Switched Reluctance Motor Drive Challenges - A review

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ABSTRACT

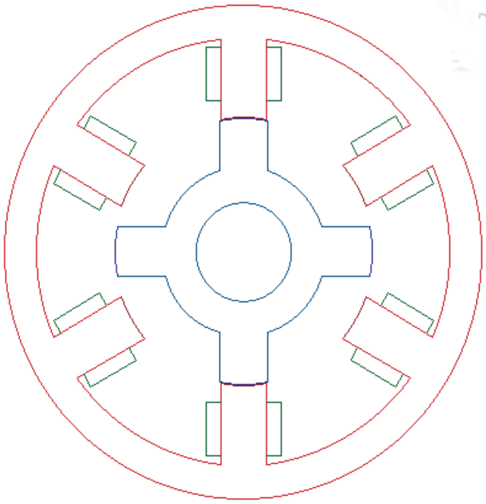
Due to its inherent characteristics, the Switched Reluctance Motor (SRM) is an up-and-coming contender for further investigation and analysis across diverse industrial domains. One of these domains is the field of electric vehicles(EVs), but this is no exclusive category. The mechanical design of the motor is notable for the inherent simplicity it possesses as well as the cost-effectiveness it offers. This article presents a comprehensive analysis of SRMs, including detailed descriptions, an in-depth review of their advantages and disadvantages, an investigation of their applications, and torque-speed profile and power speed profile graphical representations. The discussion incorporates the most recent findings from research on the methodologies and control strategies used.

Keywords- Switched reluctance motor (SRM), SRM applications, Electric vehicles(EVs), SRM control.

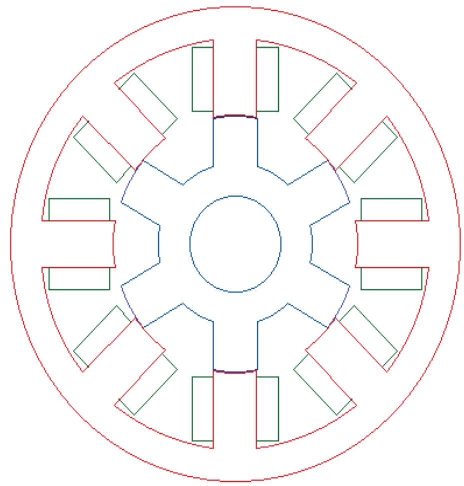
I. INTRODUCTION

Since 1969, a switched reluctance motor (SRM) for adjustable speed appliances has been proposed. This motor was manufactured in 1842, but introducing economical, high-power switching apparatuses enabled its “reinvention”. The machine is a strong candidate for EV and electric aircraft appliances because of its constructional qualities and high robustness. In addition, the ongoing advancements in power electronics, the decrease in the price of semiconductor devices, and the rise in the processing power of microprocessors have accelerated this process [1]. As the largest electrical energy consumer, electric motors are crucial in the expanding electrification market. SRMs are highly desirable to industrial applications due to their mechanical construction to meet the growing necessity for high-performance drive, high system efficiency, and low cost. Significant progress has been made in the design and control of SRMs over the past two decades [2].

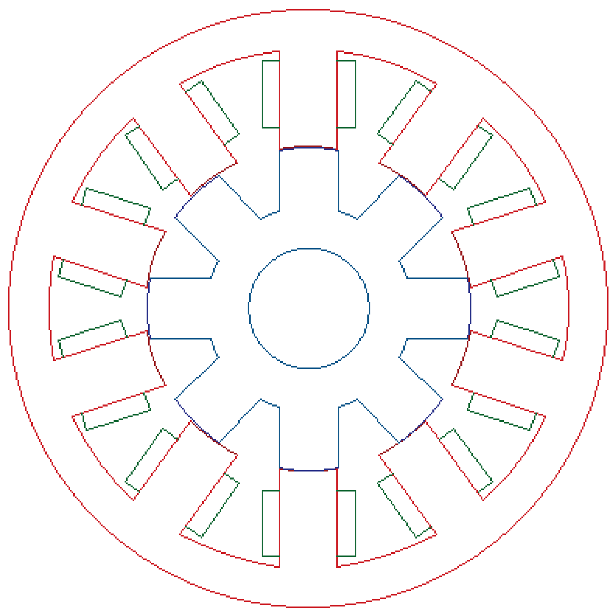
There are many possible combinations of numbers of stator and rotor teeth. Each of these has its advantages and disadvantages. Popular types of designs are 6/4, 8/6, and 10/8, as specified in Figure (1) (a,b,c), respectively. 6/4 SRM is three phase machine, 8/6 four-phase machine, and 10/8 five-phase machine. The coil's diametrically opposite poles are connected in series/parallel to form one phase. The type of pole configurations proposes discrete properties for each SRM. Many poles offer reduced percentage torque ripple. However, it is important to note that the proposed solution should incorporate a greater average switching frequency[2,3].



(a) Three-phase 6/4 SRM



(b) Four-phase 8/6 SRM



(c) Five-phase 10/8 SRM

Figure (1) SRM geometries with different numbers of phases.

Equations (1-4) establish the necessary conditions that need to be met by the number of stator poles (N_s), the number of rotor poles (N_r), stator pole arc(B_s), and rotor pole arc (B_r) [2,3,4].

$$\mathrm{LCM}(N_s, N_r) = qN_r \quad \text{.....(1)}$$

And

$$\mathrm{LCM}(N_s, N_r) > N_s > N_r \quad \text{.....(2)}$$

Where N_s and N_r are even, q is greater than 2, and the LCM symbol represents the lowest common multiple. Additionally, it can be demonstrated that for pole arcs:

$$\min(B_s, B_r) > 2\pi/qN_r \quad \text{.....(3)}$$

And

$$B_s < 2\pi/qN_r - B_r \quad \text{.....(4)}$$

The SRM typically has an even number of poles on both the rotor and the stator to guarantee the magnetic duality required to create a flux path. When the rotor and stator poles align, a path of minimal reluctance is formed. The number of poles on the rotor and stator must differ to achieve motoring operation. Thus, improving the starting torque for any given rotor position is possible, considering that the stator poles of one of the machine's phases will always be out of alignment with the rotor poles. Note that other aspects, such as the rotor geometry, also affect the starting capability at any rotor position. Functional patterns of pole numbers used for self-starting adjustable drives are given below [3,4,5]:

