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Modelling methods and structure topology of the switched reluctance synchronous motor type machine: a review

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ABSTRACT

The switched reluctance synchronous motors (SRSM) have been utilised as replacements for induction motors (IM) and permanent magnet synchronous motors (PMSM). The SRSM is a feasible solution for electric motors because of its robust and straightforward structure, resulting in low maintenance, manufacturing, and operating costs. However, the SRSM has several flaws, including low mean torque, low torque density and excessive torque ripples. The SRSM performance can be improved by considering the structure topology and driving system. This paper reviewed the performance characteristic of SRSM based on the structural topology. Several literature studies on the segmented structure topologies of SRSM were compared with the conventional structures. The performance of the SRSM can be estimated by using either numerical or analytical methods. The FEA and BEM are numerical techniques extensively used to optimise electrical motor performance. Although the numerical method can accurately estimate motor performance, the significant drawback is quite complicated, time-consuming, and difficult to implement the control algorithm with FEA software. However, the analytical method, especially the MEC method, is faster in evaluating motor performance and significantly reduces computational complexity, either with or without solving high-dimensional system matrices.

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1. INTRODUCTION

Several substantial research on implementing electric motors in industrial and domestic applications have been undertaken in the last few years. For industrial electric motors and household application systems, there are numerous options. The first candidate is an induction motor (IM) equivalent to an electric motor's rotation type but has low power performance [1], [2]. The second option is the permanent magnet synchronous motor (PMSM) [3], [4]. Although the PMSM is a high-performing electric motor, its main drawback is the cogging torque, which affects the position tracking and control [5]. Furthermore, the properties of the permanent magnet (PM) vary with temperature. If the PM is operated at temperatures higher than the curie temperature, the magnetisation may be lost [3], [4].

The switched reluctance synchronous motor (SRSM) is a viable option for electric motor drives and is the best selection for industrial applications. The SRSM has a durable and uncomplicated structure consisting of a stator or mover with concentric windings, contributing to easy maintenance, low manufacturing costs, and capital expenditures [5]-[[9]. In addition, the absence of a PM from the SRSM could improve the cost performance of synchronous motors (SM) [10]. With the advancement of manufacturing technology, the efficiency of the new SRSM is comparable or even better than the PMSM [11]. Because of these qualities, there has been substantial success in raising the awareness that SRSM can be used as a replacement for the DC and the PM motors. Several experiments and simulations have also been conducted and reported in the literature to increase these motors' performance as a viable contender for AC (asynchronous and synchronous) motors [11], [12].

The SRSM, however, has a number of flaws that include low mean torque, low torque density and excessive torque ripples. Torque ripples cause mechanical wear, vibration and acoustic noise [8]. Altering the shape or employing an appropriate control approach can reduce or eliminate the thrust ripple, improving the SRSM performance [12]-[14].

The literature review compares the segmented SRSM (SSRSM) with the conventional SRSM (CSRSM) structure topology in predicting and evaluating the EM performances of the SRSMs. How the effect of changing the topological structure of the SRSM can improve torque and torque ripple, which leads to acoustic noise and vibration, is studied and explained in detail in section 3. The control approach is not covered in this review.

The performance of the SRSM based on altering the shape/structure topology can be determined and evaluated using machine modelling approaches. Several numerical methods have been devised for calculating the SRSM performance [11], [12]. Depending on modifying the SRSM structure topology, each method has advantages and disadvantages. The details are explained in section 2. Overall, this paper is divided into two overview sections: modelling methods, which can be used to estimate the SRSM performance. The second section reviews SRSM topologies, comparing segmented and conventional SSRM topology structures.

2. MODELLING METHODS

Comprehensive modelling of the electromagnetic (EM) properties of the SRSM is the heart of performance analysis or torque management. The key metrics to be considered are average torque, torque ripple, loss density, and radial forces on both stators and rotors. The calculation for forecasting the performance of an SRSM system is expressed by (1) [15].

$$\frac{d\varphi}{dt} = V - Ri \tag{1}$$

Where φ is the flux linkage of a phase, V is the voltage applied to a phase winding, i is the phase current, R is the stator phase resistance, and t is the time. Modelling the dynamic characteristics and hence, the performance parameters of an SRSM necessitates predicting the variation of φ.

