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REVIEW ARTICLE

Control strategies and power converter topologies for switched reluctance motors in electric vehicle applications: A comprehensive review

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ABSTRACT

Transportation electrification is a cornerstone in addressing climate change, primarily through the adoption of electric vehicles (EVs), which significantly reduce greenhouse gas emissions. Among various electric motor technologies, switched reluctance motors (SRMs) have emerged as promising alternatives due to their simple design, fault tolerance, and robustness. However, challenges such as torque ripple, high acoustic noise, and efficiency limitations hinder their widespread adoption. This paper presents a comprehensive review of contemporary SRM control strategies and associated power converters, aimed at improving the performance of EV applications. The study explores fundamental electromagnetic principles, highlights torque control strategies (e.g., indirect torque control, direct torque control, and artificial intelligence-based torque control), and evaluates their efficacy in minimizing torque ripple and optimizing motor performance. Additionally, the paper assesses various power converter topologies, emphasizing asymmetric half-bridge, novel integrated power converter, and T-type converters for their suitability in EV systems. Based on an extensive review, a four-phase SRM driven by a T-type converter, coupled with direct instantaneous torque control, is identified as the optimal configuration for EVs, providing a cost-effective, reliable, and high-performance solution for sustainable transportation.

1. Introduction

Due to global climate change, researchers have been searching for alternative, greener energy sources. Transportation is a significant source of carbon emissions; consequently, the importance of electrification is increasingly paramount. The adoption of electric vehicles (EVs) reduces pollution, achieving environmental sustainability.[1] Figure 1 illustrates the anticipated decrease in greenhouse gas emissions from 2024 to 2034 due to the

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electrification of transportation systems. It is predicted that over 500 megatons of CO_2 equivalent will be reduced by 2034.[2]

Electric vehicles employ a diverse range of electric motors, including the switched reluctance motor (SRM), squirrel cage induction motor (SCIM), brushless direct current (DC) motor, synchronous reluctance motor, and permanent magnet synchronous motor (PMSM).[3]

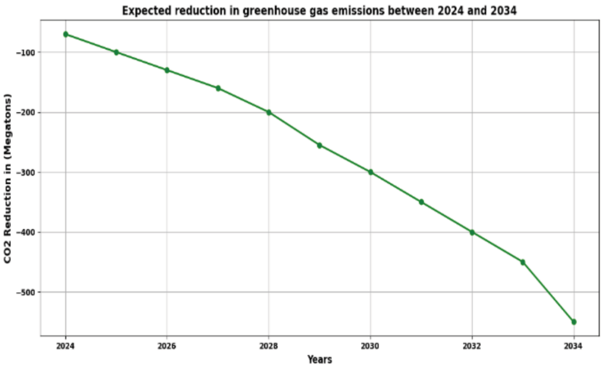


Figure 1. Anticipated reduction in greenhouse gases. Adapted from Haidar et al.[2]

The PMSM is commonly utilized in traction motors due to its high efficiency, wide torque–speed range, and high power density.[4] However, new alternatives were sought after due to the increasing prices and limited availability of rare earth materials used in PMSMs. Ferrite permanent magnets are unsuitable alternatives due to their low residual flux, susceptibility to demagnetization, and lower torque density in comparison to rare-earth PMSMs.[5] Therefore, researchers are moving toward the development of magnet-free motors. While SCIMs are employed in specific commercial EVs,[6] their performance is reduced in comparison to other traction motors. Synchronous reluctance motors represent a feasible option for key drivetrains due to their absence of permanent magnets.[7] However, these motors exhibit a lowered power factor, increased core losses, notable torque ripple, reduced efficiency, and lower torque density.[8]

On the other hand, SRMs provide various advantages over other electric motor technologies, including a simple design, adaptability in control methods, enhanced efficiency, cost-effectiveness, and resilience in operating under fault conditions. Due to the lack of windings and permanent magnets, the machine rotor is suitable for applications requiring extremely high-speed drives.[9,10] The operating principle of SRM is to produce torque by varying magnetic reluctance. SRM has dual saliency—saliency in both the stator and the rotor. Figure 2 illustrates common arrangements of a 4-phase 8/6 SRM.

