Design and Analysis of Rolled Rotor Switched Reluctance Motor

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Abstract: *In the conventional SRM with multi-rotor teeth the air gap must be very small to drive the SRM in the saturation region that is necessary for high output torque. But that leads to the problem of overheating particularly in the small size SRM. So the paper addresses the design and analysis of a new type of SRM which is the rolled rotor SRM, this new type needn't more than one region of very small airgap. That solves the overheating problem in the small size SRM. Moreover, using the rolled rotor instead of the conventional toothed rotor grades the air gap; that gives smooth variation of the reluctance consequently smooth current and torque shapes which is required in many applications.*

Key words: *rolled rotor, switched reluctance motor, finite element, smooth reluctance variation, absence of shaft, modelling, Matlab software*

1 Introduction

The electric motors used in the drive applications are the induction motors, permanent magnet motors and the switched reluctance motors. The permanent magnet motors have the problem of expensive magnets and the induction motors have the problem of high copper losses in both the rotor and the stator. So the motor designers focus on the SRMs because of their advantages particularly they have high specific output torque (torque/volume) and the absence of any kind of copper windings or permanent magnets on the rotor [1].

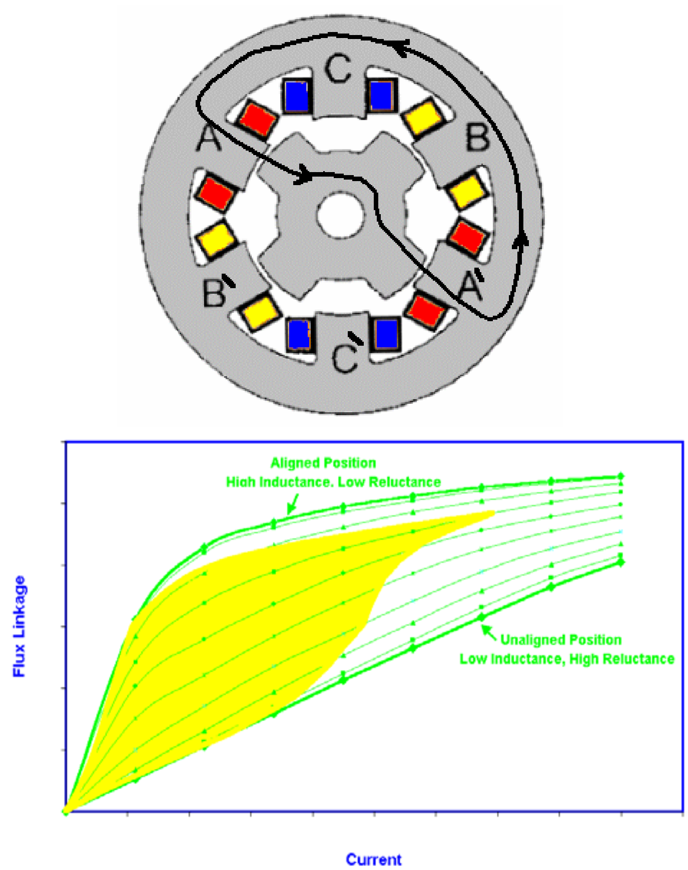


Fig. 1 6/4 SRM and the Flux-Linkage Characteristic under Voltage Control

Fig.1 shows cross section of 6/4 short pitch SRM and the Flux-Linkage trajectory under voltage control. The area between the aligned and the unaligned positions is proportional to the output torque. The SRM must work in deep saturation region to deliver much output torque. So the air gap must be very small; it can be said the minimum possible airgap (the mechanical considerations put limitation on minimizing the air gap length). That can cause overheating to the SRM consequently stands against the use of the SRM in many applications or to load it less than its full capacity to avoid overheating. From this point of view the paper introduces a new design of the SRM has less areas of narrow airgaps but the same performance of the conventional toothed-rotor. The rolled rotor SRM has only one small region of airgap.

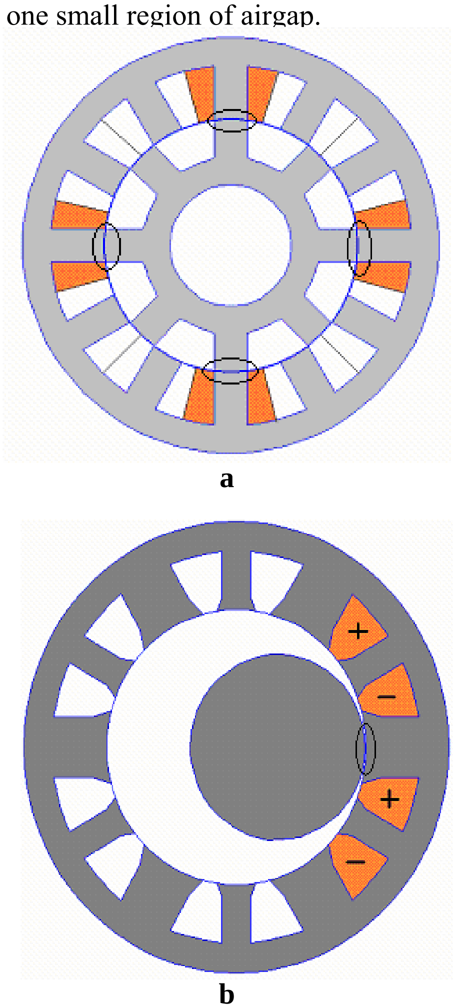


Fig. 2 Shows the Regions of the Narrow Airgaps in both the Designs

Fig. 2.a (as an example) shows the regions of narrow airgaps, in 12/8 conventional toothed-rotor SRM; there are four regions of narrow airgap in the aligned position but on the contrast the rolled rotor SRM (Fig. 2.b) has only one region of narrow air gap. Also in the rolled rotor SRM the airgap is graded. That can avoid the problem of overheating. In addition, the rolled rotor has smooth variation in the reluctance consequently smooth shape of current and torque when the switching on angle is selected properly [2-3].

3 Theoretical background

If one phase of the stator of the rolled rotor SRM is switched on the rolled rotor moves from any position to align itself with this energized phase because the aligned position is the only stable position of the rotor (maximum inductance position). The unaligned position is the position of minimum inductance. If the rotor rotates from the unaligned position to the aligned position this is half mechanical cycle.

The diameter of the rotor is directly proportional to the output torque. But large diameter of rotor minimizes the gap between the maximum inductance and minimum inductance consequently decreases the output torque. In addition, large rotor diameter makes the rotor weight heavy and increases the rotor iron losses. Small rotor diameter makes the SRM delivers few torque but the rotor is light that means it can rotates with high speeds with low iron losses. From this point of view there must be optimum diameter of the rotor or at least best rotor diameter. This section is dedicated to determine the best diameter of the rolled rotor SRM.

