CHAPTER 1

INTRODUCTION

1.1 GENERAL

SRM drive technology developed in the last three decades is considered as a viable alternative to conventional drives employing induction and brushless dc machines in industrial applications. SRMs are preferred for variable speed applications due to its simple and rugged motor construction, low weight, potentially low production cost, easy cooling, excellent power-speed characteristics and inherent fault tolerance (Krishnan 2001). The basic concepts of SRM and fundamentals of control have been introduced by Lawrenson et al (1980). The design procedure and analysis of SRM have been explored in detail by Krishnan et al (1988), Miller (1990), Radun (1995), Radun (1999), Praveen (2001) and Anwar et al (2002). In recent years machine designers have focused greatly on evolutionary computation based design optimization techniques to fulfill the desired performance requirements under various constraints such as converter rating, winding configuration and outline dimensions (Uler et al 1995). For optimal design of SRM, progressive quadratic response surface method (Jae-Hak Choi et al 2003), artificial neural network based approach (Sahin et al 2000, Sahraoui 2007), evolutionary computation based approach using Genetic Algorithm(GA) (Raminosoa et al 2010, Mirzaeian et al 2002) and taguchi based approach (Omekanda 2006) have been proposed. As the design of SRM for a specific application is a compromise among various performance criteria, improvement of a performance parameter may result in the degradation of other important
features. Consequently the designer has to search for solutions that are feasible with respect to all performance parameters. To deal with this trade off and achieve efficient design, multi-objective optimization based design techniques seem to be the most suitable approach. Hence the focus of this thesis is on the application of evolutionary computation and swarm intelligence techniques for two kinds of multi-objective design optimization problems of SRM.

The main disadvantage of SRM is higher torque ripple which contributes to acoustic noise and vibration. Two different approaches are considered for torque ripple minimization in SRM (Iqbal Husain 2002). One is to pursue a motor geometry which reduces torque ripple and the other is to manipulate motor current to improve performance. It is to be noted that even if electronic torque ripple reduction techniques are used, it is desirable to look for an optimum geometry for inherent improvement (Sahin et al 2000). The research reported in this work pays attention to shapes of the stator and rotor pole arcs as they directly influence inductance and torque determination. In SRM, torque output and torque ripple are sensitive to stator and rotor pole arcs and their selection is a vital part of SRM design process (Miller 1993, and Iqbal Husain 2002). It means that these parameters need to be investigated at the very first stage of the design. Hence the design problem is formulated as a multi-objective optimization problem with the objective of maximizing average torque, minimizing torque ripple and copper loss. In order to account for the geometry as well as for the nonlinearity of material utilized, the Finite Element Analysis (FEA) is used to predict the performance of the machine.

The second kind of optimization focuses on structural optimization of SRM considering design variables and performance objectives to suit EV applications. SRM is gaining attention in the field of electric and hybrid EV
applications because of its advantages (Rahman et al 2000). While designing SRM for EV applications average torque, torque density and efficiency have been considered as performance parameters (Xue et al 2010). Hence the design of SRM is formulated as a multi-objective optimization problem with the objective of maximizing average torque, torque density and minimizing copper loss.

From the literature it is evident that GA based approach has been widely used for design optimization of SRM. However some deficiencies have been identified in the performance of GA. The degradation in GA is apparent when the parameters being optimized are highly correlated and the premature convergence reduces its search capability (Sakthivel et al 2010). Hence the relevance of other modern computational intelligence techniques and their feasibility with respect to design optimization of SRM needs to be explored. Therefore in this work an attempt has been made to investigate the applicability of swarm based PSO algorithm and DE, a branch of evolutionary algorithm for design optimization of SRM. The applicability of the algorithms is investigated by reducing the multi-objective problem to a single objective problem using classical approach. In addition, an effort is made to enhance the performance of traditional optimization techniques by introducing the concept of repellor and craziness factor in case of PSO and introducing chaotic sequences in case of DE. Further, this thesis describes the application of a true multi-objective optimization method, to determine optimal design by computing the Pareto-optimal solutions. The validity of the proposed methods is tested on an 8/6 SR motor and the results demonstrate that the optimization approaches can be successfully applied for design optimization of SRM.

