well as the rotor position, the dynamic analysis is performed. The external electric circuit equation is as follows:

$$V_s = R_m i_m + L_m \left( \frac{di_m}{dt} \right) + E_m \quad (1)$$

Where  $R_m$ ,  $L_m$  and  $E_m$  are winding resistance of each phase, the inductance and EMF induced on the winding.

## III. COMPARISON OF SRM ACCORDING TO SEVERAL TYPE FLUX BARRIERS

In order to analyze the effect of the inserted flux barriers on the rotor of the conventional SRM, seven models of 6/4 SRM having each different barrier width are selected as shown in Fig. 3. Model m1 is conventional SRM without the barrier. Model m2, m3 and m4 have a different width of flux barrier, 1, 2 and 3 [mm] respectively on the same rotor.

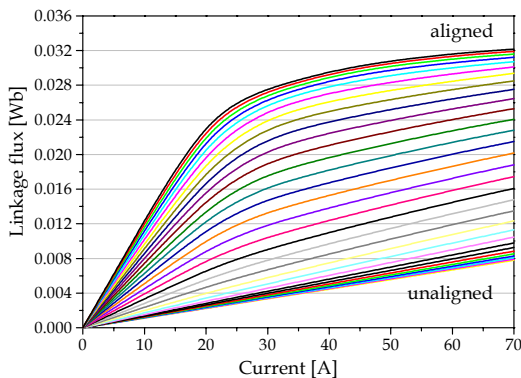
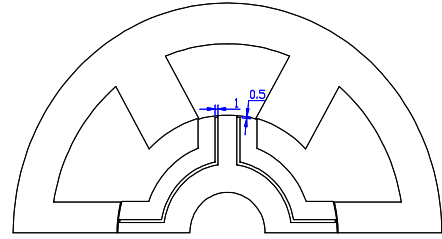


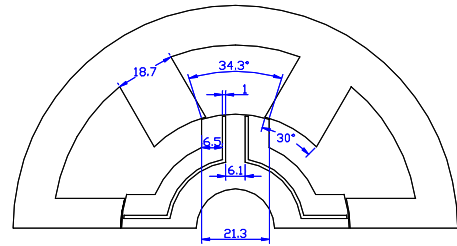
Fig. 2 Linkage flux due to the current at the several rotor positions.

Also Model m5, m6 and m7 are extended the pole arc of the rotor as the width of flux barrier inserted for model m2, m3 and m4 for a same core area. The overall comparison of the generated torque and their input power for seven models are described in Fig. 4.

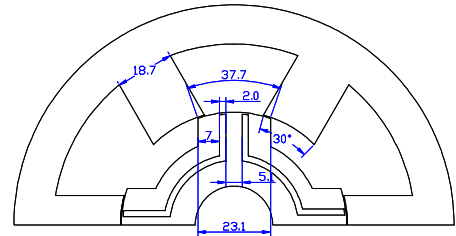
As shown in Fig. 4, the torque characteristics of the barrier type SRM become improved compared to the conventional one and also the current is increased. From these results, one knows that the flux barriers have a great influence on the torque and are very important design factor for improving the characteristics. In order to verify this result, the current waveform for each phase of the SRM is investigated. As it is generally known, the torque characteristics of the SRM are decided according to the input currents and flux linkages, which are described as the inductance profile.



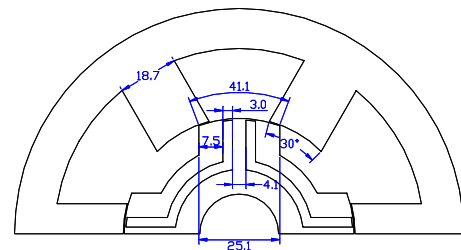
(a) Model m2, m3, m4 (barrier width 1, 2, 3[mm]).



(b) Model m5 (m2 + Pole arc 2[mm]).



