# Fuzzy Logic Controller based Torque Ripple Minimization of Axially Laminated Switched Reluctance Motor with Two Phase Excitation

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**Abstract**

**Axially laminated rotors enhance the presence of electromagnetic torque more than the radially laminated rotors. Two phase excited motors solve the energy circulation problems which exist during commutation in a conventional motor and also aids in enhancement of torque. The torque ripples present in the motor will be higher than the radially laminated SRM. The ripples are minimized by using Fuzzy Logic Controller. The fuzzy logic controller is designed for the regulation of $\theta on$ and $\theta off$ in order to reduce the torque ripples present in the motor. The input is rotor speed. This paper presents a scheme to minimize torque ripples by using fuzzy logic controller by selecting the suitable turn-on and turn-off angles for a 4-phase,5 hp,12/8 SRM. The motor is designed using Magnet 7.13 as the CADD package. The machine is developed as a nonlinear model using Matlab/Simulink**

*Key Words*— **Axial laminated rotor, doubly excited SRM, Non linear model , Matlab /Simulink ,Fuzzy Logic Controller.**

## I. INTRODUCTION

In recent years there is increasing interest in variable speed drives due to the use of power electronics as a means of power conditioning. The switched reluctance motors are making their presence felt in variety of applications, from power steering to washing machines to traction. This is due to the control operation of torque which makes it suitable for high speed automotive applications. The power density of such drive is high and they operate at a high power factor and efficiency The SRM drives have additional attractive features of fault tolerance and the absence of magnets. There is no $I^2R$ loss because there are no windings on the rotor. Finite element method (FEM) has gained widespread acceptance and popular analysis of SRM .Even though, Switched reluctance motor has excellent advantages, the two disadvantages of SRM are its torque ripple and acoustic noise. The theoretical comparison of torque production is made between a conventional SRM having conventionally laminated rotor and a novel structure that uses a cylindrical anisotropic rotor comprised of axially laminated rotor made of magnetic and non-magnetic spacing in [1].The investigation of SRM with axially laminated rotor is done. This increases the ripples present in the torque than in the radially laminated SRM [2].The design procedure for a 4 phase,5 hp,8/6 non-linear model of SRM to calculate the torque [3].The machine can be have a higher output with the same power converter because of the improvement of the energy conversion ratios present in the SRM .The energy circulation problems which exist during commutation in conventional motors are reduced due to two phase excitation [4,5].A simple non-linear model of the SRM which requires a minimum of precalculated or measured input data. This provides reliable results in the dynamic regime [6, 7].

Standard PID controller suffers from reduced performance when a pure time delay is introduced into the system. The reduction in gain, which is necessary for accurate steady state control, is not often a viable solution [8].The Fuzzy Logic Controller performs a PI –like control strategy giving the current reference variation based on speed error and its change. It has good accuracy than the conventional control [9,10]. Neuro-Fuzzy compensation is used to control current in order to reduce the torque ripples in SRM [11,12].The fuzzy parameters are initially chosen randomly and adjusted to optimize the control. The controller produces smooth torque up to the motor base speed [13,14] .The turn-off angle, as a complex function of motor speed and current is automatically changed for a wide motor speed range to reduce torque ripples [15,16,17,18].A new type of indirect rotor position estimation method using fuzzy inference rules is designed. Angle of rotor position measured changes continuously and smoothly in the required scope with accurate results [19].

## II. AXIALLY LAMINATED SRM

The Axially laminated rotor configuration shows a saliency ratio more than 20 in linear conditions Because of several laminations that are thin and divided one to the others, the finite element simulation requires a mesh with a very large number of elements. For this reason, it is necessary to reduce the analyzed domain as much as possible making use of any symmetry of the machine. The cross section of the machine is shown fig 1. Homogeneous Dirichlet conditions are assumed and solved. The current density for d-axis surface current density is defined as

$$Jsd = -\frac{mNI}{\pi D} Sin(Vr) \qquad (1)$$

and q-axis current density as

$$Jsd = -\frac{mNI}{\pi D} Cos(Vr) \qquad (2)$$

Where m is the number of phases, N is the number of series conductors, Vr is the electrical angle referred to the rotor axis (d, q) and D is the bore diameter.

