Geometry Modification of Switched Reluctance Motor

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Abstract

The aim of the project work is to design and simulate a new geometry of Switched Reluctance Motor (SRM) which has higher number of rotor poles than stator poles. By using a newly defined pole design formula, a new combination of the stator–rotor poles has been proposed. A new SR motor with ten rotor poles and six stator poles is modelled. Owing to a rigid structure and the absence of magnetic source on the rotor, a switched reluctance motor (SRM) is inherently robust and cost effective. In spite of these advantages, several challenges in the control of this motor remain an issue, including high levels of torque ripple, acoustic noise, and a relatively low torque density. Thus a new model is presented which reduces torque ripple and increases torque production density. From the simulation analysis of a 6/10 configuration, it has been observed that this machine produces higher torque per unit volume and torque ripple when compared to 6/4 SRM.

Keywords*: - Low torque ripple, High torque density, Switched reluctance motor (SRM).*

INTRODUCTION

The Switched reluctance motor is an electric motor in which torque is produced by the tendency of its movable part to move to a position where the inductance of the excited winding is maximum. The origin of the reluctance motor can be traced back to 1842, but the "reinvention" has been possibly due to the advent of inexpensive, high-power switching devices. The reluctance motor is a type of synchronous machine. It has wound field

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coils of a DC motor for its stator windings and has no coils or magnets on its rotor. Fig.1 shows its typical structure. It can be seen that both the stator and rotor have salient poles; hence, the machine is a doubly salient machine.

The automotive sector has undergone significant changes in the last few years. Major emphasis has been placed on increased efficiency, enhanced performance, reduced emissions, and developing a sustainable environment. This has led to an increased interest in the area of hybrid electric vehicles (HEVs) over the last decade [1]–[4]. In order to improve the effectiveness of an HEV, there are several areas that require optimization, which include efficiency of the drive, reduction in size, ruggedness of the overall system, and cost effectiveness of electric machines and associated drive electronics [4]–[6]. Hybrid vehicles require an electric drive to convert electrical energy into mechanical energy, which are more energy efficient with a better power capability, thus providing substantially greater torque at low speeds [7], [8]. Owing to the critical nature of the application, there exists a need to design and implement robust and fault-tolerant drives for propulsion systems. In addition, they should also show high grade performance and be relatively cost effective. This paper presents the design and implementation of a novel family of switched reluctance machines (SRMs), which addresses these specific issues and provides a potential solution.

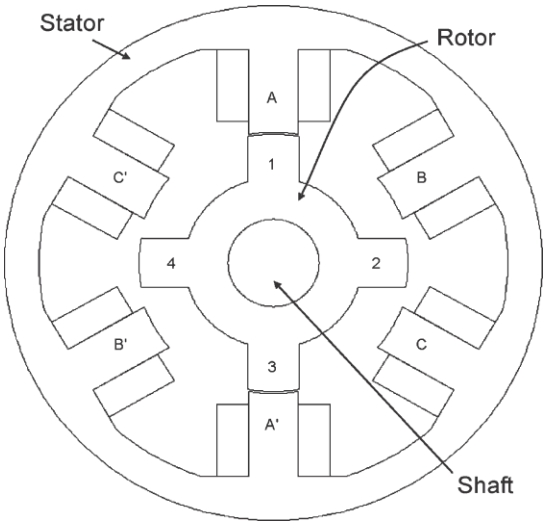


Fig.1 6/4 SRM

The performance of an electric machine can be described by the following key parameters:

- power density
- structural integrity
- manufacturing cost

Owing to its rigid structural configuration and the absence of magnetic source on the rotor, an SRM is inherently robust and cost effective [16]. In spite of these advantages, the SRM demonstrates a highly nonlinear

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and complex behaviour due to local and bulk saturation in various parts of the stator and rotor cores, respectively. This affects the overall efficiency of the drive and makes them slightly less favoured candidates over the commonly used permanent-magnet synchronous machine and induction machine [17], [18].This paper introduces the design and development of a novel topology for an SRM with more rotor poles than stator poles. Since this machine preserves the key construction all details of the SRM, it enjoys all the structural benefits of a conventional design. Another contribution of this paper is a new pole design (PD) formula that describes all the combinations possible for SRMs. For the study of inherent benefits of the proposed design, the design process of a 6/10 machine along with a comprehensive analysis of various operating parameters has been presented. Based on the results obtained, this machine shows the potential for a robust machine with high-grade performance and increased torque per amperes. Simulation and experimental results have been reported to validate the claims.

SUMMARY OF SRM TECHNOLOGY

SRMs are typically designed such that stator and rotor poles are symmetrical and Evenly distributed around the circumference. In addition, they are expected to be capable of self-start and continuous torque production. Over the years, researchers have proposed several configurations for the SRM. These include various combinations of rotor and stator poles. They also include topologies in which the more than four phase excitations are employed. Some well-known configurations with higher phase numbers are five-phase 10/8 SRM and seven phase14/12 SRM [30]. A summary of known configurations with regular stator and rotor poles is given as follows for at-a-glance review [30]:

- three-phase SRMs: 6/2; 6/4; 6/8; 6/14; 12/8; 18/12; 24/16;
- four-phase SRMs: 8/6; 8/10; 16/12; 24/18; 32/24;
- five-phase SRMs: 10/4; 10/6; 10/8; 10/12;
- six-phase SRMs: 12/10; 12/14; 24/20;
- Seven-phase SRMs: 14/10; 14/12; 14/16.

The concept of optimization of the geometry of the SRM has been addressed by several researchers [31], [32]. In addition to varying the combination of stator–rotor poles, several design

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adjustments have been proposed to improve the efficiency of the machine and minimize losses. For redundancy, lower noise, and starting torque improvement, Horst illustrated the stepped rotor construction for 12/4 and 6/2 and multiple teeth per pole [33].The stator and rotor teeth ratios have been defined as 6(*n*):2(*n*),6(*n*):4(*n*), 6(*n*):8(*n*), 8(*n*):6(*n*), and 8(*n*):10(*n*), where n is a positive integer from one to four. Kalpathi *et al.* [34] showed a6/14 SRM, closely resembling two teeth per pole configuration, to illustrate method and apparatus of acoustic noise reduction.