The flux linkages correlate nonlinearly with the rotor position and phase current. As a result, modelling the SRSM with first-order differential voltage leads to nonlinear effects. Furthermore, the magnetic properties of an SRSM are more difficult to characterize than those of conventional three-phase electric machines. The air gap is irregularly spread in the peripheral direction due to the double central poles of the stator and rotor [16]. Thus, the dimension of the flux paths in the air gap fluctuates, resulting in a nonlinear correlation among the flux path and the rotor position. The SRSM often operates in the magnetic saturation area to achieve a nonlinear high torque density of the phase current. Several investigations have been carried out to model the EM properties of the SRSMs [17]. These approaches to EM analyses are classified into two types: numerical methods and analytical methods.

2.1. Numerical methods

Numerical techniques are extensively used to optimize electrical motors, particularly for the SRSM [10]. The boundary element method (BEM) and finite-element analysis (FEA) are the two most common/popular numerical techniques [12], [17]-[19]. The static and dynamic properties of the SRSM may be determined with reliability. The magnetic field may also be computed for various rotor orientations and excitation current strengths, predicting the SRSM magnetization properties.

2.1.1. Finite element analysis (FEA)

Without making the assumptions of analytical methodologies, the FEA is a numerical analysis tool that is frequently used to validate EM analysis for practically any machine design. One advantage of implementing FEA to design SRSM is the ability to customize the element and increase the resolution domain. So, any complicated or irregular machine geometry can be solved with FEA. Additionally, FEA can offer a correct solution for distribution magnetic fields in subdomains [20]-[23].

In some machinery analyses, determining the variational expression is challenging. In such cases, the entire solution region is divided by the FEA into small regions called finite elements (FE). The variation and Galerkin techniques are the two common approaches for obtaining the FE equations and weighted regression [1]. The Galerkin approach is more commonly used in commercial FEA solvers due to its greater generality [17].

A significant disadvantage of FEA in optimization-based designing is the requirement for the volume mesh to covers the whole solution space, which is a computationally expensive process. The difficulty increases when the volume mesh is applied to a small dimension. A high level of mesh refinement is required for specific locations in the air gap region of electric machines and results in a large number of high-resolution elements [8], [24]. Furthermore, the accuracy of field solution is directly proportional with the number of elements in simulations [22], [25].

FEM is computationally extensive, yet it provides good precision and consistency. Even with a fast-processing engine, the process cannot be completed within the simulation time step to meet real-time simulation significant and severe execution time constraints [22], [25]. Formalized paraphrase FEM is computationally extensive while providing good precision and correctness [22]. FEM, on the other hand, is more significant for final validations.

The T-Ω (electric vector potential–magnetic scalar potential) formulation can enhance FEA speed [15], [14], [23], [26]. In addition, the domain decomposition method (DDM) is utilized to improve the efficiency of electrical machines [20], [24]. Thus, parallel computing technologies that utilize several processors to significantly reduce total simulation time are used to solve subdomain problems concurrently [16], [20].

2.1.2. Boundary element method (BEM)

The BEM [19] is another numerical method used in the study of SRSM. Integral equations are used to represent the boundary value problem and given basis functions are used to approximate the boundary conditions. The unknowns are resolved throughout the entire space. Integral equations are post-processed to construct numerical solutions at any point within the solution domain [20], [22]. The advantage of BEM over FEA is that it only requires a surface mesh along the boundaries. Because the volume meshes are defined across the entire space, the problem of mesh generation for the air gap is eliminated. As a result, the dimensionality of the structure matrix is reduced as well as the overall computation time [22].

However, there are two shortcomings of BEM. First, the BEM system matrix is dense, with no symmetry or diagonal dominance [16]. The BEM system matrix requires *O*(N2) memory storage, and the computational complexity is O(N2), whereas the FEA only requires *O*(N) [16], [17]. The multilevel rapid multipole technique, for example, can minimize the operational and storage complexity of the system matrix to O(NlogN*)* [27]. The next drawback of the BEM is the critical impediment in the design of electric machines. As a result, there is a lack of precise treatment of the effect of inhomogeneous substantial features, such as stator/rotor steel nonlinear permeability [16].

