# OPTIMUM PERFORMANCE OF 6/4 POLE SWITCHED RELUCTANCE MOTOR FOR HIGH EFFICIENCY AND MINIMUM TORQUE RIPPLE

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**Abstract—** *Electric mobile vehicle applications nowadays replacing dc motors opens the wide scope for switched reluctance motors. The design, modeling and simulation of low powered switched reluctance motor with the specification of 0.75 kW, 1500 rpm, 6/4 pole for automobile mobile robot application is discussed in this paper. The possible combinations of stator and rotor pole angles are derived based on Lawrenson's feasible triangle and corresponding machine dimensions are calculated by using a program. The performance of the SRM for the designed machine parameters is simulated. The design modules are analyzed and presented for torque ripples, torque profile, air-gap flux distribution and inductance variations in aligned and unaligned positions.*

***Index Terms***— *switched reluctance motor, torque profile, minimum torque ripple.*

## I. INTRODUCTION

SRM is the true reluctance machine in the sense that both rotor and stator have variable reluctance magnetic circuits. The stator and rotor of SRM is constructed with salient poles. The SRM is a doubly salient machine [1]. Switched reluctance motor is considered for a number of applications for its unique characteristics. The application requirements are high reliability, fault tolerance, high efficiency, high-speed operation, efficient variable speed and low cost. Its inherent speed controllability and ability to produce full torque at wide range of operating speed makes SRM a promising as a direct power drive for automobiles. The objective of this paper is to design, model and develop simulation based low powered switched reluctance motor with the specification of 0.75 kW, 1500 rpm, 6/4 pole for automobile mobile robot application. The stator carries coils on each pole and the coils surrounding the opposite poles will be connected in series. For each phase of supply two opposite poles and its corresponding coils are in the function. The rotor has neither winding nor magnets. The rotor is simply laminated. The SRM is a singly excited motor. The separate converter circuits energize the stator windings. The Switched reluctance machine must be operated in a continuous switching mode, which is the main reason the machine developed only after the development of good power semiconductors. Due to the development of power semiconductor technologies relatively low current, low voltage type of control is sufficient for SR machines. SR motors eliminate permanent magnets (PMs), brushes and commutators[3].

The primary disadvantages of SRMs are the torque ripple and acoustic noise. There are primarily two approaches for reducing the torque ripple. One method is to improve the magnetic design of the motor, while the other is to use sophisticated electronic control techniques. The machine designers are able to reduce the torque pulsation by changing the stator and rotor pole structures, but only at the expense of some specific motor outputs. The electronic approach is based on optimizing the control parameters, which include the supply voltage, turn-on and turn-off angles, and current level. The minimization of torque ripple through electronic control may lead to a reduction in the average torque, since the motor capabilities are not being fully utilized at all power levels. Torque pulsation are inherent in SRMs due to the doubly salient structure of the machine[3].

The reluctance principle for torque production is utilized in these machines, where the phases operate independently and in succession. The machine torque is essentially defined by the nonlinear phase torque–angle–current characteristics and the magnetization of the phases. The magnetization pattern of the individual phases together with the characteristics of the motor dictate the amount of torque ripple during operation[4]. This paper presents the performance study for the prototype models and the analyses corresponding to the design.

## II.DESIGN OF SWITCHED RELUCTANCE MOTOR

For the Power output $P_o$ in kW, Speed N in rpm, Supply voltage V in volt, torque to be developed by the machine as

$$T = \frac{60 * P_o * 10^3}{2 * \pi * N}$$

Frame size standards can be obtained from IEC recommendations. The preliminary selection of frame size automatically fixes the outer diameter of the stator.

$$D_o = (H-3) \text{ x2}$$

The 3-mm subtraction is used in industry to account for the foot of the machine, which is used for mounting. The core length (L) of the SRM is initially assumed to a value by comparing with induction motor. The diameter of bore is initially taken as equal to frame size.

$$D=H$$

This paper focuses on the popular combination of 6 stator and 4 rotor poles, also commonly known as the 6/4 machine. The standard design normally has the stator pole arc angle $ß_s$ smaller than the rotor pole angle $ß_r$. The constraints on the values of pole arc angles are derived by Lawrenson feasible triangle.

