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Design and Configuration Optimization of 3kw Switched Reluctance Motor for Commercial Electric Vehicle Application

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Abstract: This paper illustrates the characteristics of Switched Reluctance Motor (SRM) which makes it more favourable for commercial Electric Vehicle (EV) application compared to the other types of motors that are being used in automobiles. The design procedure for SRM to use in commercial electric vehicle application is presented. Based on the presented design procedure geometrical parameters for 3kw SRM is derived. Using Finite Element Analysis (FEA) based software tool obtained geometrical parameters of SRM are optimized. Further performance analysis and selection of optimal SRM configuration among 6/4, 8/6 and 12/8 is carried out using FEA. For the selected SRM configuration analytical and FEA results are compared and presented to validate the performance of designed 3kw SRM for commercial electric vehicle application.

Keywords: Electric Vehicle, Machine Design, Switched Reluctance Motor, Optimization, Finite Element Analysis

I. INTRODUCTION

In last decade, curiosity on commercial electric vehicle development sector is more as EV are very efficient, providing a wide range of operation speed (without or with fewer gears) and producing less pollution compared to the internal combustion engine vehicles [1].

As the EV industry and in particular commercial vehicle sector expands globally, the demand for electric motors are increasing. Motors that have the characteristics of long life, low costs, high reliability, low acoustic noise, high efficiency, variable speed control and integrated protection functions will be in high demands [2]. As a result, feasibility test and performance comparison of DC motor, PMSM motor, induction motor, BLDC motor and other types of motors are carried out by many authors for commercial EV to select the motor that provides the optimal requirements for effective operation of commercial EV.

The dynamic performance and power density of DC motor and induction motor drives are not as good as compared to the permanent magnet synchronous motor (PMSM) and brushless dc motor (BLDC). As well as the usage of gears in DC and induction motors drive system for reducing the size of the motor increases the transmission loss, emit noise and requires frequent maintenance [3]. However, PMSM and BLDC are compact in size, light in weight and can be used in direct drive system without major drawbacks. On the other hand, PMSM and BLDC have the rare earth material with high coercivity on its rotor by which its price becomes costly every year and suffers from demagnetization at a higher temperature which are undesirable in commercial vehicle segment [4]. The SRM, which is doubly salient controlled reluctance machine, replaces the PMSM to a few hundred kilowatts power range [5].

Due to low production costs and high efficiency of SRM as it has no permanent magnet and field winding on its rotor, simple construction of rotor and stator, high power density, high torque per ampere, robust structure, high fault tolerance capability, wide range of speed, and control system with integrated protection makes SRM as the main candidate of the commercial EV applications [6-7].

The design procedure of SRM for commercial electric vehicle application is presented in this paper, by using the output power equation of SRM, along with analytical calculation process for inductance at the aligned, unaligned position and average torque [8]. The pole number and pole shape of stator and rotor are optimized using FEA to obtain the required performance from the SRM [9-10]. Following the presented design procedure, design of SRM was carried out for commercial EV application.

For many applications, it is found that an electric motor of output power between 2-3kW is used, for example, the motor used in a golf cart, based on which designing of the 3kW prototype model of SRM is carried out. The design procedure and obtained geometrical parameters of SRM are presented in the next section. The FEA results and analytical results are compared for the designed 3kW SRM to validate the obtained geometrical parameters. Fig.1 shows a schematic of a switched reluctance motor with eight stator poles and six rotor poles.

