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INWHEEL SRM DESIGN WITH HIGH AVERAGE TORQUE AND LOW TORQUE RIPPLE

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ABSTRACT

Switched reluctance motors are widely used in various applications due to its inherent simplicity, robustness, and fault tolerance. The design of outer rotor type (inwheel) Switched Reluctance Motor plays a vital role in Electric vehicle. In SRM, the values of stator pole arc and rotor pole arc has greater impact on average torque and torque ripple. This paper deals with the multiobjective optimization of stator pole arc and rotor pole arc to obtain correct compromise between maximum average torque and minimum torque ripple. The optimization procedure is done on 6/8, 5HP, 1500 rpm SRM. The optimized stator pole arc and rotor pole arc are used to model the machine analytically. The results are validated by Finite element analysis Software Package MagNet7.1.1. The proposed method holds good for the Optimum SRM design for electric Vehicles.

Keywords: inwheel SRM, optimization, finite element analysis, MagNet7. 1.1.

1. INTRODUCTION

Switched reluctance machines are used in electric vehicles, washers, dryers and aerospace applications as the machine is brushless, fault tolerant, maintenance free, rugged and simple in construction. However, some of its limitations are noise, torque ripple and low torque to volume [1-2]. Furthermore, the driving power converter of SRM has an independent circuit for each phase, which provides the great advantages of inherent fault tolerance and the potential of high reliability. The SRM has excellent torque speed characteristics with high torque density [3-4]. The requirements of electric vehicles on electric motor drives can be summarized as: i) a high instant power and a high power density ii) a high torque at low speed for starting and climbing as well as a high power at high speed for cruising iii) a very wide speed range with constant-power region; iv) a fast torque response; v) a high efficiency over the wide speed range vi) a high efficiency for regenerative braking vii) compact size, low weight and low moment of inertia viii) a high reliability and robustness for various vehicle operating conditions ix) a reasonable cost; x) fault tolerance. Therefore switched reluctance motor drives are found to be much suitable for electric vehicles applications.

The effects of the stator and rotor pole arc angles on the constant power range and the rated torque [5]. Continuing researches on in-wheel SR Motor applications are focused on performance improvements by novel and optimized magnetic designs such as axial flux magnetic circuits and applying modern control methods to the motor controllers, as given by [6-9]. In recent years to achieve efficient design of electrical machines, researchers have focused on computer-aided electromagnetic design approach and evolutionary programming approach. An approach to determine optimum geometry of SRM with minimum torque ripple is given [10]. Optimization techniques like Genetic Algorithm and Taguchi algorithm have been applied for switched reluctance machine design (Kano *et al*., 2010; Mirzaeianet *al*., 2002; Nabeta *et al*., 2008). From the literature it is evident that computational intelligence techniques like genetic algorithm and artificial neural network have been successfully applied for design optimization of SRM. Multi objective design optimization of in wheel SRM is investigated with the objective of Maximizing average torque, average torque per copper loss, average torque per motor lamination volume [11]. This work aims at pole arc optimization of 6/8 (in wheel) SRM with the objective of maximizing average torque and minimizing torque ripple. The in wheel SRM is designed with the optimized values of pole arcs and electromagnetic analysis for the designed proves to be good. The static characteristics are obtained. The results are promising.

2. IN-WHEEL SRM

The SR motor is a doubly salient and single excited machine. Both the inner stator and outer rotor consist of stacks of non-oriented steel laminations. Only the inner stator has excitable copper windings. The outer rotor has no phase windings or permanent magnet materials, as shown in Figure-1. The Design data of the machine is given in Table-1.

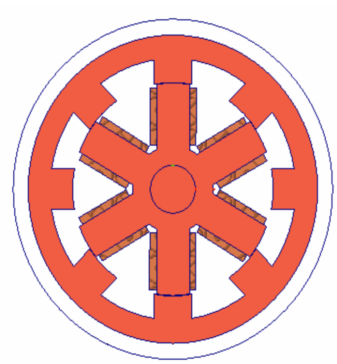

Figure-1. Structure of 6/8 SRM.

Table-1. Design data of 6/8 SRM.