1. The stator pole arc angle is less than the rotor pole arc angle, i.e., $ß_s < ß_r$.

2. The effective torque zone is lesser than the stator pole angle ßs but greater than the stroke angle ε. The stroke angle is defined as

$$\varepsilon = \frac{2 * \pi * (P_s - P_r)}{P_s * P_r}$$

The ideal inductance profile of the SRM in Fig.1 can be illustrated to understand this phenomenon better [2].

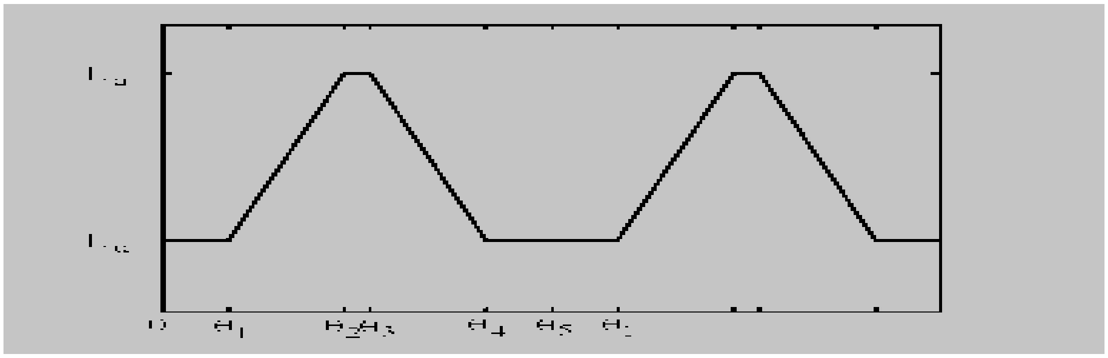
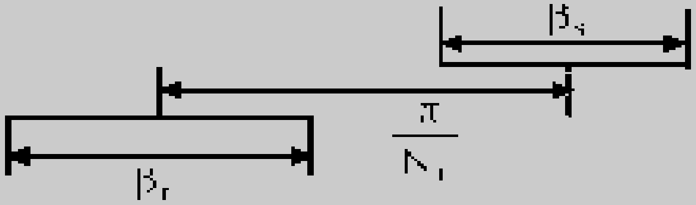
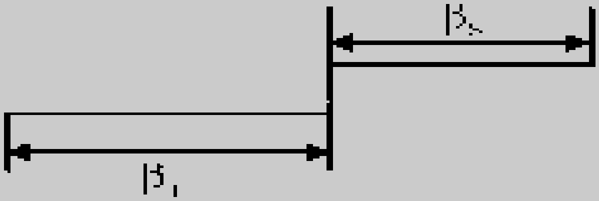


Fig. 1 Ideal Inductance profile of SRM

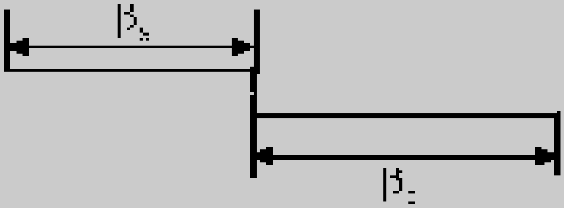
In Fig. 2, as long as the stator and rotor pole arcs do not overlap, the phase inductance remains at the unaligned value $L_u$. The inductance profile of a phase repeats at every ($2\pi/P_r$) radians.



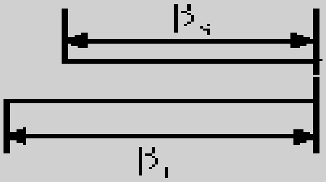
(a) Rotor position from unaligned position 0 to $\theta_1$



(b) Rotor position from position $\theta_1$ to position $\theta_2$



(c) Rotor position from position $\theta_1$ to position $\theta_5$



(c) Rotor position from position $\theta_2$ to position $\theta_3$

Fig. 2 Movement of rotor poles on stator poles

The torque equation of SRM under linear condition is given by

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta}$$

From torque equation it is observed that positive rate of change of inductance leads to positive torque. If $ß_s > \varepsilon$,

$$\frac{2 * \pi}{P_r} - \beta_r > \beta_s$$

then, phase b has a rising inductance before phase a reaches its maximum value and there will be no problems during starting as at all times, one of the phases has a rising inductance profile. If $ß_s < \varepsilon$, then, phase b has a rising inductance only after phase ‘a ‘reaches its maximum value and there will be certain rotor positions when no phase has a rising inductance profile and this could cause problems during starting [6]. Therefore, the requirement that the stator pole arc should be greater than the stroke angle. The angle between the corners of adjacent rotor poles must be greater than the stator pole arc or there will be an overlap between the stator and rotor poles in the unaligned position.

