Chapter 1

Introduction

1.1 Motivation

In the growing demand for high-performance electrical machines (EMs), permanent magnet (PM) machines currently prevail as a primary choice for industrial applications because of their high torque/power density and high efficiency [1–6]. However, the existing PM resources are limited, and their cost is quite unpredictable and increasing. The instability of the cost of rare-earth metals can be noticed that the cost of NdFeB was increased from \$250/kg in 2005 to \$437/kg in 2012 [7]. Because of this, the cost-sensitive industries such as electric vehicles (EVs), renewable energy production and agricultural appliances are trying to avoid the use of high-cost rare-earth metals. The ferrite PMs are a low-cost alternative; however, they have only one-third flux of NdFeB based magnets. Moreover, they have stability issues and can easily demagnetized in field weakening operation [8]. Therefore, the researchers are interested in PM-free electrical machines to limit the price hikes of rare earth metals.

Induction machines show their presence in most household and industrial appliances. Now they are being improved according to newer application-specific requirements. BMW is using induction motors in its Mini E and BMW Mini models. Toyota Motor Corporation is also developing a lighter and more efficient variant of induction motor for automotive applications. Owing to their rugged structure and low cost, switched reluctance motors (SRMs) are also a solid alternative for PM based motors. These motors are gaining much attention in several applications because of their simple construction, fault-tolerant capability, ability to work in harsh environments, wide-speed range and low cost [9–12].

Its unipolar current excitation allows the possibility to design low-cost inverters, requiring only one controlling switch per phase. The development of double-stator SRM (DSSRM) as a new SRM topology exhibits significant improvement in its torque/power density. The adaption of single-tooth winding structure further improves its compactness, fault-tolerance capability and high-efficiency speed range. The high torque ripple is the key issue for such motors, which should be resolved to increase their suitability for high-performance industrial applications. In literature, several active and passive methods of torque ripple reduction are proposed for different SRM topologies. However, it is observed that DSSRM with single-tooth winding topology still faces the lack of such effective methods of torque ripple reduction. In this regard, research is required to improve the torque pulsation behaviour for this motor topology. Moreover, the research is also required to investigate the possibility of some further performance improvements for such motor topology.

1.2 Switched reluctance motor

The switched reluctance motor (SRM) has one of the simplest structure among all electrical machines (EMs). It has a doubly-salient structure, i.e. stator and rotor both have salient poles. The windings are concentrated type and only wound on the stator poles. The rotor has no windings. This simplifies the mechanical construction and increases its fault tolerance because no electrical power is to be delivered to the rotating parts. However, it requires a switching system such as an inverter to deliver the electrical power to its different phase windings. Fig. 1.1 represents the structure of a conventional 3-phase 12/8 pole SRM with only phase A winding shown. Phase B and phase C windings will be 60° and -60° mechanically apart from phase A. As shown in the figure, the position of the rotor is in completely unaligned condition with phase A. When a phase winding is electrically excited, the nearest rotor pole tries to align with that phase to minimize the magnetic reluctance. To continue the rotation of the rotor, the successive phase windings should be switched sequentially through the inverter. For SRM shown in Fig. 1.1, if the phases are energized correctly in the sequence of A-B-C, the rotor will continue rotating in the counter-clockwise direction.

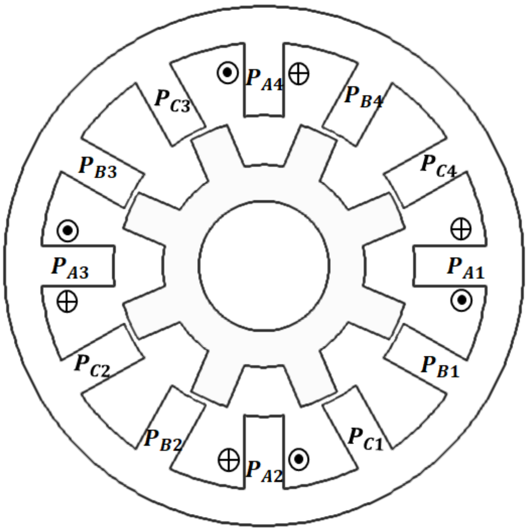

Figure 1.1: Structure of conventional 3-phase SRM with only phase A winding shown.

1.2.1 Merits and demerits SRMs

Switched reluctance motors (SRMs) are strong contenders for a variety of industrial and home appliances, including washing machine, water pumping system, aircraft system, and electric bicycle [17–20]. This type of motor exhibits numerous merits, which are listed below.