(c) Model m6 (m3 + Pole arc 4[mm]).



(d) Model m7 (m4 + Pole arc 6[mm]).

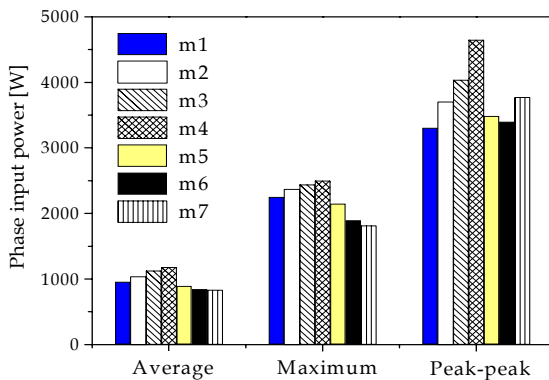
Fig.3. Proposed SRM model inserted flux barriers.

The nonlinear relationship between flux linkages and currents has made it much difficult on exact prediction of the phase inductance profile or the phase flux linkage as a function of current and position for the entire ranges of operation. Furthermore, the input current waveform itself is also very important factor for predicting the torque characteristics. Figure 5 shows the current waveforms for each type barrier model and also Fig. 6 shows the inductance profiles. The Comparison of input power and current for one phase of seven models is shown in Fig. 7.

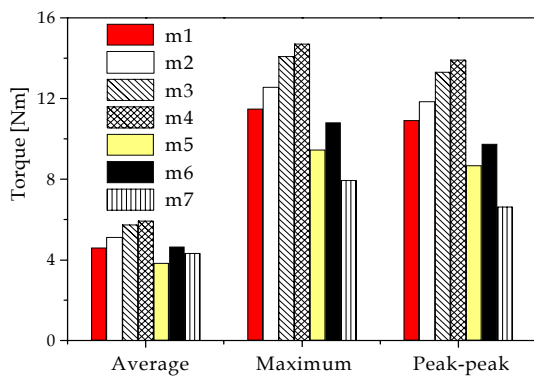
As shown in Fig. 6, the slope of inductance of barrier type m2, m3 and m4 according to the rotor position increases more steeply from the unaligned position. This slope determines the torque amplitude, so that it can obtain a better performance than the conventional one, m1. The comparison for analysis results of seven models are given in Table 1.

However, in Models m2, m3, and m4, the reason of increasing torque is caused by the increased slope of inductance profile and the input power. Otherwise, in Model 6, the ratio of torque to input power is higher than the other types of motors as shown in Fig. 8.

From these results, it is noted that the decision of an optimal barrier width and their pole arc is very important and one can get a SRM with the much improved torque characteristics in the same volume. Therefore, in this paper, an optimization of the barriers in the SRM has been performed in order to get the much torque in the same volume.