For 3-phase SRM motors: $N_s = 6$, $N_r = 4$
For 4-phase SRM motors: $N_s = 8$, $N_r = 6$
For 5-phase SRM motors: $N_s = 10$, $N_r = 8$

The pole configuration of the machine is highly linked to its application. For motor operation, a greater number of phases helps to mitigate electromagnetic torque ripple. Moreover, it contributes to the robustness of the system, presenting a greater fault tolerance, a desirable characteristic in electric vehicle applications [6,7]. However, with more phases, the space available for windings within the machine's stator slots becomes more restricted. In addition, a greater number of phases raises complexity and the system's overall cost, given that a more complex converter will be required to drive the machine [8,9].

II. ADVANTAGES

The modem SRM drive possesses several advantages for EVs or industrial applications. Its particular features may be summarized as follows[1,3,10,11]:,

1. The structure is simple and rugged, which leads to its high reliability.
2. The stator windings are concentrated, which facilitates maintenance.
3. The windingless rotor has low inertia, allowing a quicker dynamic response.
4. The stator, which can be efficiently cooled, is the source of most losses.
5. Because of the extremely low rotor losses, the issues with rotor cooling are resolved.
6. The motor and converter are fault-tolerant by nature.
7. High starting torque with no surge current issues.
8. Because the machine's torque is unaffected by the polarity of the feeding phase current, a power converter with fewer power semiconductor switches can be used.
9. It is a brushless machine, like other AC machines, making it superior to DC machines in terms of maintenance.
10. Skewing is not necessary to reduce crawling or cogging torque. This machine does not produce cogging or crawling torques.
11. Because the induced emf depends on the phase current, there is no induced emf in the SRM when there is no current flowing through the winding, and a phase winding fault cannot persist if the input current is cut off. As a result, an SRM is more reliable than any other electrical machine.
12. The SRM can operate with any number of phases, contributing to high reliability even if one or more phases malfunction.
13. It can operate over a wide speed range.
14. High efficiency at high speeds.

III. DISADVANTAGES[1,3,12,13]

1. Complex control is necessary due to the independent phases and non-linearity characteristics.
2. Although acoustic noise levels are high, their causes are being researched, and some suggestions have led to a significant reduction in noise compared to first-generation machines.
3. The salient rotor at high speeds causes significant friction and windage losses.
4. To operate, the SRM needs an electronic power converter. It cannot be started from the line.
5. Position data is essential to control the SRM drive performance.
6. The double salient structure causes inherent acoustic noise and torque ripple.

IV. APPLICATIONS OF SWITCHED RELUCTANCE MOTOR DRIVES

Due to the absence of magnets, rotor conductors, and brushes, its simple construction makes it an attractive alternative to AC and DC motors for general-purpose industrial drives, high-performance automotive drives, and other applications. Applications for SRM drives include (but are not limited to)[1,14]:

1. The SRM is ideally suited for high-speed applications due to its high power density and simple mechanical construction.
2. EVs with increasing environmental concerns and conservation, electric vehicles will ultimately assume a dominant share of the transportation market. In addition to ordinary cars and trucks, this type of vehicle includes electrically powered bikes and scooters, industrial utility vehicles, station cars and wheelchairs [15].
3. Aerospace: SRM has a long life cycle, high reliability and low cost. It is appropriate for high-performance aerospace applications, where a smaller weight is qualified[16,17].
4. Household appliances: washing machines and vacuum cleaners [18,19].
5. Robotics: SRMs primary appeal in robotics is their use as direct drive actuators. [20].
6. Variable speed wind turbine appliances [21].
7. Actuator system for the door, the medical centrifuge, the gas turbine engine, the hand power tools, the fans, the pumps, and the drives for the refrigerators and freezers [1].

V. Torque-Speed Profile

The most crucial performance of an electric motor is the torque-speed profile, typically described by a two-dimensional plot. The output performance of an electric motor is defined by its ability to operate at any torque/power level that is equal to or less than the torque-speed profile. Since the standard torque-speed profile supposes uninterrupted obligation, it describes working circumstances subject to continuous operation thermal limits. Non-continuous duty operation above this profile is feasible if the transient thermal limits for the specific motor/controller are not exceeded [22,23]. The average maximum torque values at various speeds characterize the torque-speed profile of an electric motor. The rated torque of the motor is the peak average torque in the constant torque region. The torque-speed profile is limited by the max/min allowable current (RMS value of phase current constraint) and the DC link voltage. A typical torque-speed profile for an SRM has three regions: constant torque, constant power, and falling power. The generic form of the torque/speed capability curve is presented in Figure (2)[24].

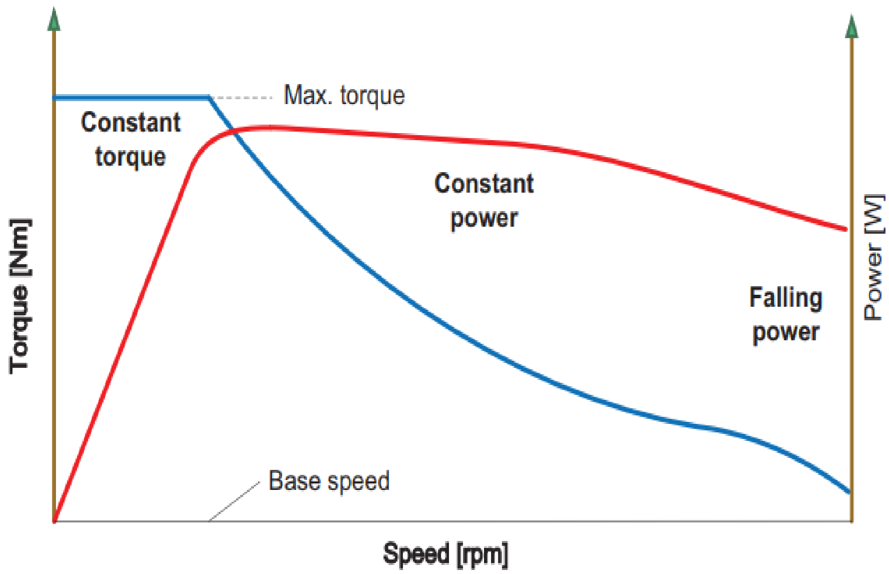


Figure (2) Typical torque-speed and power-speed profiles for an SRM.

