IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

A Comprehensive Review Of Research And Development On Switched Reluctance Motors For Electric Vehicle Applications

[1]Khushal Borad, [2]Jaydipsinh Zala
[1]Reserch Scholar, [2]Assistant Professor
[1,2] Electrical Engineering Department,
[1,2] Dr. Subhash University, Junagadh, India

Abstract: In recent years, switched reluctance machines (SRMs) have attracted significant attention from the research community owing to their distinctive advantages. The efficiency of SRMs is comparable to that of induction motors with equivalent ratings, as both exhibit similar friction and windage losses. Extensive studies have been conducted on SRMs, their associated systems, and the challenges they present. This paper provides a comprehensive review of SRM structures, highlighting their advantages and limitations. Various SRM topologies are examined, with a discussion of their respective merits and constraints. Furthermore, the paper categorizes the most widely adopted control strategies for SRM drives and summarizes the state-of-the-art research addressing key challenges, particularly in torque ripple minimization and vibration reduction.

Index Terms – SRM Motor, Electric Vehicles (EVs), Advanced Motor Control, Torque Ripple Reduction

I. Introduction

The rising shortage of energy resources and increasing environmental concerns are largely linked to the extensive use of automotive vehicles powered by internal combustion engines (ICEs). Electric vehicles (EVs) have emerged as a promising alternative, offering localized energy utilization, improved efficiency, and zero-emission operation [1]. A key element in EV performance is the electric motor, making its selection crucial for overall system effectiveness.

Over the past decades, various electric motor technologies have been examined for EV applications. Among them, switched reluctance motors (SRMs) stand out due to their simple construction, high efficiency, flexible control, low manufacturing cost, and robustness under fault conditions. The absence of rotor windings and permanent magnets further enhances their suitability for high-speed drive applications [2], [3]. Nonetheless, compared to conventional DC and AC motor drives, switched reluctance motor drives (SRDs) require more sophisticated control strategies. Their primary drawbacks include torque ripple, acoustic noise, and vibration [1].Significant research efforts have focused on optimizing SRM design to maximize torque output and minimize torque ripple. These investigations highlight the influence of key geometrical parameters on overall performance.

The remainder of this paper is organized as follows. Section II outlines the operating principles of SRMs, including SRD systems, with their respective advantages and limitations. Section III reviews conventional and advanced SRM structures. Section IV discusses the most common control strategies. Section V addresses current challenges and research directions for overcoming SRM limitations. Finally, Section VI presents the conclusions.

- **Advantages and limitations**

Switched reluctance machines (SRMs) are typically designed with stator windings and a rotor that is free from windings and permanent magnets. This configuration enables SRMs to withstand higher operating temperatures while offering reduced manufacturing costs, compact dimensions, and a mechanically robust structure [3]. An additional advantage is their inherent fault tolerance: in the event of a phase or winding fault, the machine is capable of continued operation at a reduced load. Such resilience is particularly valuable in applications such as pumps and fans [3], and it is also of great relevance to the electric vehicle (EV) industry.

However, SRMs are characterized by nonlinear magnetic behavior due to saturation effects, which makes precise torque control challenging. Although permanent magnet (PM) machines have been widely employed in small- and medium-sized EVs, their adoption in heavy-duty applications is constrained by the increasing cost and limited availability of permanent magnets. Consequently, SRMs, alongside induction machines, are emerging as promising alternatives for EV applications due to their ruggedness, cost-effectiveness, and capability to operate reliably in high-temperature environments.

The main advantages and disadvantages of SRM technology are summarized in below.

• **Strengths**	• **Limitations**
• Economical to manufacture	• Produces significant torque ripple
• Durable and reliable (simple structure, robust materials)	• Generates considerable acoustic noise (sometimes useful for EV safety)
• Compact and mechanically simple	• Susceptible to electromagnetic interference (EMI)
• Improved cooling (no rotor windings, concentrated stator windings)	• Causes high DC bus current ripple
• No permanent magnets (rare-earth free, thermally resilient)	• Converter design must be optimized for each motor
• Fault-tolerant (phase independence allows operation under fault)	• Requires more conductor connections than IM, PMSM, or SynRel
• Supports high-speed operation with low inertia	• Electromagnetic behavior is highly nonlinear
• Simple converter (unidirectional current, one switch per phase, no shoot-through risk)	• Nonlinear magnetic saturation complicates modeling (needs FEM or experimental data)
	• External control schemes more complex than induction and DC machines