By merging BEM and FEA, it is possible to address the problem solution. The hybridization of the methodologies accomplished of nonlinear analysis, for example the FEA, is the solution for the SRSM EM analysis [7], [20], [25]. Figure 1 depicts an example of FEA and BEM mesh assignment hybridization in the solution domain [20]. The illustration shows how the homogeneous airgap ring is handled using the BEM approach, whereas the quadrangular FEA components for the heterogeneous stator and rotor areas are defined separately. The BEM implemented to the airgap area also gets rid of mesh formation issues. The stator and rotor's system matrices are reduced due to the decoupling of the FEA solutions, which also enhances the nonlinear analysis, thus, computing effort can be reduced at the expense of accuracy.

2.2. Analytical methods

The analytical method is another alternative proposed by researchers to study motor performance. The analytical methods can review the motor's operating characteristics and quickly evaluate the performances of various control algorithms. The analytical techniques can be categorized as curve-fitting methods (CFM), magnetic equivalent circuits (MEC) and maxwell's-equation approaches (MEA).

2.2.1. Curve-fitting methods (CFM)

Curve-fitting techniques utilize closed-form analytical purposes, interpolation approach or computational intelligent patterns to estimate the fluctuation of the phase inductance or flux linkage shape in terms of both phase current and rotor position. Curve-fitting algorithms for SRSM design optimization benefit from the ability to calculate the flux linkage profile or any magnetic properties of the SRSM using a small amount of data gathered via FEAs or experiments. As a result, when compared to numerical technique investigations that need an entire collection of data. As a result, lower processing efforts. The field reconstruction method (FRM) is an innovative curve-fitting technique. Instead of simulating the flux linkage or inductance of the SRSM, the FRM try to determine the magnetic field at specific points in the SRSM by using closed-form analytical purposes based on numerical analysis data [28], [29].

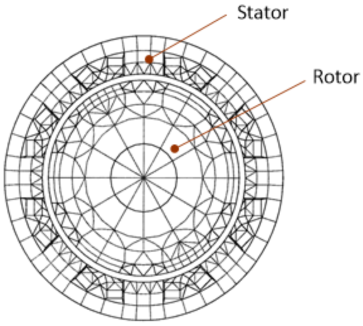


Figure 1. Finite component and boundary component mesh in the SRSM [21]

A Fourier series approach is a closed-form function used to distinguish the nonlinearity of the SRSM flux linkage [30], [31]. Based on the observed DC voltage and phase current waveforms, the flux linkages at different rotor angles are approximately determined. The Fourier series of second-order flux linkage approach derives the coefficients [32]. A similar method was used to get the SRSM's static torque characteristics [33]. On the other hand, the Fourier series coefficients with flexible terms are derived from machine geometry-dependent flux linkage at the aligned and unaligned positions. This approach is suited for real-time controller implementation [31], [34]. The Kriging model explains flux linkage and torque features based on the Fourier series. Combining the benefits of the Fourier series and the Kriging model may significantly enhance the exactness of the standards used for torque balancing. The Fourier series has the most significant advantage, in which the torque model may be determined mathematically from the flux linkage model. The flux linkage model can be expressed using the Fourier series as (2) [24], [34].

$$\varphi(i,\theta) = \sum_{n=0}^{\infty} h_n(i)cos\,(nN_r,\theta) \tag{2}$$

Where $h_n(i)$ is the Fourier series coefficients and N_r is the number of rotor poles. In (3) represents the flux linkage of an SRSM modelled using a simplified second-order Fourier series [18]:

$$\varphi(i,\theta) = h_0(i1) + h_1(i)co\,s(N_r,\theta) + h_2(i)cos\,(2N_r,\theta) \tag{3}$$

Table 1 shows the measured time of flux linkage between the suggested approach, the experiment, and the FEM by [35]. Each FEM model takes roughly four minutes to compute under a given current level, and since there are 24 current levels spread across the range of 0 to 120 A, the entire computation time is around 96 minutes. The experimental approach requires 216 minutes to complete 72 sets of measurements in one period. While only the data from five places are used in the suggested method, taking the flux linkage measurement takes roughly 15 minutes. Additionally, the Fourier series and Kriging model computation times are 0.03 s and 4.87 s, respectively. The proposed approach, which takes just 15.6% and 7% as long as the FEM and experiment methods do in one cycle, is shown to be the least time-consuming of the three [35].