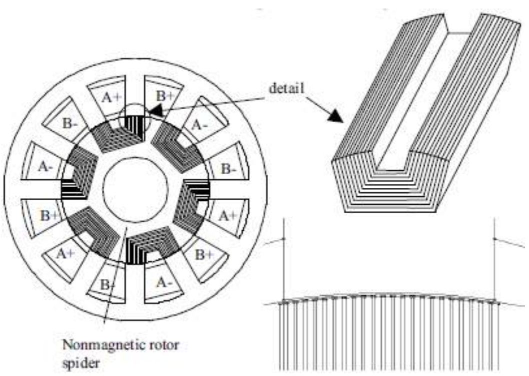


**Fig 1. Cross section of SRM with Axial Laminated structures**

## III. DOUBLY EXCITED SRM

For efficient operation of Variable Reluctance Motor, it is necessary to decrease the current in each phase to zero after the phase is turned off in order to develop the maximum torque possible and to avoid negative torque intervals. It is therefore necessary to extract the energy trapped in the magnetic field as rapidly as possible. Unfortunately trapped energy cannot change instantaneously. A better means to deal with trapped energy would be to retain the energy within the motor converting a part of energy into useful work and remaining part of the field energy is transferred to the next phase. The new machine is equipped with both conventional short pitches as well as long pitch.The turn-off of short pitch windings is similar to the conventional motor. But the turn off takes place closer to the point of stator/rotor pole aligned. The full pitch windings are used as commutation windings to turn-off phases The torque developed in the short and full pitch windings are same

## IV .FINITE ELEMENT ANALYSIS

Among numerous numerical methods, FEA is the most frequently used approach .There are many software's that can be used to analyze and calculate the electromagnetic field of the motor accurately in two-dimension (2-D) and three-dimension (3-D) ways. Magnet 7.13 Software is used to get the static characteristics and dynamic performances of the motor. 2-D FEA model of four ph ase 12/8 SRM is shown in Fig 2.

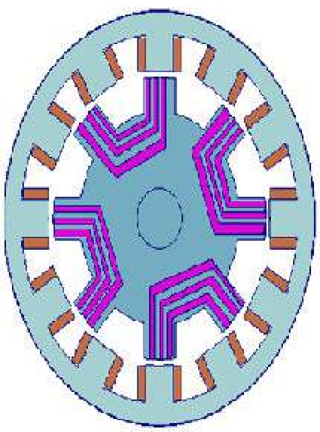

**Fig. 2. 2-D FEA model of a four-phase 12/8-pole SRM.**

Finite element analysis (FEA) is used to predict the torque produced at various currents and as well as to calculate the phase inductances.Fig.3 shows the magnetic field distribution inside the motor at aligned position. Fig.4 shows the magnetic field distribution inside the motor at unaligned position.Fig.5 shows the static flux linkage characteristics of the SRM obtained by FEA. Fig.6 shows Flux Linkage Vs Theta Vs Current Plot.Fig.7 shows Torque Vs Theta Vs Current Plot.