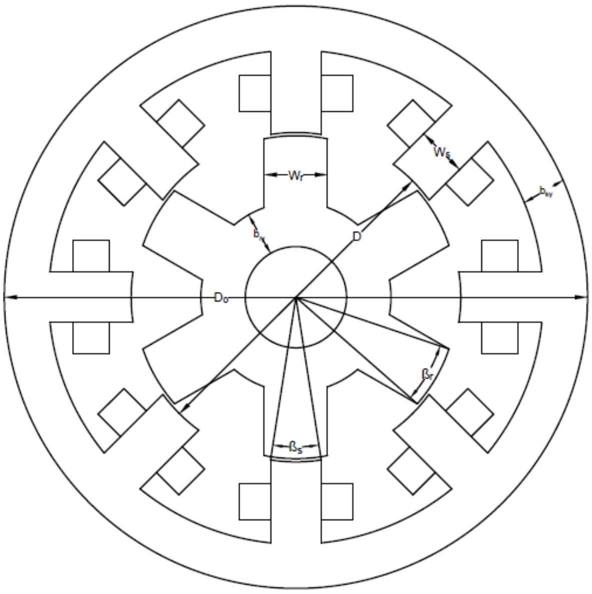

Fig.1 Schematic of Switched Reluctance Motor

II. DESIGN PROCEDURE

Following the output power equation to design a SRM for a commercial electric vehicle, a design procedure is summarized. The specification for a designed 3kW prototype model of SRM is mentioned with the obtained geometrical parameters in Table 1 and Table 2 respectively.

A. Bore Diameter and Stack Length

The bore diameter (D) and stack length (L) of SRM is obtained by using output power equation [8, 11] of SRM. Where output power is given as:

$$P_{out} = K_e K_d K_1 K_2 B A_s D^2 L N_r \quad (1)$$

Where,

K_e = efficiency of SRM

K_d = duty cycle

$K_1 = \frac{\pi^2}{120}$

$K_2 = 0.65 < K_2 < 0.75$

B = stator pole maximum flux density

A_s = specific electric loading and

N_r = speed of motor in rpm

And the stack length to the rotor bore diameter is related by

$$L = KD \quad (2)$$

Where

$$0.25 \leq K \leq 0.75 \quad (3)$$

The specific electric loading is given by:

$$A_s = \frac{2T_{ph} im}{\pi D} \quad (4)$$

Where m is a number of phases excited at the same time and i is peak input current. The specific electric loading value in ampere per meter can be between [11]

$$25000 \leq A_s \leq 90000 \quad (5)$$

B. Selection of Pole Arc and Widths

Before selecting the pole arcs for the rotor (β_r) and stator (β_s), selection of pole width is carried out. Initially different value of pole width to pole pitch of stator and rotor are chosen [12-13]. Depending upon the performance obtained by a different combination of pole width to pole pitch, the pole width to pole pitch ratio for rotor and stator are chosen for the better performance.

Stator pole width (W_s)

$$W_s = D\sin\frac{\beta_s}{2} \quad (6)$$

Rotor pole width (W_r)

$$W_r = (D - 2l_g)\sin\frac{\beta_r}{2} \quad (7)$$

For selection of stator and rotor pole arcs following constraint must be satisfied:

$$\beta_r \geq \beta_s \quad (8)$$

$$\min[\beta_s] = \frac{4\pi}{P_s P_r} \quad (9)$$

$$\beta_s + \beta_r \leq \frac{2\pi}{P_r} \quad (10)$$

$$\beta_r - \beta_s \geq 5° \quad (11)$$

Where,

P_s= stator pole number and

P_r= rotor pole number

Above Eq. (6) and (7) will provide the stator and rotor pole arcs. The obtained pole arcs are verified from the various constraints given in Eqn. (8-11).

C. Stator and Rotor Back Iron

The obtained the stator back iron thickness (b_{sy}) and rotor back iron thickness (b_{ry}) based on the minimization of vibration to lower the acoustic noise and maximize flux density in SRM, following constraint is presented [11].

$$W_{sp} > b_{sy} > 0.5W_{sp} \quad (12)$$

$$0.5W_{sp} < b_{ry} < 0.75W_{sp} \quad (13)$$

D. Stator Outer Diameter

The stator outer diameter is obtained from the ratio between the rotor bore diameter (D) to the stator outer diameter (D_o) which varies from 0.4-0.7 [14].