The main concept underlying the interpolation types is to estimate the nonlinear flux linkage or inductance using suitable piecewise interpolation roles based on recorded magnetic data. The flux linkage connected to the phase current is incorporated using a quadratic interpolation approach. On the other hand, a linear function expresses the flux linkage relationship between the current and the rotor position [26]. Quadratic interpolation is also utilized to derive the flux linkage and rotor position relationship for a given set of current values [35].

The coefficients of computationally intelligent systems innovative models express the nonlinear nature of the flux connection. The accuracy of an approach is extremely dependent on the quantity of data. For example, an artificial neural network (ANN) is determined by focusing it on a more extensive set of given magnetic data obtained via experiments or computer methodologies. The structure of an ANN is defined by the number of neurons in its hidden layer [35]. Online and real-time training of a 2-D B-spline neural network is used to understand the nonlinear flux linkage properties of an SRSM [36], [37].

Evolutionary neural networks were used to develop the SRSMs model [32]. The features of the flux linkage are determined by applying a support vector machine using a few measured data. A backpropagation neural network is utilized to explain the reconstructed flux linkage and computed static torque parameters.

The disadvantages of CFM are primarily empirical and heuristic in nature. No rigorous demonstration proves that they are universal for any SRSM topology or geometry. Instead of analyzing the heart of the magnetic field in an SRSM, CFM fits the flux linkage or inductance curves. Additionally, CFM requires the data acquired from FEAs. As a result, curve-fitting methods have a more significant computational complexity than other analytical approaches [19].

Table 1. Time comparison [34]

FEM	Experiment	Proposed Method [34]		
		Torque-balanced	Fourier series	Kringing model
96 min	216 min	15 min	0.03 s	4.87 s

2.2.2. Magnetic equivalent circuit (MEC)

The MEC method is a well-known and influential instrument intended for analyzing EM and designing various electric machine types [38]. The application of this method in the dynamic modelling of the electric machine is less challenging. The MEC model can assess machine function correctly and quickly in various scenarios. Additionally, the MEC can optimize machine performance in multiple applications with high accuracy and precision [30].

MECs are equivalent to electrical circuits. Moreover, magneto-motive force (mmf) sources are used instead of voltage sources generated by phase winding currents in the SRSM. In addition, permeances of flux paths replace the admittances, and fluxes in permeance components substitute for currents [33]. Figure 2 shows the physical arrangement and schematic diagram of the MEC of the SRSM when the exciting stator and rotor poles are slightly overlapping. The permeability and the permeance function represent each machine zone in the MEC. For the MEC of the SRSM, the yoke permeances and reluctances are often non-ideal and are allowed to saturate before being assigned individually to denote the rotor and stator for poles and yokes.

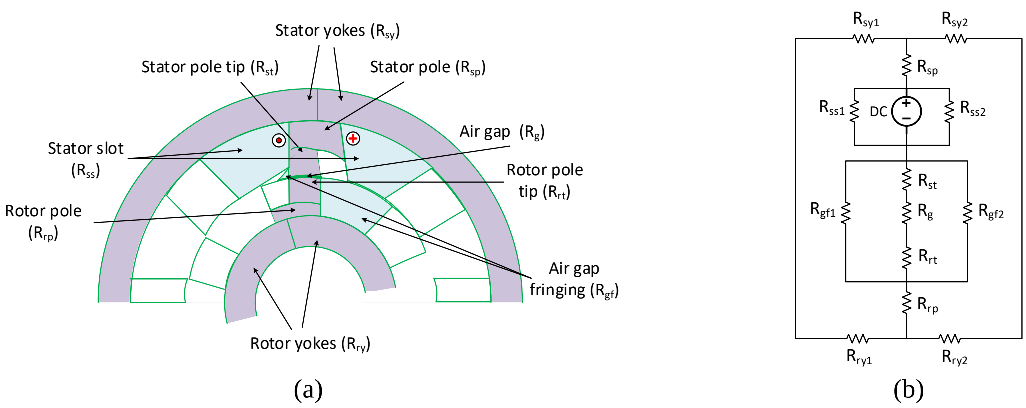


Figure 2. Physical structure and sample of SRSM MEC model (a) Physical structure of the magnetic circuit of an SRSM and (b) MEC of the SRSM when the stator and rotor poles are partially aligned [33]