- Robustness and ruggedness
- Simple and low-cost manufacturing
- High-speed operability
- Absence of PMs and windings on rotor
- Harsh-environment standability
- Fault tolerance capability
- Simple cooling

Although SRMs inherit a bunch of favourable characteristics, they suffer from some drawbacks, which are as follows.

- Low torque density
- Low power density

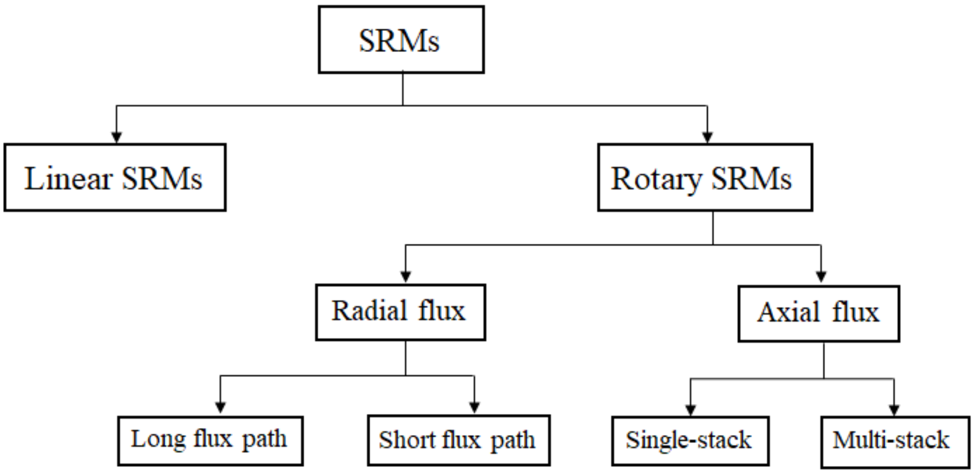

Figure 1.2: Classification of SRMs based on type of motion, flux pattern and stacking.

- High torque ripple

- High acoustic noise

1.2.2 Classification of SRMs

Classification of SRMs is as shown in Fig. 1.2. SRMs can be initially classified based on their nature of motion, i.e. linear SRMs and rotary SRMs. Linear SRMs find their application from railway transportation to industrial servo applications. Rotary SRMs can be further categorized based on their nature of flux path with respect to the axial length of the machine, i.e. radial flux and axial flux SRMs. In radial flux SRMs, the magnetic fluxes are perpendicular to the shaft, which further move along the circumference of the stator and rotor back iron. On the contrary, when the magnetic fluxes are along the axial direction, the machine is called axial flux SRM. Radial flux SRMs have low-cost and straightforward construction because of the simple stacking of the laminations. Axial flux SRMs are favourable for applications where a high D/L ratio is desired, like EVs. However, this configuration requires the folding of one lamination layer over another one. This increases the manufacturing complexity and cost of such machines. Differentiation of SRMs can be further extended based on their specific flux distribution, specific structure, number of operating machine layers etc.