Power	**5Hp**
Rated current (Amp)	45A
Number of rotor poles	6
Number of stator poles	8
Air-gap thickness	0.4mm
Stack length	50 mm
Bore diameter	200mm
Shaft diameter	45 mm
Rotor outer diameter	290 mm
Back-iron thickness	22mm
Turn/phase	120

3. NEED FOR OPTIMIZATION

Under normal rolling friction conditions and using 185/75 R14 type tires, 2.5kW per wheel will be enough to reach a top speed around 90 km/h on a flat road. This means that the in-wheel SRM has to be able to give a torque output of at least 35Nm at 800 rpm as given in [12]. The torque value and motor speed are quite important parameters for in-wheel traction motors. Torque ripple is the characteristic problem in the Switched Reluctance topology. To obtain higher driving comfort and mechanical strength of moving parts of drive train, smoother torque waveform is preferred in electric vehicles. The inwheel SRM has to be designed with high average torque and low torque ripple. The stator pole arc and rotor pole arc are the important parameters to be optimized in design process to satisfy the ripple free torque demand.

4. OPTIMISATION DESIGN OF IN-WHEEL SRM

4.1. Criteria

In this work two criteria are proposed to evaluate the design of inwheel SRM in Electric vehicles. They are average torque, and % Torque ripple represented by (1) and (4). The computation of the average torque is given as:

$$\text{Tave} = \frac{(\text{Wa} - \text{Wu})\text{NsNr}}{4\pi} \quad (1)$$

$$\text{Wa} = \int_0^{I_r} L_a \, i di \quad (2)$$

$$\text{Wu} = \frac{1}{2} I_r^2 L_u \quad (3)$$

Wa = Coenergy at aligned position
Wu = Coenergy at unaligned position
Ns = Number of stator poles
Nr = Number of rotor poles

Where I_r represents the rated phase current, L_a represents the inductance at the fully aligned position, and L_u represents the inductance at the completely unaligned position.

$$\text{Tripple}(\%) = \frac{(\text{T max} - \text{T min}) * 100}{\text{Tave}} \quad (4)$$

$\text{T max} - \text{T min}$ = Torque dip

Tave = Average torque

Where the torque dip is the difference between the peak torque of a phase and the torque at an angle where two overlapping phases produce equal torque at equal levels of current.

4.2. Multi-objective optimization function

The correct compromise between the maximum average torques, minimum torque ripple is defined as the optimization function, which is expressed as:

$$F_{opt} = \max\left(\omega_t \frac{\text{Tave}}{T_b}\right) + \min\left(\omega_{tr} \frac{T_r}{T_{rb}}\right) \quad (3)$$

Where

$T_b = \max\{\text{Tave}\}$

$T_{rb} = \max\{T_r\}$

Tave = Average torque in Nm

T_r = Torque ripple in %

T_b & T_{rb} = Base values of Average torque and Torque ripple, respectively.

4.3. Constraints on stator and rotor pole angles

To obtain maximum average torque, the stator and rotor pole arc angles should be limited by the constraints, which are given as:

$$0.4 < \frac{\beta s}{\theta s} < 0.5 \quad (5)$$

$$0.3 < \frac{\beta r}{\theta r} < 0.45 \quad (6)$$

$$\theta s = \frac{360}{Ns} \quad (7)$$

$$\theta r = \frac{360}{Nr} \quad (8)$$

Where θs represents the stator pole pitch angle, θr represents the rotor pole pitch angle, Ns represents the number of stator poles, and Nr represents the number of

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rotor poles. If the self-starting requirement is considered, the rotor pole arc angle to the stator pole arc angle should be confined in the range as (9).

$$1.0 < \frac{\beta r}{\beta s} \leq 1.2. \quad (9)$$

$$\beta s > \frac{720}{NsNr} \quad (10)$$

In summary, the optimization of stator pole arc angles and rotor pole arc angles are constrained by equations (5)-(10).

4.4. Weighted sum method of optimization

The algorithm of the proposed multi-objective optimization is given below. The weight factors are selected and the multi-objective optimization function is established. Matlab programming is done to obtain the optimized pole arcs. The stator and rotor pole arc angles are optimized to maximize average torque and to minimize torque ripple.