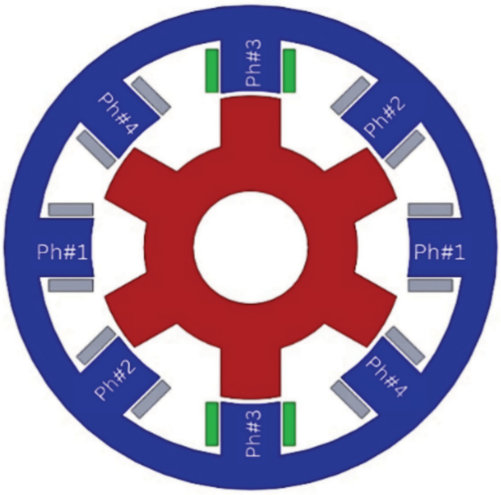


Figure 2. Cross-sectional view of a typical 4-phase 8/6 switched reluctance motor. Adapted from Petrus et al.[11]

Robert Davidson constructed the world's first electric locomotive for the Edinburgh–Glasgow railway line in 1842, a locomotive that was then used to power a motor he created in 1839.[12] Davidson's motor worked and went on to become one of history's most notable inventions. Figure 3 illustrates the structure of Davidson's motor.

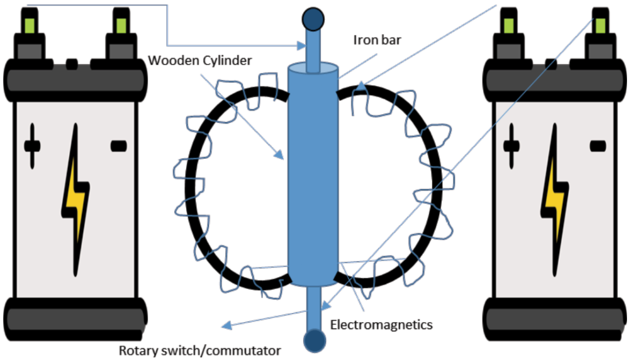


Figure 3. Davidson's motor. Adapted from Ahn and Lukman.[12]

Recent developments in high-power SRMs for EVs highlight the competitive advantages of PMSMs in terms of torque-speed range, power density, and efficiency.[13,14] Figure 4 illustrates a brief performance comparison among the DC motors, SCIM, PMSM, and SRMs.

These figures illustrate that DC motors are large, expensive, and heavy, with less ruggedness and fault tolerance, but they provide consistent torque and possess a simple cooling mechanism. Meanwhile, SCIMs are medium in size and weight, inexpensive, and rugged, with a medium power density, low efficiency, and a complex cooling mechanism. PMSMs are medium in size and weight, provide a wide constant-torque range, high power density, and high efficiency; however, they are costly and require permanent magnets. In contrast, SRMs are compact, low-cost, lightweight, and have excellent fault tolerance and overload capability.

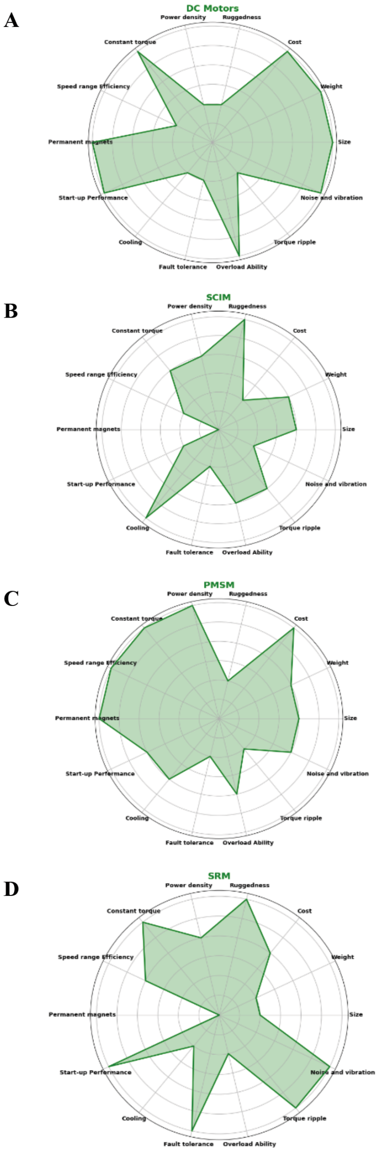


Figure 4. Performance-based comparison among (A) direct current (DC) motor, (B) squirrel cage induction motor (SCIM), (C) permanent magnet synchronous motor (PMSM), and (D) switched reluctance motor (SRM). Images created by the authors using Python software.