The torque-speed profile characteristically involves distinct operating regions[25,26]:

1. The region of the motor's operating speeds at which it can deliver rated average torque, which corresponds to a constant torque throughout this region. As shown in Figure (2.9), reaching the specified torque at a speed equal to the base speed, which acts as a knee on the curve, is achievable.
2. The constant power region of the torque-speed profile is where the maximum mean torque and motor speed provide constant power. The base speed determines the lower boundary of this operational zone. As the speed increases, the torque gradually reduces until it reaches its minimum value. Keeping in mind that power and torque are related through the formula ($P_e = w_m * T_e$).
3. The natural operating region refers to the range in which the maximum available torque has diminished to a level that prevents the sustained maintenance of constant power. The maximum average torque in this mode decreases in opposition to the speed square.

VI. Literature Review

In order to reduce the likelihood of conducting a disorganized literature review, scholarly search tools may prove indispensable. Scopus (Elsevier) and Web of Science (Clarivate Analytics PLC) are good databases for any research topic and literature review. Scopus database uniquely merges a complete, well-curated database of abstracts and citations with enriched data and linked academic works from various subjects. Scopus quickly locates related and confident studies, classifies authorities, and offers admission to dependable data, metrics, and analytic tools. Scopus is a research database that indexes and connects the work of millions of international researchers, institutions, and businesses. Improving Research and Development (R&D) productivity is an industry priority. To increase productivity, R&D teams should have access to the most recent innovations in R&D, which Scopus provides. Daily content numbers are increasing. It is estimated at 27950 journals,292000 books,11.6 million conference papers,94000 affiliation profiles, and 17 million researcher profiles(up to 8/2023) [27].

2. 1 Analyzing Search Results on SRM Using Scopus Database

It is possible to look at different components of our results list by analyzing search results tools to support confident decisions around research strategy. These factors include the number of times an article has been published over a given period, its origin, author, affiliation, country, document type, subject area, and funding sponsor. These tools can be utilized to succinctly encapsulate the primary influence of the authors on a particular subject related to SRM. In this particular instance, Professor Chen Hao has the most number of works that have been published, as in Figure (3).

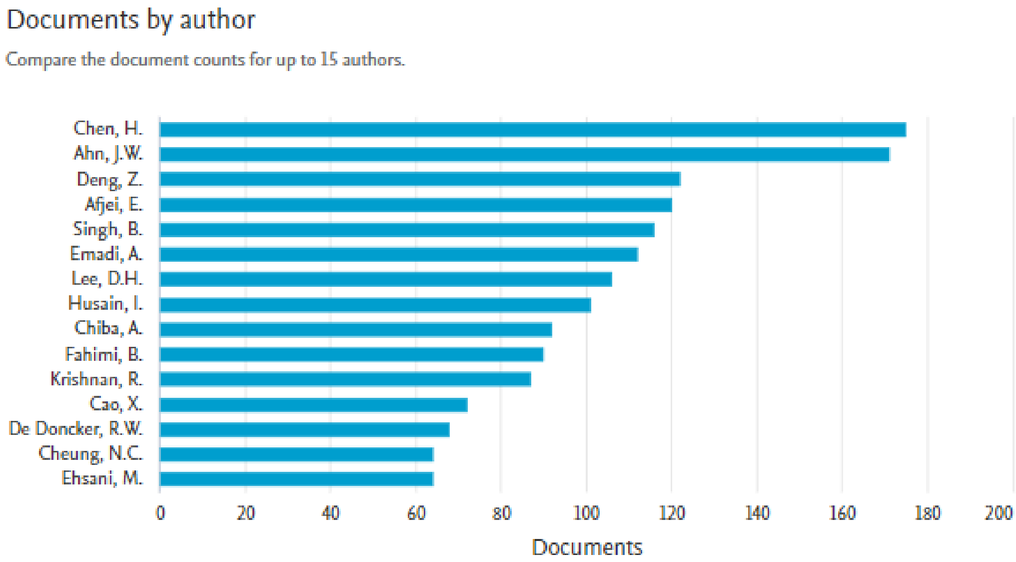


Figure (3) Documents by authors (up to 8/2023).

Figure (4) presents data about the total number of papers added to the Scopus database[10]. Note the interest of researchers in recent years and the number of research papers published in this field.

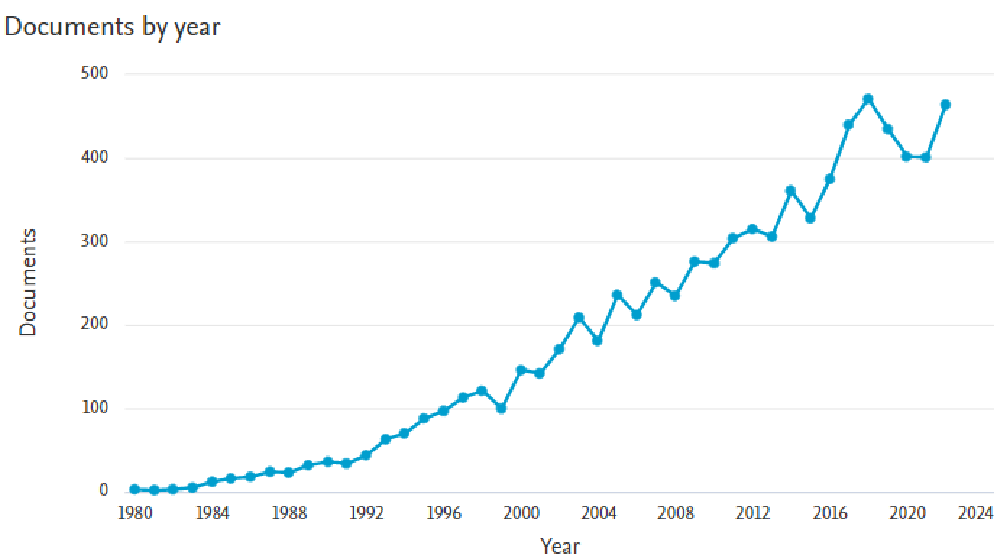


Figure (4) Number of documents by year in the SCOPUS database (up to 8/2023).