The air permeances are regarded as ideal [38]. They are caused by leakage, fringing, and overlapping fluxes between the excited stator poles and the rotor poles. The flux tube analysis produces the air-region permeances and it is necessary to make assumptions regarding the geometry of the flux paths [31], [33]. Typically, the architecture of a MEC of SRSM varies with rotor angle. One method of solving a MEC is by solving the flux flow in every single component, which is equivalent to solving an electric circuit using Kirchhoff's voltage law. A more efficient and common way is to solve the magnetic scalar potential at each point/nodal in the MEC. The flux through each element is calculated using its element and mmf drop, which is equivalent to solving an electric circuit similar to Kirchhoff's current. Iterative approaches are necessary to revise the permeances and flux densities in the stator and rotor components due to the nonlinear effects of yoke [39].

Processing numerical approaches are faster using MEC methods since the elements, and size of the system matrix is smaller in a MEC. On the other hand, the MEC construction of an SRSM is practical and specific expectations regarding magnetic flux patterns are made. The regions and segments of fringing reluctance are parametrically nonlinear in the air region. The magnetic flux is chosen at various rotor positions based on previous FEA results, limiting their accuracy and generality when analyzing SRSMs with random geometries [19].

The air gap reluctance and magnetic saturation models are also crucial to accurate computation. Modelling is challenging when MEC is used on a double salient machine like the SRSM since the reluctance and magnetic saturation quantities change significantly with rotor position. The following are improvements: The issue of whether poles are aligned [1] affects how the reluctance is calculated using a direct technique [19]. As an alternative, an approach that works well regardless of the position of the rotor is suggested in [20], [21]. An FE-assisted lookup methodology [22], [24] or a direct measurement method [25] are reported concerning magnetic saturation. On the other hand, MEC frequently lacks harmonic analysis and experiences individuality issues if the machine structure changes.

2.2.3. Maxwell's-equation approaches (MEA)

The MEA approaches allow for a detailed investigation of magnetic fields in the SRSM Maxwell’s equations. Maxwell’s equations are typically expressed in magnetic scalar or vector potentials [18]. As a result, the solution for the unknown distributions is distinctive, allowing the development of boundary conditions. In nonconductive locations, the Laplace equation for the magnetic scalar potential simplifies the analysis.

The method for calculating the magnetic field in the air region and the phase inductance of the SRSM in the unaligned position is presented by [36], [40]. This method can be generalized to analyses the magnetic field at any rotor angle by allocating adaptable limit requirements to the air gap, rotor slot, and stator slot sub-regions that vary with rotor position. To simplify the analysis in cartesian coordinates, the stator and rotor slots are restructured into quadrangular proportions. To enable in the solution of the magnetic vector potential, the boundary circumstances of the tangential flux at the ends of stator/rotor slots are defined independently. To reduce the error caused by the reshaping of the stator and rotor slots, the formulation is based on polar coordinates [41]. This method is further developed by employing individual conformal mappings in the stator/rotor slots to eliminate the error introduced by misrepresenting the geometry [42].

For the air sub-region connecting the stator and rotor slots within a pole pitch, conformal mapping is used. To simplify the analysis, the hypothesis of reliable tangential field intensity at the stator and rotor slot boundaries is made [36]. The pole-pitch region’s peripheral borders are subjected to a periodic boundary condition [36], [43]. The significant complexity of this method is due to the need to solve a set of high-order transcendental equations associated with a larger number of vertices in the Schwarz-Christoffel transformation.