II. Switched Reluctance Drive (SRD) Systems

Switched reluctance drive (SRD) systems have recently been developed as advanced mechatronic systems, comprising four main components: the switched reluctance motor (SRM), power converter, controller, and position detector [7]. In SRMs, the generated torque is independent of the polarity of the excitation current; therefore, only a single switch per phase winding is required in SRD systems. Each phase winding is connected in series with its respective switch. In the event of a shoot-through fault, the winding inductance limits the current rise rate, thereby providing a short time window to trigger protective relays and isolate the fault. A key advantage of SRMs over other motor technologies is that their phases are electrically independent. Consequently, if a fault occurs in one phase, the motor and drive can continue operating at reduced power.

A comprehensive review of power converter topologies for SRDs is presented [8]. Among these, the asymmetric bridge converter is the most widely adopted, as illustrated in Fig. 1. This topology employs two transistors and two diodes per phase [8]. Compared to conventional AC and DC motor drives, SRDs require more advanced control techniques. Nonetheless, several inherent drawbacks remain, including vibration, acoustic noise, and the reliance on position sensors, which increase system complexity and reduce overall reliability. The complexity of SRDs is further compounded by their nonlinear operating characteristics, arising from the following factors [8]:

1. Nonlinear B–H characteristics of the magnetic material.
2. Dependence of phase flux linkages on both current magnitude and rotor position, unlike other machines where trigonometric transformations eliminate rotor position dependency.
3. The reliance on a single excitation source.

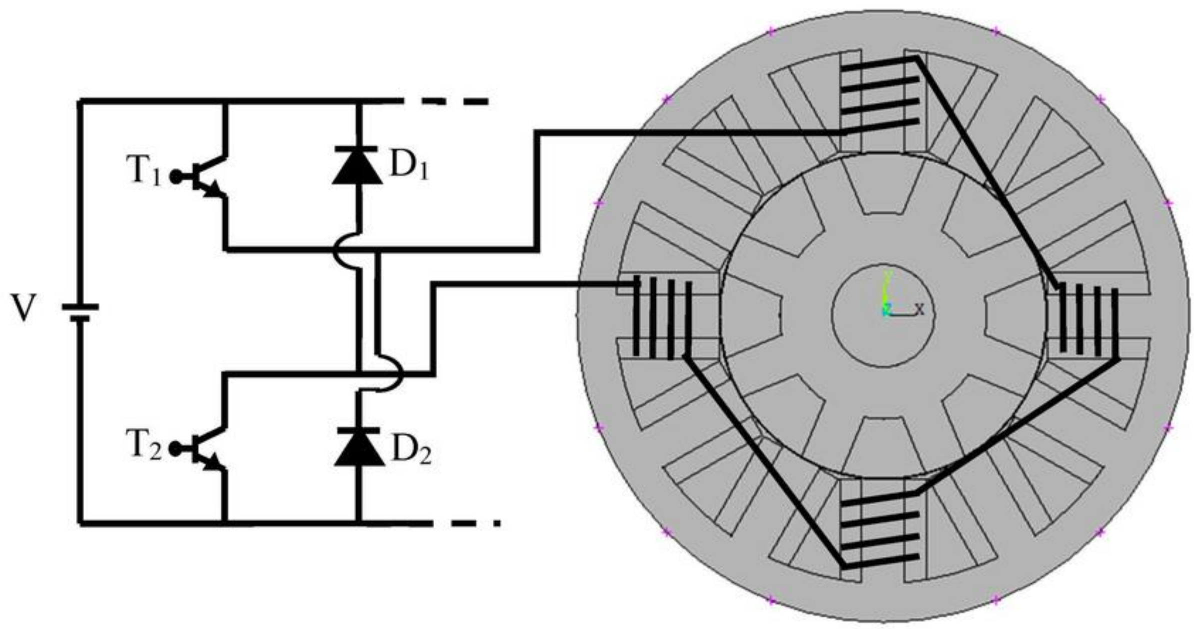

Figure 1.Asymmetric bridge converter for SRD.