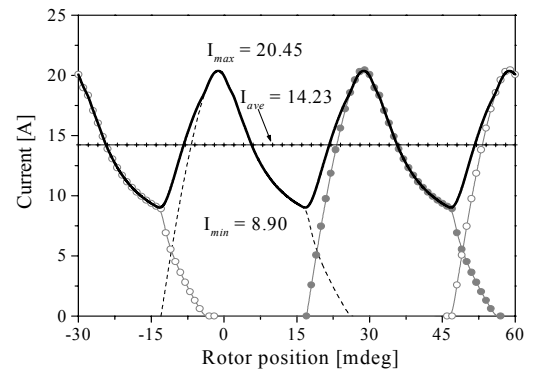


(a) Input power

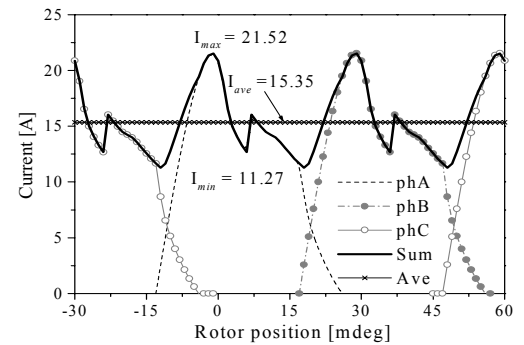


(b) Torque

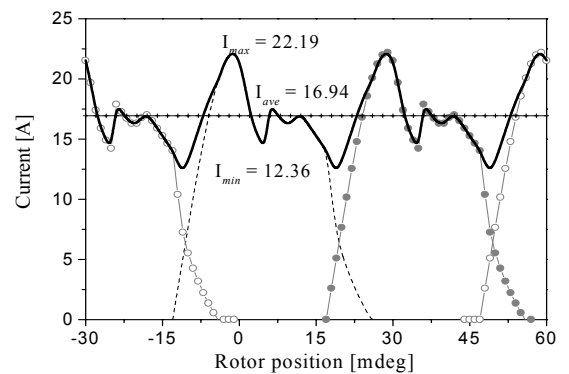
Fig. 4 Comparison between conventional type and proposed six model with barrier.



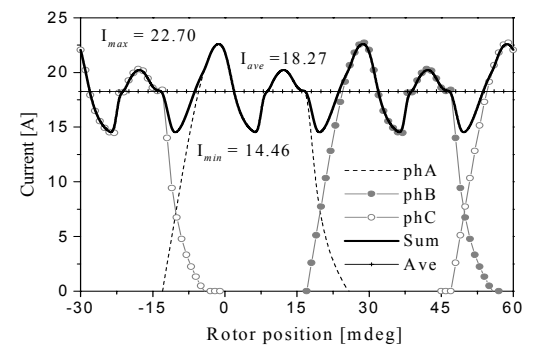
(a) Model m1 (Conventional SRM model)



(b) Model m2 (Barrier width 1[mm])



(c) Model m3 (Barrier width 2[mm])



(d) Model m4 (Barrier width 3[mm])

Fig. 5. Comparison between conventional type and propose type with barrier.

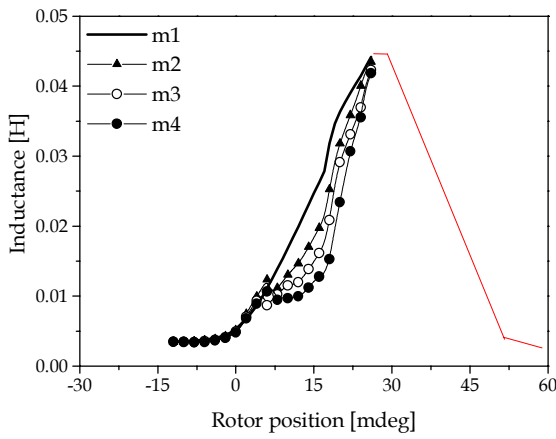


Fig. 6 Inductance profile.

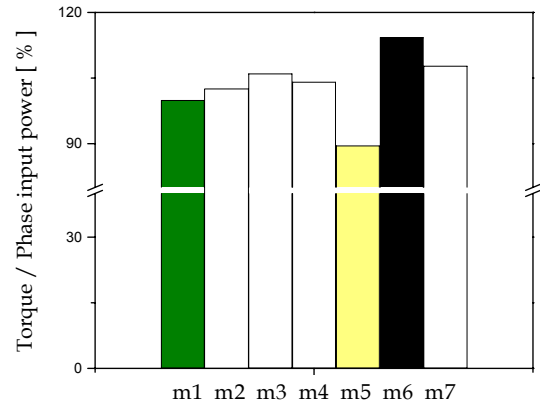


Fig. 8 Torque per phase input power.