1.3 Literature review

In the literature, the researchers have taken interest in the SRMs because of their simple construction, fault-tolerant capability, high-temperature stability, absence of PM, low-cost and wide speed range [12–16]. The property of the unipolar current excitation attracts the researchers to design low-cost converters with fewer controlling switches per phase [21–23]. SRMs have shown their ability in a wide variety of applications such as electric vehicle applications [24, 25], agricultural applications [26, 27], aerospace applications [28, 29], flywheel energy system [30, 31], and household appliances [32–34]. Its low cost and robust structure attract for designing small size motors for 2-wheelers [35, 36]. However, the issues of lower efficiency, lower torque/power density and high torque ripple demand further improvements in these machines. To improve these performance parameters, several research articles have been reported in the earlier literature works. H. Hayashi et al. [37] have reported that the low power rating SRMs below 2 kW have low efficiency of less than 85%. However, in this power range, interior PM (IPM) motors have high efficiency about 95%. The authors' team have worked for more than 18 years to improve the efficiency of SRMs continuously. The authors' have reported that using high silicon steel (up to 6.5%) or using amorphous iron core increases the efficiency by 5%. 1% additional efficiency is achieved by using the high slot fill factor of windings. The authors have also suggested that using high silicon steel is more economical than high-cost amorphous iron. P. Desai et al. [38] reported that in toothed SRM (TSRM), increasing the number of rotor poles than stator significantly increases the torque per unit volume with comparable manufacturing cost. The authors have compared the performance of 6/10 pole motor with 6/4 and concludes that 6/10 pole motor has improved the torque output without the change in power electronics circuitry. In [39], a novel 2-phase 6/10 pole E-core SRM is proposed which has a segmented stator and acquires higher torque density and efficiency because of reduced consumption of steel in the stator and low flux path. However, the rigidity of the stator has been compromised. In [40], it is reported that in the above 6/10 pole motor, the stator may get deformation and ovalization due to the strong radial forces. The authors have also proposed an improved 2-phase 9/12 pole E-core SRM. It is reported that 9/12 pole motor has 38% more torque per unit volume, 14% more torque to weight ratio; however, it requires 31% more copper volume. The new topology of the rotor with segmented structure is introduced in [41] to improve the performance of SRM. In such motors, the rotor is formed by a series of discrete segments which are isolated from each other. In the aligned position, these segments bridge the adjacent stator poles and create the minimum reluctance condition. Changing the configuration from multi-tooth winding to single-tooth winding for such rotor topology further improves the compactness, and fault-tolerant capability of motor [42, 43]. It is reported that this motor requires lower copper volume and has increased flux linking per turn, and subsequently has nearly 40% more torque generation capability than conventional SRM. A new doubly-fed SRM with additionally mounted copper windings on the rotor poles is introduced and experimentally tested to enhance the output torque and power in [44]. The control strategy for excitation of rotor and stator windings is presented. However, the cost and complexity increases because of the need for carbon brushes, slip rings, additional windings and a complex control strategy. SRMs face the problem of high acoustic noise and vibrations because of high radial forces due to the doubly salient structure. The vibration and acoustic noise for different topological SRMs can be reduced by accurate calculations of radial force, improved radial force control strategies and design of improved motor structures [45–48]. The methods of accurate calculation of radial force and frequency of highest magnitude acoustic noise are presented in [45] and [46] for 6/4 pole tooth SRM and 12/8 pole bearingless SRM, respectively. A schematic to produce a controlled radial force for a 12/8 pole SRM is proposed in [47] by controlling all the pole currents independently. To reduce the vibration and acoustic noise, skewing of stator and rotor poles are proposed and experimentally tested in [48]. To reduce the windage loss and acoustic noise for higher rotational speed, a cylindrical rotor SRM is proposed and tested in [49]. In this motor, the salient poles were connected by thin ribs so that the outer rotor surface is almost cylindrical. At the speed of 13,900 rpm, the windage loss and noise are reduced by 1.3 kW and 14.2 dB, respectively. Several patents have been filed in the literature which highlight the improvements and potentiality of SRMs technology [50–52]. In patent [50], a segmented external rotor SRM has been claimed with the objectives of a hub motor for an electric vehicle having advantages of high torque, high efficiency, compact size and a suitable substitute for brushless DC motor. In patent [51], a simple and improved SRM drive with 2-phase 30/45 poles low flux path pattern has been claimed for the application of hybrid electric vehicles. In patent [52], an SRM with permanent magnets mounted between the adjacent stator poles has been claimed with improved efficiency with lower back EMF. Double-stator SRM (DSSRM) as a new SRM topology with two stators further emerges improvements in the performance [53–56]. In [53] a 4-phase 8/6 pole full-pitch DSSRM has been introduced. It is reported that unlike conventional SRM, where the majority of the electromagnetic forces are applied in the radial direction, in DSSRM, their shares are significantly reduced. Therefore, DSSRM exhibits lower vibration and acoustic noise with significant improvement in its torque output. In [54], the development of an equivalent magnetic circuit is done through the Genetic Algorithm approach to rapidly optimize the DSSRM for maximum value to torque to volume ratio. The single-tooth winding configuration suggested in [42] is further investigated for DSSRM in [55]. It is reported that this winding configuration has lower copper losses because of which high efficiency in the wider speed region is plausible. The comparison of single-tooth winding DSSRM with other EMs is made in [56]. It is reported that this DSSRM topology has comparable torque generation capability as in interior PM (IPM) motor and can be a strong contender for the electric propulsion system. Furthermore, this topology has the advantage of lower saturation, which improves the torque to copper loss ratio up to higher current density. To extend the speed range of SRM with nearly zero friction loss, bearingless SRM (BSRM) is introduced in the literature [57–60]. Traditional BSRM faces the problem of strong coupling between torque and suspension windings [58, 59]. In [60], a novel double stator bearingless segmented rotor SRM (BSSRM) is proposed. In this motor, the magnetic flux path is isolated between the torque and suspension system. Because of this, BSSRM has an improved and self-decoupling property between torque and suspension system.