## III. SRM PROTOTYPE DESIGN

For the prototype model, it is chosen as 0.75kW, 230V, 1500rpm, 6/4 machine. For 0.75kW, 1500 rpm induction machine, the IEC recommendation specifies the frame size of 80 mm [6] and corresponding stack length is 100mm. The air-gap value is selected as nominal value of 0.5 mm. The specified value of the torque is calculated as 4.6N-m. Pole Angle Selection Conditions as below

Condition 1**:** The stator and rotor pole angles should be more than stroke angle ε .

$\varepsilon = 2\ \pi\ x(P_s \sim P_r) / P_s\ P_r$

$= 360\ x\ (6\text{-}4) / 6x4 = 30$ and

Condition 2: $(2\ \pi/P_r) > ß_s + ß_r$

$ß_s + ß_r < 360/4$

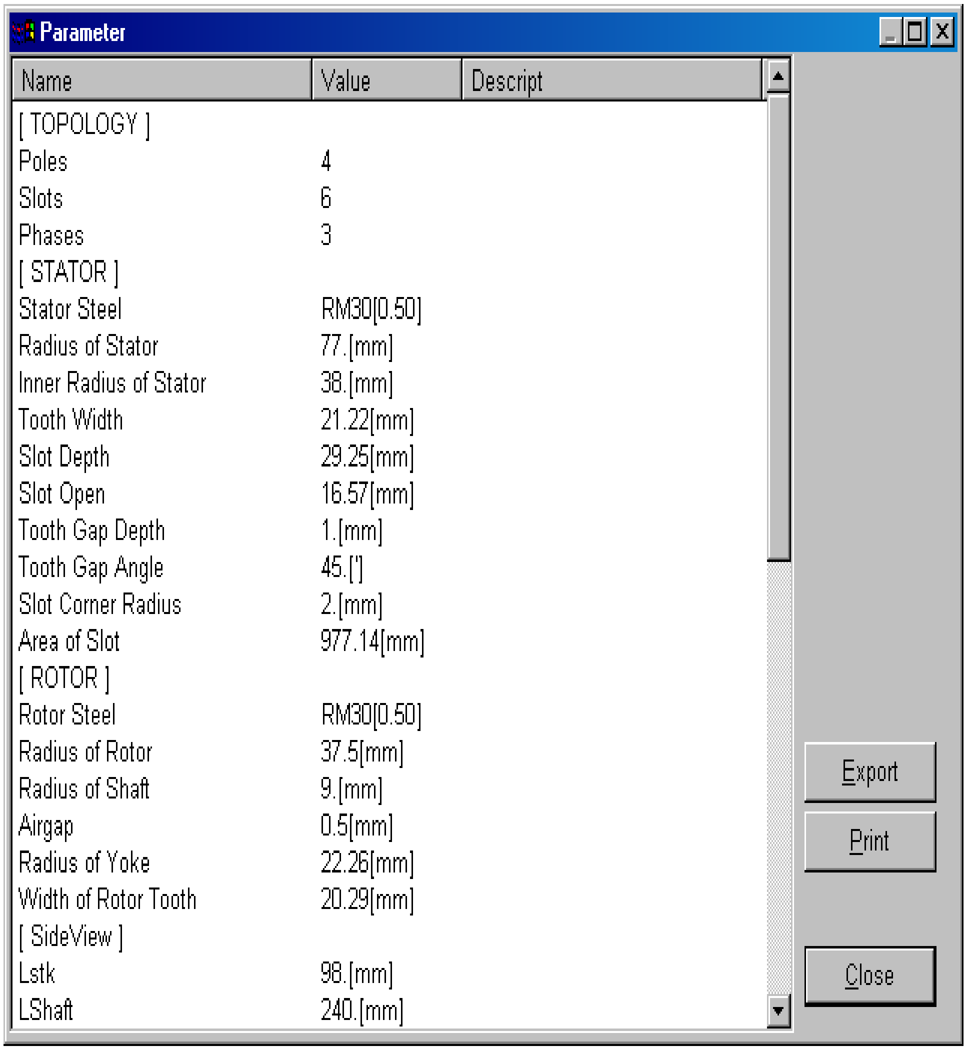
Condition 3: $ß_s + ß_r < 90$ and $ß_s > ß_r$.