#### IV. OPTIMIZATION OF SRM WITH A FLUX BARRIER

The SRM has a strong nonlinear characteristic in the core. Therefore, with attention to the aligned position, it is seen that the maximum value and slope of inductance vary considerably by input current. This effect is caused by the partially saturation of the magnetic core by energized winding. Therefore, the optimization of the barrier type SRM has to be performed by the numerical optimization using distributed parameters.

In this kind of shape optimization, although the numerical method for this kind of shape optimization can be complicated, it is time-consuming job because the numerous design variables are used and have usually a lot of interactions each other as well as the analysis model is redraw and re-mesh.

So, in this paper, the response surface method (RSM) is employed for the effective optimization. The RSM is very powerful method, which seeks the relationship between the input variables and the output variables through statistical fitting method in order to make simple model for a complex problem and is used to model the barrier type SRM using some function built by the results of time-stepped FE analysis coupled with voltage equation and kinetic motional equation.

This function is utilized as an objective function or constraint in the optimization process. In order to enhance the accuracy of the function, the regression coefficients in the RSM are estimated by using the moving least square method (MLSM) [7], [8]. This method combined RSM with the MLSM is confirmed to represent the torque performance according to the design variables of the barrier shapes as shown in Fig. 9. Optimization algorithm employed a genetic algorithms and Fig. 10 shows response surface for the torque due to the design variables, which is used as the objective function in the optimization.

This response surface may be expressed by using a fitted response vector and the objective function by changing the design variables is easily calculated using this vector. Their optimized results for a design variables shows in Table 2. In order to consider the nonlinear nature of inductance as a function of exciting current and rotor angular displacement, the differential circuit equations considering the appropriate

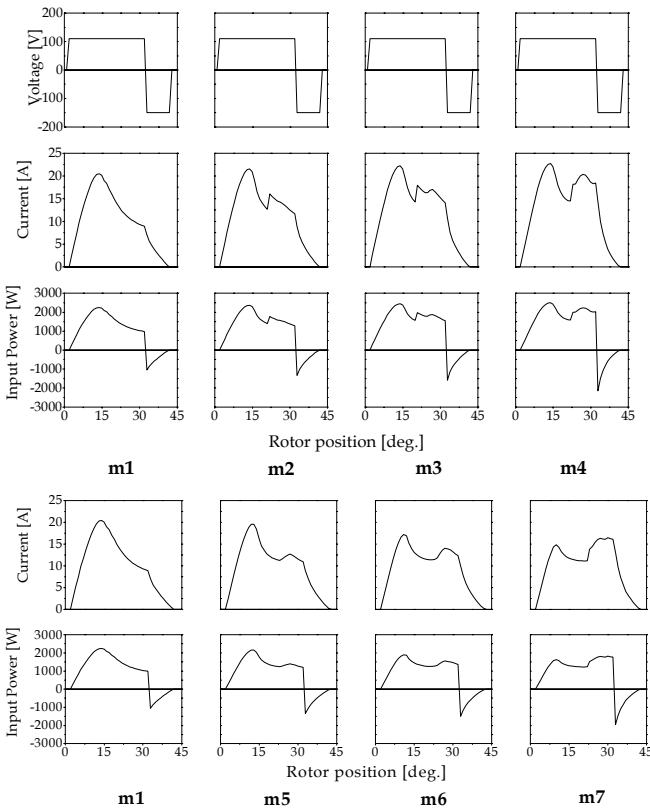


Fig. 7 Comparison of input power and current for seven models

TABLE 1 ANALYSIS RESULT FOR SEVEN MODELS

Parameter		m1 [%]	m2 [%]	m3 [%]	m4 [%]	m5 [%]	m 6 [%]	m7 [%]
Torque	Average	100	110.82	124.87	128.82	83.47	<b>101.03</b>	94.02
	Max.	100	109.21	122.61	128.09	82.33	<b>94.19</b>	69.26
	P- P	100	108.43	121.86	127.46	79.55	<b>89.25</b>	60.78
Input per phase	Average	100	108.11	117.75	123.66	93.18	<b>88.35</b>	87.22
	Max.	100	105.19	108.48	111.00	95.48	<b>84.08</b>	80.65
	P- P	100	111.95	122.23	140.68	105.58	<b>102.79</b>	114.31

switching condition is solved.