Figure (5) illustrates that China, India, and the United States of America have the leading position in publishing in this particular field.

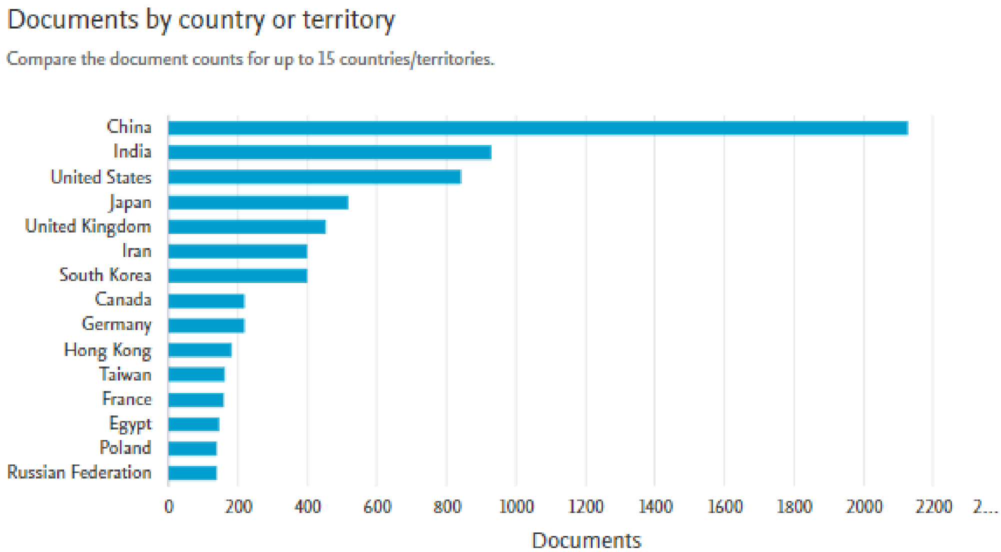


Figure (5) Documents by country or territory up to (8/2023).

Compared to the research carried out and published in other fields, the amount of study carried out and published in Iraq on the subject of our investigation presented in Figure (6) is very limited. Figure (7) represents the published papers by affiliation in Iraq.

1	Article • *Open access* **Speed control of switched reluctance motors based on fuzzy logic controller and MATLAB/Simulink** Show abstract ⌄ Locate full text Related documents	Hameed, H.S., Al Azze, Q., Hasan, M.S.	Indonesian Journal of Electrical Engineering and Computer Science, 31(2), pp. 647–657	2023
2	Article • *Open access* **Comparison of electric motors used in electric vehicle propulsion system** Show abstract ⌄ Locate full text Related documents	Mohammad, K.S., Jaber, A.S.	Indonesian Journal of Electrical Engineering and Computer Science, 27(1), pp. 11–19	2022
3	Article **Switched Reluctance Motor Drives Speed Control Using Optimized PID Controller** Show abstract ⌄ Locate full text Related documents	Ibrahim, M.A., Alsammak, A.N.B.	Przeglad Elektrotechniczny, 98(11), pp. 46–50	2022
4	Conference Paper • *Open access* **Various control strategies on Torque Ripple Minimization for Switched Reluctance Motor** Show abstract ⌄ Locate full text Related documents	Atyia, T.H.	IOP Conference Series: Materials Science and Engineering, 454(1), 012085	2018
5	Article **A Practical Drive System with Accurate Rotor Position Detection for a Switched Reluctance Motor**	Salim, H., Alshammery, A.O.H.	Arabian Journal for Science and Engineering, 38(10), pp. 2765–2772	2013

Figure (6) Document title published in Iraq on SRM (up to 8/2023).

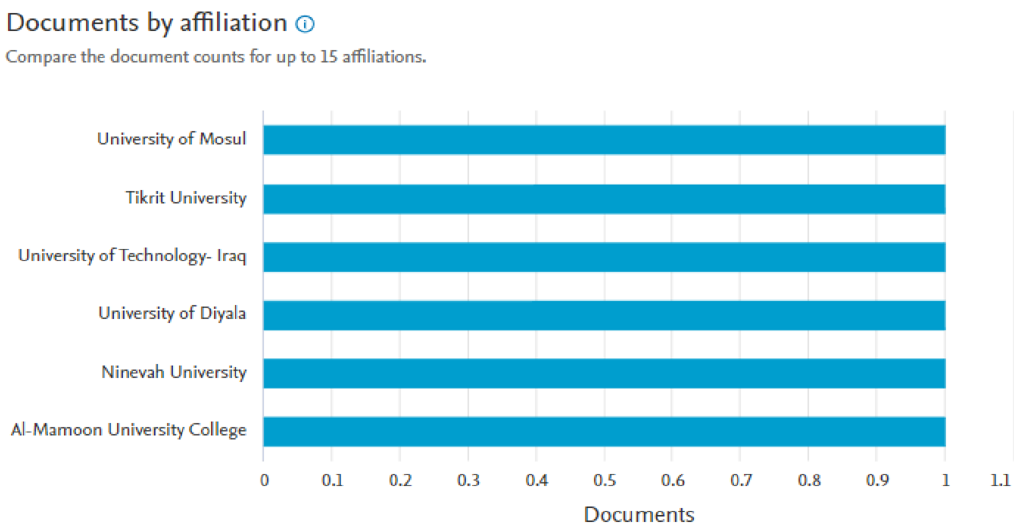


Figure (7) Document by affiliation in Iraq on SRM (up to 8/2023).