The possible integer combination of stator and rotor pole angles within the feasible triangle, an objective function to meet the above constraints is solved.

## IV. SIMULATION RESULTS

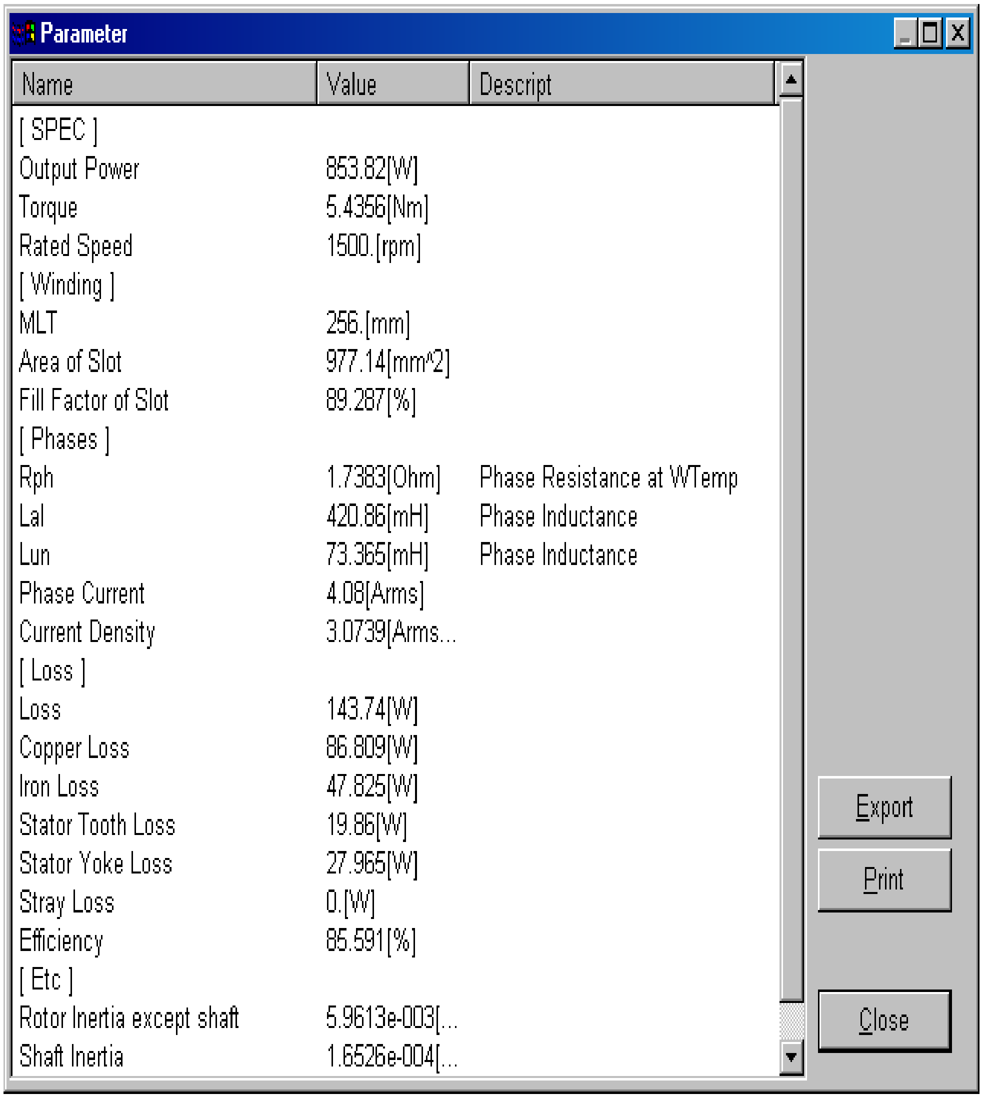
The machine dimensions obtained for the possible stator and rotor pole combinations are simulated and results are analyzed. The torque developed by the SRM is simulated for the 196 combinations of the pole angles. For each combination the torque developed, the power output and efficiency are noted. With the available combinations, the machine develops the torque nearer to the rated torque of 4.7 N-m is only for 7 combination of pole angles. Whereas for other combinations, the machine develops torque lesser than that of required one.