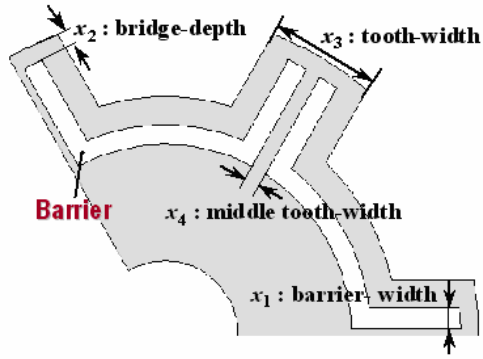


Fig. 9 Design variables of barrier shape for the proposed SRM.

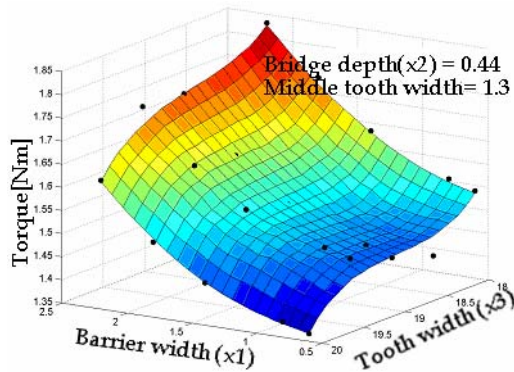


Fig. 10 Response surface of torque with both fixed  $x_2$  and  $x_4$ .

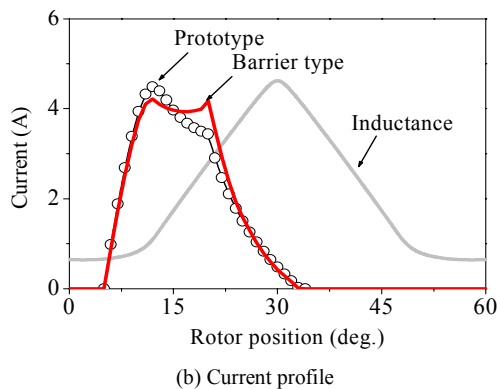
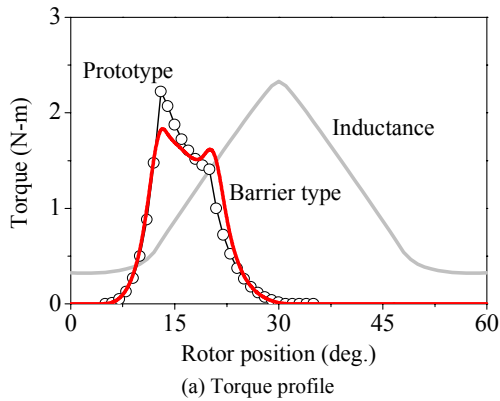


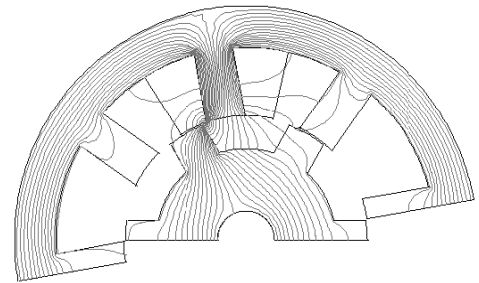
Fig. 11 Analysis results of the barrier type SRM for one stroke.

Fig. 11 shows the comparison of analysis results of the conventional SRM and the optimized barrier type SRM. These results show that the torque ripple is reduced by applying the flux barrier type. Fig. 12 shows the distribution of magnetic flux density for conventional model and optimized model, proposed type I and II. The type II is new shape barrier model eliminated the radial path of the basic shape.