E. Stator Pole and Rotor Pole Height

The stator pole height (h_s) can be calculated as:

$$h_s = \frac{D_{os}}{2} - \frac{D}{2} - b_{sy} - l_g \quad (14)$$

And rotor pole height (h_r) can be finding [2] as:

$$h_r = K_3 \frac{D}{2}\left(\frac{2\pi}{P_r} - \beta_r\right) \quad (15)$$

Where K_3 is the ratio of rotor pole height to the rotor inter polar gap and K_3 lies between [2]

$$0.55 \leq K_3 \leq 0.75 \quad (16)$$

F. Shaft Diameter

The rotor shaft diameter (D_{shaft}) of SRM is calculated as:

$$D_{shaft} = \frac{D}{2} - h_r - b_{ry} \quad (17)$$

G. Winding Design

For a supplied peak current, the number of turns per phase in SRM is found by Eqn. (4). The conductor area is then calculated as:

$$a_c = \frac{i}{j\sqrt{q}} \quad (18)$$

Where,

i= peak current,

j= current density and

q= number of phases.

There should be some space left on the top of the stator pole to place wedge which supports the pole stator winding and there should be a minimum gap of 3mm between two neighbor poles winding [15].

H. Design Specification for 3kW SRM

The following machine specification presented in table I are assumed to design the prototype of SRM.

Table I Machine Specification

Parameters	specification
Output power (P_o)	3kw
Rated speed (N_r)	2000rpm
Peak current (i)	35A
Supply voltage (V)	96V
Torque at 2000rpm	14N-m
Air gap (l_g)	0.5mm

The geometrical parameters of SRM found using the analytical calculation are presented in table II.

Table II Parameter Value Of 3kw SRM

Parameter	Value	Unit
Stator pole number	8	-
Rotor pole number	6	-
Outer diameter	210	mm
Rotor bore diameter	110	mm
stack length	66	mm
Air gap	0.5	mm
Stator bore diameter	111	mm
Stator pole height	37.74	mm
Rotor pole height	27	mm
Stator pole angle	20.4	Deg.
Rotor pole angle	22.95	Deg.
Stator back iron	11.76	mm
Rotor back iron	10.94	mm
Shaft diameter	34.12	mm
Number turns per phase	100	turn

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III. ANALYTICAL CALCULATION

The aligned inductance, unaligned inductance and average torque are calculated by using the equiflux tube method mentioned in [15].

A. Aligned Inductance (L_a)

The inductance of SRM at aligned position, when rotor pole is aligned with respect to stator pole can be found as:

$$L_a = L_{aligned} + 4L_{aleakage} \quad (19)$$

Where

$$L_{aligned} = \frac{mmf \times B_s \times A_{sp}}{i^2} \quad (20)$$

And

$$L_{aleakage} = \frac{mmf \times B_{smin} \times A_{spleak}.}{i^2} \quad (21)$$

B. Unaligned Inductance (L_u)

The inductance at unaligned rotor position is calculated by assuming the equiflux tubes in unaligned rotor position and calculating the length of the equiflux lines in vacuum and then account for the paths in the iron portion [13]. Then, the unaligned inductance is given by:

$$L_u = L_{u1} + 2(L_{u2} + L_{u3} + L_{u4} + L_{u5}) + 4(L_{u6} + L_{u7}) \quad (22)$$

Where

$$L_{u1} = \frac{mmf_{t1} \times B_{smin} \times A_{t1}}{i^2} \quad (23)$$

The others tube inductance is calculated similarly using the Eqn. (23) with different mmf, flux density and tube area.

C. Average Torque

The relationship between the flux linkages vs. current over the rated value is obtained first for aligned and unaligned rotor position, which is shown in Fig. 4. Then the average torque is calculated as

$$\text{Average Torque} = \frac{W \times P_s \times P_r}{4\pi} \quad (24)$$

$$\text{Work done (W)} = W_{aligned} - W_{unaligned} \quad (25)$$

Where, $W_{aligned}$ is aligned work done, and is determined as:

$$W_{aligned} = \delta_x(\lambda_1 + \lambda_2 \ldots + \lambda_{n-1}) + \frac{\delta_x \times \lambda_n}{2} \quad (26)$$

Here, $\delta_x = \frac{i}{n}$ in which i is peak current and n is number segment. And λ_1 flux linkage at $i_1 = \delta_x$, λ_2 is flux linkage at $i_2 = i_1 + \delta_x$ and so on.