Before starting the analysis and design of the rolled rotor SRM it is important to mention here that the SRM generally is high non-linear electric motor so accurate prediction of the magnetic circuit parameter and static torque characteristics of this motor need two dimensions finite element [4-7].

A twelve teeth stator is used here. Six teeth are wide teeth carrying the main flux of the machine and the rest are return flux paths. The width of the main flux tooth is double the return flux tooth width.

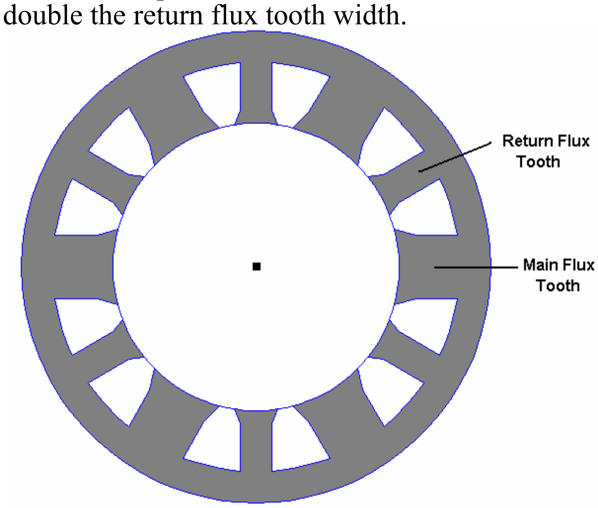


Fig. 3 The Stator of the Proposed New SRM

Fig.3 shows the stator of the new SRM, the width of the main flux tooth is double the return flux path in order to increase the flux crossing from the stator to the rotor cylinder in the aligned position. The stator bore diameter is about 60% the stator outside diameter as the conventional SRM.

The rotor of this new SRM is cylindrical iron rotor. It has outside diameter less than the stator bore diameter. Its centre shifted from the centre of the stator. That makes the air gap length varying (narrow in some regions and wide in other regions). Consequently the reluctance is varying that produces reluctance torque.

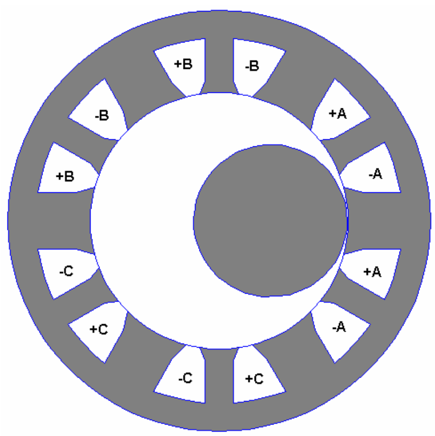


Fig. 4 Windings Distribution

Fig. 4 shows the windings distribution in the stator. The proposed rolled rotor SRM has three phases in the stator each phase fills four stator slots. In Fig. 4 the rotor diameter is 0.6 the stator bore diameter.

4 Determination of the Best Rotor Diameter

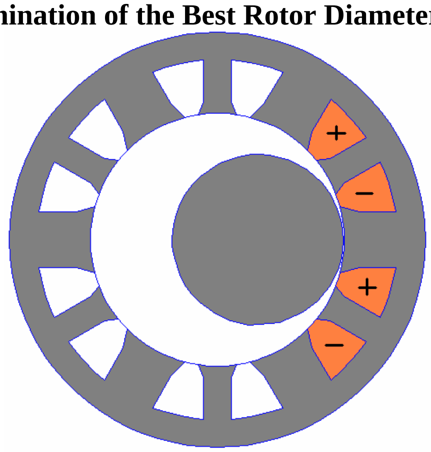


Fig. 5 Rotor Diameter = 0.68 Stator Bore Diameter Aligned Position

Initially the rotor diameter is assumed to equal 0.68 the stator bore diameter. When one stator phase is energised all the rotor positions will be unstable except one position which is the maximum inductance (the aligned position), the rotor rotates to stand in front of the wide tooth of the stator energized phase because this is the minimum reluctance position.

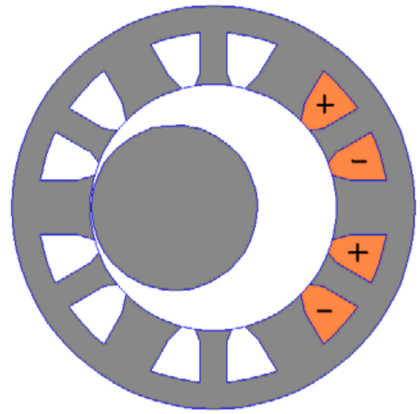


Fig. 6 Rotor Diameter = 0.68 Stator Bore Diameter Unaligned Position

The unaligned position is the position of minimum inductance which is on the opposite diameter of the main energized pole.
The area between the aligned position and the unaligned position in the Flux-Linkage/Current characteristic of the SRM is proportional to the output torque. So the area enclosed between these two lines gives indication about the output of any design of the SRM. For different rotor diameters these areas are compared to find the best diameter of the rotor.