As the torque developed in SRM is mainly dependent on the phase inductance variation with respect to the rotor position, which is eventually dependent on the stator and rotor pole geometry, researchers have focused on
torque ripple minimization using modified pole shapes (Moallem et al 1992, Besbes et al 1998, Sheth et al 2005, Jung-Pyo Hong 2002 and Shang-Hsun Mao et al 2005). This thesis presents a comparative study of SRM with modified pole shapes such as stator pole taper, stator pole face with non-uniform air gap, pole shoe attached to rotor pole and rotor notch. The effects of design modification on torque ripple and average torque are analysed and a proposal for a design with stator pole taper and stator pole face with non-uniform air gap is described.

1.2 LITERATURE REVIEW

Literature review in the following areas is presented:

(i) Design and performance analysis of SRM
(ii) Design aspects for torque ripple minimization in SRM
(iii) Performance requirements and design aspects for EV applications
(iv) Application of modern computational intelligence techniques
(v) Analysis of SRM with modified pole face shapes

1.2.1 Design and Performance Analysis of SRM

The prospective of SRM has been realized by Lawrenson et al (1980). The basic principles, fundamental design considerations and control aspects of SRM and the non-linear features of the machine have been analysed in detail with a view to aid the practical design of SR motor.

The application of two-dimensional FEA of a doubly salient switched reluctance motor has been discussed by Arumugam et al (1985). The
results have demonstrated that the method can be applied to determine the flux linkages and hence inductances precisely.

A design procedure for SRM based on the output equation similar to that of conventional ac machines has been developed by Krishnan et al (1988). In addition, the procedures for selection of major dimensions, number of turns, and thermal considerations have been discussed. Analytical techniques have been employed to verify the design.

Analytical models for the design and prediction of the performance of SRM have been developed by Radun (1995). The model included the effects of iron saturation and required only geometry and material parameters as an input. In addition, the machine parameters used to determine the power factor has been identified and the value has been validated with a similarly defined power factor for an ac machine.

Boundary element analysis for modeling and performance prediction of SRM has been applied by Tang (1996). In addition magnetic forces that cause noise and vibration have been discussed to include the effects of motor and control design variations in the design process.

An improved magnetic equivalent circuit method to predict the performance of SRM has been presented by Moallem et al (1998). The effect of saturation has been included in the method for accurate performance prediction. The results of the proposed method have been compared with experimental and Finite Element Method (FEM).

A step-by-step design procedure for the design of SRM from the basic principle of electromagnetics has been discussed by Praveen (2001). A procedure for calculation of unaligned inductance, inductances vs. rotor position and iron loss of the machine has been discussed.
A comprehensive design methodology for SRM has been presented by Anwar et al (2001). The effects of machine geometry, material properties, configuration, design parameters, and design ratios on the overall performance of the SRM have been analyzed. The critical issues to be considered during the design process have been discussed. Further a design methodology to enhance the performance of the machine has been presented.

The optimal design aspects of SRM have been presented with new equations by Miller (2002). The physical characteristics required to achieve satisfactory performance with reduced acoustic noise has been discussed.

The design optimization of SRM using a combination of two-dimensional electromagnetic and thermal FEA has been discussed by Wei Wu (2003). Minimization of the material cost of the motor and power electronics has been considered as the objective.

The outlined survey offers an insight into the design aspects and methods for modeling and analysis of SRM.

### 1.2.2 Design Aspects for Torque Ripple Minimization in SRM

The sensitivity of the pole arc/pole pitch ratio of the stator and rotor on the performance of SRM has been analyzed by Arumugam et al (1988). The average torque developed for different stator as well as rotor pole arc/pole pitch ratios have been analyzed and the ratio that produced the greatest value of average torque has been determined. The results have demonstrated that the changes in stator pole arc greatly influence the average torque compared with the changes in rotor pole arc.

An approach to determine optimum magnetic circuit parameters to minimize low speed torque ripple in SR motor has been described by Sahin
et al (2000). ANN has been used to extract the data needed to predict the torque produced by a given geometry and excitation at any position of teeth. The method has proved that the ripples predicted from this approach agree well with those determined through the FEM. The main drawback is that the optimum value has been determined heuristically and hence presents some complexity and lengthy procedures in optimum determination.