And
$W_{unaligned}$ refer to the unaligned work done, is determined as:

$$W_{unaligned} = \frac{1}{2} \times i^2 \times L_u \quad (27)$$

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IV. DESIGN VERIFICATION BY FEA

The geometrical parameter presented in table II is simulated using FEA software. To optimize the design for improving the performance of SRM, a different combination of pole width to pole pitch is simulated by keeping other parameters unchanged. Based on the simulation results, best combination which provides the required result is chosen. Motor performance (keeping the outer diameter, stack length and electric loading same for all 3 configurations) for 6/4, 8/6 and 12/8 configurations are obtained using FEA software. Comparing the results obtained from the FEA, the performance obtained for the 8/6 is better than the 6/4 and 8/6 configurations of 3kw SRM. The main performance characteristics for comparison of mentioned three configurations are presented in table III. By observing the table 3, the torque per unit volume for the 8/6 configuration is more than that of 6/4 and 8/6 configurations. As well as the output power and torque at rated speed obtained from FEA for the 8/6 SRM is closed to the expected value 3kw and 14.32N-m respectively.

Table III Performance Comparison of SRM

Parameter	6/4	8/6	12/8	Unit
Torque density	2.01×10^{-5}	2.25×10^{-5}	1.72×10^{-5}	N-m/mm^3
Torque at 2000 rpm	12.6	14.3	10.7	N-m
Torque ripple	High	medium	low	–
Output power	2.64	2.96	2.25	kw

Motor characteristics such as static torque, torque vs. speed, inductance at aligned and unaligned rotor position, flux linkage at different rotor position and current value, and flux density are obtained by using FEA are shown in next section along with the calculated analytical results for 8/6, 3kw SRM.

V. RESULTS AND COMPARISON

Analytically calculated values of inductance at aligned and unaligned rotor position by using the procedure mentioned in section 3 have been compared with the results obtained from FEA and presented in table IV. The average torque obtained by using analytical method is meeting the required torque of 14N-m hence no redesign of SRM is required.

Table IV Analytical And FEA Results

Parameter	Analytical result	FEA result
$W_{aligned}$	6.35469J	–
$W_{unaligned}$	1.17287J	–
Unaligned inductance	1.915mH	1.8mH
Aligned inductance	8.179mH	7.1mH
Torque at 2000rpm	14.32N-m	14.3N-m

The aligned and unaligned rotor position flux path obtained by FEA result is shown in Fig. 2 and Fig. 3 respectively.

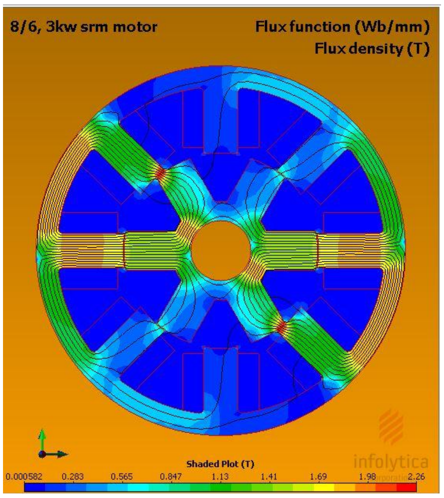

Fig. 2 Flux Path at Aligned Rotor Position

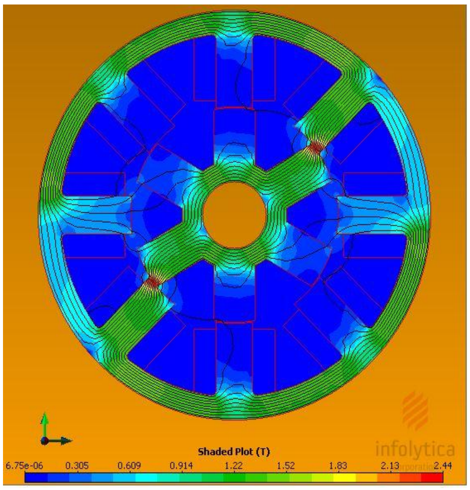

Fig. 3 Flux Path at Unaligned Rotor Position

The flux linkages calculated by the analytical method and flux linkages obtained through the FEA are presented in Fig. 4 and Fig. 5 respectively. It can be observed from Fig.4 and Fig. 5, the flux linkage calculated from both methods is the same for aligned (0º) and unaligned (30º) rotor position.