The maximum efficiency is delivered by the machine when the stator pole angle is 32 and rotor pole angle is 31.The corresponding torque and power output is also the maximum value in the simulation results. The analyses are made on the optimum pole angle selection. The performance analysis comprises of Inductance profile variation in aligned and unaligned positions, static torque, torque ripple and air-gap flux distribution in aligned and unaligned positions. The algorithm developed to calculate the machine parameters for the possible combination of core length and bore diameter by keeping the optimum stator and rotor pole angle is as follows. For the concluded prototype design analyses are made for the optimum bore diameter and core length at the selected optimum pole angle. The analysis comprises of Inductance profile variation in aligned and unaligned positions, static torque, torque ripple and air-gap flux distribution. The Fig. 3 lists the various input parameters for the optimum prototype model and Fig. 4 delivers the output parameters. The flux line distribution of the model is shown in the Fig. 10 and generated mesh for finite element analysis is shown in Fig. 11



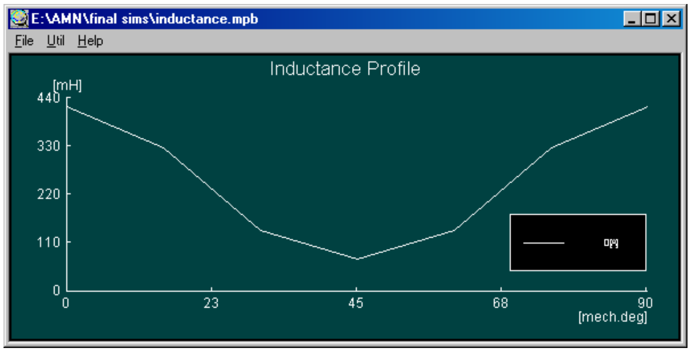
| Name | Value | Descript |
|---|---|---|
| [ TOPOLOGY ] | | |
| Poles | 4 | |
| Slots | 6 | |
| Phases | 3 | |
| [ STATOR ] | | |
| Stator Steel | RM30[0.50] | |
| Radius of Stator | 77.[mm] | |
| Inner Radius of Stator | 38.[mm] | |
| Tooth Width | 21.22[mm] | |
| Slot Depth | 29.25[mm] | |
| Slot Open | 16.57[mm] | |
| Tooth Gap Depth | 1.[mm] | |
| Tooth Gap Angle | 45.['] | |
| Slot Corner Radius | 2.[mm] | |
| Area of Slot | 977.14[mm] | |
| [ ROTOR ] | | |
| Rotor Steel | RM30[0.50] | |
| Radius of Rotor | 37.5[mm] | |
| Radius of Shaft | 9.[mm] | |
| Airgap | 0.5[mm] | |
| Radius of Yoke | 22.26[mm] | |
| Width of Rotor Tooth | 20.29[mm] | |
| [ SideView ] | | |
| Lstk | 98.[mm] | |
| LShaft | 240.[mm] | |

Fig. 3 Input parameters



| Name | Value | Descript |
|---|---|---|
| [ SPEC ] | | |
| Output Power | 853.82[W] | |
| Torque | 5.4356[Nm] | |
| Rated Speed | 1500.[rpm] | |
| [ Winding ] | | |
| MLT | 256.[mm] | |
| Area of Slot | 977.14[mm^2] | |
| Fill Factor of Slot | 89.287[%] | |
| [ Phases ] | | |
| Rph | 1.7383[Ohm] | Phase Resistance at WTemp |
| Lal | 420.86[mH] | Phase Inductance |
| Lun | 73.365[mH] | Phase Inductance |
| Phase Current | 4.08[Arms] | |
| Current Density | 3.0739[Arms... | |
| [ Loss ] | | |
| Loss | 143.74[W] | |
| Copper Loss | 86.809[W] | |
| Iron Loss | 47.825[W] | |
| Stator Tooth Loss | 19.86[W] | |
| Stator Yoke Loss | 27.965[W] | |
| Stray Loss | 0.[W] | |
| Efficiency | 85.591[%] | |
| [ Etc ] | | |
| Rotor Inertia except shaft | 5.9613e-003[... | |
| Shaft Inertia | 1.6526e-004[... | |