In addition, several researchers have explored irregular spacing and shapes of stator and/or rotor poles to reduce core losses and realize better efficiency using shorter flux paths [8] and lower flux reversal frequency [35]. Heese and Heidrich [36] illustrated unique configurations, e.g., 9/6, 12/9, 9/5, and 12/7, to reduce the noise, where two or three asymmetric and/or uneven stators formed a phase while the rotor may also be asymmetric and/or uneven. Gilman [37] described the pulsed duration modulated control technique with reference to 4/6 SRM with stepped rotor construction. Kolomeitsev [38] illustrated a 6/8 SRM with longitudinally different cross-sectional shapes for stator and rotor poles. He also explained bifurcated n stator poles with 2nteeth and 2n + 2 rotor poles, where n is an integer, through an example of 6/14 SRM. Morinigo [39] showed a 6/8 SRM with rotor laminations stacked in a particular spiral pattern to deliver constant torque from three-phase sinusoidal voltages. It can be seen that the machine topologies that have been proposed do not exploit the ability of increasing the number of rotor poles without causing a corresponding increase in the number of phases.

FUNDAMENTALS OF SRM

The design and analysis of the novel SRM involve a thorough understanding of the fundamentals of energy conversion in a conventional SRM. This section briefly discusses the saturation effects and constraints posed on the design of the proposed configuration.

Magnetization Curve or Flux Linkages

In an SRM, reluctance (and, hence, inductance) is a function of excitation current and rotor position. At an aligned position or at higher current levels, the ferromagnetic material in the rotor and stator poles begins to saturate. Due to

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secondary effects such as saturation, fringing, and leakage, nonlinearities are introduced in the relationship between inductance, current, and rotor position. This has been demonstrated in Fig. 2 for the 6/4 SRM under consideration.

At an unaligned position, phase inductance has a minimum value due to high reluctance offered by large air gap. Magnetic saturation is unlikely to occur at an unaligned position, and hence, the flux linkage shows a linear behaviour until the start of overlap, labelled as 100◦rotor position in Fig. 2. At a fully aligned position where rotor poles completely overlap with stator poles, magnetic field density tends to saturate at high current levels, making flux linkage a nonlinear function of position and current. This behaviour is clearly seen in Fig. 2.

Phase Winding Circuit Description

The analysis of the geometry of the proposed SRM is based on the constraints set by flux through the system, as described in the previous section. In order to accurately assess this quantity, the circuit description of the phase windings of the SRM has been used. **See Figure: 3**

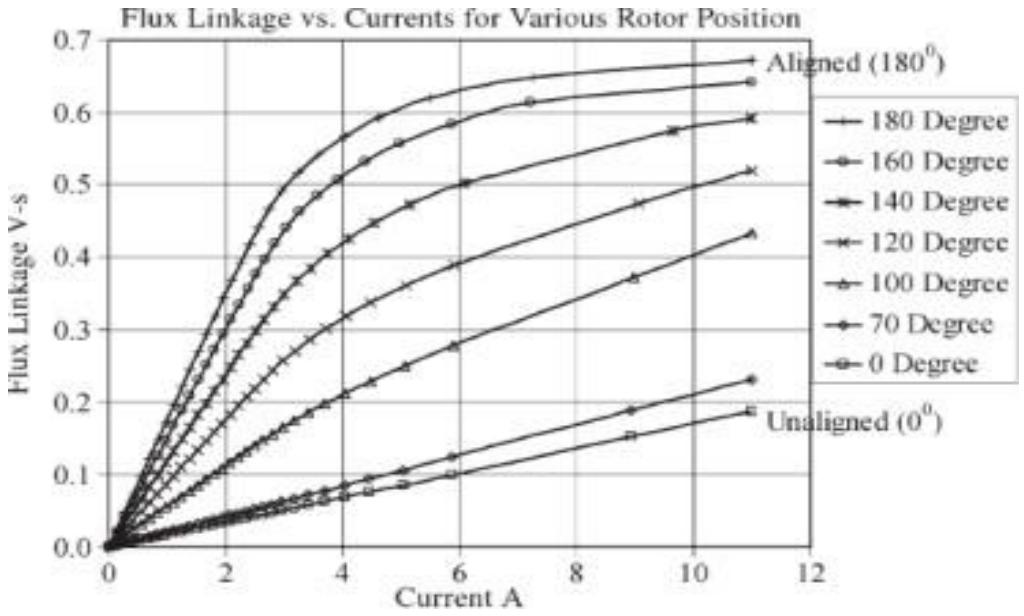


Fig .2. Flux linkage versus currents for various rotor position for the 6/4 SRM.

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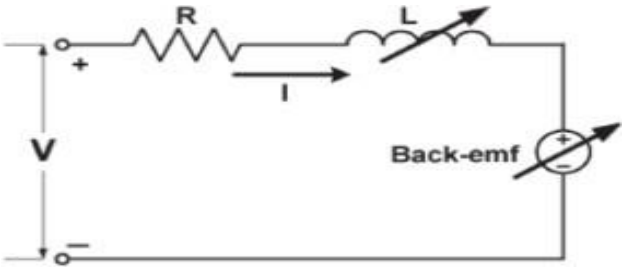


Fig. 3.Per phase equivalent circuit of an SRM: Nonlinear inductance and back EMF.