III. SRM STRUCTURES

1. Conventional SRM structures

Switched reluctance machines (SRMs) with a greater number of stator poles than rotor poles represent the most commonly adopted structures (Fig. 2) [8], [9]. In [9], three SRM topologies with varying phase numbers and different stator–rotor pole combinations were designed and compared for electric vehicle (EV) applications: 6/4 (three-phase), 8/6 (four-phase), and 10/8 (five-phase). The results demonstrated that the 10/8 and 8/6 configurations are the most suitable for EV propulsion. However, the 10/8 SRM requires a more expensive converter, while the 8/6 SRM exhibits higher torque ripple. Therefore, the optimal topology depends strongly on the specific application requirements.

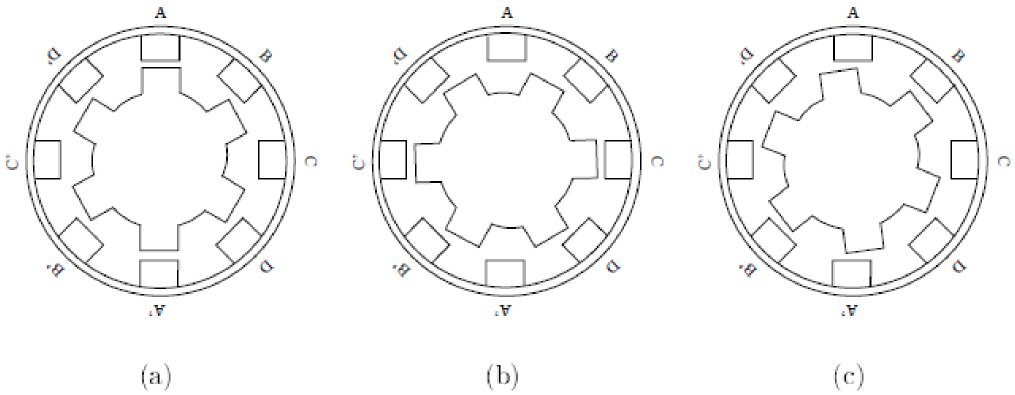

Figure 2.Most common SRM topologies.

The issue of high torque ripple can be mitigated by employing appropriate control strategies. The study further highlighted that, in the absence of optimized control techniques, the 6/4 SRM topology is not efficient for EV and automotive applications [9].

2. Advanced SRM structures

In [10], a multilayer SRM (MSRM) was introduced, consisting of two conventional single-layer machines mounted on a common shaft. By displacing the rotor poles of each layer, torque ripple was effectively reduced. This configuration achieved three primary objectives: (i) increased space for coil windings, (ii) faster turn-on capability through the use of a centrifugal switch, and (iii) improved starting torque [11]. Subsequently, an alternative MSRM design was developed to further suppress torque ripple and acoustic noise while maintaining high starting torque [12]. This prototype (Fig. 3) was experimentally validated, though the improvements came at the expense of increased structural complexity.