One of the severe issues of SRMs that limits their applicability in several industrial applications is the high torque ripple [61–64]. Several techniques have reported in the literature to reduce the torque ripple for the different configurations of SRMs. These methods can be categorized into three types: increasing the phase numbers, modifying the machine design, and via electronics control. The torque ripples may be 70% or more for 3-phase SRMs [61, 62], 50% or above for 4-phase SRMs [64, 65], and up to 40% for 6-phase SRMs [66]. Although increasing the phase number reduces the torque ripple, it requires more circuit elements and increases the cost of the inverter. Therefore, in the literature, some techniques have been reported to reduce the cost and complexity of the inverter for the higher number of phases. A standard 3-phase VSI is utilized in [67] to drive a 6-phase SSRM. However, this system requires 6 extra diodes connected with its phase windings. A new drives system has been proposed in [66] to drive a 6-phase SRM, which does not require any additional component as compared to the conventional 3-phase half-bridge converter. The electronics control techniques utilize the shaping of phase currents for minimizing the torque ripple. Torque Sharing Functions (TSF) [68–70] and Direct Instantaneous Torque Control (DITC) [71, 72] have been developed in this regard. In TSF, the total torque demanded is distributed among all phases and by controlling the current profile of each phase, the total torque is achieved with reduced ripple. In DITC, a digital torque hysteresis controller is employed, which produces the switching signals to each phase accordingly. Some modern control strategies have also been suggested to reduce the torque ripple in SRMs [73–76]. In [73], the optimization of the shape dimension and drive current of SRM are discussed to improve the output torque and minimize torque ripple through FEM and the robust particle swarm optimization (RPSO). A second-order sliding mode speed controller is presented to reduce the torque ripple and suspension force ripple of a bearingless DSSRM in [74]. Unlike hysteresis controller, which is used in traditional DITC, a PWM switching is introduced to modulate torque ripple in [75]. A fixed switching frequency deadbeat control algorithm is used in place of the hysteresis control method to reduce the torque ripple in [76]. However, these methods increase the complexity and cost of the controller side.

Design parameters of the machine, for example, the air gap, winding arrangement, shape and dimensions of the pole and back iron, have a significant influence on its torque ripple [77]. Therefore, the structural modifications in the machine have also been researched to reduce the torque ripple [78–89]. These methods change the magnetic field distribution inside the motor in such a way that more uniform torque is generated. In [78], the effect of changing the position of moulding clinches in SRM is studied. It is reported that if the moulding clinches are closer to the rotor pole head, the torque ripple is reduced by 17.1% in a full pitched SRM. In [79], a method to reduce the torque ripple in mutually-coupled SRM (MCSRM) is investigated. It is observed in the MCSRM that the derivatives of the self and mutual inductances become simultaneously zero at some rotor positions. Because of this, the torque reduces considerably near these rotor positions, resulting in a high torque ripple. The authors have introduced a punching hole on one side of each rotor pole. This omitted the simultaneous occurrence of zero derivatives of self and mutual inductances, which subsequently reduces the torque ripple. In [80], the structural modification in the leading edge of the stator/rotor poles of a tooth SRM with fillet reduces the torque ripple. It is reported through the simulation results that torque ripple is reduced by 58%. In [81], introducing a segmental dip at the centre of rotor segments is reported to reduce the torque ripple in SSRM. The addition of a semi-oval auxiliary core on both sides of the rotor tooth alleviates the torque ripple in 12/8 pole SRM [82]. It is reported that the optimized turn-on and turn-off angles together with the optimized core structure lessens the torque ripple by 72%. However, the average torque is also reduced by 25%.