Neglecting mutual inductance between phases, the applied voltage to a phase can be described by.

$$v = R \cdot i + \frac{d\lambda}{dt}(\theta, i) \qquad (1)$$

where v is the phase voltage, R is the phase resistance, i is the phase current, λ is the flux linkage, and θ is the rotor position. The flux linkage and inductance are a function of current and rotor position, and their nonlinear relationship can be seen in Fig. 2. This relation can be expressed in terms of angular velocity ω_m and phase inductance Las

$$v = R \cdot i + L(\theta, i) \cdot \frac{di}{dbt} + i \cdot \omega_m \cdot \frac{dL(\theta, i)}{d\theta} \qquad (2)$$

As per (2), phase voltage comprises a resistive drop, an inductive drop, and an induced electromotive force [(EMF) or back EMF] *e*, where *e* can be expressed in terms of back EMF constant Kb as

$$e = i \cdot \omega_m \cdot \frac{dL(\theta, i)}{d\theta} = K_b \cdot i \cdot \omega_m \qquad (3)$$

Equation (3) is similar to the one for the dc series excited machine. Furthermore, using the description of energy stored in an inductor, the expression for torque can be obtained as

$$Te = \frac{1}{2} \cdot i^2 \cdot \frac{dL(\theta, i)}{d\theta} \qquad (4)$$

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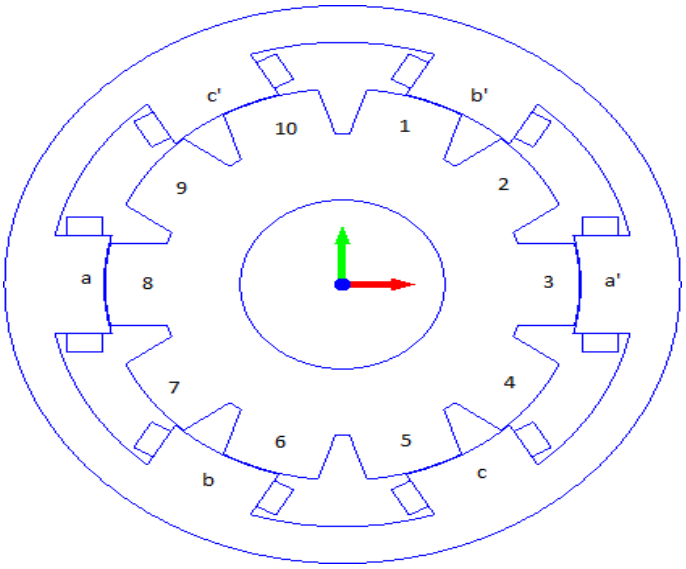


Fig.4. Design of 6/10 SRM

DESIGN OF 6/10 SRM

This paper introduces a novel PD relationship expressed as $N_r = 2N_s - 2$, where N_s >4 and denotes the number of stator poles having one tooth per pole and N_r is the number of rotor poles. In particular, this paper focuses on the design and development of an SRM, whether operated as a motor, generator, or both, based on this novel formula and investigates such a design for peak and average torques, torque ripple, efficiency, torque density, and low-cost manufacturing for high volume applications. Although the PD formula has principally been explained with reference to a rotary 6/10 SRM configuration with internal rotor, machines of other sizes, different phase/stator pole counts, and other forms (linear, external rotor, etc.) may be designed in accordance with the formula. Some examples for SRM designs based on the PD formula would have *S/R* pole count configurations of 6/10, 8/14, 10/18, etc.

TORQUE RIPPLE MINIMIZATION USING GEOMETRY MODIFICATION

A new configuration of SRM with ten poles is designed. A new 6/10 configuration is designed for torque ripple minimization and to increase the torque production rate. By increasing the number of rotor poles the torque production density is increased compared to conventional 6/4 SRM. The operation of the 6/10 design is similar to the concept

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involved in conventional SRMs. When excitation is applied to a stator phase, there are two adjacent rotor poles that can potentially be attracted to the stator pole. However, it must be noted that there is a significant difference in the magnitude of attraction. For example, when the rotor is aligned with phase A, then exciting phase B will influence mostly one rotor pole pair that is only 12° away rather than influencing another rotor pole pair that is 24° away. This produces continuous rotation without any dead zone. Since the torque production at an unaligned position is comparatively low, this does not have a major negative influence on the torque.

Torque Production

The angular travel per stroke or excitation for the 6/10 prototype SRM is 12° in comparison to 30° for the 6/4 test SRM, leading to higher fundamental frequency. It is apparent that the 6/10 prototype SRM needs 2.5 times more strokes for a mechanical revolution, which is an advantage since the average torque is proportional to the magnetic co energy and the number of strokes .

The 6/10 prototype SRM design was optimized for 120° conduction interval and θon/θoff as 30°/150° this does not necessarily work for the 6/4 test SRM, and optimized θon/θoff is found from the intersection of individual static torque profiles and was set to 50°/170°.The operation of the SRM in practice is limited to a maximum continuous current rating, as defined by the thermal response. A comparison of flux linkages for a current rated within the thermal limits is shown in Fig which shows that the area under the flux linkage curve is comparable for both the SRMs. As a result, the average torque can be higher for the 6/10 prototype SRM due to a higher stroke factor.

COMPARISON OF 6/4 SRM AND 6/10 SRM

Flux linkage Comparison

The Fig shows the flux link- age characteristics for the 6/10 prototype and 6/4 test SRMs. The area enclosed between the unaligned and aligned flux linkages is comparatively much smaller for the 6/10 prototype SRM than that of the 6/4 test SRM. This is expected due to several reasons: relatively higher stator pole arcs, smaller rotor interpolar air gap, and smaller pole widths.

Torque Comparison

Torque ripple is defined from instantaneous torque Ti as the difference

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Between the maximum and minimum torques, ex-pressed as percentage of the average torque. This can be expressed as

$$\text{Torque Ripple} = \frac{\max(Ti) - \min(Ti)}{Tavg} \times 100\%$$

In order to make a fair comparison between the two machines, similar limits were imposed on the width, volume, outer diameter, and electrical power of the new machine design. In order to incorporate the increased number of poles without violating any of the constraints, the poles were optimized to have acceptable widths with optimal conduction angles. In addition to higher peak torque, some other benefits of 6/10 prototype SRM can be observed from the shape of the torque profiles with respect to the rotor position.