2.2 Summary of Existing Research Related to SRMs Drive

This section aims to provide a comprehensive analysis and summary of existing research, theories, and applications related to SRMs. The subsequent publications introduce the work done over the past two decades.

(P. Srinivas and P. V. N. Prasad., 2011)[28] presented a high dynamic control method named direct instantaneous torque control (DITC) for minimizing torque ripple in four Phase 8/6 SRM drive systems. The method keeps torque within a hysteresis control band by varying the switching conditions of the phases, consequential in inherent torque ripple minimization and rapid torque response. It investigates the operation of the drive system essentially in terms of torque ripple during acceleration and steady-state situations with DITC in MATLAB/SIMULINK environment. It concludes that an 8% torque hysteresis control band can be chosen for the proposed drive. At lower hysteresis control bands, switching frequencies are higher, consequential in higher switching losses and diminished efficacy.

(Alireza Siadatan and Ebrahim Afjei.,2012)[29] designed a 6/8 SRM consisting of two layers of the rotor and the stator parts. The rotor shifting method (RST) technology reduces the ripple torque. The three-dimensional (3D) finite element method represents and modifies the motor. The characteristics of the motor, typical analysis of its performance, and torque analysis with and without RST were obtained. Finally, the motor prototype was fabricated, and experimental analysis was conducted to validate the results. This motor can achieve the desired profile as it is promising for servo applications and numerous other industries. However, this research did not address the cost of the motor that the researchers devised as creating a motor consisting of two layers for each rotor, and the stator is more expensive. It requires a more complex control circuit than the control circuits in other ordinary motors.

(C. Lin and B. Fahimi.,2012)[30] examined the optimal current required to achieve maximum torque per amper by employing the field reconstruction method (FRM). The technique under consideration has been implemented at different velocities, and the outcome of the simulation or experiment has been observed. According to the FRM framework, an iterative optimization technique is proposed. This technique determines the optimal commutation angles for reference torque and speed. This method has effectively enhanced the torque per ampere (TPA), as evidenced by both simulation and experimental findings.

(Song, Ai Juan, and Jiang Tao Lv.,2014)[31] proposed a fuzzy logic controller (FLC) for SRM drive with robustness characteristics. The Fuzzy-PID control method exhibits superior adaptability and stability, reduced overshoot, enhanced response speed, and increased precision compared to the conventional PID control approach. The paper also discusses the boundaries of the conventional PID controller and the advantages of utilizing the intended FLC. The simulation outcomes display that the aimed approach is practical and suitable for situations where the system model is reliable.

(Liu, X., and Z. Q. Zhu.,2014)[32] investigated winding configurations, stator-rotor poles, and electromagnetic performance of novel SRMs.Using finite-element analyses, the authors examine the static torque, self- and mutual inductances, back-electromotive force (emf), and torque ripple. They discovered that various stator/rotor pole combinations are feasible for 12-pole stator SRMs. Five prototype SRMs with 12 stator poles and various rotor poles have been designed, fabricated, and verified to validate the investigations. Increasing the number of poles on the rotor increases the average torque and reduces torque ripple.

(Tomczewski, Krzysztof, and Krzysztof Wrobel.,2014)[33] presented a new power converter for SRM drives that reduces switching losses, particularly at low speeds, and eliminates source energy intake during the energy discharge process. It increases the efficiency of the drive across the entire range of rotational speed. It presents a computer-based model of the drive and a comprehensive analysis of the relationship between output power and rotational speed for a sample two-phase motor-based drive. The paper concludes that the proposed C-dump converter with 2q(q number of phase) transistors has higher maximum power than the C-dump converter with a single transistor. It simultaneously eliminates current flow via the voltage source during energy discharges, reducing commutation losses at low speeds for this type of converter.

(Yang, Zhi, et al.,2015)[34] compared three applicant motor topologies for traction applications in electric and hybrid vehicles. The topologies considered interior permanent magnet synchronous motor (IPMSM), induction motor (IM), and SRM. The paper presents a fast FEA modelling approach for IM design and optimal current trajectories for IPMSMs and IM to achieve high motor efficiency. Additionally, optimal commutation angles with current chopping control (CCC) and angular position control (APC) are established for SRM. The simulation and analytical results demonstrate that each motor topology for EVs and hybrid electric vehicles (HEVs) possesses a unique characteristic. The most efficient region of each motor is located at different torque-speed regions based on the criteria specified. Noise, vibration, and harshness (NVH) performance is differentiated based on stator geometry, pole/slot combination, and control strategy.

(Hairik, Haroutuon A and et al .,2015)[35] presented a speed control proposal for an SRM drive established on a PID controller. The researchers have proposed a non-linear mathematical model of four phases 8/6 poles SRM and simulated it through Simulink/MATLAB facilities. The control procedure involves a hysteresis current controller to diminish the torque ripple and a PID speed controller. The consequences present the promising performance of the intended control model and prove the ability to change and reverse the speed. The control design results are then validated in real time by Simulink/MATLAB software package.

(Song, Jiancheng and et al., 2016)[36] proposed the adaptive PI speed controller with the system running an operation to ensure the good dynamic performance of the SRM in the whole speed range. A first-order dynamic model in the (s) domain is obtained from the basic SRM model. The relationship between average voltage, actual speed, and the PI parameters was determined based on the first-order dynamic model. Then, adaptive adjustment of PI parameters is implemented. The dynamic response performances of the proposed adaptive PI speed controller and the traditional PI controller have been compared. The results show that the adaptive PI controller has a better dynamic performance than the traditional PI controller.

(Besharati, M.,2016)[37] investigated the design, analysis, and prototype manufacture of a high-speed, high-power SRM that can operate at 50,000 rpm and meet the output mechanical power of the PM machine utilized in the Toyota Prius. The paper examines the disputes of designing an SRM that can work at high speeds level, focusing mechanical restrictions on the rotor. The suggested rotor topology is investigated for both mechanical and electromagnetic aspects, and a series of criteria is accomplished to assess the operation of the motor and justify the Finite Element Analysis (FEA) consequences. The paper shows that the suggested SRM design is promising for high-speed function. However, further research is necessary to optimize the design and address potential drawbacks such as windage loss and manufacturing costs.