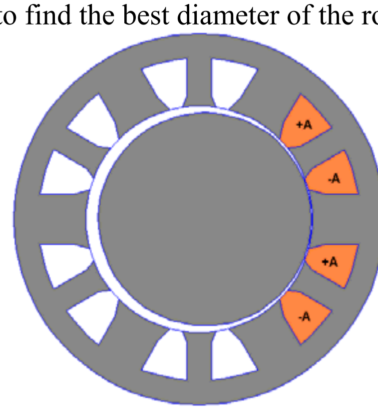


Fig. 7 Rotor Diameter = 0.95 Stator Bore Diameter Aligned Position

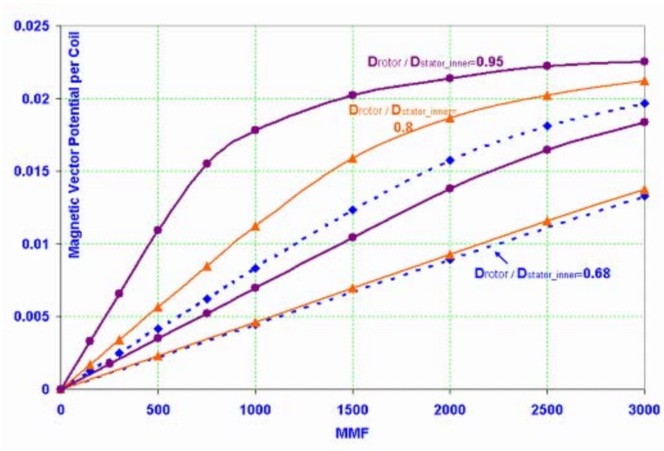


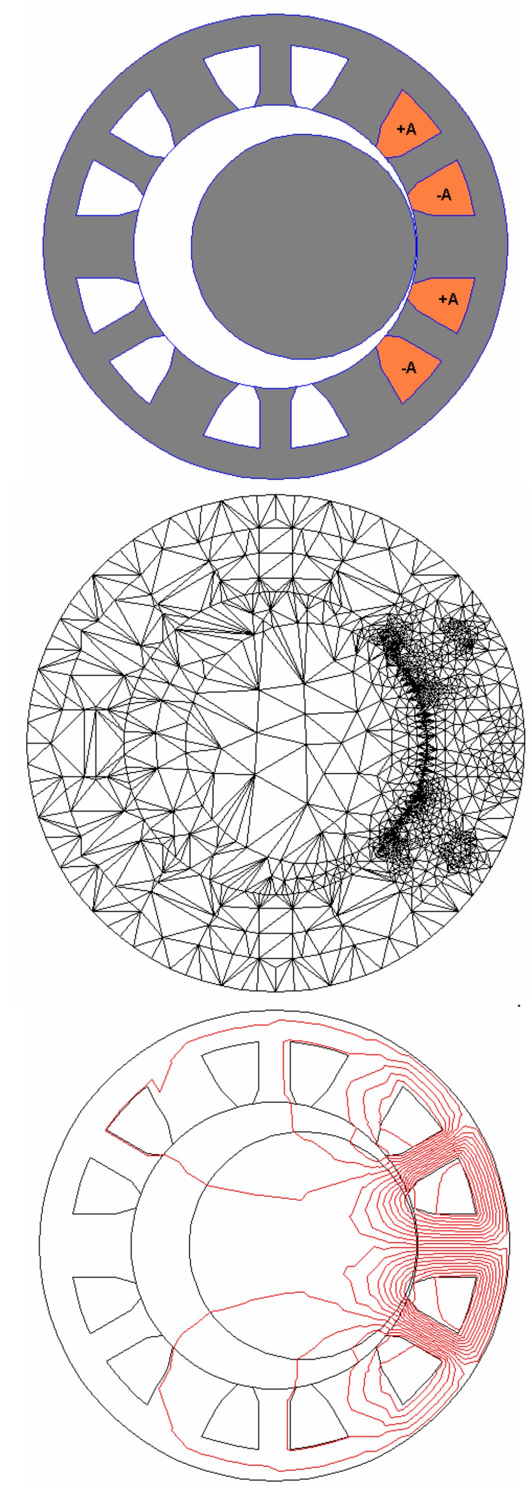
Fig. 8 Comparing the Characteristics of Different Rotor Diameter

Fig. 8 shows comparison between the aligned and the unaligned positions for different designs of the rolled rotor SRM. All SRMs have the same stator dimensions the only thing changed is the rotor diameter.
The small rotor diameter delivers few torque (the area enclosed between the aligned and the unaligned position is proportional to the output torque). Increasing the rotor diameter increases the area between the aligned and the unaligned position until the ratio between the rotor diameter to the stator bore diameter equal 0.8. Increasing the rotor diameter more than this ratio increases the area enclosed slightly. So the best rotor diameter =0.8 stator bore diameter. To be clear more than this ratio increases the torque slightly but increases the weight of the rotor much and also increases the rotor iron losses that is the reason for selecting this rotor diameter.

5 Complete Details of the Proposed New Design

From the previous section the selected rotor diameter equals 0.8 the stator bore diameter.

5.1 Aligned Position



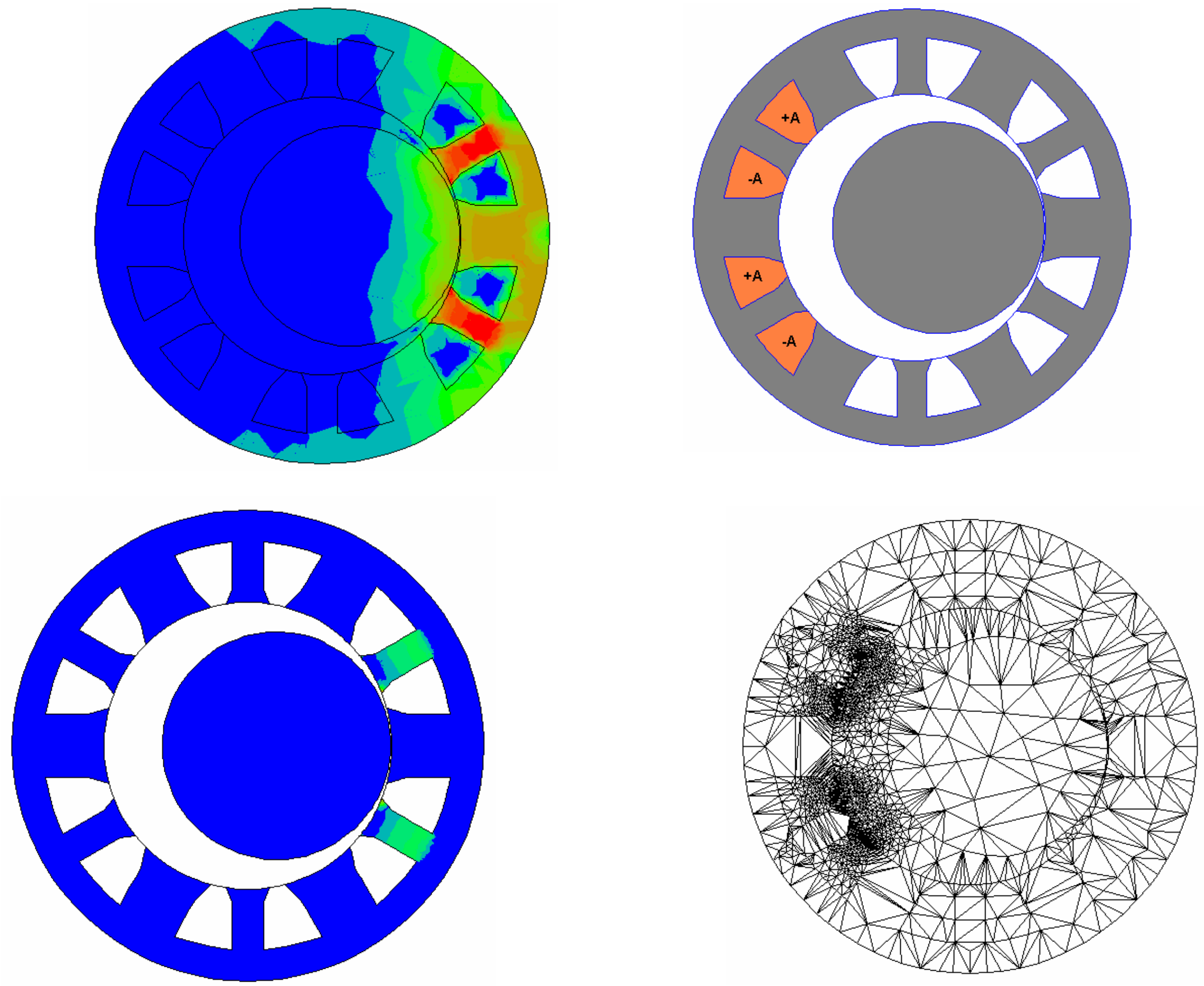


Fig. 9 Aligned position for the New Design

Fig. 9 shows the aligned position for the new design of the rolled rotor SRM and the adaptive mesh. The magnetic flux plot, the flux density and the saturation all are shown at 3000MMF per slot. In the aligned position the cylindrical rotor moves from any position to align itself with the energised phase.