The crucial issue in solving the Maxwell’s equation-based approach is involving nonlinear property of the yoke. Generally, it is nearly impossible to acquire an accurate solution for a partial differential equation with an undetermined heterogeneous factor related with nonlinear permeability. As a result, a solution using the Maxwell’s equation is only feasible in the air region [20], [43], [44]. The magnetic field in the air region is substituted into a MEC, which contains the effects of nonlinear yoke [36], [40], [45]. The saturation in the stator and rotor poles is considered in the subdomain harmonic modelling through an iterative process. The stator and rotor yoke permeability are supposed to be boundless, and the non-uniform circumferential dispersal of yoke permeability in the poles is not modelled [29].

3. STRUCTURE TOPOLOGY OF SRSMs

Constructing an accurate and efficient Multiphysics model of the motor is the foundation in the initial design procedures of the SRSMs. The SRSM configuration has been experiencing different topologies in recent years. In some attempts, a slight change in the SRSM configurations was done to improve its performance, such as obtaining low torque-ripple or high torque density [46]. In some others, the motor topology is changed significantly. Subsequently, to improve the performances of the SRSMs, including the reduction of torque ripple and acoustic noise. Thus, the improvement of efficiency and torque density, various topologies of the SRSMs were proposed by the researcher. This section reviews the comparison between conventional and segmented structures of the SRSMs to improve the performance of the SRSMs.

In recent decades, a variation of segmented-structure SRSMs, specifically the C-core and E-core stator SRSMs, was proposed for generation of wind power, fault-tolerant drive system and EV implementations [44], [47]. Each structure has been validated to have higher torque output production, higher performance, and less weight than conventional SRSM (CSRSM). A segmented structure of the SRSM, called segmented SRSM (SSRSM) was proposed to solve this problem. The SSRSM had increased the

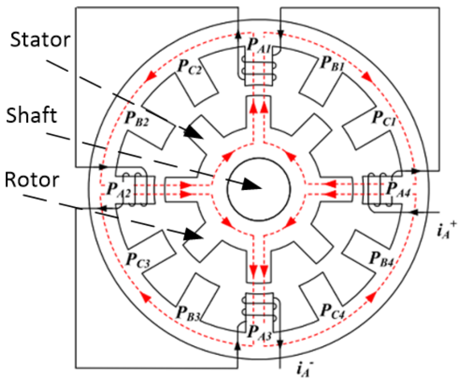
SRSM's torque efficiency by approximately 50% compared to the conventional design of the same size and at the same time reduced the torque ripple [7], [48].

The segmented topology's rotor is composed of several electrical steel structures connected by a nonmagnetic holder attached to the shaft [39]. Each segment completes the magnetic circuit and produces reluctance torque by acting as a shunt for nearby stator poles. As a result, the machine constantly intends to minimize reluctance. Due to better air gap and iron material usage, the segmented structure was shown to increase torque output [39]. According to [43], an SSRSM with full pitch provided 40 to 80% more torque than a CSRSM with the same frame size, which is due to increased aligned flux. On the other hand, SSRSM torque increases when full pitch winding is used.

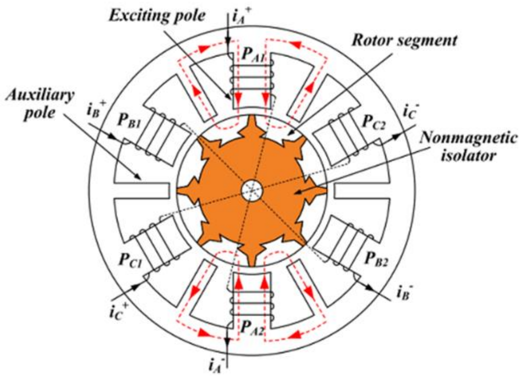
The study on segmented-rotor configuration of the SRSMs was pioneered by [48]-[50]. These studies concluded that the segmented-rotor SRSM outperformed the conventional SRSM by increasing the motor torque capability by nearly 40%. Improved segmented-rotor SRSMs with new pole configurations were investigated by Widmer and Mecrow [51]. The improved SRSMs provided considerable torque and power density. The design methodology for high-performance segmented-rotor SRSM with an outer rotor was comprehensively discussed in various aspects, including the stator slot/rotor pole combinations and several phases [52], [53]. Similar segmented-rotor SRSMs with single-stator/single-rotor structure was proposed by Kabir and Husain [54]. The rotor had segments in its design as compared to the conventional SRSMs. The results showed that the proposed segmented rotor SRSM had a lower torque ripple and higher torque than its traditional counterparts.