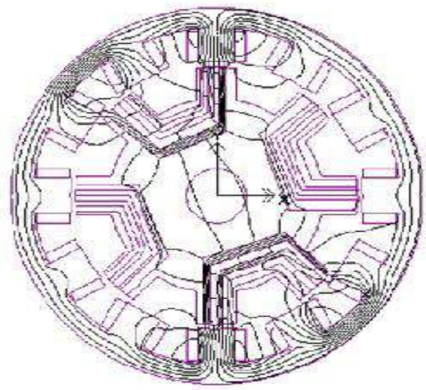

**Fig. 3. Magnetic field distribution inside the SRM at aligned position.**

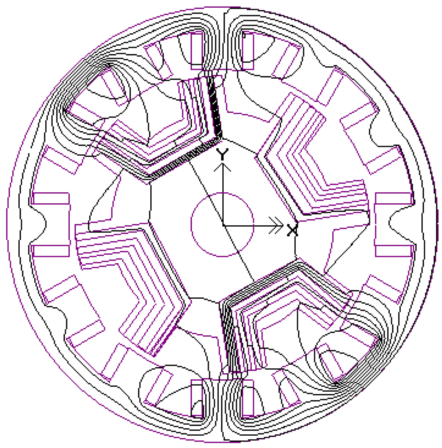


**Fig .4. Magnetic field distribution inside the SRM at Unaligned position**

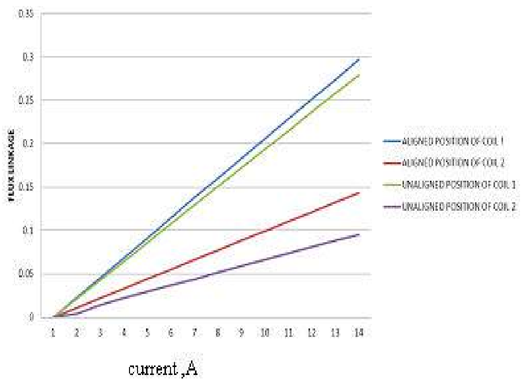

**Fig.5. Flux Linkage Vs Current characteristics of Axially Laminated 12/8 SRM**

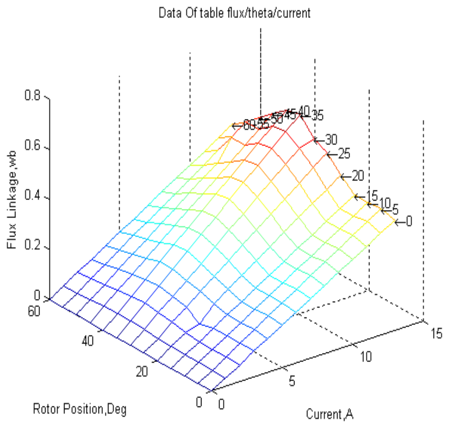


**Fig.6 .Flux Linkage, Theta, Current Plot**

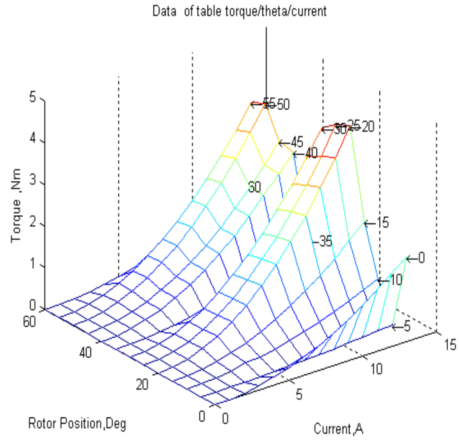


**Fig.7 .Torque, Theta, Current Plot**

# V. MATLAB/SIMULINK MODEL

The non-linear characteristic of the SRM lies in the relationship of flux linkage with stator currents and rotor angles. It is essential to develop a model based on its magnetization characteristics. The equations of SRM are given by

$$U_K = R_k i_K + \frac{d\Psi_k}{dt} \quad (4)$$

$$T = T_{e-} T_j = J\frac{d\omega}{dt} + D \quad (5)$$

(5)

Where $U_K, R_K, i_K$ and $\Psi_k$ are voltage, resistance, current and flux linkage of the phase winding respectively, $\omega$ is the rotational velocity , $T_e$ are the electromagnetic torque of phase winding and SRM respectively, m is the number of phase, D is the viscous friction coefficient ,J is the moment of inertia of rotor and load of SRM. Fig 8.shows the non-linear model of the axially laminated SRM.Fig.9 shows the single phase non-linear model of the axially laminated SRM.