Step-1: Defining the multi-objective optimization function (Scalarize the set of objectives into a single objective by multiplying each objective with a weight).
Step-2: Specify the variables to be optimized.
Step-3: Specify the design constraints.
Step-4: Give the nonlinear design equations of inwheel SRM.
Step-5: Specify the value of weights depending on the importance of objective.
Step-6: Obtain the base values of average torque and torque ripple.
Step-7: Obtain the optimal values of Stator pole arc and rotor pole arc.
Step-8: Find the maximum value of average torque and the minimum value of torque ripple.

4.5. Optimized parameters

Taking into account the constraints on the stator and rotor pole arc angles, which are given by (5) - (10), for the design requirements proposed in this paper, the stator pole arc angle has to be confined as:

$$18 < \beta s < 22.5 \quad (11)$$

Consequently, the rotor pole arc angle has to be selected in the range, given as:

$$18 < \beta r < 27 \quad (12)$$

5. RESULTS OF OPTIMIZATION

The optimized values of stator pole arc and rotor pole arc are obtained for the change in weighting factors. The result of multi-objective optimization is given in Table-2.

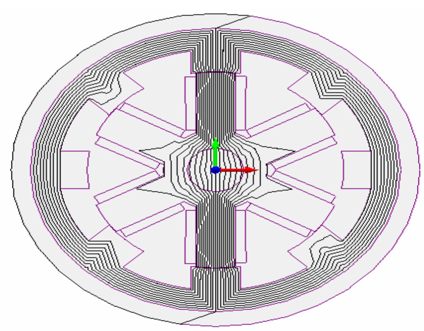
Table-2. Result of optimization.

Weight	**Optimal design**		**Average**	**%**
	βs(deg)	βr(deg)		
$\omega_t = 1\ \omega_{tr} = 0$	19.12	21.03	43.6	75.2
$\omega_t = 0\ \omega_{tr} = 1$	19.56	22.43	15.2	33.9
$\omega_t = 0.5\ \omega_{tr} = 0.5$	18.27	22.47	44.68	38.46

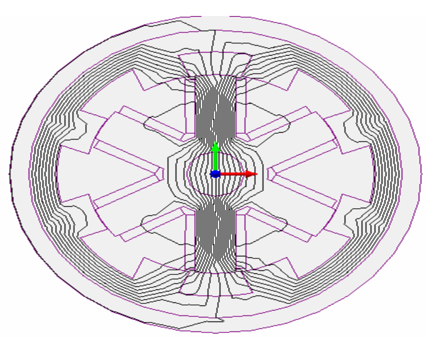
Once the optimized values of stator pole arc and rotor pole arc are obtained, the inwheel SRM with $\beta s = 18.27\ \&\ \beta r = 22.47$ is modeled analytically as given by [13] and the aligned and unaligned inductance is obtained. Electromagnetic analysis is done by FEA Package MagNet7.1.1 to validate the design. The results are given in Table-3. Figures 3(a) and (b) illustrates the distribution of the flux lines at the fully aligned and completely unaligned positions for the machine with $\beta s = 18.27\ \&\ \beta r = 22.47$. The flux linkage-current characteristics obtained by analytical model and FEM model are presented in Figure-4.

Table-3. Analytical Vs FEM results.

	Aligned inductance (mH)	**Unaligned inductance** (mH)
Analytical model	0.821	0.554
FEM model	0.833	0.564



(a) Distribution of flux lines in fully aligned position.



(b) Distribution of flux lines in fully unaligned position.

Figure-3. Flux line distribution at fully aligned and unaligned position.

The variation of inductance of a phase winding with respect to θ for the rated current is shown in the Figure-5. The flux linkage versus phase current for different values of rotor position is shown in the Figure-6. Figure-7 shows the static torque characteristic. From the characteristics, it is observed that the optimized stator pole arc and rotor pole arc gives the best design with high average torque and low torque ripple.