This figure also shows that the instantaneous torque at most positions is higher for 6/10 prototype SRM than that of 6/4 test SRM. Therefore, it produces higher average torque with comparable. Therefore, the evaluation of static torque ripple provides us with valuable information. For three-phase machines such as the 6/4 test and 6/10 prototype SRMs, the conduction angle needs to be at the least 120◦ electrical in order to produce torque at every position. Current rise and fall times also need to be considered for the selection of conduction interval, turn-on angle θon, and turnoff angle θoff.

DIMENSIONS OF 6/10 SRM

Stator Inner and Outer Diameter	66 and 76 mm
Rotor Inner and Outer Diameter	23 and 41 mm
Stator Pole arc and Rotor Pole arc	32° and 24°
Air gap length	0.25 mm
Stack length	90 mm

SIMULATION RESULTS

The machine design and analysis was done using MAGNET V6 .The 6/10 machine was analysed using finite element analysis .Static 2D analysis was done and the results are presented. The simulation results comprises of both the conventional 6/4 SRM and the new machine configuration 6/10.

Flux plot

The Flux plot for the conventional 6/4 machine is given with phase A energized with excitation current – 10 A . The flux plot is presented for various positions.

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Aligned position

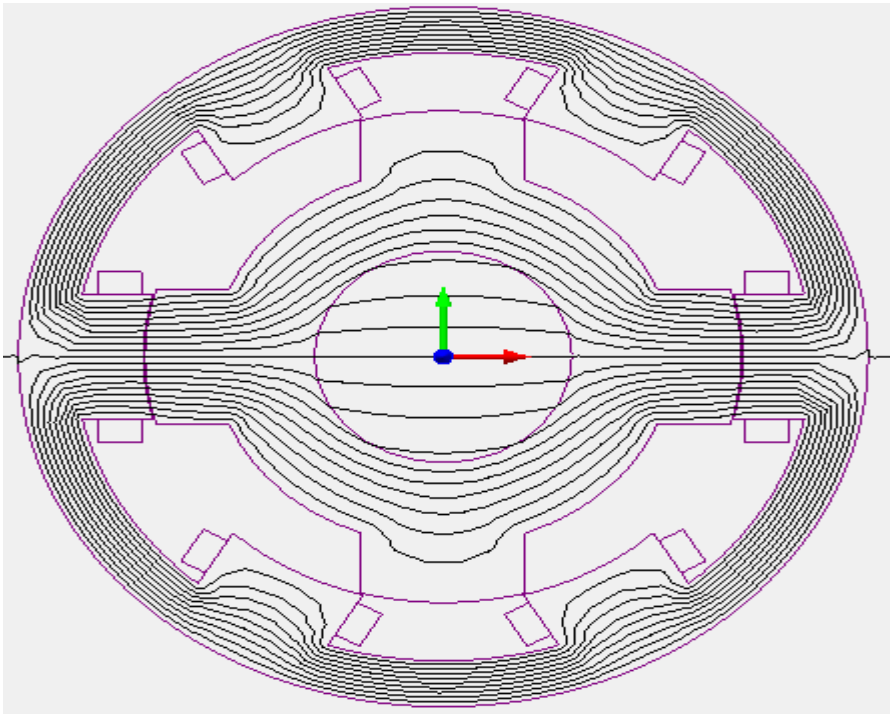


Fig.5. Flux plot θ=0 deg

Mid Aligned Position

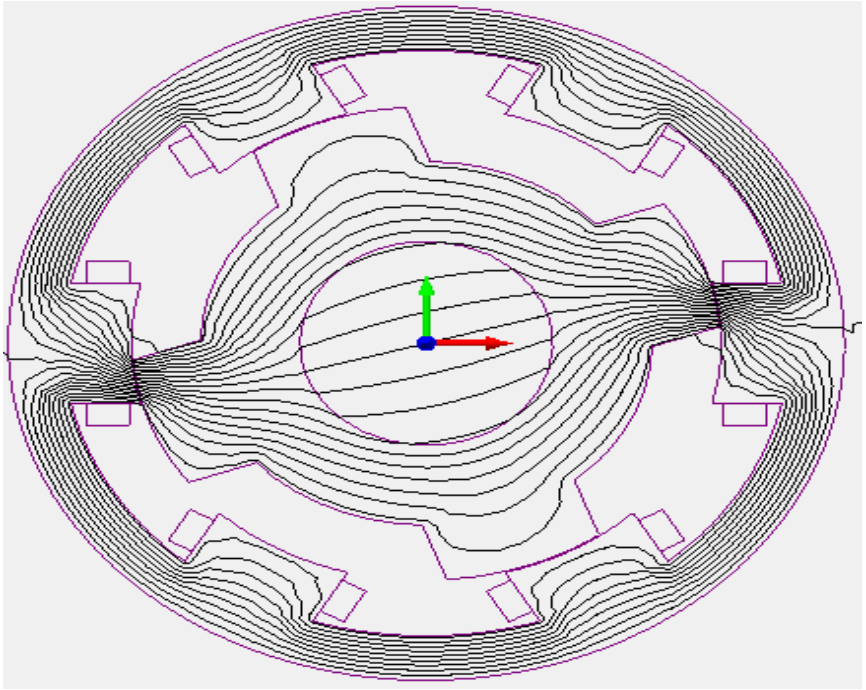


Fig.6. Flux plot θ=20 deg

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Unaligned Position

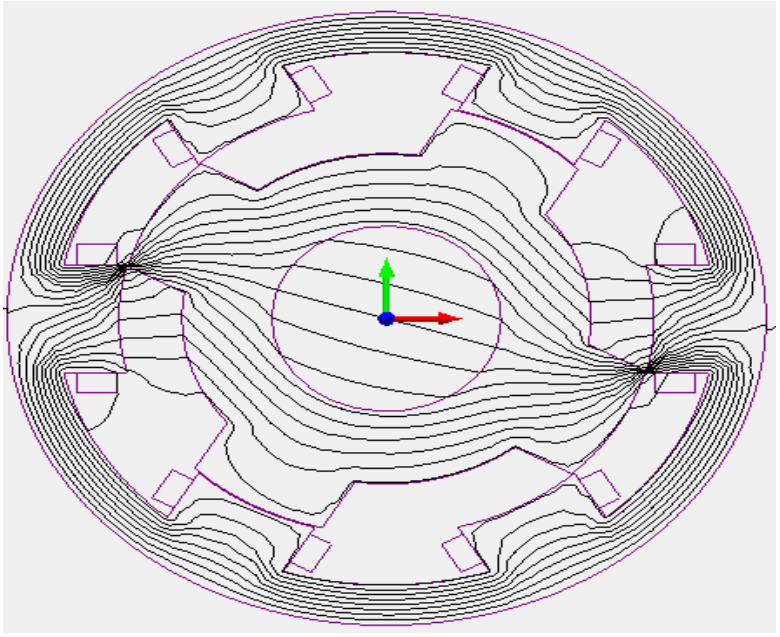


Fig.7. Flux plot θ=60 deg

The Flux plot for the conventional 6/10 machine is given with phase A energized with excitation current – 10 A. The flux plot is presented for various positions.

Aligned position

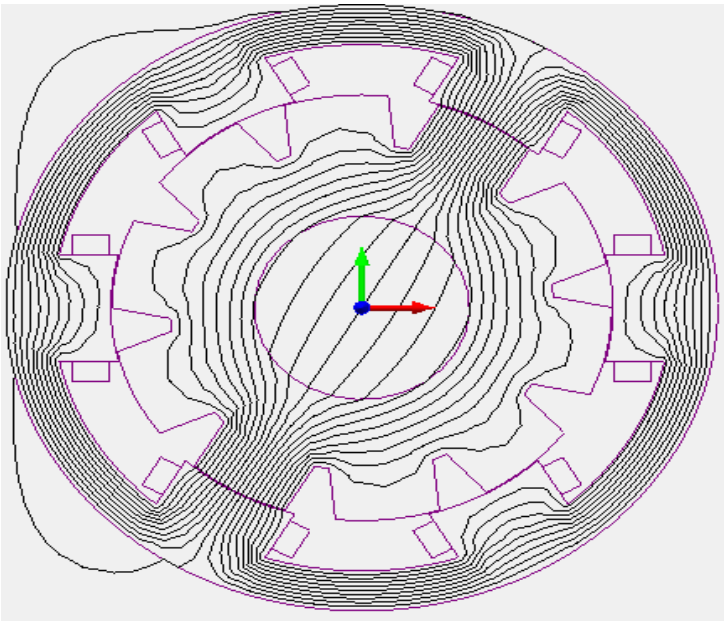


Fig.8. Flux plot θ=60 deg

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Mid Aligned Position

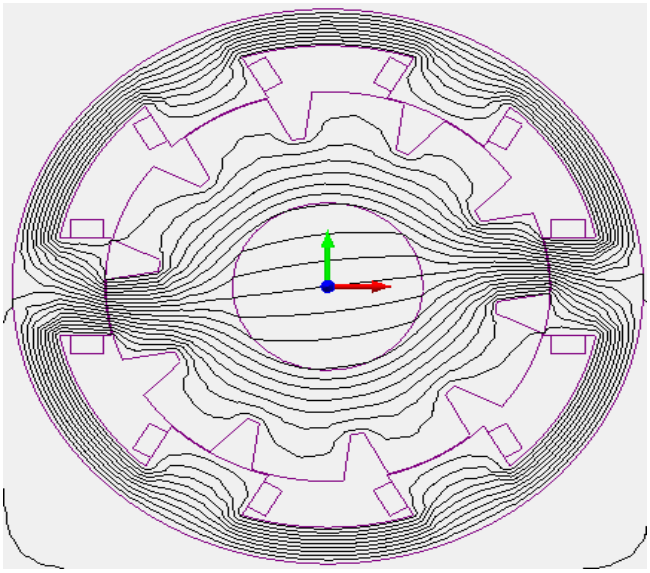


Fig.9. Flux plot θ=10 deg

Unaligned Position

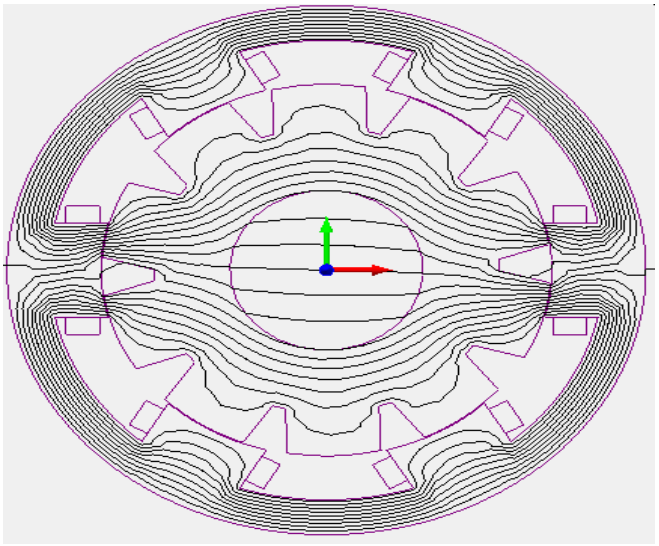


Fig.10. Flux plot θ=60 deg

By comparing the flux plots of the two machines the flux flow is maximum in the new configuration 6/10 machine. Due to increased no of poles the flux lines are greater when compared to 6/4 machine. So the torque produced will be maximum.

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Flux Linkage Characteristics of 6/4 SRM

The Flux Linkage Characteristics for various rotor positions with varying excitation current is plotted for 6/4 machine.