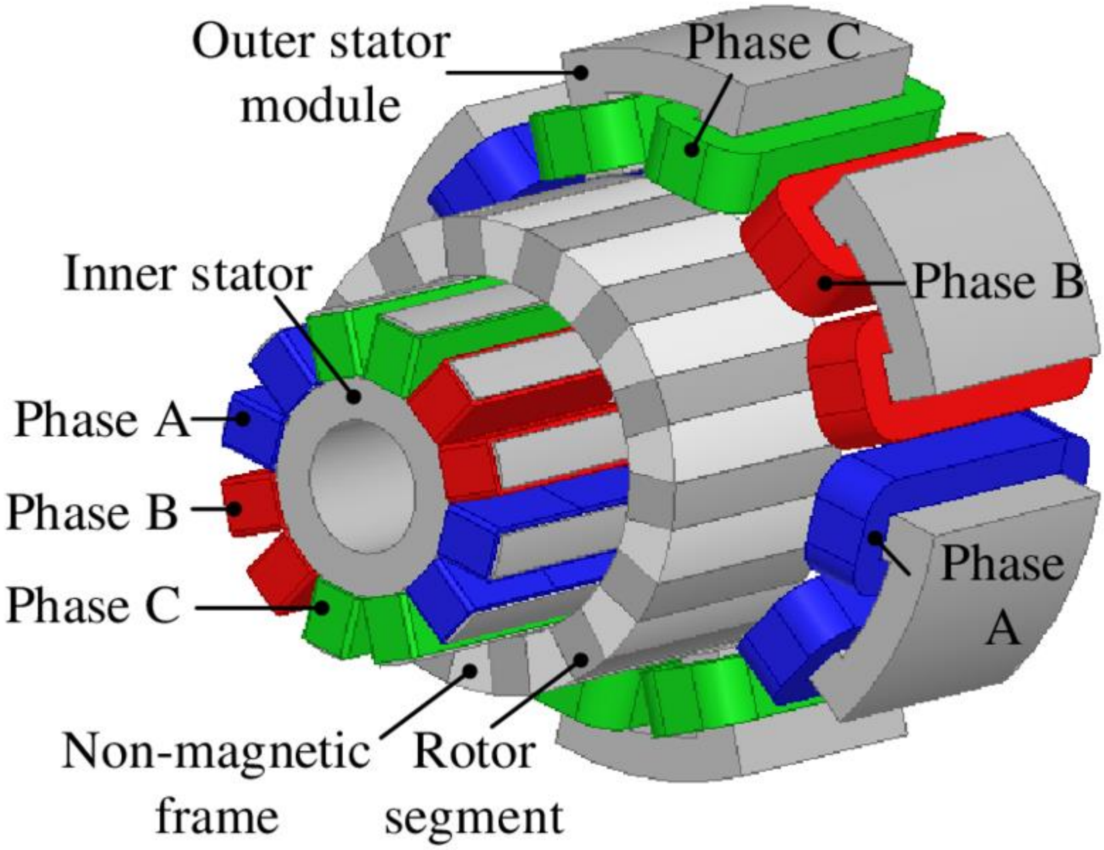

Figure 3.Illustration of the MSRM

Another category of SRMs utilizes configurations with fewer stator poles than rotor poles. enhanced torque density, reduced torque ripple, and lower production costs compared to conventional 6/4 SRMs of equivalent size and phase count [13]. Similarly, a two-phase SRM topology with phase groups denoted as Aj and Bj (j = 0, 1, 2) was presented in [14]. This design offered several advantages, including: (i) absence of flux reversals in the stator, leading to lower core losses and reduced acoustic noise, (ii) three-quadrant operation capability for improved efficiency, and (iii) a specially shaped rotor pole structure that generates overlapping torque, thereby enhancing self-starting performance.

Distinctive stator geometries have also been explored. For instance, an E-core SRM with two phases was proposed in [15]. The reported benefits include: up to 22% reduction in stator core material, near flux-reversal-free stator operation, lower copper losses due to reduced conductor volume, balanced radial forces, and overall improvements in efficiency and power density [15]. Later, three additional E-core topologies were introduced in [17], focusing on reducing cost, enhancing performance, and simplifying manufacturability. Likewise, a C-core SRM design was analyzed in [16], demonstrating further improvements in performance characteristics.

In [18], a double-stator SRM was proposed for electric vehicle applications, consisting of inner and outer stators with a single rotor sandwiched between them (Fig. 3). This design was shown to deliver higher torque-to-mass ratio compared with conventional machines.

In summary, these advanced SRM structures have demonstrated promising improvements in torque density, noise reduction, and efficiency. However, their adoption is often constrained by added manufacturing complexity and higher associated costs.

IV. SRM CONTROL STRATEGIES

Switched Reluctance Machines (SRMs) are increasingly considered for traction and industrial applications due to their simple structure, fault tolerance, and low cost. However, their widespread adoption is still hindered by drawbacks such as torque ripple, acoustic noise, and nonlinear magnetic characteristics. These challenges directly affect drive performance, making the control strategy a critical factor in SRM systems. Unlike conventional AC or DC motors, where torque control is relatively straightforward, SRMs require more sophisticated methods due to their double-salient structure and the nonlinear dependence of flux linkage on both current and rotor position.

Control strategies for SRM drives (SRDs) are generally designed to:

- Improve efficiency.
- Reduce torque ripple and vibration.
- Ensure smooth torque production across a wide speed range.
- Maintain robustness under varying load and fault conditions.

Broadly, SRM control strategies can be grouped into indirect torque control, direct torque control, and intelligent or hybrid control methods. In addition, position, speed, and current control play important roles in ensuring accurate operation under different application requirements.

1. Indirect Torque Control Strategies

Indirect methods control the phase currents in a way that indirectly shapes the torque profile. These approaches are simpler to implement and computationally less intensive compared to direct methods [1].

1.1 Current Profiling

Current profiling regulates the current waveform in each phase to achieve smoother torque output. By adjusting current rise and fall intervals, torque ripple can be minimized [2]. However, it requires accurate knowledge of machine characteristics and is sensitive to parameter variations [3].