The global EV market is experiencing significant developments in charging infrastructure, focusing on ultra-fast charging networks (350–500 kW), high-power wireless charging, and battery-swapping solutions to address range limitations. Governments are emphasizing the development of smart charging hubs that incorporate vehicle-to-grid technology, facilitating the stabilization of renewable energy grids through EVs while concurrently lowering charging expenses. SRMs are gaining recognition in motor technology as a viable and economical substitute for PMSMs due to their robust design, inherent fault tolerance, and the elimination of rare-earth materials in their construction.[9,10,15] However, they demonstrate an increased torque ripple ranging from 10% to 15% under traditional control methods, alongside elevated acoustic noise levels that are 5–10 dB greater than those of PMSMs.[16] These factors significantly influence the smoothness of the drivetrain and the comfort of passengers.

Notwithstanding these limitations, SRMs can achieve overall vehicle efficiencies of 85–92% under optimal control, owing to their reduced core losses at high speeds and their ability to operate over a wide speed range without field weakening.[17] A significant challenge exists in integrating SRMs with regenerative braking systems due to the complexities introduced by their nonlinear inductance profile, which hinders accurate torque control during deceleration. Advanced strategies such as predictive torque control enhance regenerative energy recovery rates, achieving efficiencies of 75–80%, in contrast to the 85–90% efficiency observed in PMSMs.[18] Moreover, the absence of standardized inverter–motor interfaces in SRMs necessitates the development of tailored power electronics, thereby augmenting system complexity. Prospective advancements in wide-bandgap semiconductor inverters and artificial intelligence (AI)-optimized torque-ripple suppression have the potential to address existing challenges, positioning SRMs as a competitive option for next-generation EVs.

This paper presents a comprehensive review of popular control technologies and power converters utilized in SRM. The organization of the paper is as follows: after introducing SRM in Section 1, Section 2 outlines the fundamental electromagnetic equations significant to SRM. Section 3 provides a comprehensive review of the popular control strategies employed in SRM applications. Section 4 introduces and compares the most common power converter topologies utilized for driving the SRM, emphasizing the advantages and disadvantages associated with each topology. Section 5 presents a conclusion and recommends the most suitable SRM drive for EV applications. Additionally, some future research domains have also been highlighted.

2. Fundamentals of switched reluctance motors

The fundamental electromagnetic equation that determines the behavior of the SRM individual phase is as follows[16]:

$$V = iR_m + L(\theta, i) + \frac{d\theta}{dt} KB(\theta, i) \frac{d\theta}{dt} \quad (1)$$

where V represents the phase voltage, i represents the phase current, R_m represents the phase resistance, $L(\theta, i)$ represents the instantaneous inductance, and $KB(\theta, i)$ represents the instantaneous back emf.

Upon excitation of each stator pole, the corresponding adjacent rotor pole tends to align itself in a configuration that minimizes reluctance. The torque generated by the current in a designated phase serves to drive the rotor in a direction that minimizes reluctance, thereby improving inductance. The torque generated by the motor, excluding the effects of magnetic saturation, can be expressed as follows[17]:

$$T_{em} = i^2/2\frac{dL}{d\theta} \quad (2)$$

From Equation (2), it is evident that torque remains unaffected by the polarity of the stator current, as indicated by the square term. Furthermore, torque generation is contingent upon a variation in inductance. Consequently, a positive torque is generated in the region with rising inductance, whereas a negative torque is observed in the area of decreasing inductance.

By using the Maxwell stress tensor, the radial force, F_r, and tangential force, F_t, as shown in Figure 5, can be calculated as follows[16]:

$$F_r = \frac{1}{2\mu_\circ}\int_s (B_r^2 - B_t^2)ds \quad (3)$$

$$F_t = \frac{1}{\mu_\circ}\int_s B_r B_t ds \quad (4)$$

In Equation (3), B_r, B_t, μ_0, and ds represent the radial flux density, tangential flux density, vacuum permeability, and infinite increment of the integral surface area, respectively. The torque is generated by the tangential force exerted on the rotor poles.