5.2 Unaligned Position

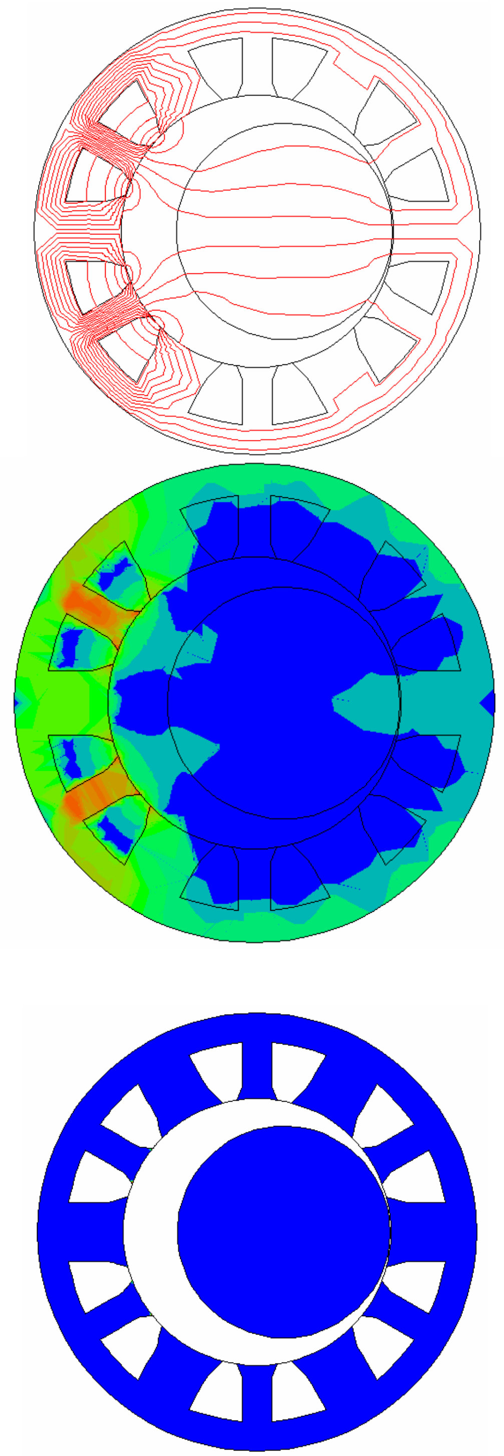
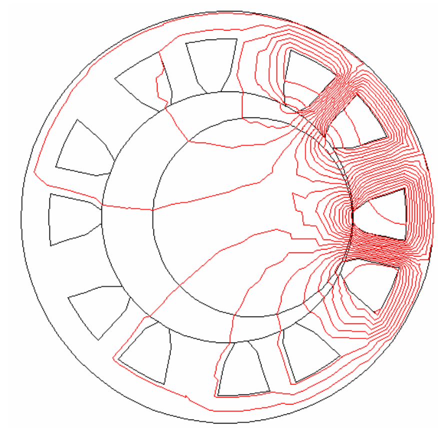


Fig. 10 Unaligned Position for the New Design

Fig. 10 shows the unaligned position of the proposed new design and the adaptive mesh. The magnetic flux plot, the flux density and the saturation all are shown at 3000MMF per slot. The unaligned position when the rotor in a position of maximum reluctance with respect to the energised phase.

6 Determination of Flux-Linkage Characteristic

Different models are built using 2D finite element for different rotor positions to determine accurately the magnetic vector potential characteristic.



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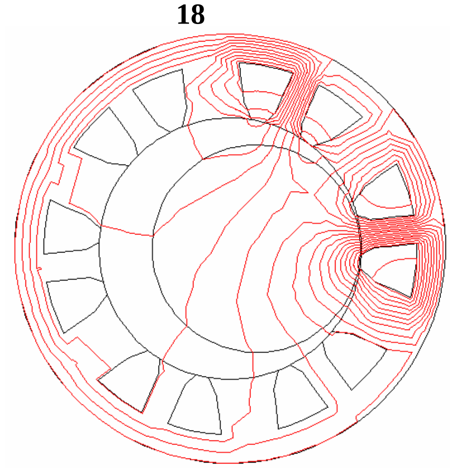

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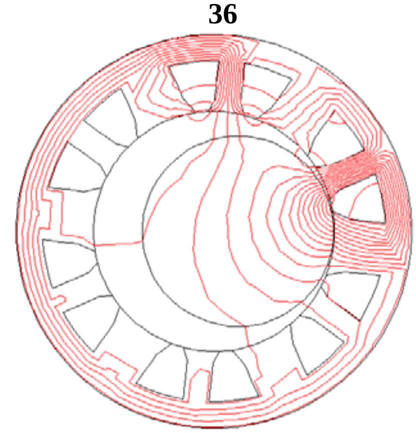

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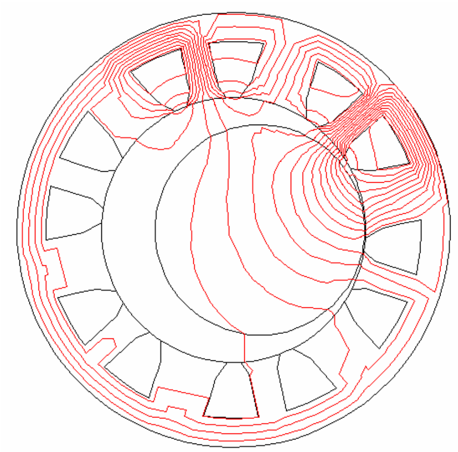

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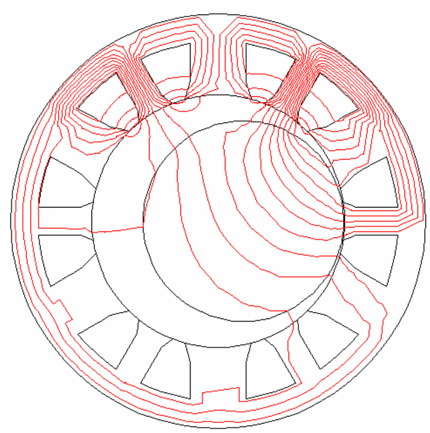