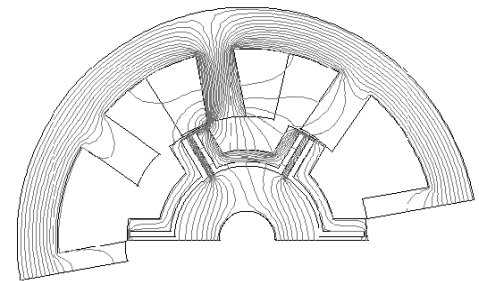
As shown in Fig. 12, the tangential magnetic flux density, which is contributed to the generated torque, is changed according to the inserted flux barriers. From this analysis, it is noted that the generated torque can be improved by the properly inserted flux barriers.

## V. EXPERIMENTAL RESULTS AND DISCUSSION

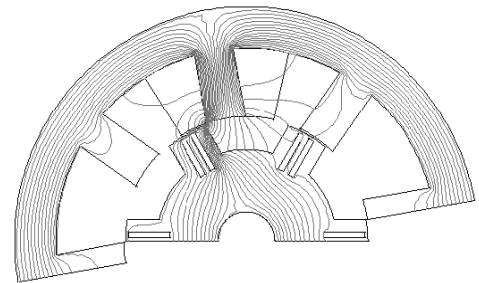
The inductance characteristics of the optimized model are analyzed and measured to verify the effectiveness and the improved torque characteristics of the barrier type model. Fig. 13 shows the prototype for experimental validation. The experimental results of these tests were obtained for two methods, a measuring method of rising current at constant voltage and AC power.



(a) Conventional SRM, C1



(b) Proposed type I inserted a barrier, B1



(c) Proposed type II inserted a barrier, B2

Fig. 12 Distributions of magnetic flux density



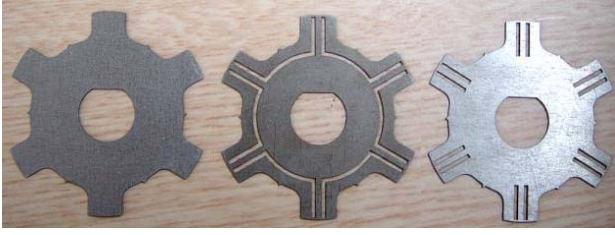


Fig. 13 Prototype for comparative study

The rising current is measured when the step voltage is applied to the test phase winding at desired position [8], [9]. From the measured data, their maximum inductance can be obtained using Eq. (2).

$$i = i_o + \frac{V_{step} \left(1 - e^{-Rt/L}\right)}{R}, \quad \tan(\theta) = \frac{V_{step}}{L} \quad (2)$$

Secondly, in other method used AC power, the inductance was calculated by measured voltage, current and phase angle using Eq. (3).

$$R = \frac{V_{rms} \cos \theta}{I_{rms}}, \quad L = \frac{V_{rms} \sin \theta}{\omega I_{rms}} = \frac{V_{rms} \sin \theta}{2\pi f I_{rms}} \quad (3)$$

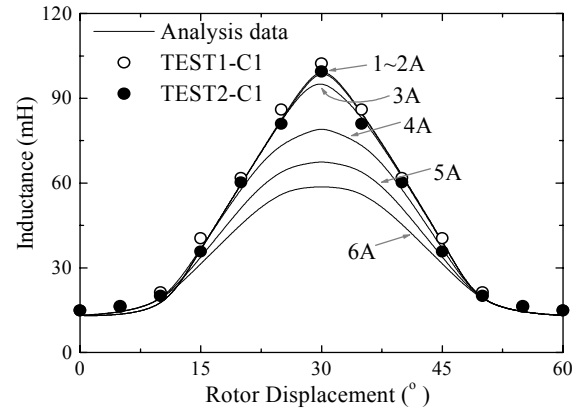
From the comparison of results measured by two methods, the inductances match very well. Also, the analytical and experimental inductances are in substantial agreement as shown in Fig. 14. In Fig. 14, experimental results base on three type 8/6 pole SRM, conventional, proposed type I and proposed type II, are compared to the finite element analysis (FEA) results. Table 2 gives the comparison between the conventional type SRM and the proposed type SRM with optimized barrier obtained by FEA