The nonlinear properties of the intrinsic double salient structure make it difficult to represent flux linkage, torque, and inductance as functions of phase current and rotational angle. Therefore, several numerical and analytical methods have been developed to obtain an exact model.[19] Table 1 summarizes various methods; the details are available in the previous review.[19]

3. Control strategies of switched reluctance motors

The switched reluctance motor is an admirable solution for enhancing traction motor applications, including e-bikes and EVs, due to its robustness, reliability, and a wide constant-power operating range. However, it suffers issues such as acoustic noise and torque ripple caused by the double salient structure, leading to discontinuous current commutation and highly nonlinear magnetic characteristics,[20] as illustrated in Figure 6.

Torque ripples can be reduced by employing different control techniques or improving motor design. Various control strategies are available to enhance SRM performance by increasing efficiency, minimizing torque ripple, and providing a wide speed range. Figure 7 illustrates existing machine-controlling schemes employed in SRM.

3.1. Torque control strategy

Due to advancements in semiconductors, integrated circuits, and power electronics converters, control technologies have become the optimal strategy for mitigating torque ripple. These advancements have significantly increased the potential for controlling and enhancing SRM performance. Based on SRM operating principles, small inductance gradients between the minimum and maximum inductance zones lead to low phase torque in these regions. Consequently, torque decreases in the phase commutation region, resulting in significant torque ripple.[20] This subsection provides a review of various control strategies used to reduce SRM torque ripple, including indirect torque control, direct torque control (DTC), and AI-based torque control.

3.1.1. Indirect torque control strategy

Indirect torque control is a widely used strategy in electric drive systems, designed to achieve accurate torque regulation by decoupling the control of flux and torque components. Unlike DTC, indirect torque control utilizes mathematical models and reference frame transformations to determine voltage commands indirectly. This strategy offers lower torque ripple, better steady-state performance, and higher efficiency, making it ideal for high-performance industrial applications. From the recent literature, some of the most used indirect torque control strategies are discussed in the following subsections.

3.1.1.1. Average torque control

A new strategy for estimating and controlling the

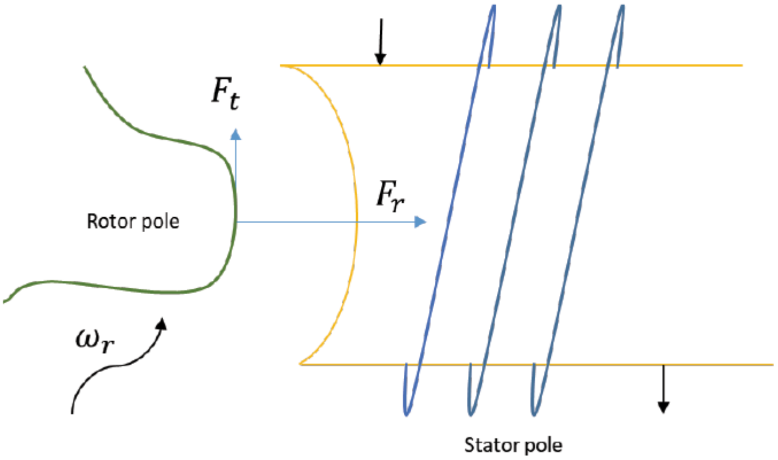


Figure 5. Tangential and radial forces generated in a switched reluctance motor. Adapted from Fang et al.[16]