1.2 Torque Sharing Control (TSC)

TSC is one of the most widely adopted indirect methods. Here, the total torque demand is divided among adjacent phases during commutation [4]. This reduces torque ripple and ensures smoother transitions, which is particularly important in traction applications. Nevertheless, improper distribution of torque may still result in localized ripple or efficiency loss [5].

1.3 Average Torque Control

This method focuses on maintaining the average torque within each commutation interval. While simpler than TSC, it may not fully suppress instantaneous torque variations. It is typically suitable for low-speed or constant-load applications [2].

1.4 Vector Control

Vector control, adapted from AC drives, uses reference frames to regulate current components. For SRMs, its application is more complex due to strong nonlinearity, but it enables improved dynamic response and efficiency in certain operating conditions [6], [5].

2. Direct Torque Control Strategies

Direct torque control (DTC) methods act directly on the instantaneous torque rather than indirectly through current shaping. These strategies provide faster dynamic response but are computationally more demanding [1].

2.1 Direct Instantaneous Torque Control (DITC)

DITC directly estimates and regulates instantaneous torque using feedback. It ensures rapid torque response but requires accurate machine models. Performance is often affected by parameter variations and magnetic saturation [7].

2.2 Advanced DITC

To overcome the limitations of basic DITC, advanced variants incorporate improved torque estimation, adaptive hysteresis controllers, or predictive models [8]. These reduce ripple while maintaining high responsiveness, though at the expense of increased controller complexity.

2.3 Model Predictive Torque Control (MPTC)

MPTC uses predictive algorithms to calculate future torque values and select optimal voltage vectors for the converter. It offers excellent performance in ripple reduction and transient response [9]. However, its real-time implementation requires powerful processors and accurate machine models, making it more suitable for high-performance applications [10].

3. Intelligent and Hybrid Control Strategies

With advancements in computing, intelligent control techniques have been extensively explored to address the nonlinear and uncertain behavior of SRMs.

- **Fuzzy Logic Control (FLC):** Handles uncertainties without requiring detailed mathematical models. Effective for ripple reduction but performance depends on rule design [11].
- **Artificial Neural Networks (ANNs):** Learn machine dynamics through training, offering adaptive and nonlinear mapping. Require large datasets for reliable operation [12].
- **Neuro-Fuzzy Inference Systems (NFIS):** Combine the strengths of fuzzy logic and ANN, providing adaptive and robust control under diverse operating conditions [13].
- **Iterative Learning Control (ILC):** Suitable for repetitive operations, improving accuracy over successive cycles [14].
- **Machine Learning-Based Approaches:** Recently proposed methods exploit data-driven models to optimize torque control in real time, showing promise for next-generation SRDs [15].

Hybrid methods, combining model-based and intelligent approaches, are also being developed to balance accuracy, adaptability, and computational efficiency [4].

4. Position, Speed, and Current Control

In addition to torque regulation, SRMs require effective control of rotor position, speed, and phase currents.

- **Position Control:** Essential for precise motion applications such as robotics and actuators. Typically relies on position sensors or sensorless estimation based on flux linkage [2].
- **Speed Control:** Ensures stable operation across wide speed ranges. Often implemented using PI/PID controllers in conjunction with torque-sharing or predictive strategies [1].
- **Current Control:** Distinct from torque control in SRMs (unlike in DC motors). Includes methods such as current chopping, hysteresis control, and model-based predictive current regulation [5].

These control levels work in coordination, ensuring reliable SRM operation under varying operating conditions.

5. Summary and Comparative Analysis

Strategy	Advantages	Limitations	Applications
Current Profiling	Simple to implement, effective at low speed	Sensitive to machine parameters	Low-speed drives
Torque Sharing Control	Reduced ripple, smoother commutation	Complex distribution tuning	Traction, EVs
Average Torque Control	Maintains mean torque	Ripple not fully eliminated	Constant-load drives
Vector Control	Improved dynamic response	Complicated by nonlinearity	High-performance drives
DITC	Fast torque response	Sensitive to modeling errors	Dynamic load drives
Advanced DITC	Reduced ripple, high accuracy	Computationally intensive	Research prototypes
MPTC	Excellent ripple reduction	Requires powerful processors	High-performance EVs
Fuzzy Logic	Model-free, robust to uncertainties	Rule design is critical	General-purpose control
ANN	Adaptive, learns nonlinearities	Requires training data	Adaptive systems
NFIS	Combines fuzzy + ANN	Higher complexity	Fault-tolerant drives