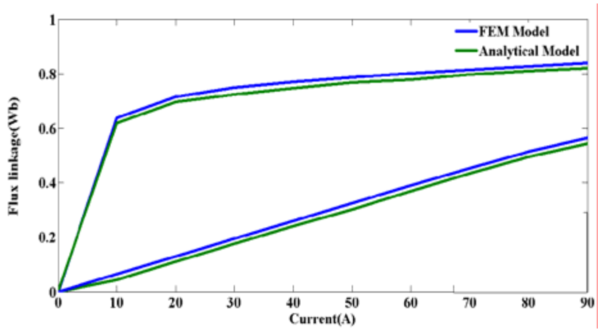


Figure-4. Flux linkage characteristics (Analytical Vs FEM).

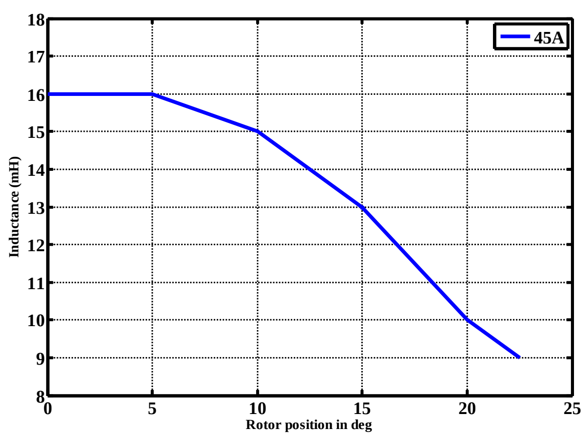


Figure-5. Inductance waveform.

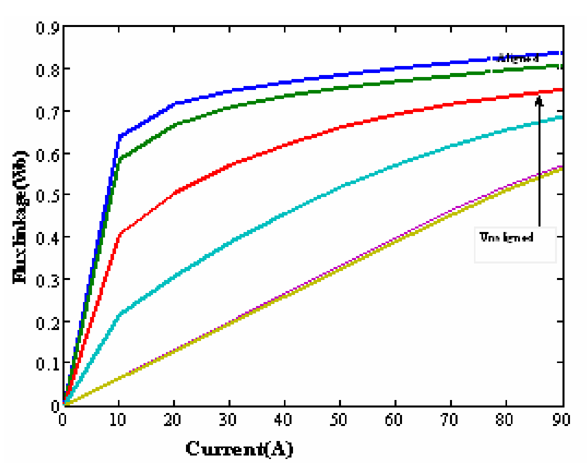


Figure-6. Flux linkage characteristics.

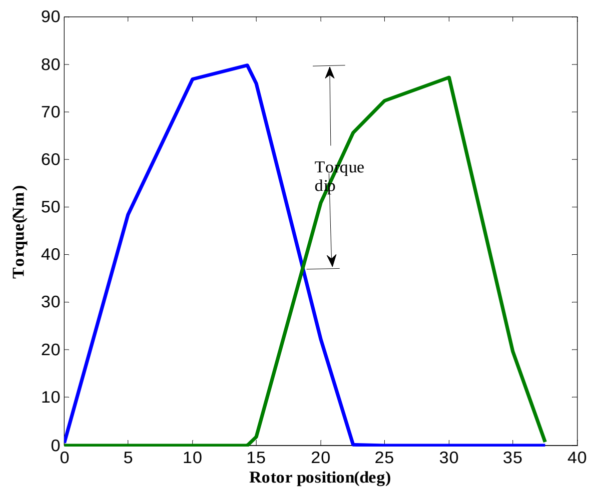


Figure-7. Static torque characteristics.

CONCLUSIONS

Conventional method of multi-objective optimization is employed to determine the optimal values of stator pole arc and rotor pole arc with the objective to maximize average torque and to minimize torque ripple. As a result of optimization for $\beta s = 18.27$ & $\beta r = 22.47$, the average torque is maximum and torque ripple is minimum. These optimal values of pole arc angles are used to design the machine. The electromagnetic analysis using Finite Element Analysis Package Magnet 7.1.1 helps to obtain the static characteristics. From the torque characteristics, average torque is obtained. From the torque dip, % Torque ripple is obtained. Thus the optimal design of the machine is done and is verified with the results obtained from finite element analysis.

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