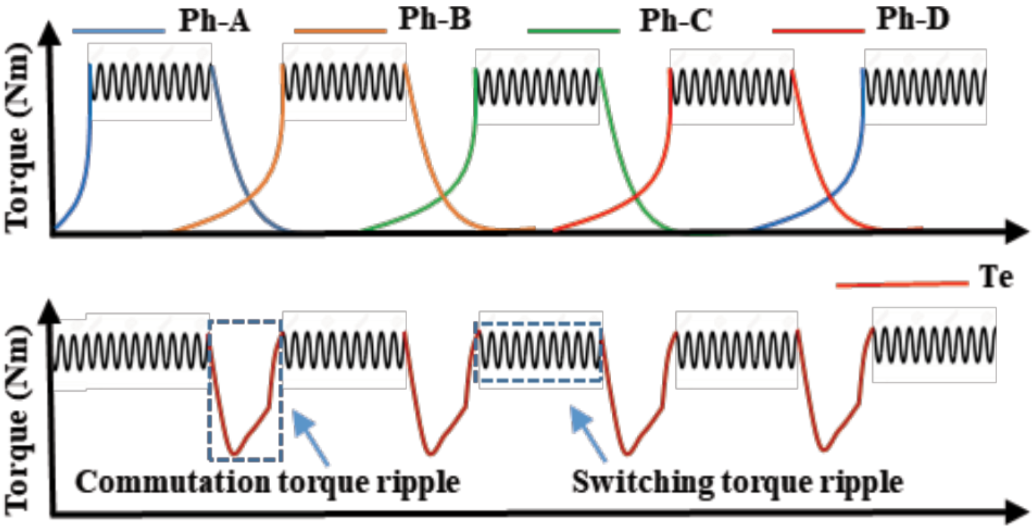


Figure 6. Torque ripples for each phase and the overall torque waveforms. Adapted from Fang et al.[16]

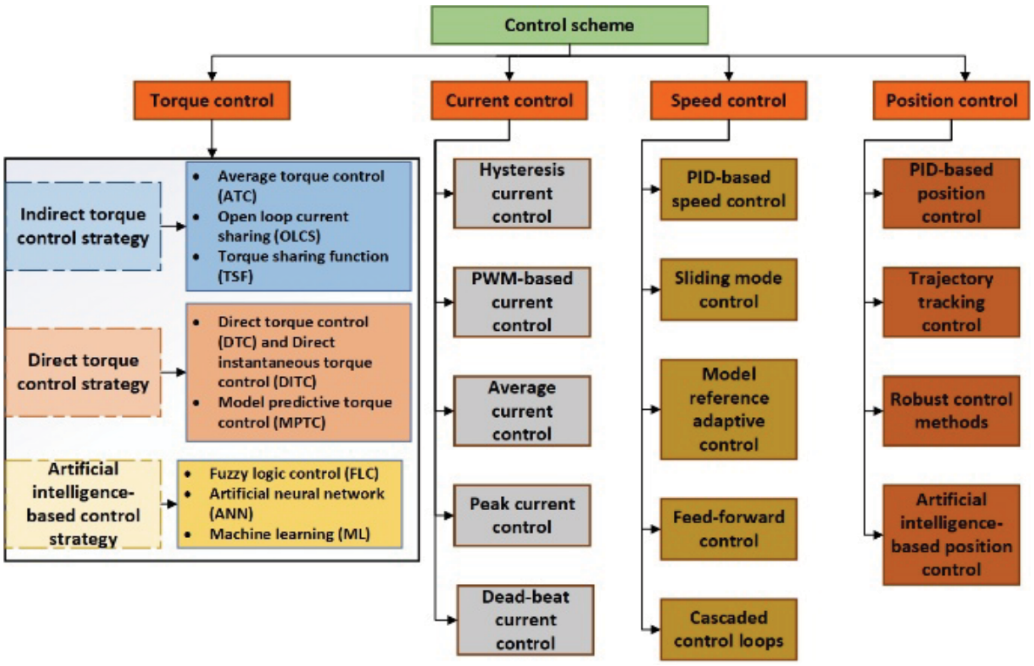


Figure 7. Classification of control schemes for switched reluctance motors. Figure created by the authors. Abbreviations: PID: Proportional integral derivative; PWM: Pulse-width modulation.

Table 1. Classification and characteristics of switched reluctance motor modeling techniques

Classification	Methodology	Advantage	Disadvantage
Numerical methods	Finite element analysis	Exhibiting high precision, this approach is proficient in managing complex configurations, effectively capturing field distributions while accommodating 3D effects, such as skewing and winding impacts.	Prolonged computational time and complex modeling procedure for 3D geometry.
	Boundary element method	Outstanding accuracy and acceptable computational efficiency.	System matrix with a high population density, limited capacity to address saturation or nonlinear issues, and requires the resolution of boundary conditions.
Analytical methods	Maxwell's equations-based approach (curve fitting method)	Fast computational speed, obtains magnetic properties directly, effective computation, and infers patterns from a small set of data.	Increased complexity, constrained ability to tackle saturation or nonlinear challenges, the need for empirical and heuristic approaches necessitate pre-established data, and the introduction of new data is essential in the event of a topology alteration.
	Magnetic equivalent circuit	Minimal computation time and satisfactory accuracy.	Depend on empirical conventions related to fringing and leakage reluctances, necessitating a predefined description of flux paths prior to analysis.