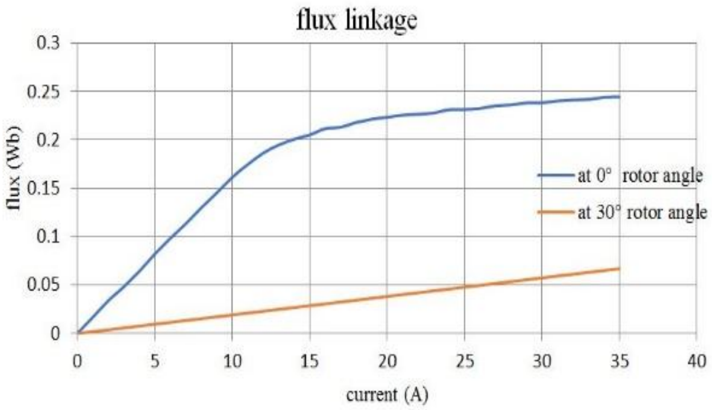

Fig. 4 Flux linkage vs. current at different rotor position (Analytical Calculation)

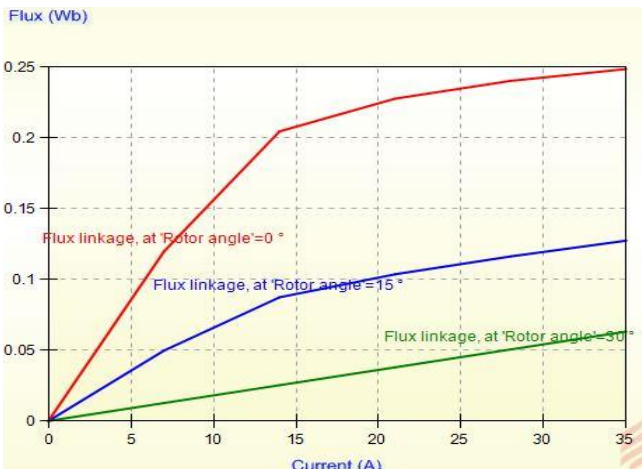

Fig. 5 Flux Linkage vs. Current at Different Rotor Position (FEA)

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The inductance obtained through FEA at aligned & unaligned rotor position for different current value is in Fig. 6.

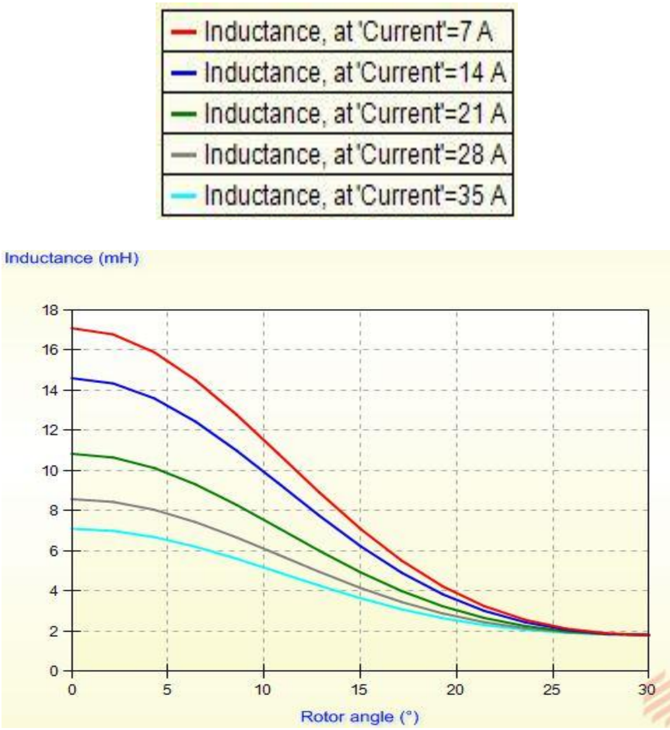

Fig. 6 Inductance profile obtained from FEA.