(Ali Basher, Dhiya, and Omar Ghayath Ibrahim., 2017) [38] intended two approaches to obtain the aligned and unaligned inductance values of the SRM. The authors have utilized a simulation model to calculate the inductance values. They have compared the performance of the simulation model with the practical performance and found that the first test is the nearest 93% of the practical value compared with the second test, which reaches a matching ratio of 79%.

(Bostanci, Emine, et al.,2017)[39] provided a complete evaluation of various electric machines, including new SRM topologies. In addition to conventional electric machines like PMSM, induction machine (IM), synchronous reluctance machine (SynRel), and PM-assisted SynRel are also utilized. The analysis is based on torque ripple, efficiency, vibration, power density, and fault tolerance. The research concludes that SRM drives, specifically the double stator SRM, can be a cost-effective and dependable alternative to permanent magnet machines in electric propulsion applications due to their straightforward configuration, fault-tolerant design, and rigid construction.

(Omer Ghayath Ibrahim., 2017) [40] discussed SRM performance in variable speed drives. Through modelling and simulation in the MATLAB program, the authors of this paper present the results of an investigation into the drive's performance for the SRM by utilizing various types of converters and various techniques for triggering. In addition, a practical drive for one of the converters and one of the triggering techniques are included so that the modelling and simulation performed in MATLAB can be compared with the practical results. The overall effectiveness of the system is the primary focus of this study, especially the torque ripple. In addition, the paper investigates the effect of changing certain aspects of the motor on its performance in general and the percentage of ripple in particular.

(Nimisha, K. K., and R. Senthilkumar.,2018)[41] discussed the design of controllers for SRM using the particle swarm optimization (PSO) technique. The paper focuses on achieving the minimum integral squared error and identifies the controller parameters kp, ki, and kd through the PSO algorithm. The developed controller is robust and is implemented using MATLAB/SIMULINK software.

(Dos Santos Barros and et al.,2018)[42] introduces an automatic system that offers high-resolution capabilities for conducting magnetic characterization tests. The system is designed to acquire the necessary data to develop accurate SRM models. Utilizing the smoothing splines technique in data processing resulted in acquiring a precise model that aligns with the genuine functioning of the SRM. The study involved conducting simulations to analyze the effectiveness of voltage control and implementing the proposed control strategy in an experimental setting. The obtained model demonstrated high accuracy and fidelity, as evidenced by similar results.

(Zhang, Chao, et al.,2018)[43] presented an advanced robust controller for the speed regulation system of an SRM in the existence of nonlinearities and external turbulences. The proposed controller uses adaptive fuzzy control to control the inner loop motor shaft speed and a detector to acquire rotor detection in the inner loop. The fuzzy parameters are corrected online, concurring with the transient period error and speed change. The designed detector can precisely attain the rotor position in each phase segment. The paper also includes contrastive simulations between the proposed controller and PID controller and an actual SRM control system experiment at 220 V 370 W. The research consequences demonstrate that the intended robust controller has strong robustness.

(Atiya, Thamir Hassan. ,2018)[44] presented a study on various control strategies for minimizing torque ripple in a 6/4 SRM using MATLAB-Simulink software. The study reviewed and compared the simulation results of four control methods: current control, torque control, torque and flux control, and torque and speed control. The simulation results confirmed that torque ripple minimization was achieved. The paper contributes to the field of SRM control by providing a comparative analysis of different control strategies for torque ripple minimization.

(Divandari, Mohammad and et al.,2019)[45] proposed a novel fast terminal sliding mode control (FTSMC) method-based speed controller scheme for SRM drive. In both the time and frequency domains, the proposed method is contrasted with the proportional-integral and traditional sliding mode control (SMC) methods. MATLAB TM/SIMULINK generates the simulation results under various speed and load-torque conditions. Furthermore, a digital signal processor-based controller produces valuable results for a three-phase 12/8-pole SRM. The findings show that the intended controller responds more quickly than the conventional SMC, significantly reducing chattering effects even under abnormal circumstances.

(Gundogmus, Omer, et al,.2020)[46] proposed a method to reduce the acoustic noise of SRMs by placing rectangular windows in the rotor and stator poles. The location and sizes of the gaps are adjusted via electromagnetic FEA, and Multiphysics FEA is achieved to calculate the vibration and acoustic noise of the improved design. The study confirms that placing windows in both the stator and the rotor of the SRMs can notably decrease the acoustic noise compared to typical SRMs. The paper also mentions using a performance index to assess the effectiveness of each design. It evaluates the noise reduction method by measuring the peak radial force and peak-to-peak variation of the total sum of the radial forces.

(Jing, Jianli., 2020)[47] A buck converter-fed SRM drive was proposed to suppress torque ripples and correct the power factor. The proposed method controls the DC-link voltage to reduce the torque ripple in a wide speed range and significantly improves the power quality at AC mains. The experimental results show that the proposed drive possesses an improved function with suppression of torque ripples and power factor correction.

(Souza, Darielson A., et al.,2021)[48] analyzed metaheuristic algorithms to design the linear quadratic regulator with integral action (LQI) controller and made a thorough comparison between these algorithms and the proportional-integral-derivative (PID) controller in order to select the optimal technique for the LQI controller design and adjustment of the Q and R parameters in SRM control system. In addition, a method for selecting Q and R parameters based on the genetic algorithm (GA) algorithm was presented. The effectiveness of the controller was validated through the collection of experimental results. The LQI + GA control presented advantages in terms of computational cost and response time compared to the standard LQI control and PID controllers. Finally, the LQI+GA method quickly yields the optimal solution.

The main contribution of this paper is the detailed study and comparison of the performance of major types of electric motors used in electric vehicles (EVs) applications. (Mohammad, Khalid S., and Aqeel S. Jaber.,2022)[49] reviewed and compared the major electric motors used in EVs based on the EV propulsion system requirements. The advantages and disadvantages of these motors (DC motors, Induction motors, SRM motors, and PMBL motors) are analyzed and evaluated. The paper aims to select the most suitable electric motor for EVs based on its efficiency, dynamic response, starting torque, and reasonable price. The paper also overviews several artificial intelligence (AI) techniques used in EV applications.