A novel axial-gap segmented-rotor SRSM was introduced by Madhavan and Fernandes [55]. It was demonstrated that the novel motor had higher torque density, more compact design, and higher fault-tolerance capability than the non-segmented-rotor SRSM. A novel double segmented rotor SRSM was proposed by Guo *et al.* [56], which achieved an overall volume reduction with a significant increase in torque density.

A novel double-stator SRSM (DSSRSM) with eight rotor segments was presented by Maharjan *et al.* [57], which had superior torque density, acoustic noise, and torque pulsation. The performance comparison of SRSM for conventional and segmental type motors as shown in Figure 3, with the same dimension. The conventional SRSM 12/8 form is quite popular and frequently utilized. The stator is associated with the element of stator poles, namely the exciting and auxiliary poles. The construction of a segmented rotor-type motor comprises a succession of distinct segments. The flux path of this motor is short and there is no flux reversal in the stator.



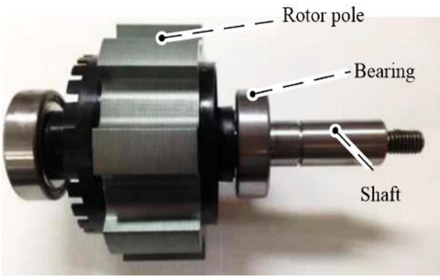
(a)



(b)

Figure 3. The flux of (a) conventional 12/8 SRSM and (b) segmented 12/8 SRSM [8]

The auxiliary poles provide the flux return path, which is not coiled by the windings. Compared to CSRSM, the segmental construction enhances the machine's electrical usage and saves core losses, resulting in better efficiency [8]. The static and dynamic properties of both SRSMs were obtained using FEM to validate the segmental structure. Both conventional and segmental 12/8 SRSM prototypes, shown in Figures 4 and 5, were tested for characteristics comparison. Both conventional and segmental rotor types had the same dimension, and input parameters reported that the segmental rotor had 13.1% greater average torque than the conventional rotor. Besides that, the torque ripple can be optimized by regulating the turn-on and off angles to lower the motor torque ripple. Table 2 shows the torque ripple comparison: the torque ripple of segmental SRSM is higher than that of conventional one when exciting was varying from 10 A to full load 100 A.



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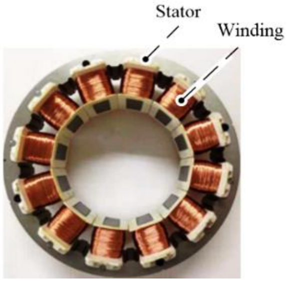
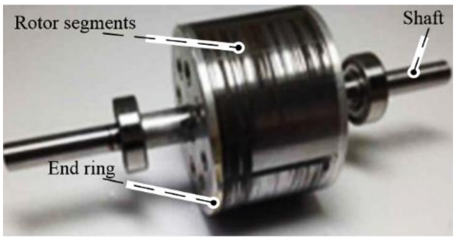
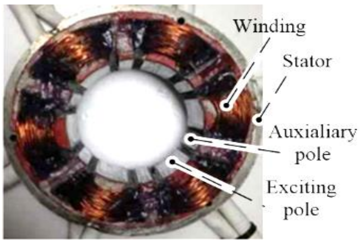


(b)

Figure 4. Conventional 12/8 SRSM prototype: (a) rotor and (b) stator with windings [8]



(a)



(b)

Figure 5. Segmental 12/8 SRSM prototype: (a) rotor and (b) stator with windings [8]

Table 2. Torque ripple comparison of the conventional and segmental type SRSMs [8]

Exciting current (A)	Conventional type (%)	Segmental type (%)
10	87	138.8
30	82	138.9
50	82	137.3
70	86.9	127.8
90	93.2	118
100	95.7	111.4