The accuracy of the analysis results would appear to be roughly consistent with that of measurement. Overall, it is reasonable to claim that the method provide results within about 10% of the actual values. It can be seen that the optimized barrier type SRM is remarkably improved on the side of average torque and torque ripple.

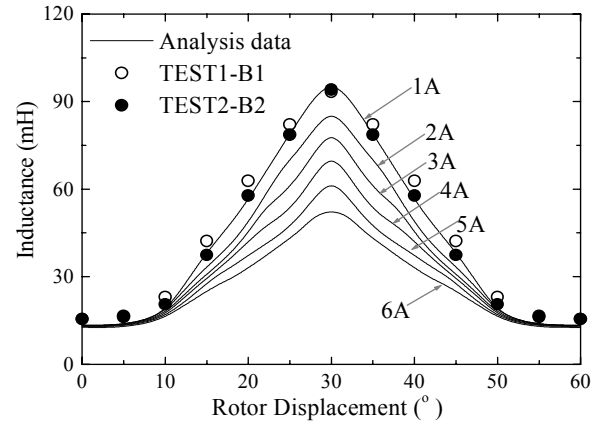
On the basis of these results it is clear that not only the SRM design inserted flux barrier is improved, but that the characteristics of the SRM are also improved in relation to the conventional one.

TABLE 2 ANALYSIS MODEL AND DESIGN VARIABLES

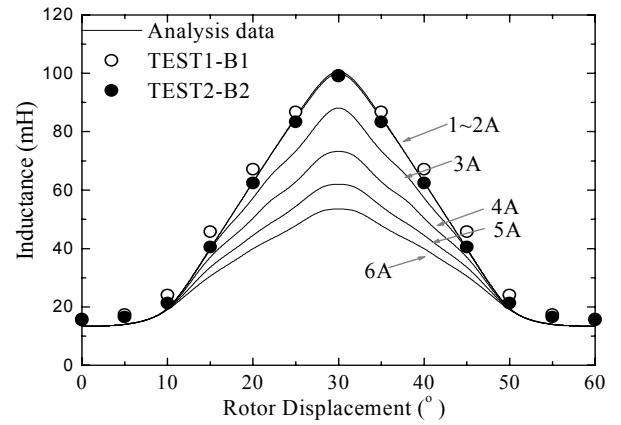
Item	Conventional type SRM	Barrier type SRM	
Torque	1.37 (N-m)	1.4 (N-m)	
Torque ripple	1.65 (N-m)	1.27 (N-m)	
Optimized shape of barrier in the proposed motor			
Barrier-width ( $x_1$ )	Bridge-depth ( $x_2$ )	Tooth-width ( $x_3$ )	Middle tooth-width ( $x_4$ )
1.0 (mm)	0.44 (mm)	20 (deg.)	1.3 (mm)