Fig. 4 Output parameters



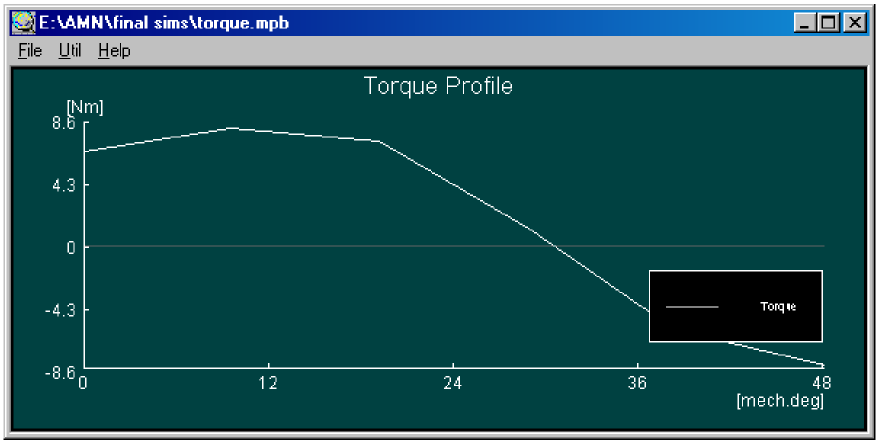


Fig. 5 Inductance Profile:

Fig. 6 Static Torque

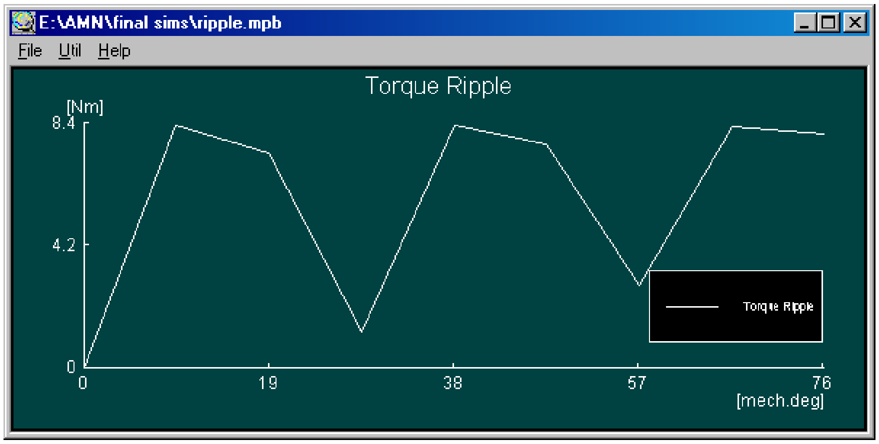
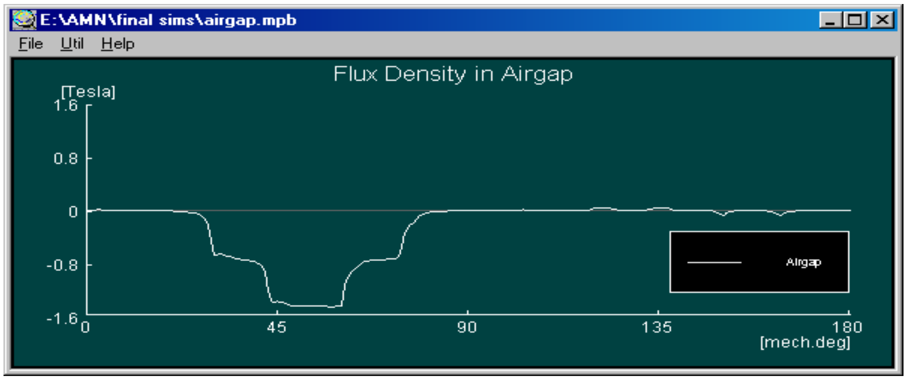