The torque profile at different current level and rotor position from 0º at the aligned position to 30º at the unaligned position is shown in Fig. 7. Observing Fig. 7, range from more than 5º to almost 18º the torque produced is found out more than 10N-m. As the peak torque produced for the rated supply current is more than the required 14N-m, no redesign of the of the SRM is required.

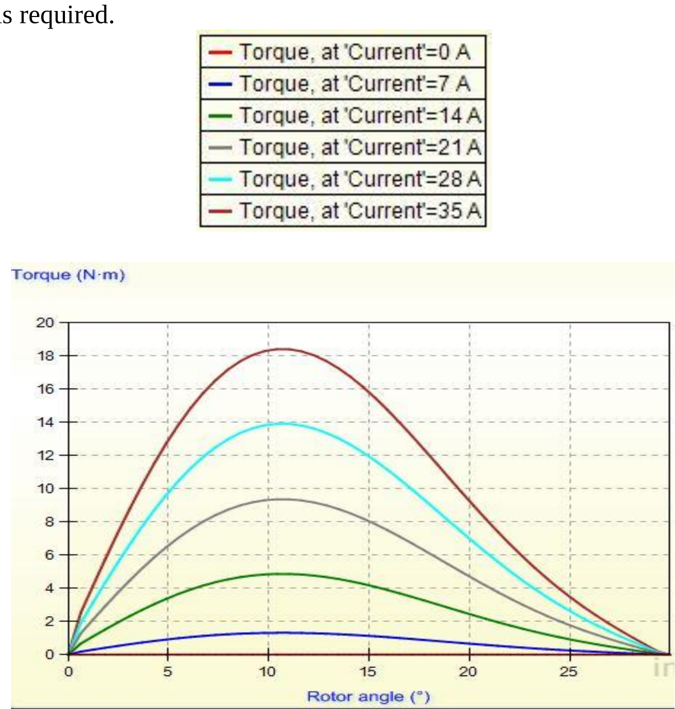

Fig. 7 Torque profile at various rotor position and different current value.

The torque measured at motor speed up to 2500 rpm by using FEA is presented in Fig. 8. By observing speed torque characteristics curve presented at Fig. 8, the expected value of torque (14.3N-m) at 2000 rpm speed is obtained.

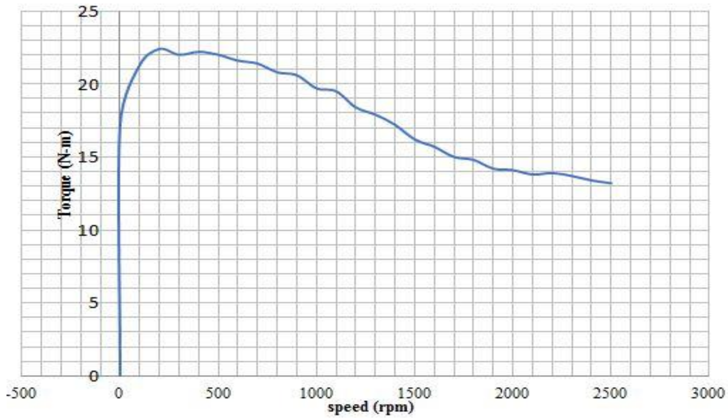

Fig.8 Torque vs. speed characteristics

CONCLUSION

A 3kw, 8/6 SRM is designed for commercial electric vehicle application. Based on the volume availability for the motor initial apportionment is made and geometrical parameters are arrived by analytical method. The designed SRM is analysed by FEA based software to validate the required output torque of 14.32N-m at 2000rpm speed. Further, FEA is adopted for shaping the pole width and configuration selection to optimise the structure parameters of SRM. Analytical and FEA results are compared to validate the performance of designed SRM to use in commercial EV application.

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