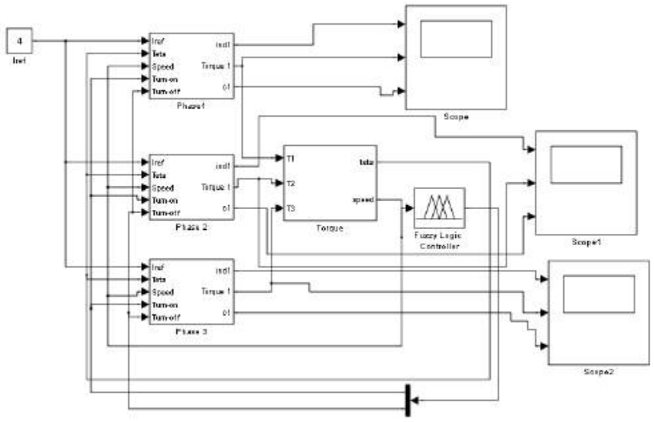


**Fig.8 Non-Linear Model of SRM**

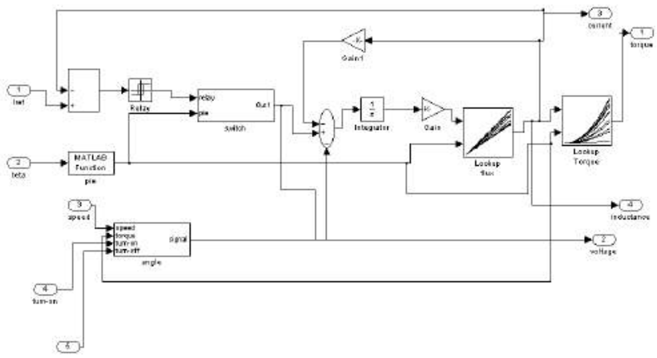

**Fig.9 Single Phase Model of Non-Linear SRM**

# VI. FLC BASED TORQUE RIPPLE MINIMISATION

Fuzzy logic controllers are based on the fuzzy set and fuzzy logic theory. In a fuzzy controller adjustments are handled by a fuzzy rule based expert system which is a logical model of human behavior of the process operator. Fuzzy uses a variable known as Linguistic variable.FLC usually demonstrates better results than those of the conventional controllers in terms of response and robustness. A fuzzy logic controller is designed for the regulation of θon and θoff .The input variable to this controller is rotor speed n, which is defined in the range of 0-3000 rpm for the SRM. Turn-On and Turn-Off values for various values of speed is given in Table.1.If the aligned position is assumed to be 21.5, then the turn-on angle θon is defined as 19.5 to 24 and if the unaligned position is assumed to be 0.5, then the output turn -off angle θoff is within 0.3 to 0.9.The variable spaces for the rotor speed, turn-on angle and turn-off angle are divided into 7, 3 and 5 regions respectively. Each region is assigned a fuzzy membership function with triangular or trapezoidal shapes.We have the following rules for fuzzy rule base

***If speed is b1, then turn-on is b, and turn-off is m;***
***If speed is b2, then turn-on is m, and turn-off is b2;***
***If speed is b3, then turn-on is s, and turn-off is b1;***
***If speed is b4, the turn-on is s, and turn-off is b1;***
***If speed is m, the turn-on is s, and turn-off is sc1;***
***If speed is s2, the turn-on is s, and turn-off is sc2;***

***If speed is s1, the turn-on is s, and turn-off is sc2***

Finally defuzzification by means of centroid is applied. Fig.10 shows rotor speed membership function. Fig.11 shows membership function for Turn-On Angle.Fig.12shows membership function for Turn-Off Angle.