Segmental rotor SRSMs have been shown to produce greater torque than toothed rotor SRSMs, by comparing a CSRSM with the same lamination length and outer dimensions with a six-phase segmental rotor SRSM. The segmented-rotor SRSM was explored in both fully pitched (FP) and single-tooth wound (STW) motor designs [48]. When the same phase conduction angles were utilized, the FP winding machine produced more torque than the single-tooth winding machine. However, it had excessively lengthy end windings. The single-tooth, segmented-rotor SRSM was fitted with optimized conduction widths and current shapes. The SSRSM had been proven to provide approximately 10% more rated torque with less core and copper loss over the whole speed range than the CSRSM. The 2D FEA torque output results obtained from FP segmented, STW and toothed rotor SRSMs are shown in Figure 6. An FP winding connection is also depicted as an alternate connection option for the segmented-rotor SRSM. It had a maximum torque of 33.4 Nm, 48.4% higher than the single-tooth winding connection [48].

The mutually coupled SRSM (MCSRSM) with a segmented rotor, fractional slot and tooth wound with a notched rotor design was presented in [58]. It had a shallow torque ripple compared to other machine types in the SRSM family. The torque ripple was reduced by 3.6% without current profiling techniques or torque sharing functions. The ripple minimization was achieved primarily through rotor segment shaping, which strongly influenced the stator flux densities, flux linkages and torque harmonics.

The study on the magnetically separated stator segments of a high-torque three-phase switching SRSM was done by Moallem and Dawson [59]. Each element of the proposed segmented stator of the 6/22 SRSM contained a concentric winding on its center body and two opposing windings that made up the motor phase. There were four salient poles in the stator segment. Two of the central segment bodies shared their flux path. The rotor was composed of a robust framework with twenty-two salient poles. The motor was evaluated using the FEA technique, and comparisons with conventional 6/4 and 6/22 SRSM designs were made. The comparisons found that the average torque and torque density of the segmented-stator 6/22 SRSM were the highest. The proposed SRSM produced 58.6 and 17% higher torque than the 6/4 SRSM and 6/22 SRSM, respectively. The comparison between two conventional topologies (6/4 and 6/22) showed that the increase in the rotor poles had no direct effect on the torque capacity. Therefore, torque production is mainly affected by the main SRSM topology.

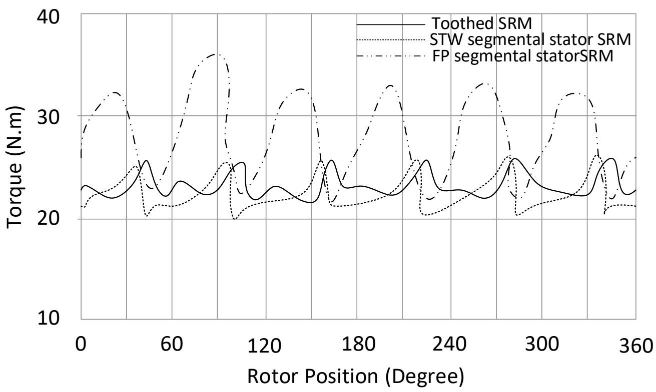


Figure 6. 2D FEA torque output comparison under multiphase excitation [44]

4. CONCLUSION

This paper presents an overview of the electrical machine modelling technique and segmented topology types of SRSM. The characteristics of each modelling method were reviewed and evaluated in terms of accuracy and computational complexity. Among the numerical methods, FEA is the most frequently used. Numerical methods can accurately obtain the machine's static characteristics and dynamic performance but are quite complicated and time-consuming. Moreover, it is difficult to implement the control algorithm with the FEA software. This is due to the assumptions made to facilitate the analysis. Compared to numerical approaches, analytical techniques can considerably diminish computational complexity at lower accuracy costs, with or without a minor requirement to solve high-dimensional system matrices. Analytical methods are commonly used to briefly study the operating characteristics of a motor and rapidly evaluate the performance of various control algorithms.

The comparative review for predicting and evaluating the EM performance between the segmented SRSM (SSRSM) model and the conventional SRSM (CSRSM) model. Studies have shown that the SRSM torque performance of the segmented structure is better than that of the conventional structure. In addition, the segmented structure has a lower thrust ripple than the conventional structure. SRSM performance of segmented and conventional structures can be accessed via mathematical modelling using numerical methods (FEA and BEM approach) or analytical methods (MEC, CFM and MEA).

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