(Boumaalif, Youness, and Hamid Ouadi ., 2023)[50]presented a non-linear control design for SRM vehicle applications using the backstepping approach. The proposed controller is developed based on a model that accounts for magnetic saturation, thereby mitigating torque ripple and minimizing vibrational effects. In order to enhance the optimization of torque ripple, the control angles are modified by the machine's speed and torque measurements. A look-up table has been constructed to provide efficient control angles for different operating points of the motor. The proposed control methodology was verified via simulation, utilizing a precise MATLAB SRM model that accounts for magnetic saturation phenomena. The comparative analysis demonstrated the proposed regulator superior performance to a proportional-integral (PI) controller. The obtained results suggest the efficacy of the proposed regulator.

(Sheng, Linhao and et al.,2023)[51] suggested a novel control strategy that integrates fast terminal sliding mode control (FTSMC) and radial basis function (RBF) neural network to enhance the speed-tracking efficacy of the SRM. The outcomes of the simulation and experimental analyses conducted on the SRM drive system indicate that the suggested control approach exhibits exceptional performance concerning tracking precision, response velocity, and robustness.

(Kumar, Prince and et al.,2023)[52] presented a simple 8/6 SRM drive for a ceiling fan. The paper examines the asymmetric half-bridge (AHB) converter selected due to its separate phase control and straightforward scheme. The intended four-phase asymmetric bridge converter-based SRM drive has no speed and current feedback loops, excluding current sensors and complicated computational logic. Hall-effect sensors in the intended drive carry out position sensing. Simulation investigations and the outcomes are represented. A prototype of the SRM and drive are constructed. Experimental results illustrate that the intended SRM drive has acoustic noise and low current ripple, essential in ceiling fan appliances.

(Hussein Ali Bardana, Amer MejbelAli.,2023)[53] discussed the thermal analysis of SRM using a combination of RMXprt/Motor-CAD software. The attained consequences demonstrated the rise of SRM portions temperature with rising the SRM loading. Also, these consequences demonstrated the significance of choosing a suitable cooling technique (using housing fins and a cooling fan) to minimize the motor temperature, which will steer the motor designer to enhance the SRM thermal design without requiring to make and examine expensive prototype motors.

The previous literature review examines the variety of research conducted in the field of SRM drives. Despite the manifold benefits attributed to SRM, it is imperative to acknowledge the presence of several significant challenges that necessitate examination and investigation. The concise summary of contemporary advancements in SRM modelling, design, and control effectively highlights the significance of this motor in present-day technology. The motor under consideration exhibits highly non-linear magnetic characteristics. It poses significant challenges in developing an accurate SRM model and achieving superior dynamic performance, especially concerning torque ripple reduction and speed regulation systems.

Designing a motor is vital and essential when establishing a manufacturing facility within the motor industry[29,32,37,39,46,53]. A prime goal of the motor design is to achieve a speed torque performance for an application with compact size and higher efficiency. Most researchers working on the design goal belong to the R&D department of an industry rather than the academic research scholar. The summary of SRM drive challenges in the design field for selected published articles is presented in Table (1).

Table 1. The summary of SRM drive challenges in the design field

Method	Adopted technique	Advantage	Limitations	Reference
Stator/rotor poles configuration	Two layers of the rotor and the stator parts.	One practical approach to mitigating torque ripple in multilayer SRM	-The stator is more expensive. -It requires a more complex control	[29]
Design the rotor with more pole numbers.	The traditional methods for identifying stator/rotor pole combinations, the associated winding configurations, and winding factors.	It identifies achievable stator/rotor pole patterns for 12-stator-pole SRMs, including 12/8, 12/10, 12/11, 12/13, and 12/14.	Increased rotor materials	[32]
The rotor mechanical design methodology	To address the high hoop stress, the mechanical design methodology of high-speed, high-power SRMs implements a flywheel topology for	Very high-speed application	The windage loss investigation of high-speed	[37]

	the rotor.			
Stator/rotor pole shape	Reduce the acoustic noise of SRMs by inserting quadrilateral holes in the rotor and stator poles.	Lower electromagnetic torque ripple, enhanced torque–speed capability	Complicated optimization	[46]
cooling method to minimize the motor temperature	Thermal analysis of SRM using a combination of RMXprt/Motor-CAD software	Suitable guide the motor designer Simple procedure	Electrical model description	[53]

Research trends in the mathematical modelling of the motor are presented in [38,42]. However, numerous researchers are currently engaged in the development of an enhanced mathematical model for the SRM. The study of mathematical modelling to SRMs holds significant importance for researchers, regardless of their specific area of focus. This is primarily because it offers valuable insights into the constraints associated with the SRM model, which is utilized to validate and evaluate control strategies. The summary of SRM drive challenges in the mathematical model field for selected published articles is presented in Table (2).

Table 2. The summary of SRM drive challenges in the modelling field

Method	Adopted technique	Advantage	Limitations	Reference
Inductance profile measurement	AC test and DC test approach for inductance profile measurement	Straightforward method and accurate for analytical model implementation	Need transient analysis investigation	[38]
SRM magnetization curve modelling	Mathematical interpolation techniques for accomplishment of magnetic characterization assessments and acquiring the data required to achieve consistent models for SRM	Accurate and reliable consequences for the SRM operation	A control algorithm test is necessary	[42]

Previously, literature has focused on utilizing a suitable converter for the SRM drive system[33,40,47]. Consequently, many researchers choose a power electronics converter topology appropriate for their specific application and concentrate on controller design rather than converter topology. As a result, the opportunities for research in converter topology for the SRM are minimal. The summary of SRM drive challenges for the converter topology field in the selected published articles is presented in Table (3).