(a) Conventional SRM, C1



(b) Proposed type I inserted a barrier, B1

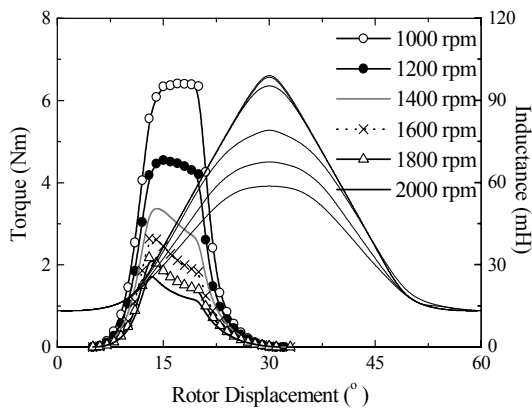


(c) Proposed type II inserted a barrier, B2

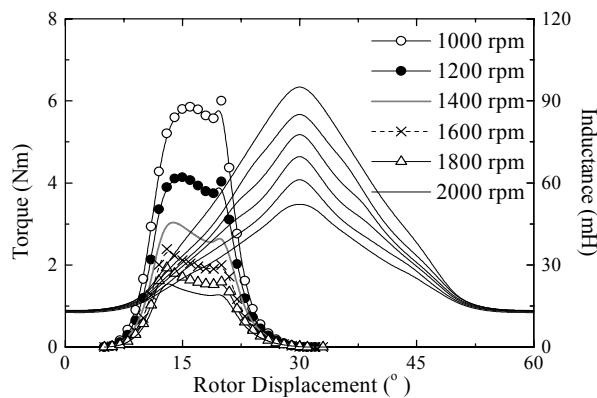
Fig. 14 Experimental results.

Also, the torque profile of the proposed model is shown in Fig. 15 and the comparison results for the torque ripple is described in Fig. 16, which is improved by the flux barrier on the rotor.

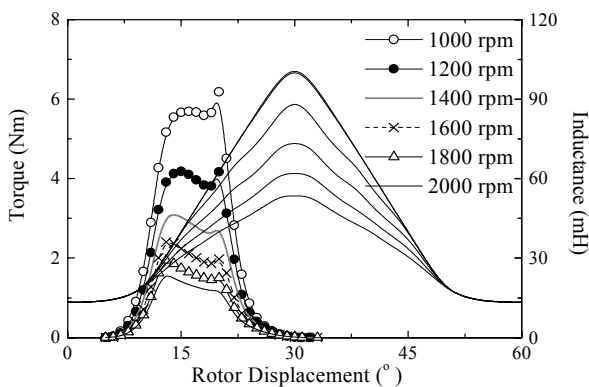
From the result, more fluxes contributed on the torque in the motor, which increase the average torque and reduce their ripple. Therefore, this kind of rotor of SRM, if the flux barrier is well designed, one can dramatically improve the characteristics.



(a) Conventional SRM



(b) Proposed type I inserted a barrier



(c) Proposed type II inserted a barrier

Fig. 15. Comparison of Torque characteristics

## VI. CONCLUSION

This paper has shown that the barrier structure of SRM is proposed and the proposed type SRM has been analyzed for comparison with the conventional SRM.

From the analysis results, the feasibility and performance of the proposed type have been verified by seven models with a different barrier shape. Moreover, an optimization of the barrier has been carried out with the help of RSM and MLSM methods.

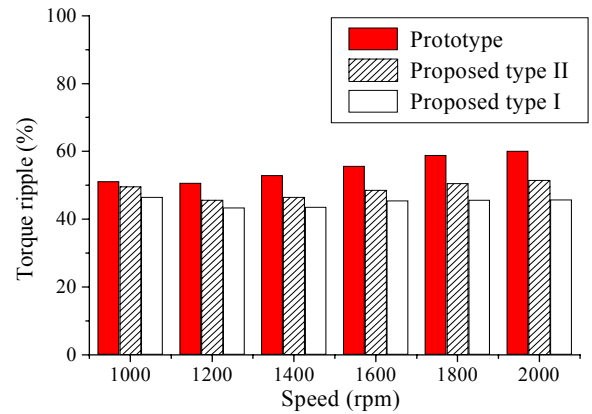


Fig. 16 Comparison of Torque ripples.

Optimized barrier type model has been also presented and tested. The performance in terms of torque to motor volume ratio and torque to torque ripple ratio is higher than in the conventional model from the simulation and experimental results.

So, it is highly expected that the proposed SRM with barrier can be applied to various industry applications with low torque ripple, high average torque, and high power density.

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