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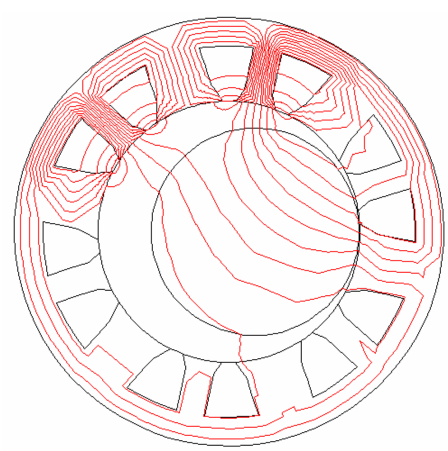

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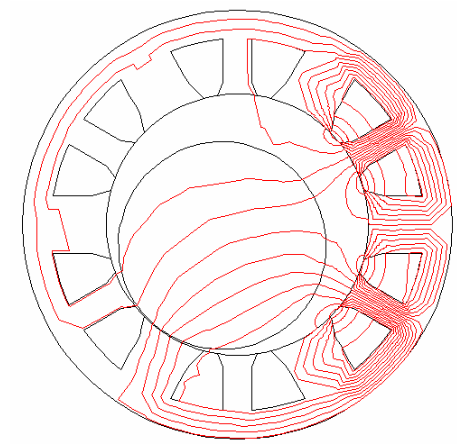

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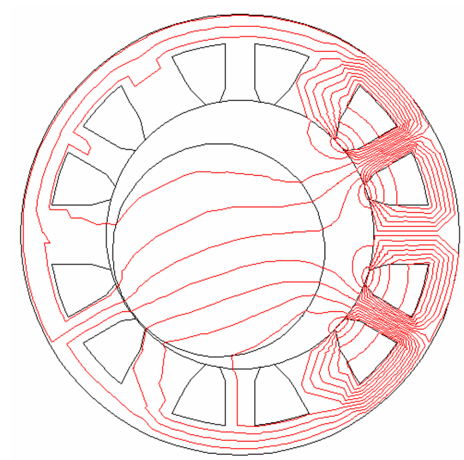

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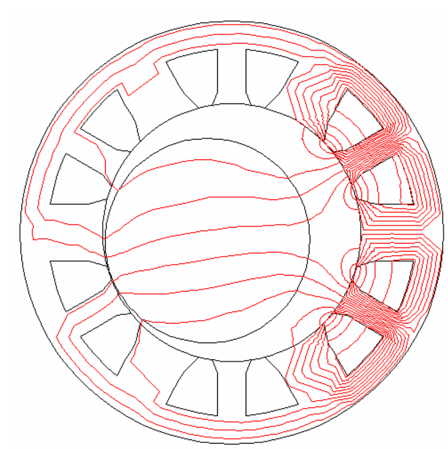

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Fig. 11 New Rolled Rotor Models for a Rang of Rotor Positions

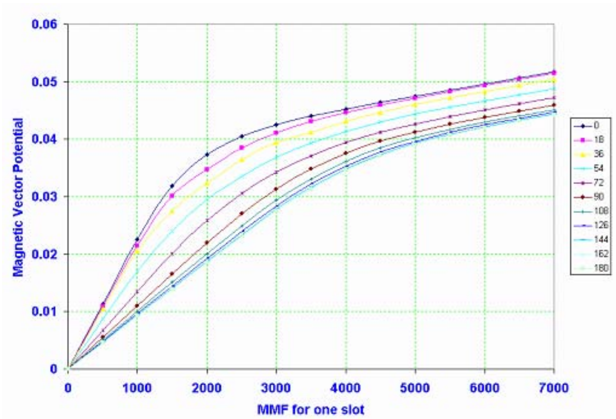


Fig. 12 Magnetic Vector Potential for the Rolled Rotor SRM for different Rotor Positions

7 The Flux-Linkage Characteristic and the Static Torque Characteristic

The flux linkage characteristic can be obtained from the magnetic vector potential characteristic assuming the number of turns. There are six coils two for each phase. Assume number of turns of each coil 300 so 150 conductors per slot.

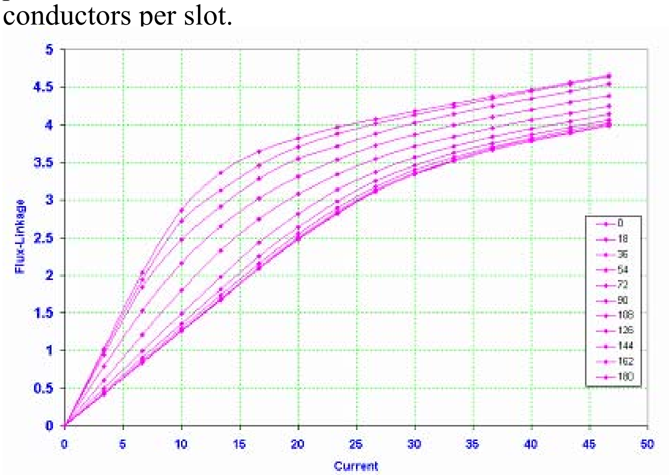


Fig. 13 Flux-Linkage Characteristic for the New Rolled Rotor SRM
Assume 150 conductors per slot

Consequently the static torque characteristic can be obtained from the following equation

$$T(\theta,i) = \left.\frac{dW'(\theta,i)}{d\theta}\right|_{i=const}$$

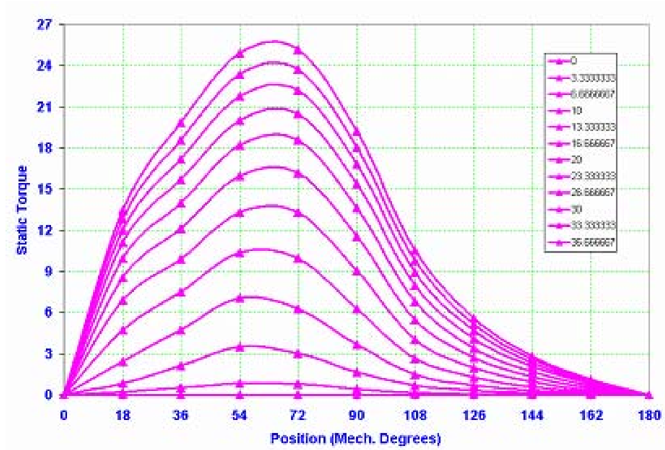


Fig. 14 Static Torque Characteristic of the New Rolled Rotor SRM

8 The Performance of the New Rolled Rotor SRM

The machine performance has been predicted analytically from the fundamental equation of the terminal voltage of any machine

$$\mathrm{v} = \mathrm{R.i} + \frac{\partial \psi}{\partial \mathrm{t}}$$

Then by solving one of the following 1st order differential equations [8-11]:

$$v = R \cdot i + \frac{di}{dt} \cdot \frac{\partial \psi}{\partial i}(\theta,i) + \omega \cdot \frac{\partial \psi}{\partial \theta}(\theta,i)$$

$$v = R \cdot i + \frac{di}{dt} \cdot \frac{\partial \psi(\theta,i)}{\partial i} + \omega \cdot \frac{\partial \psi(\theta,i)}{\partial \theta}$$

$$v = R \cdot i + \frac{di}{dt} \cdot L(\theta,i) + \omega \cdot i \cdot \frac{\partial L}{\partial \theta}(\theta,i)$$

$$v = R \cdot i + \frac{di}{dt} \cdot L(\theta,i) + \omega \cdot i \cdot \frac{dL(\theta,i)}{d\theta}$$