Table 3. The summary of SRM drive challenges in suitable converter topology field

Method	Adopted technique	Advantage	Limitations	Reference
Power electronics converter topology	Proposes a converter with a C-dump capacitor, including 2N transistors allow for achieving higher maximum power than the C-dump converter with a standard transistor,	It allows the reduction of the switching and reduces energy consumption from the source during the energy discharge process.	Does not provide a comprehensive analysis of the converter's performance across different motor types or configurations	[33]
Power electronics converter topology	Study the performance of the SRM drive using various kinds of converters.	A simple way for performance evaluation	-Transient analysis investigation -Limited range of performance evaluation	[40]
Power electronics	A buck converter-powered SRM	Improvement of power	Does not provide a	[47]

converter topology	drive is introduced to mitigate electromagnetic torque ripple and improve power factor.	quality at AC mains accurate speed control	comprehensive analysis of SRM modelling	

Research scope in controller design is challenging for the SRM drive system [28,30,31,35,36,41,42,43,44,45,48,50,51,52]. Hence, a significant opportunity exists for research and development in the domain of controller design for the SRM drive system. Achieving high levels of reliability and accuracy across all operating points requires employing a motor representation model that closely approximates the actual system. It minimizes assumptions through intelligent control techniques when dealing with SRMs. In comparison, machine optimization may mitigate torque ripple in SRMs. Modifying geometric dimensions post-manufacture can be complex and challenging. An alternative approach to further reduce electromagnetic torque ripple in an existing machine is implementing an advanced electromagnetic torque ripple reduction and speed control system technique within the control system approach. The summary of SRM drive challenges in the control strategy field for selected published articles is presented in Table (4).

Table 4. The summary of SRM drives challenges in the control strategy field

Method	Adopted technique	Advantage	Limitations	Reference
Direct instantaneous torque control (DITC)	Regulate torque by hysteresis controller	Minimizing electromagnetics torque ripple	-Need current –torque –position characteristics -limitations of the look-up tables obtained through FEA	[28]
Commutation angles optimization	Utilizes the field reconstruction method (FRM) for optimization purposes in the control of SRM	A rapid and accurate numerical tool for optimization.	Complexity and large memory requirement	[30]
SRM drive system speed control	Develop a fuzzy logic controller (FLC) for the SRM dive speed controller.	The Fuzzy-PID control method exhibits superior adaptability, enhanced response speed, and increased precision.	Linear SRM model limitation Complex computational algorithm	[31]
SRM drive system speed control	Speed control design for an SRM drive system established on a PID controller	The proposed control proves the ability to change and reverse the speed of the SRM drive system	Limitations regarding the selection of parameters for the PID controllers	[35]
SRM drive system speed control	Speed control design for an SRM drive based on an adaptive PI controller	Rapid response High robustness.	Linear SRM model limitation	[36]
SRM magnetization curve modelling	Mathematical interpolation techniques of achieving magnetic characterization(Torque and current) analyses and acquiring the data necessary to accomplish consistent	More precise and reliable outcomes in the context of the SRM operation	A control algorithm test is necessary	[42]

	models for SRM			
SRM drive system speed control	Adaptive fuzzy control regulates the motor speed within the outer loop. Additionally, the detector is utilized to acquire rotor detection within the inner loop.	Accuracy and robustness	Complex computational algorithm	[43]
Control strategies on torque ripple minimization for SRM drive system	Torque and speed control analysis	Improved torque quality	Does not provide a comprehensive analysis of SRM modelling	[44]
SRM drive system speed control	Novel fast terminal sliding mode control (FTSMC) method-based speed controller scheme for SRM drive	Strong robustness Anti-interference ability	Complicated controller design, existential chatting	[45]
SRM drive system speed control	Metaheuristic algorithms to design the linear quadratic regulator with integral action (LQI) controller	Computational cost faster response	Linear SRM model limitation	[48]
Control strategies on torque ripple minimization for SRM drive system	Backstepping SRM controller while considering magnetic saturation effects and guarantee a torque ripple minimization	Reduced electromagnetic torque ripple, less vibrations faster response	Commutation angle calculation details	[50]
SRM drive system speed control	Novel control strategy that integrates fast terminal sliding mode control (FTSMC) and radial basis function (RBF) neural network	Strong robustness Anti-interference ability	Complicated controller design	[51]
SRM drive system speed control	The proposed drive system utilizes a four-phase asymmetric bridge converter with an SRM. The suggested SRM drive has four phases, excluding speed and current control loops.	Low current ripple , low acoustic noise	Commutation angle calculation details	[52]

Although there are numerous advantages associated with the SRM drive system, it is crucial to recognize several significant challenges that require investigation. The SRM drive system with nonlinearity makes it hard to achieve satisfying performances with conventional controllers as its parameters are nonadjustable. The torque quality and controller complexity issues are regarded as the most significant barrier to the widespread adoption of SRM for EV applications; however, its resolution must be more straightforward. To generate different perspectives, it is essential to employ different research methods to influence study findings for high-performance SRM drives. Speed control, energy efficiency, and torque quality are necessary as multi-objective optimization for a wide range of operating points with all nonlinearity in the SRM model.

VII. CONCLUSION

The utilization of switched reluctance motor drives is gaining traction in the growing electric propulsion industry. While the current market for electric propulsion is primarily dominated by IPMSMs, the need for a reliable alternative arises due to the volatility of rare earth metal prices and supply chain challenges. The SRM exhibits clear advantages in terms of material cost. Due to its inherent limitations in high noise levels, significant torque ripple and low torque density, the SRM is infrequently utilized in Electric EVs. Significant advancements have been made in enhancing the torque quality of SRMs, resulting in comparable torque performance to that of permanent magnet synchronous motors (PMSMs).Additionally, advancements have been made in noise and torque ripple reduction techniques, encompassing topology design and control approaches. The implementation of these methods does not have an impact on the material cost of the motor while simultaneously decreasing the overall cost. The study investigates the research and development expenditures incurred on SRM drive system challenges. Hence, it is anticipated that the SRM will serve as the resolution for electric vehicles (EVs).

ACKNOWLEDGMENT

The authors are grateful to (University of Mosul / College of Engineering) for their provided facilities, which helped to enhance the quality of this work.

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