Fig. 7 Torque ripple



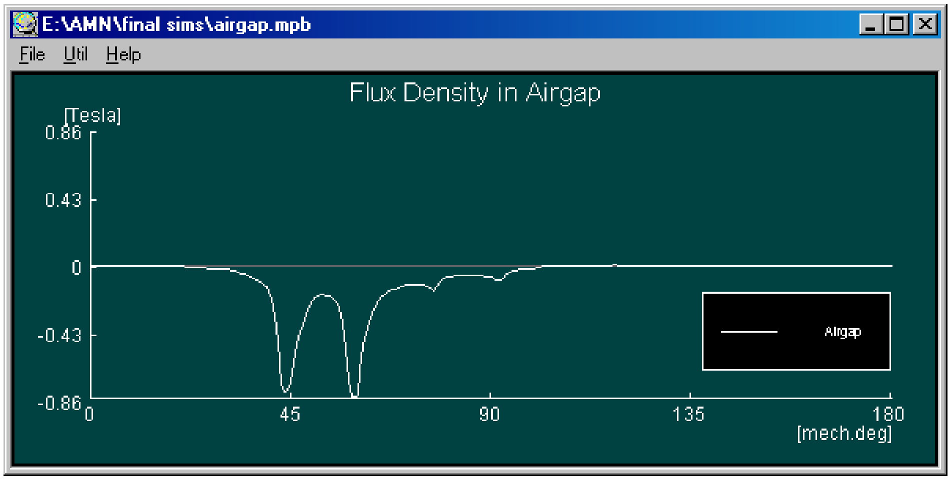


Fig. 8 Air-gap flux distribution in aligned position

Fig. 9 Air-gap flux distribution in un-aligned position

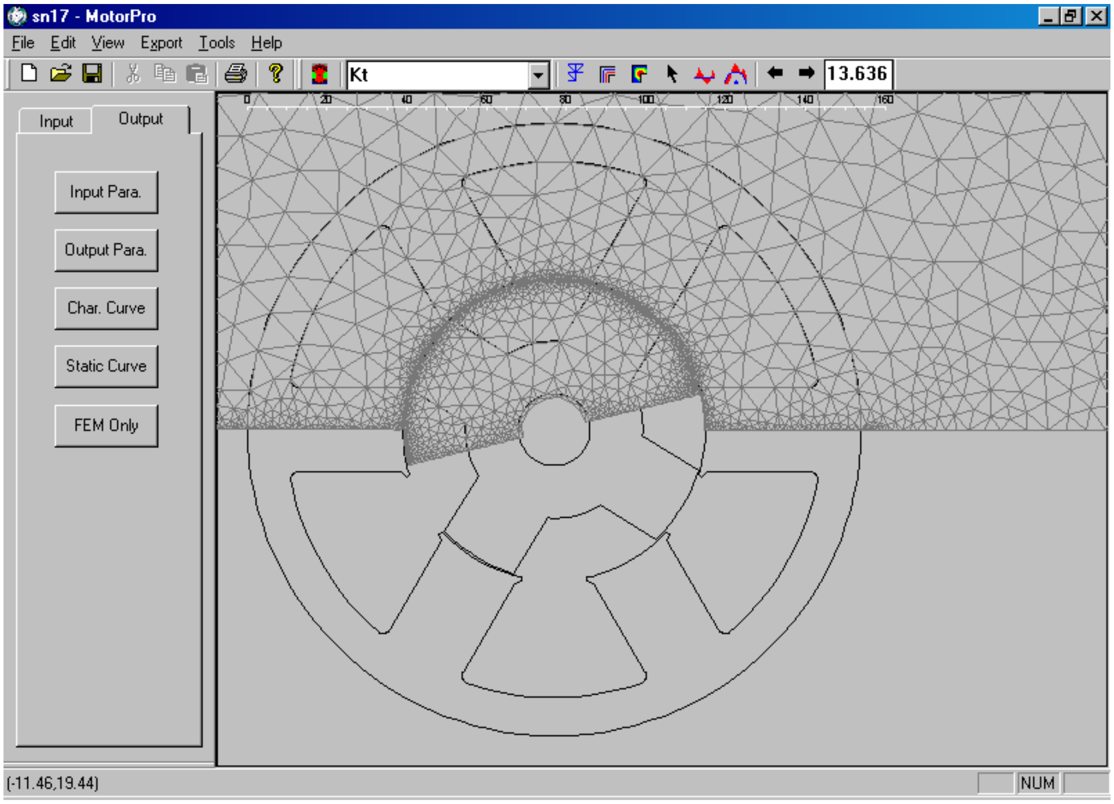


Fig. 10 Flux distribution in aligned position

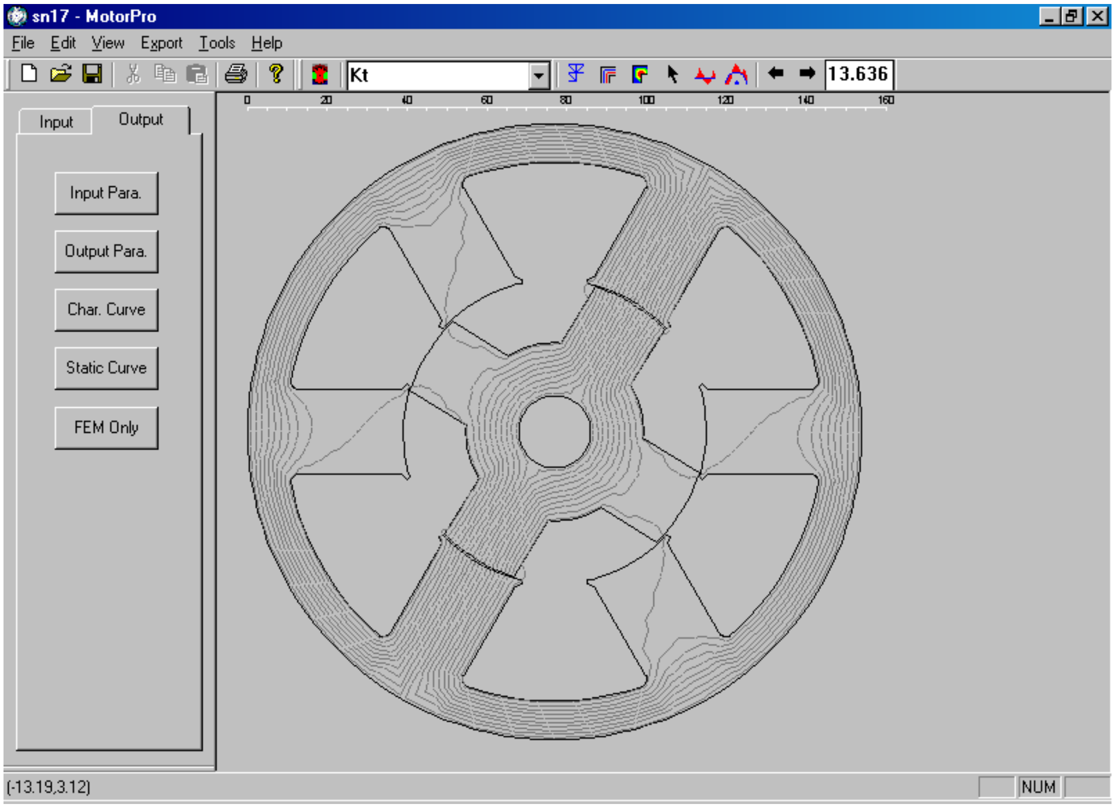


Fig. 11 Mesh formation for simulation

Fig. 5 shows the variation of inductance with rotor angles. The maximum and minimum values of inductance in the graph depict the 420.86 mH and 73.365 mH. These inductance are corresponding to aligned and unaligned positions of rotor and stator poles. The graph obtained for the prototype model is closure to the ideal characteristics. Fig. 6 displays the static torque profile. The developed torque is positive and unidirectional over the period of 0 mechanical degree to 22 mechanical degree. The corresponding torque profile is shown in Fig. 7. The ideal torque ripple is closure to rectangular shape and with minimum number of ripples. The torque ripple obtained for the prototype model is comparatively reduced for different pole angle combination. Fig. 8 and Fig. 9 represents the air-gap flux distribution in aligned and unaligned positions of stator and rotor poles. The flux density in the air-gap is non-linear due to the saliency of stator and rotor poles. The maximum flux density is calculated as 1.35 T and 0.86 T in aligned and unaligned positions.

## V.CONCLUSION

Complete machine parameters and physical dimensions of the switched reluctance motor is designed for the optimum stator, rotor pole angle combination and optimum bore diameter, core length combination. The output parameters and performance are verified by creating simulation using the software package. The optimum values and corresponding parameters are derived for getting the optimum efficiency model. By using the software package, the prototype model is analyzed for the flux distribution in the machine, mesh generation for simulation by finite element analyses, profile of inductance in aligned and unaligned positions of stator and rotor poles, static torque profile, torque ripple and air-gap flux distribution in aligned and unaligned positions of stator and rotor poles. The machine performance is verified for its optimum efficiency point.

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