A numerical approach to the simulation of SRMs has been introduced in [12-14]. The flux-linkage can be determined from this equation

$$\psi = \int (v - R \cdot i(\theta,\psi))dt$$

The torque can be obtained indirectly from the co-energy

$$W'(\theta,i) = \int_0^i \psi(\theta,i)\,di \Big|_{\theta=const}$$

$$T(\theta,i) = \frac{dW'(\theta,i)}{d\theta}\Big|_{i=const}$$

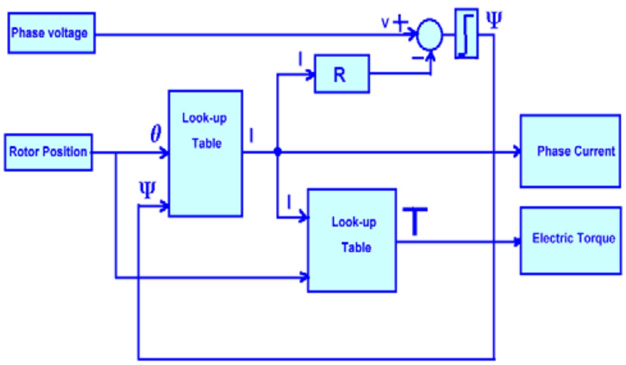


Fig. 15 Block Diagram of SRM Simulation

Fig. 15 is the block diagram of the SRM simulation package. The flux linkage characteristic data is taken from an adaptive finite element solution of the magnetic characteristics; it is stored in tables (one for the flux-linkage characteristic and one for the torque), then loaded in to a simulation of the SRM using Matlab/Simulink [15-20].

8.1 Simulation Results Speed 500 rpm

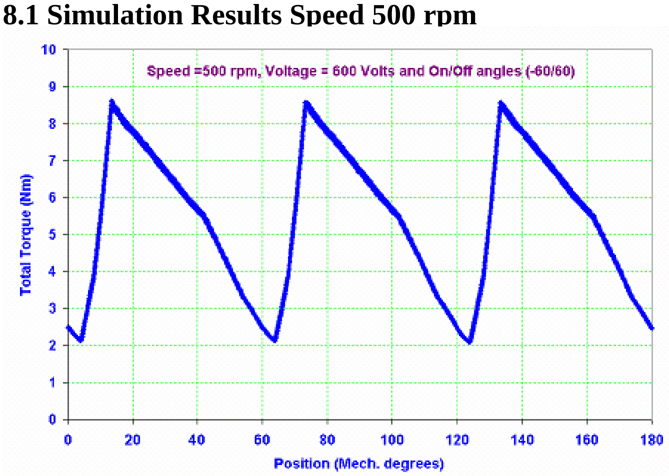


Fig. 16 Torque versus Position
Switching on angle before the unaligned position by 60 degrees

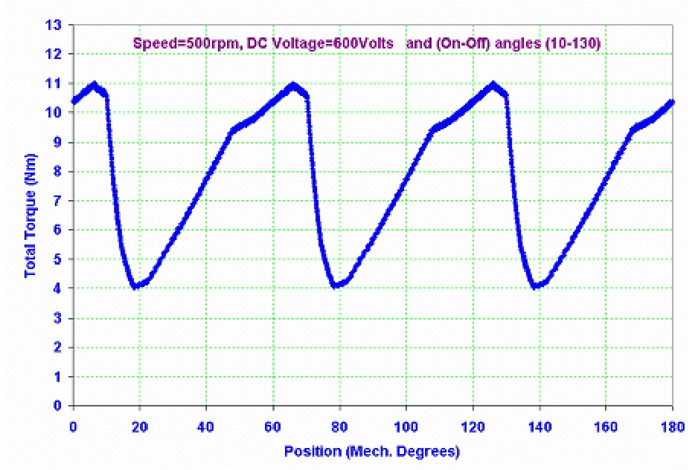
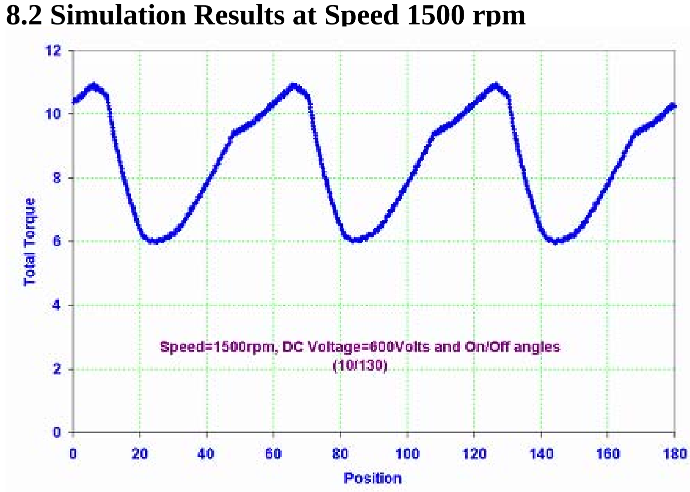
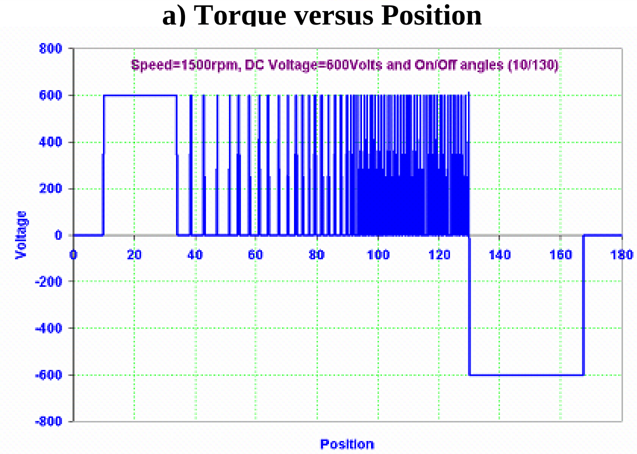