Like SRMs, PM motors also face the problem of torque ripple due to cogging effect. However, the level of torque ripple in PM motor is comparatively low than SRMs. In [84,85], various cogging torque reduction techniques have been suggested via shifting and grouping of PM, shifting the stator slots and shifting of slot openings in an axial-flux double-rotor PM motor. One of the methods discussed in [84], is further extended in [86] to reduce the torque ripple in an axial-flux double-rotor SRM. In this work, the adjacent rotor segments are angularly shifted in the opposite direction to reduce the torque ripple. The torque ripple reduction is achieved in a double-sided axial-flux SRM by angularly shifting both side rotor poles in the opposite direction in [87]. However, an undesirable axial force is created in the motor. It is also reported that if the adjacent rotor poles of each side rotor are shifted in the opposite direction, the axial force is also reduced. A low torque ripple DSSRM with the salient pole stator and rotor is claimed in patent [88]. It has been claimed that if the phase shift is given with half of the stroke angle either between inner and outer stator poles or between the inner and outer side rotor poles, torque ripple is significantly reduced. In [89], the optimization of the arc angles of stator/rotor poles is carried out through the static parametric analysis of phase torque to increase the average torque and to reduce the torque ripple in a 12/8/12 pole full pitch winding DSSRM. In this method, only 15° rotor range is considered to compare the static torque rather than 22.5° because this region includes the effective torque generation region and better differentiate the variation of pole arc angles.

1.4 Contributions

The main contributions of this thesis are summarized as follows:

- Although the superiority of the single-tooth winding DSSRM is reported in the literature, its complete design concepts are missing. This thesis bridges some of these gaps. The complete design procedure of this motor topology has been discussed, together with the investigation of some improvements. The torque equation of this topology is derived. The sizing relationship between different magnetic parts of the motor is presented. The derivation of arc angles of stator/rotor poles has been carried out for obtaining the higher difference between aligned and unaligned inductance to increase the output torque. Based on these criteria, the selection of the number of stator pole/rotor segments is discussed. The influence of winding polarities on the flux density of different motor parts is presented, and its effects on core loss and output torque of the motor are investigated.

- A schematic behind the reason for torque ripple generation in SRM family is presented. From the schematic, a possibility to reduce the problem of torque ripple has also been suggested. This is a novel schematic approach that is missing in the existing work. This schematic suggests that if any design modification is done in the machine in such a way that the torque generation by a phase increases near unaligned position, torque ripple will reduce inherently. In this way, the torque ripple reduction is investigated in this work through the angular shift of rotor segments. The procedure of shifting rotor segments and the valid slot/segment combinations for this modification is presented. The effect on the output torque and torque ripple with the incremental shift of rotor segments is presented.

- The reduction in torque ripple is also investigated through the angular shift of stator and rotor pole surfaces. It is observed that shifting the stator and rotor surfaces can significantly reduce torque ripple. Comparative analysis between different surface shifts is presented in the view of output torque and torque ripple using FEM study.

- The above design modifications may adversely affect the performance of the motor. Therefore, the effects of the segment and surface shifts on the air-gap flux density of the motor are studied. Based on this study, the influence on radial and tangential force densities and their impacts on motor performance are discussed. The variation in the core and copper losses, unaligned and aligned inductances and efficiency of the motor is also presented with the variation of the shift angle.

- Moreover, the design of a new DSSRM has also been proposed in this thesis, which has a significantly low torque ripple in the high-speed region. Most of the existing structural modification and electronic control methods are only effective to reduce the torque ripple in the current-chopping mode. Unlike these, the proposed motor has a reduced torque ripple when the single-pulse control mode is active. In the proposed motor, the outer stator is shifted by half of the stroke angle compared to the inner stator. The respective phase windings of inner and outer stator windings are excited parallelly with the same phase shift. Each rotor segment is constructed with two half rotor segments with a wide non-magnetic region between them. The calculation of the width of the non-magnetic region and the arc angles of the rotor and stator poles are discussed. Finally, the simulation results confirm the effectiveness of the proposed motor.

1.5 Thesis organization

The thesis contains six chapters.

Chapter 1, gives a brief idea of the work in the thesis. It provides the motivation behind the work, a detailed literature survey to show the research gap and the main contributions.

In Chapter 2, the design concepts of single-tooth winding DSSRM, together with some improvements, have been discussed.

In Chapter 3, the torque ripple reduction in single-tooth winding DSSRM is investigated through some design modifications.

In Chapter 4, the effect of the design modifications on the flux density distributions in different parts of the motor is studied, and their influences on the motor performances are imparted.

In Chapter 5, the design methodology of a new DSSRM which has significantly reduced torque ripple in the high-speed region is illustrated.

Finally, in Chapter 6, the summary of the research work and the scope of the future investigations are presented.