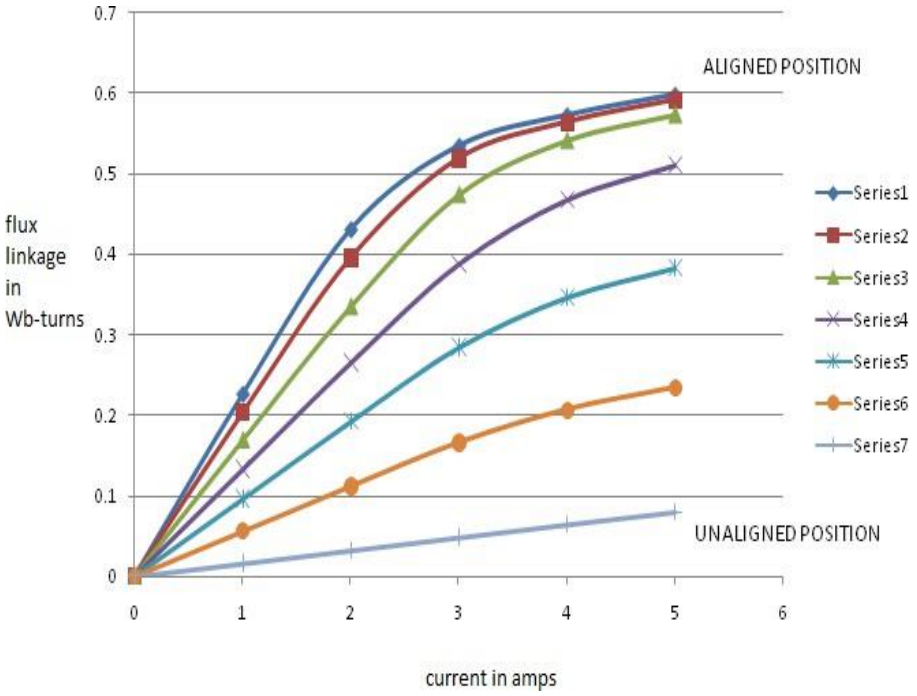


Fig.11. Flux linkage Vs various rotor position of 6/4 SRM

Flux Linkage Characteristics of 6/10 SRM

The Flux Linkage Characteristics showing various rotor positions with varying excitation current is plotted for 6/10 machine.

In the flux link-age characteristics for the 6/10 prototype and 6/4 test SRMs, the area enclosed between the unaligned and aligned flux linkages is comparatively much smaller for the 6/10 prototype SRM than that of the 6/4 test SRM. This is expected due to several reasons relatively higher stator pole arcs, smaller rotor interpolar air gap, and smaller pole widths. Thus the 6/10 configuration has once again been proved to be more efficient .Since the area enclosed by the aligned and unaligned is smaller there will be less torque ripple since the aligned and unaligned positions occur too quickly because of increased no of rotor poles.

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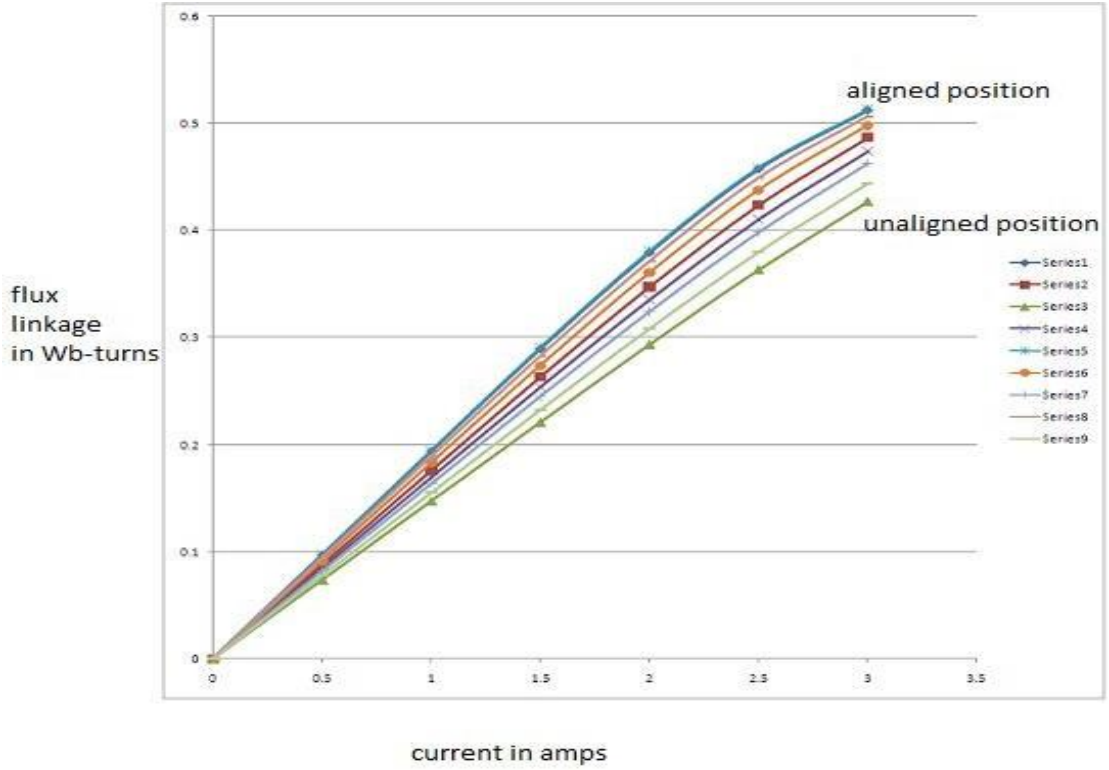