Fig. 17 Torque versus Position
Switching on angle after the unaligned by 10 degrees

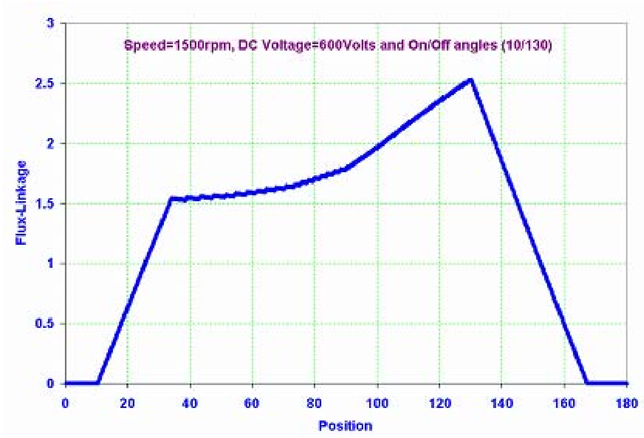
8.2 Simulation Results at Speed 1500 rpm



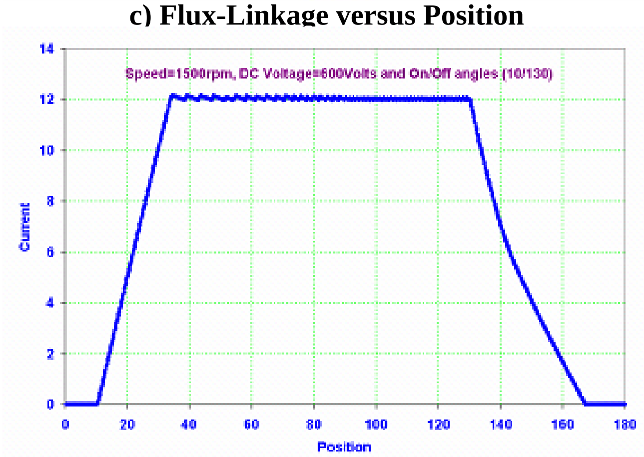
a) Torque versus Position



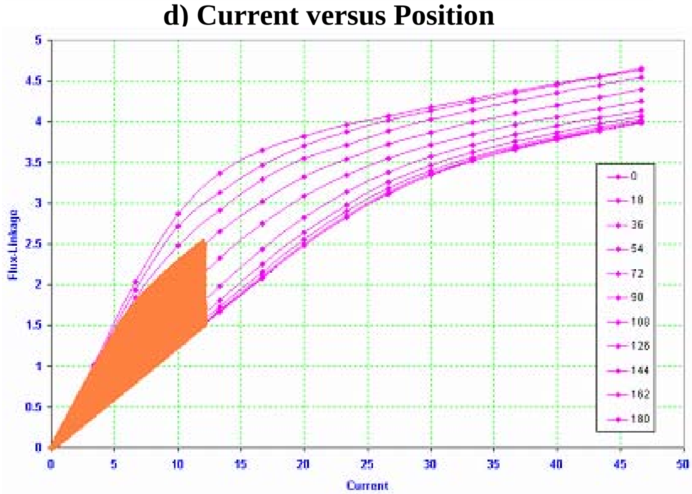
b) Voltage versus Position



c) Flux-Linkage versus Position



d) Current versus Position



e) Flux-Linkage Trajectory

Fig. 18 Torque versus Position Switching on angle after the unaligned by 10 degrees

9 Torque Speed Envelop

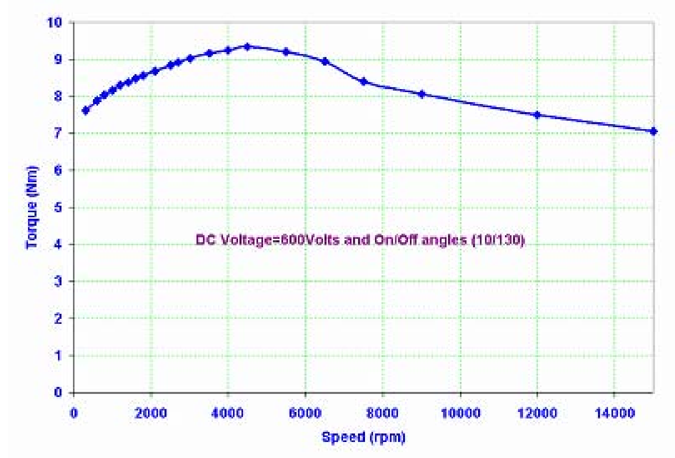


Fig. 19 Torque speed Envelop for the Rolled Rotor SRM

Fig. 19 shows the torque speed envelop for the new rolled rotor SRM. The new SRM has excellent torque/speed envelop; the machine can deliver much output torque at very high speed

10 Changing the Connection of the two Coils of Each Phase

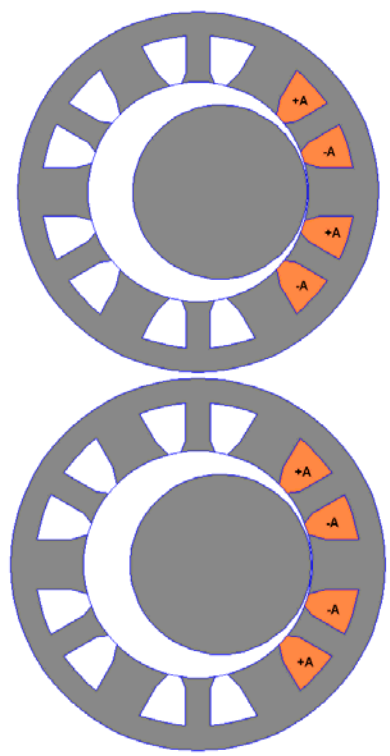


Fig. 20 Changing the Connection of the two Coils of Each Phase

Fig. 20 shows the polarity of the second coil in each phase is changed.

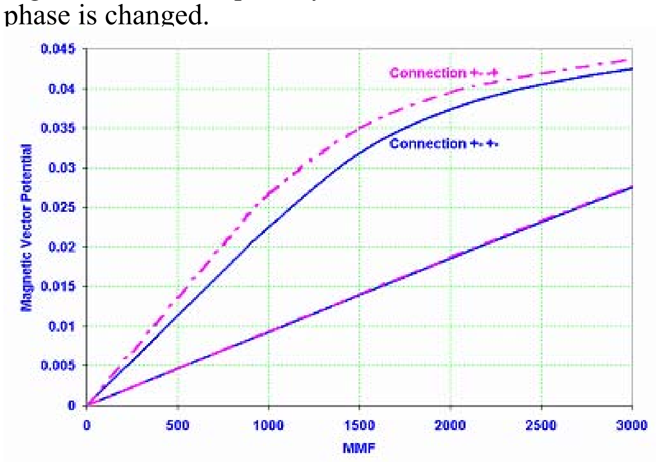


Fig. 21 The Aligned and the Unaligned Positions for the different connections

Fig. 21 shows the aligned and the unaligned position for the two different connections (the dimensions of each one similar to the second one). The aligned position came up when the connection changed. Consequently the output torque increased slightly [21-28].