Source: Details are available in the previous review by Diao et al.[19]

average torque of SRMs was introduced in previous studies.[21,22] The average torque control strategy is implemented using an online method to estimate the average torque and energy ratio within a closed-loop control system. The torque reference is dynamically regulated by adjusting the current reference and switching angles, thereby maintaining a consistent average torque at a predetermined reference level. The adaptive adjustment of system parameters further enhances the accuracy of torque estimation, thus allowing for precise torque control. As a result, torque ripple can be reduced to an acceptable level. However, during phase commutation, residual torque ripples can cause noticeable speed oscillations and variations at low speeds. A schematic diagram of the average torque control strategy for SRM is depicted in Figure 8.

3.1.1.2. Open-loop current sharing

The average torque of an SRM cannot be directly identified from phase current measurements. Consequently, an open-loop current sharing strategy can be applied. To implement this technique, it is essential to determine the switching angles and command currents (θ_{OFF} and θ_{ON}) either through offline analysis or experimental testing, as depicted in Figure 9. The generated data are stored as look-up tables in the controller's memory, enabling accurate selection of control variables for each operating mode based on shaft speed, torque command, and DC supply voltage. Although this strategy is simple, it is highly sensitive to alterations in the motor's definite variables[16] and is often considered too costly for industrial uses due to the need for storing 3D data tables for each control variable. Moreover, its simplicity may lead to significant errors in estimating the average torque. However, AI-based control strategies can enhance this strategy by facilitating online tuning of control variables.[23]

3.1.1.3. Torque sharing function

The torque sharing function (TSF) strategy has numerous benefits, including simplicity and efficiency. It is implemented using the motor's static characteristics, enabling the drive system to operate under either hysteresis or pulse-width modulation control,[23] as illustrated in Figure 10. In this method, the input command for the torque signal is divided into phase reference torques according to the rotor angle position. Each phase reference torque is then converted into a current command signal through the torque-to-current block, while the switching rule block generates switching signals using hysteresis control. The current

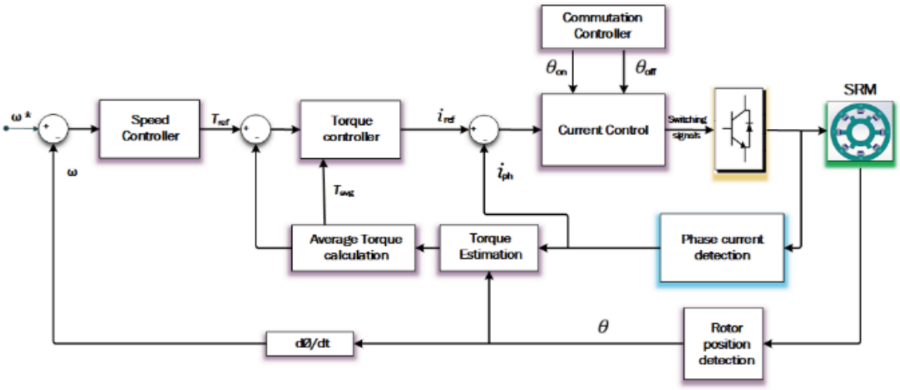


Figure 8. Average torque control strategy for switched reluctance motors (SRMs). Adapted from Wang et al.[21]

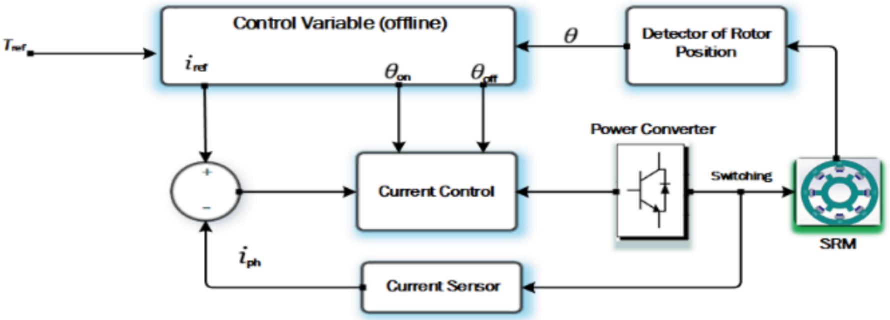


Figure 9. Open-loop current sharing control strategy for switched reluctance motors (SRMs). Adapted from Fang et al.[16]