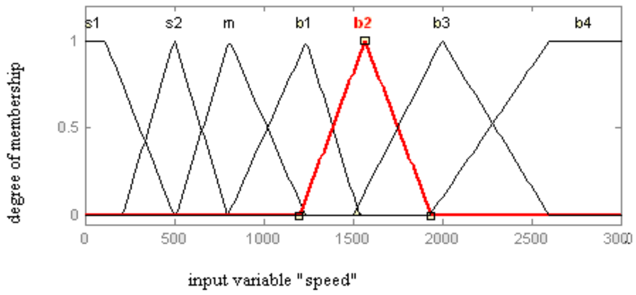


**Fig.10 Membership Function For Rotor Speed**

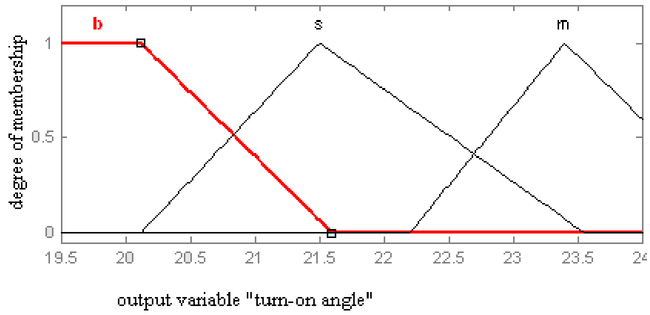


**Fig.11 Membership Function For Turn-On Angle**

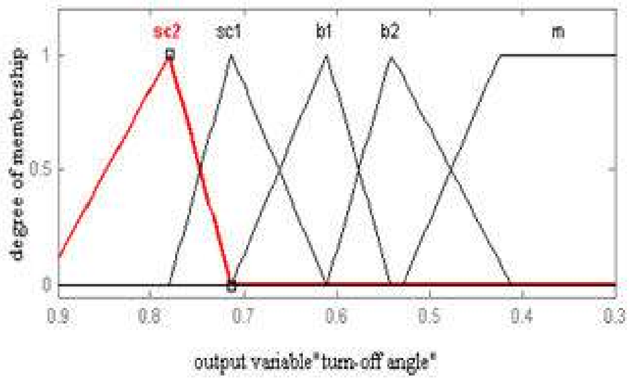


**Fig.12 Membership Function For Turn-Off Angle**

**Table 1 :Turn-On and Turn-Off values for various speeds.**

| Speed, rpm | Turn-ON Angle, Deg | Turn-Off Angle, Deg |
|---|---|---|
| 500 | 21.7233 | 0.6213 |
| 1000 | 21.7418 | 0.5443 |
| 1500 | 20.2436 | 0.6224 |
| 2000 | 20.2349 | 0.7530 |
| 2500 | 20.2726 | 0.7007 |
| 3000 | 20.5313 | 0.6936 |

## VII. SIMULATION RESULTS

The Matlab simulation is done using the motor parameters given in the Appendix 1. Fig 13 shows the Torque waveform without fuzzy logic controller and fig 14 shows the torque waveform with fuzzy logic controller. Fig 15 shows the current waveform without fuzzy logic controller. Fig 16 shows the current waveform with fuzzy logic controller. Fig 17 shows the speed waveform of the drive.