It has been concluded that torque-ripple minimization up to a reasonable desired level is possible if the issue is dealt with starting from the machine design phase Iqbal Husain (2002). The effect of different design parameters on torque ripple in SRM and the design approaches to minimize torque ripple have been discussed in detail. Further controller based torque ripple minimization techniques have also been discussed.

A novel multi-objective optimization method based on a genetic-fuzzy algorithm for SRM design has been proposed by Mirzaeian et al (2002). A fuzzy expert system is used for performance prediction during the optimization process.

An optimum design approach of combining a progressive quadratic response surface method and a time-stepping finite element method to reduce torque ripple in SRM have been presented by Choi et al (2003). The optimization variables included both design and drive circuit parameters.

Taguchi Methods based torque and torque-per-inertia optimization of SRM has been discussed by Omekanda (2006). The performance of the design generated by Taguchi based optimization has been validated by FEA.

A FEM based optimum design approach using general regression neural network aimed at maximizing the average torque and minimizing the
torque ripple considering stator and rotor pole arc as design parameters have been proposed by Sahraoui et al (2007).

A multi-objective optimization approach based on Pareto archived evolution strategy for a 4:2 switched reluctance motor with modified rotor pole geometry with the objective of minimizing torque ripple and minimizing the degradations of the starting and mean torques has been presented by Nabeta (2008).

From the literature review it is evident that the selection of optimal pole shapes is vital for performance enhancement of the machine.

1.2.3 Performance Requirements and Design Aspects for EV Applications

The capabilities of SRM for EV applications have been investigated by Rahman et al (2000). Effects of different stator and rotor pole geometries on the steady state and dynamic performance of the motor have been studied, analyzed and optimal control parameters are determined.

The machine design approaches of SRM for vehicle propulsion to achieve high efficiency and high torque density have been described by Rahman et al (2002).

A complete algorithm for design and performance analysis of SRM for starter/generator of hybrid EV has been presented by Faiz et al (2005). The SRM design from the algorithm is given as input to GA to determine the optimal design. The objective function considered is a combination of starting torque and efficiency.

A genetic algorithm based optimum design approach to a two-phase SRM compressor drive has been presented by Kano (2010). In this
work, design optimization and control parameter optimization have been carried out using GA. The validity of the proposed design approach has been verified through with 2-D FEA and experimental studies.

The design and optimization of a high speed three-phase switched-reluctance machine to drive a compressor for the air management of a fuel cell system for automotive applications has been described by Raminosoa (2010). The machine geometry is optimized by means of FEM coupled to a genetic algorithm. The stator pole arc, the rotor pole arc and the stator bore radius were considered as optimization variables with maximization of torque density as objective function.

The design optimization of SRM with multi-objectives for SRM in EV has been proposed by Xue et al (2010). Stator and rotor pole arc have been considered as design parameters and the optimization objectives suited for EV applications were devised.

The structural and material characteristics of SRM have been investigated by Chiba et al (2011) to achieve competitive torque and efficiency with respect to an interior permanent-magnet synchronous motor for hybrid vehicle applications.

The review offers an insight into the design aspects and optimization techniques applied for performance enhancement of SRM to suit EV applications.

1.2.4 Application of Modern Computational Intelligence Techniques

The results of several numerical examples to compare the performance of the Evolutionary Algorithm (EA) using random and chaotic generators with respect to the results and convergence speed have been
presented by Caponetto et al (2003). A statistical analysis using the T-test method has been performed in order to validate the improved performance of EA.


Song et al (2007) have proposed a tent-map chaotic PSO based nonlinear neural network predictive control strategy. The simulation results show the effectiveness of the proposed approach.

Swagatam Das et al (2008) have provided an insight into PSO and DE algorithms. The various parameters affecting the convergence of the algorithms and the hybridization perspectives of PSO and DE algorithms have been discussed.

Kannan et al (2009) have formulated the generation expansion planning problem as a multi-objective optimization and illustrated its solution using Pareto-based multi-objective optimization, NSGA-II. Two different multi-objective problem formulations have been provided. The performance of NSGA-II has improved with the virtual mapping procedure.