Fig.12. Flux linkage Vs various rotor position of 6/10 SRM

Inductance Vs Rotor position of 6/4 SRM

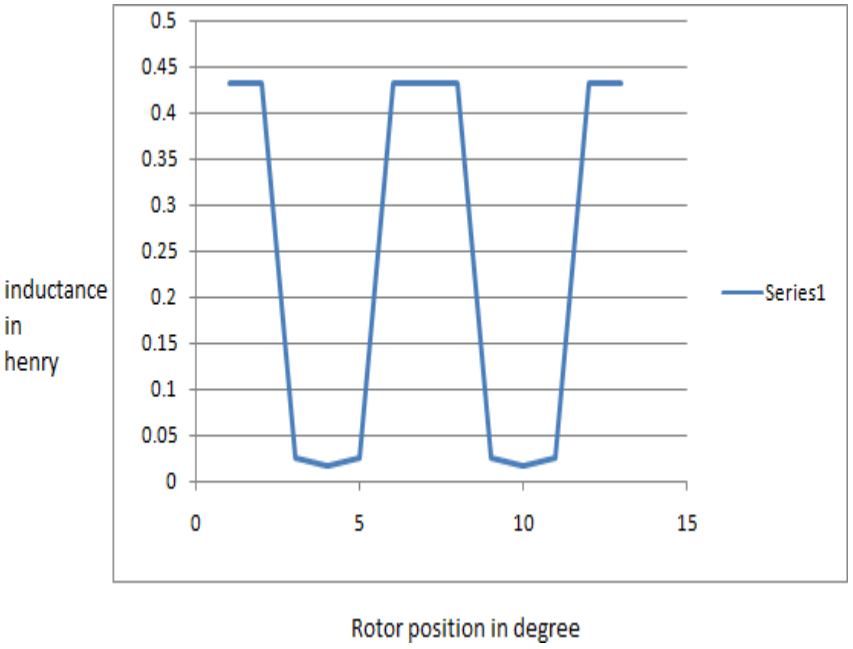


Fig.13. Inductance Vs Rotor position of 6/4 SRM

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Inductance Vs Rotor position of 6/10 SRM

The Inductance Vs Rotor position graph is taken by exciting phase A with an excitation current of 2 A for 6/10 SRM machine configuration.

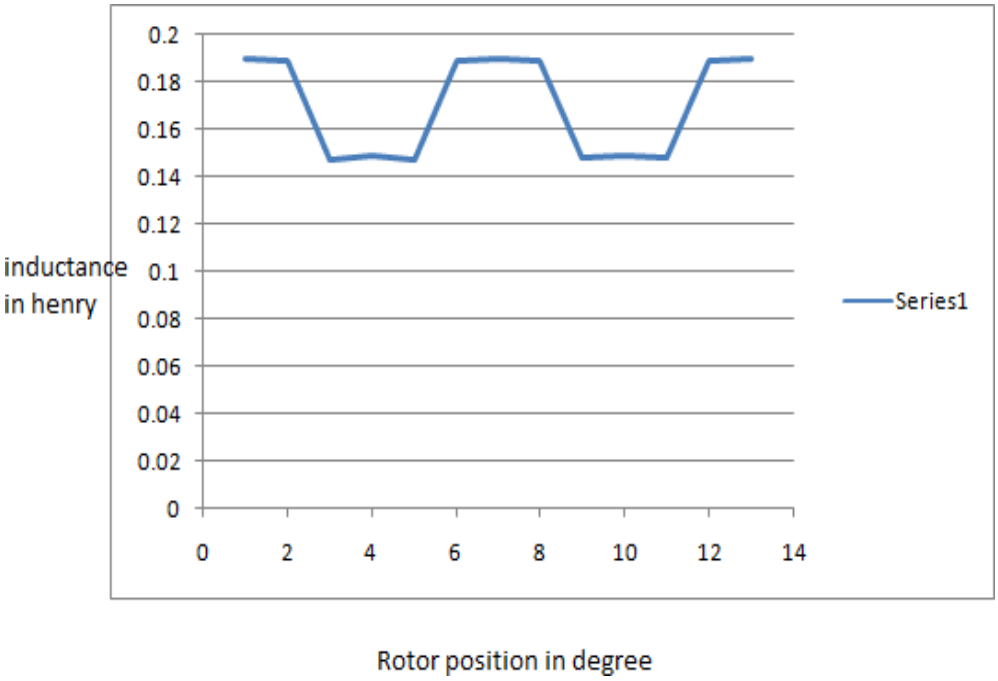


Fig.14. Inductance Vs Rotor position of 6/10 SRM

From the Inductance Vs rotor position characteristics we find out that in the 6/4 machine in the unaligned position the value of flux linkage and inductance will be very low but in the 6/10 machine even in the unaligned position the value of flux linkage and inductance will be greater than that of the conventional 6/4 machine.

Torque Profile

The torque profiles of the conventional 6/4 SRM and the new configuration 6/10 SRM are found out using FEA using Magnet software. The torque profile for 6/4 SRM is given with PHASE A excited .The torque profile graph presents three sets of torque values taken for excitation current 1A, 2A, 3A.

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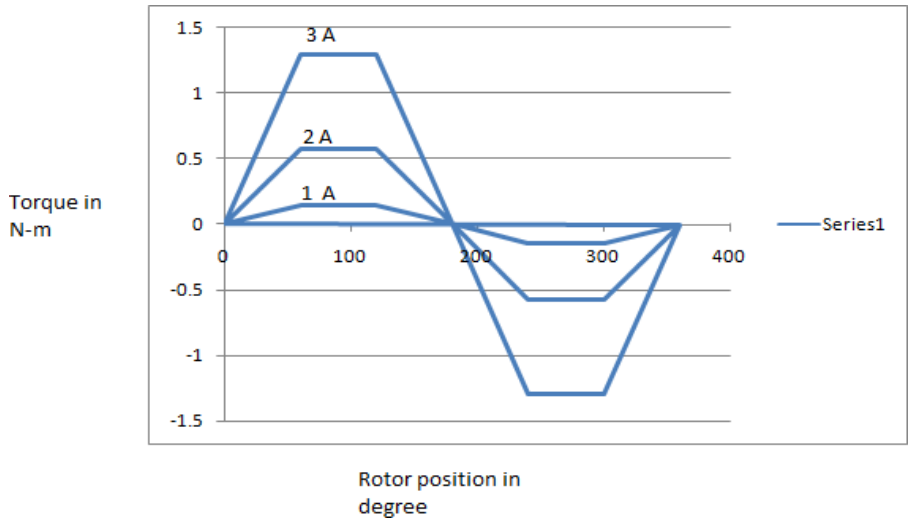


Fig.15. Torque Profile 6/4 SRM.