Conclusion

The rapid expansion of electric vehicle (EV) propulsion systems is driven by the growing demand for efficient and sustainable transportation technologies. Among the various motor options, switched reluctance machines (SRMs) have attracted considerable attention due to their simple structure, robustness, high reliability, and independence from rare-earth materials. Despite these advantages, SRMs face several challenges that limit their widespread adoption. The most prominent issue is torque ripple, which is inherent to their design and often results in acoustic noise and mechanical vibration. These effects negatively impact drive quality in EV applications and hinder further industrial deployment. Consequently, achieving low torque ripple and high efficiency is essential to meet the stringent requirements of EV propulsion systems.

To address these concerns, advancements in modeling and simulation tools are necessary for accurately predicting machine behavior and optimizing key design parameters. In parallel, the development of advanced control strategies plays a crucial role in mitigating torque ripple while enhancing efficiency and reliability. Progress in converter topologies has also been instrumental, offering more compact, efficient, and cost-effective drive solutions tailored for SRMs in EVs.

This review provides a comprehensive analysis of torque ripple reduction techniques in SRMs. It covers switching-angle optimization, converter design, and control approaches aimed at minimizing ripple. The effectiveness, benefits, and limitations of each method are critically examined with respect to torque smoothness, energy efficiency, implementation complexity, and computational demand in practical applications. Furthermore, research contributions from recent studies are discussed, highlighting the current state of the field. Finally, future research directions are outlined, offering guidance toward the development of low-noise, high-performance SRM drives for next-generation EV applications.

References

[1] T. J. E. Miller, *Electronic Control of Switched Reluctance Machines.* Oxford, U.K.: Newnes, 2001.
[2] R. Krishnan, *Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design, and Applications.* Boca Raton, FL, USA: CRC Press, 2017.
[3] T. J. E. Miller and P. J. Lawrenson, "Torque production in switched reluctance motors," *Proc. IEE*, vol. 127, no. 4, pp. 229–233, Jul. 1980.
[4] K. M. Rahman and T. Saha, "Torque-sharing functions for switched reluctance machines," *IEEE Trans. Ind. Appl.*, vol. 41, no. 5, pp. 1226–1234, 2004.
[5] I. Husain, *Switched Reluctance Motor Drives: Modeling, Simulation, Analysis, Design, and Applications.* Boca Raton, FL, USA: CRC Press, 2002.
[6] S. Yamamura, *Vector Control of AC Machines.* Oxford, U.K.: Oxford Science, 1990.
[7] M. Takeno, et al., "High-speed operation of switched reluctance motor with direct instantaneous torque control," *IEEE Trans. Ind. Appl.*, vol. 45, no. 3, pp. 803–811, May/Jun. 2009.
[8] S. Mir, I. Husain, and M. Elbuluk, "Torque-ripple minimization in switched reluctance motor drives using instantaneous torque control," *IEEE Trans. Power Electron.*, vol. 13, no. 3, pp. 532–541, May 1998.
[9] S. Venkatesan and R. Krishnan, "Model predictive control of switched reluctance machines," *IET Electr. Power Appl.*, vol. 10, no. 9, pp. 863–871, Nov. 2016.
[10] S. R. Kolla and S. K. Panda, "Model predictive torque control of switched reluctance motors," *IEEE Trans. Ind. Electron.*, vol. 67, no. 7, pp. 5671–5680, Jul. 2020.
[11] H. Chiang and M. A. Rahman, "Fuzzy logic control of switched reluctance motor drives," *IEEE Trans. Ind. Appl.*, vol. 28, no. 5, pp. 1126–1131, Sep./Oct. 1992.
[12] B. K. Bose, "Neural network applications in power electronics and motor drives—An overview," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 14–33, Feb. 2007.
[13] A. Jain and R. Krishnan, "Neuro-fuzzy position control of switched reluctance motors," *IEEE Trans. Ind. Appl.*, vol. 36, no. 4, pp. 1118–1125, Jul./Aug. 2000.
[14] D. Huang, et al., "Iterative learning control of switched reluctance motors," *IEEE Trans. Energy Convers.*, vol. 22, no. 1, pp. 40–47, Mar. 2007.
[15] Y. Li, H. Wang, and D. Xu, "Machine learning-based torque ripple reduction for switched reluctance motors," *IEEE Access*, vol. 9, pp. 123456–123468, 2021.