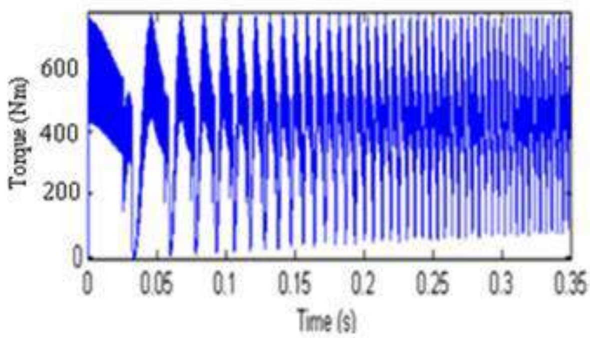


**Fig.13 .Torque waveform without fuzzy logic controller**

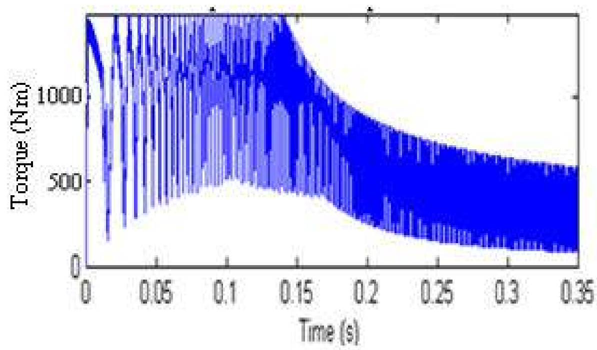


**Fig.14 Torque waveform with fuzzy logic controller**

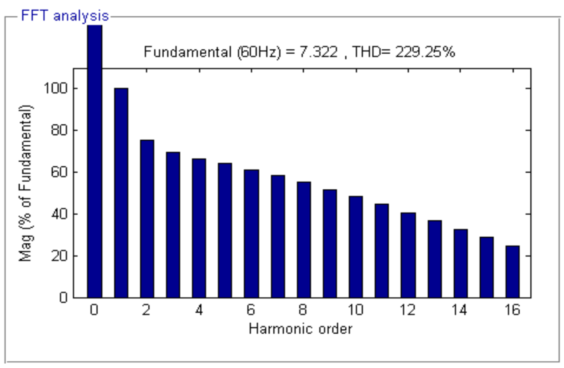


**Fig.15 Harmonics in uncompensated Torque**

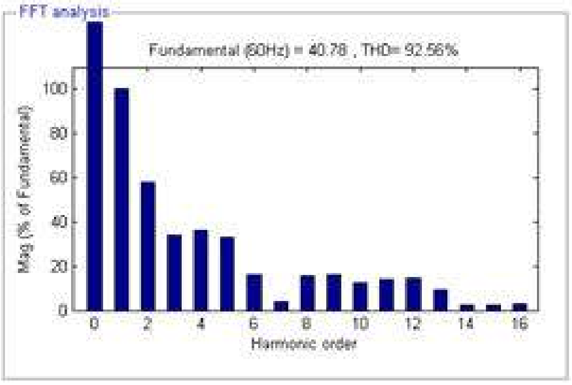


**Fig.16 Harmonics in compensated Torque**

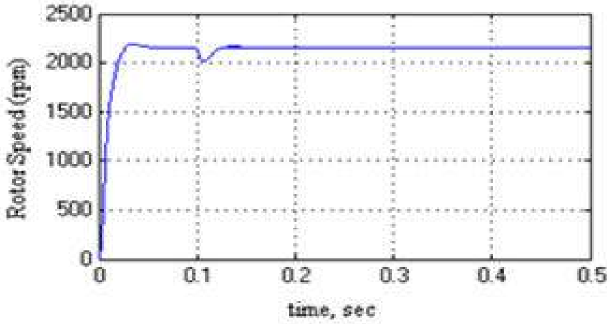


**Fig. 17.Rotor speed waveform**

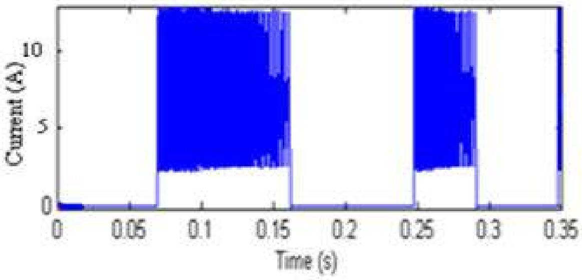


**Fig. 18. Current waveform without fuzzy logic controller**

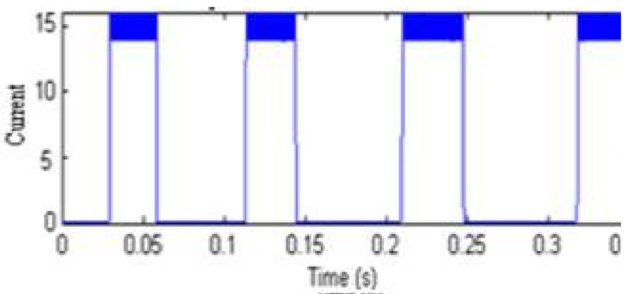


**Fig 19 Current waveform with fuzzy logic controller**

## VIII.CONCLUSION

The torque ripples are minimized through a fuzzy logic controller by adjusting the turn-on and turn-off angles. The ripples are considerably reduced to nearly 63%.The Axially laminated srm can be used for applications like aerospace, automotive applications etc. with the use of computational algorithms or their hybrids to yield higher percentage of torque with reduced ripple content in torque.

## APPENDIX-1:

| | |
|---|---|
| Power O/P=5.hp | $L_s = 37.4mm$ |
| Speed(rpm)= 1500 rpm | $L_g =$ 5x $10^{-4}$ m |
| Rated Current=13A | $L_r = 29.5$ mm |
| $Do = 180\ m$ | $L_{rc} = 56.0mm$ |
| L=193.75mm | $L_y = 27.48m$ |
| $D_{sh} = 28mm$ | $H_s = 6179.17\frac{At}{m}$ |
| g=5mm | $H_y = 238.54\frac{AT}{m}$ |
| D=100m | $H_{rc} = 960.34\frac{AT}{m}$ |
| $\beta_s = 22^{\circ}$ | $H_r = 4445.4$ At/m |
| $\beta_r = 24^{\circ}$ | $i_p = 13.007A$ |
| Max=1.65T | $L_a = 74\ mH$ |
| C=19.19mm | $L_u = 10.22$ mH |
| $h_s = 27.81mm$ | $A_s = 37190\ mm$ |
| $h_r = 23.50mm$ | $A_g = 3868.9mm$ |
| $H_g = 1257304.05\frac{AT}{m}$ | $A_r = 40165\ mm$ |

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