11 Conclusion

The paper introduces the design, analysis and simulated results of a new type of SRM which is the rolled rotor SRM to overcome some problems in the conventional toothed-rotor SRM.

The stator of the SRM was selected to have wide teeth as main flux teeth and thin teeth as return flux teeth in order to concentrate the flux on the cylindrical rotor. The diameter of the rotor was selected not very wide to be able to run at high speeds and to avoid the high value of rotor iron losses; and not very small diameter to enable the motor to deliver much output torque. Complete analysis was done to study the new design entirely. Different models for different rotor positions were built to obtain the characteristic precisely. Simulated results for different operating conditions were introduced. The torque/speed envelop shows excellent characteristic as the machine keeps its torque capability at very high speeds on the contrast of the conventional SRM. So the new design can be used instead of the conventional design of the SRM to solve many problems.

12 References

[1] J. R. Gyorki, 'Design Secrets of Switched Reluctance Motors', September 26, 1996 Journal Machine Design.

[2] E. A. Fisher, E. Richter, 'Conical Rotor for Switched Reluctance Motor' US5233254, US-Patent, 3/8/1993.

[3] T. J. E. Miller, 'Optimal Design of Switched Reluctance Motors' IEEE Transactions on Industrial Electronics, Vol. 49, No. 1, February 2002.

[4] K. M. Richardson, C. Pollock and J. O. Flower, 'Design of a Switched Reluctance Sector Motor for an Integrated Motor/Propeller Unit' IEE Electrical Machines and Drives' 11-13 September 1995.

[5] A. Michaelides and C. Pollock, 'Design and performance of a high efficiency 5-phase switched reluctance motor' IEE conference of Electrical Machines and Drives 11-13 September 1995.

[6] A. R. Eastham, H. Yuan, G. E. Dawson, P. C. Choudhuhury, P.M. and Cusack, 'A Finite Element Evaluation of Pole Shaping in Switched Reluctance Motors', Electrosoft, 1990, 1, (1).

[7] A. Matveev, T. Undeland, R. Nilssen, 'Design Optimisation Of Switched Reluctance Drives Using Artificial Neural Networks' EPE-PEMC 2002 Dubrovnik & Cavtat.

[8] J. Reinert, R. Inderka, M. Menne, and R. W. De Doncker, 'Optimisation Performance in Switched Reluctance Motor' IEEE Industry Applications Magazine, July/August 2000.

[9] M. Sanada, S. Morimoto, Y. Takeda and N. Matsui, 'Novel Rotor Pole Design of Switched Reluctance Motors to Reduce the Acoustic Noise' IEEE Conf. IA 2000, Italy.

[10] R. S. Wallace and D. G. Taylor, 'Three Phase Switched Reluctance Motor Design to Reduce Torque Ripple' International Conference on Electrical Machines ICEM'90, Pages: 782-787.

[11] M. R. Harris, A. Hughes, and P. J. Lawrenson, 'Static Torque Production in Saturated Doubly-Salient Machines', Proc. IEE, 1975, 122, (10), pp. 1121-1127.

[12] M. Sanada, S. Morimoto, Y. Takeda, and N. Matsui, 'Novel Rotor Pole Design of Switched Reluctance Motors to Reduce the Acoustic Noise', IEEE Conference on Industry Applications, Rome, October 2000.

[13] U. Bock, 'A Novel Approach of Modeling SR Motor Systems' ICEM 2002, 15th International Conference on Electrical Machines' Brugge, Belgium, August 25-28, 2002.

[14] L. Xu and E. Ruckstadter, 'Direct Modelling of Switched Reluctance Machine by Coupled Field-Circuit Method' IEEE Transactions on Energy Conversion, Vol. 10, No. 3, September 1995.

[15] A. Michaelides and C. Pollock, 'Modelling of a New Winding Arrangement to Improve Performance in the Switched Reluctance Motor', IEE Conference of Electric Machines and Drive, 1993.

[16] A. V. Radun, 'Design Considerations for the Switched Reluctance Motor' IEEE Transactions on Industry Applications, Vol. 31, No.5, September/October 1995.
[17] Z. Zuncheng and Y. Shouyou, 'Determination of the Rectangular Teeth Geometry of the VR Motor' IEEE Transactions on Magnetics, Vol. Mag-21, No. 6, November 1985.
[18] S. S. Murthy, B. Singh and V. K. Sharme, 'Finite Element Analysis to Achieve Optimum Geometry of Switched Reluctance Motor' IEEE IAS 1998 414-418.
[19] Fulton, N. Neilson, 'Operation of Switched Reluctance Machines' European Patent, EP 0959555, 24/11/1999.
[20] D. A. Staton, W. L. Soong and T. J. E. Miller, 'Unified Theory of Torque Production in Switched Reluctance and Synchronous Reluctance Motors' IEEE Transactions on Industry Applications, Vol. 31, No. 2, March/April 1995.
[21] K. Koibuchi, T. Ohno and K. SAWA, 'A Basic Study for Optimal Design of Switched Reluctance Motor by Finite Element Method' IEEE Transactions on Magnetics, Vol. 33, No. 2, March 1997.
[22] Kliman et al., 'Construction of Reluctance Motors' US patent US5053666 1/10/1991.
[23] K. Yasuyuki, 'Manufacturing Method of Stator or Rotor of Variable Reluctance Type Motor' Japanese Patent, JP10-2011 46, 3/10/1980.
[24] P. P. Acarnley, R Aggarwal, 'Inductance and Static Torque Measurement in Small Reluctance-Type Machines' Proc. UPEC, Nottingha, UK 1988.
[25] P. Andrada, E. Martinez, J. I. Perat, J. A. Sanchez, and M. Torrent, 'Experimental Determination of Magnetisation Curves of Switched Reluctance Motors' ICEM 2000, 28-30 August, Espoo, Finland.
[26] M. R. Harris, et al. 'Static Torque Production in Saturated Doubly-Salient Machines', Proc. IEE, Vol.122, No.10, October 1975. pp1121~1127.
[27] R. M. Davis, 'Variable Reluctance Rotor Structures- Their Influence on Torque Production', IEEE Transaction on Industrial Electronics, Vol.39, No. 2 April 1992.
[28] D. A. Philips, 'Switched Reluctance Drives: New Aspects' IEEE Transactions on Power Electronics, Vol. 5, No. 4, October 1990.