The torque profile for 6/4 SRM is given with PHASE A excited .The torque profile graph presents three sets of torque values taken for excitation current 1A, 2A, 3A. .

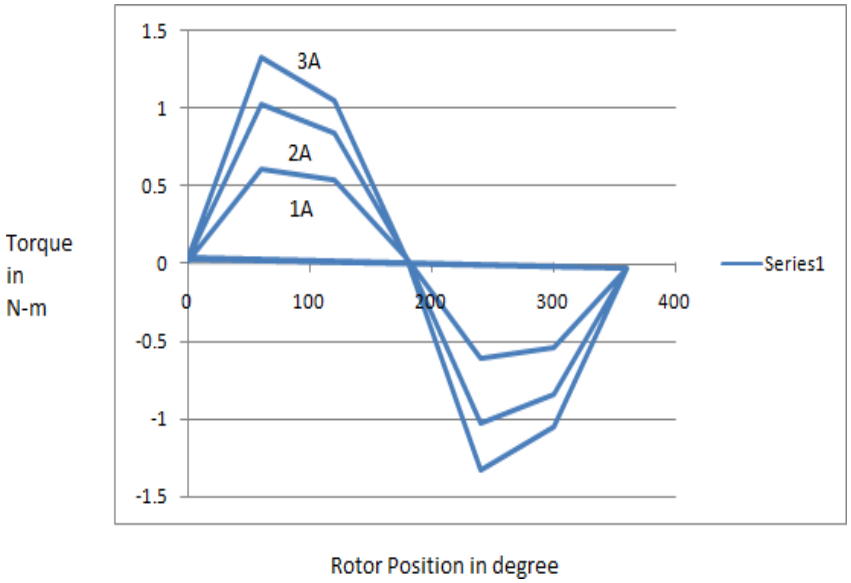


Fig.16. Torque Profile 6/10 SRM.

Analysing the torque profiles of the 6/4 SRM and the 6/10 SRM machine, the torque production rate is higher for 6/10 machine .From the simulation analysis using MAGNET V6 software we find that the torque value is greater for the proposed 6/10 machine.

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TORQUE RIPPLE CALCULATION

Torque ripple is defined from instantaneous torque Ti as the difference between the maximum and minimum torques, expressed as percentage of the average torque. This can be expressed as

$$\text{Torque ripple} = \frac{T_{max} - T_{min}}{T_{avg}}$$

The angular travel per stroke or excitation for the 6/10 prototype SRM is 12◦ in comparison to 30◦ for the 6/4 test SRM, leading to higher fundamental frequency. It is apparent that the 6/10 prototype SRM needs 2.5 times more strokes for a revolution, which is an advantage since the average torque is proportional to the magnetic co energy and the number of strokes So the average torque produced by 6/10 SRM is more compared to 6/4.

Thus it is concluded that the torque ripple in the 6/10new configuration is reduced 60% when compared to the conventional 6/4 SRM for any phase excitation. For an excitation of 0.5A the torque ripple of the conventional 6/4 SRM is 1.98 whereas the torque ripple of the new 6/10 configuration is 0.625.

0.625/1.98*100=31.6%

From this it is evident that the torque ripple is reduced by 60% for the new configuration.

Table-1: Comparison of Maximum and Minimum Torque of 6/4 and 6/10 SRM

Current in A	T_{max} in N-m		T_{min} in N-m	
	6/4 SRM	**6/4 SRM**	**6/10 SRM**	**6/10 SRM**
0.5	0.04	0.003	0.035	0.06
1	0.15	0.053	0.02	0.22
1.5	0.32	0.303	0.26	0.47
2	0.55	0.1	0.38	0.79
2.5	0.84	0.12	0.58	1.16
3	1.18	0.047	1.15	1.75

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Table-2: Comparison of torque ripple of 6/4 and 6/10 SRM

Current in A	T_{avg} in N-M		Torque Ripple	
	6/4 SRM	6/10 SRM	6/4 SRM	6/10 SRM
0.5	0.03	0.04	1.98	0.625
1	0.13	0.19	2.99	0.48
1.5	0.27	0.41	2.4	0.51
2	0.47	0.68	2.05	0.6
2.5	0.72	0.96	1.07	0.6
3	0.99	1.23	3.04	1.9

CONCLUSION

This paper has presented a new family of SRMs, which have higher number of rotor poles than stator poles. Using a newly defined PD formula, several combinations of the stator–rotor poles have been proposed. Due to an increase in the number of poles without increasing the number of stator phases, these configurations have shown superior performance with higher torque per unit volume, comparable torque ripple, and lower manufacturing costs when compared to a conventional SRM with comparable number of phases without the need for specialized power electronic circuitry. Simulation and experimental results have been presented to compare a novel 6/10 prototype designed using the PD formula with a conventional 6/4 SRM in terms of flux linkage, constructional features, and output torque. A new 6/10 Configuration of SRM has been designed using Magnet V6. The Analysis was done by using Finite Element Analysis

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IV. Novel Switched Reluctance Machine Configuration With Higher Number of Rotor Poles Than Stator Poles: Concept to Implementation Piyush C. Desai, Student Member, IEEE, Mahesh Krishnamurthy, Member, IEEE, Nigel Schofield, Member, IEEE, and Ali Emadi, Senior Member, IEEE.

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