The design of TCSC based controller structure has been formulated as optimization problem and DE algorithm has been applied to determine the optimal controller parameters by Panda (2009). The performance of the proposed controllers under various disturbances has been compared and analyzed.
Subudhi et al (2009) have applied different DE algorithm strategies for parameter estimation of induction motor. The strategies have been compared in terms of convergence time and accuracy of estimating the parameters.

Sakthivel et al (2010) have presented a parameter estimation method for induction motor using PSO. The optimization problem has been formulated as multi-objective function to minimize the error between the estimated and the manufacturer data. The performance of the proposed method is compared with the results obtained using GA and classical parameter estimation methods.

The survey provides the scope of computational intelligence techniques in various fields which can be extended for design optimization of SRM.

1.2.5 Analysis of SRM with Modified Pole Shapes

Moallem et al (1992) have analysed the effects of variation in air gap, width of the rotor poles, surface profile of rotor pole face and skewing of the rotor poles on the torque characteristics of SRM. The study using FEM has been conducted on a 60KW, 6000 rpm SR machine.

Besbes (1998) have studied the effect of stator geometry on the vibratory behaviour of SRM and proposed a new structure with less vibration while preserving a good compromise between torque and copper losses.

Sheth et al (2003) has analyzed the effect of dovetail shaped poles/slots on the performance of SRM using FEA and determined the optimum pole arc. Average torque and torque ripple have been considered as performance measures while determining optimal pole arc.
Sheth et al (2004) have studied the performance of SRM with special pole face shapes, such as noncircular stator pole face with varying air gap under a pole, flat topped rotor pole faces and noncircular air gap caused by elevated rotor poles.

Lee (2004) has introduced a notch in the rotor to minimize torque ripple and analysed the performance with conventional geometry. The optimal shape of the proposed model has been obtained by two-dimensional FEA.

Shang-Hsun Mao et al (2005) have presented a comparative study of traditional SRM and SRM with C-core stators. The results show that the proposed SRM has better characteristics in terms of torque and efficiency.

Yong Kwon Choi et al (2007) have described a proposal for a new stator pole face having a non uniform air-gap and a pole shoe attached to the lateral face of the rotor pole to minimize the undesired torque ripple. The effects of each design parameter have been simulated by using FEM and then optimized by applying a response surface methodology combined with $(1 +1)$ evolution strategy.

Based on the review it is evident that there is scope for design and analysis of SRM with special pole face shapes for torque ripple minimization.

1.3 **OBJECTIVES OF THE THESIS**

The main objectives of this thesis include

1. Pole shape optimization of SRM to minimize torque ripple using computational intelligence techniques combined with static FEA.
2. A systematic structural design optimization of SRM by considering suitable performance objectives essential for EV applications.

3. To enhance the performance of traditional optimization techniques by introducing the concept of repellor and craziness factor in case of PSO and introducing chaotic sequences in case of DE.

4. To utilize, further to weighted sum optimization, multi-objective techniques for design optimization of SRM.

5. Performance analysis of SRM with modified pole shapes and a proposal for design with stator pole taper and stator pole face with non-uniform air gap.

1.4 ORGANIZATION OF THE THESIS

The thesis contains seven chapters summarized as follows:

The optimal design aspects and techniques to enhance the performance of SRM are discussed in Chapter 1. A detailed survey of literature is carried out. The organization of the thesis is also presented.

The performance evaluation of SRM using FEA and analytical computation technique is discussed in Chapter 2.

Chapter 3 gives a brief introduction to different computational intelligence techniques. This is followed by a discussion on modifications introduced in the classical techniques to enhance their performance.
Chapter 4 describes the application of optimization techniques to determine optimal pole shapes of SRM to minimize torque ripple. Classical weight based method and evolutionary computation based multi-objective technique are applied to determine the optimal solutions.

A multi-objective design optimization approach for SRM by suitably selecting the performance parameters and design variables to meet the need for EV applications is presented in chapter 5.

Chapter 6 presents the performance analysis of SRM with modified pole shapes. The effect of design modifications are analyzed with respect to average torque and torque ripple.

Chapter 7 outlines the overall conclusions and scope for future work.