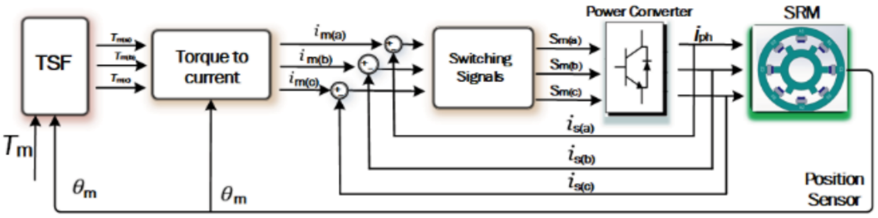


Figure 10. Torque sharing function (TSF) control strategy for switched reluctance motors (SRMs). Adapted from Mohanraj et al.[23]

signal error is calculated by comparing the commanded and actual phase currents. TSF can be applied in both linear and nonlinear forms. Although the linear TSF is relatively simple, it is prone to torque ripple, particularly at higher rotor speeds due to the nonlinear characteristics intrinsic to SRMs.[24] In contrast, nonlinear TSF achieves optimal torque-to-current ratios and provides smoother control responses.[25]

The four traditional representations of TSF include linear, cosine, cubic, and exponential forms.[22,26] Figure 11 illustrates a typical waveform for the cosine-type TSF, with θ_{on}, θ_{off}, and θ_{ov} representing the turn-on, turn-off, and overlap angles, respectively.

The overlap and turn-on angles were optimized using a genetic algorithm.[23] The TSF control strategy efficiently mitigates substantial peak currents and limits huge torque ripple. However, the slow current response poses challenges in precisely tracking the torque distribution function throughout the commutation process. The minimized torque in the initial phase cannot be compensated by higher torque in subsequent phases; therefore, maintaining a constant total torque cannot be guaranteed. Torque ripple remains particularly noticeable at high speeds and under heavy load situations. Recent works on the TSF have mostly focused on reducing torque ripples and copper loss. It has been suggested to implement a new nonlinear TSF that demagnetizes

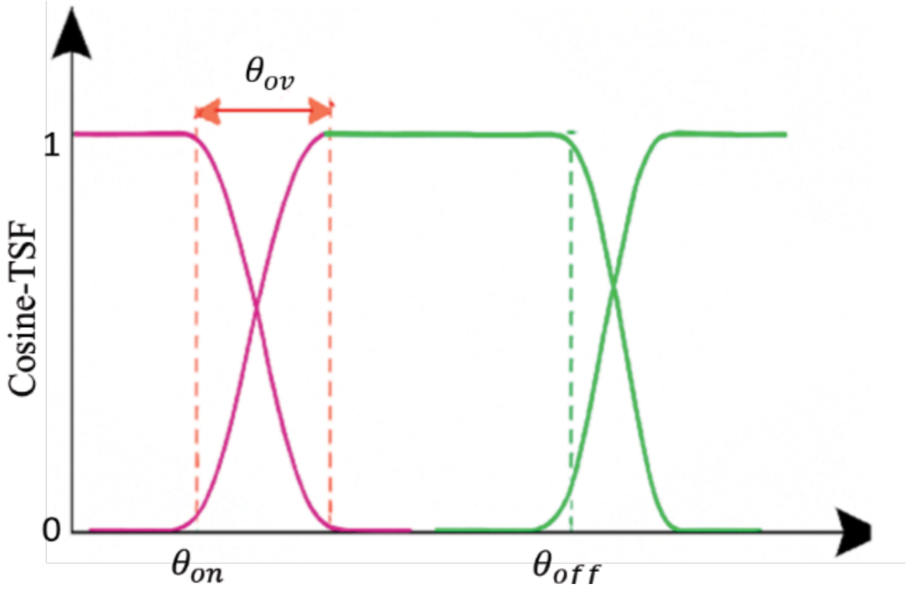


Figure 11. Cosine-type torque sharing function (TSF). Adapted from Sahu et al.[22]

during commutation to facilitate the smooth sharing of torque between two neighboring phases.[27] Additionally, several control techniques, including fuzzy logic control, iterative learning control, and neural network control, have been employed to modulate the reference torque and current.[27,28]

3.1.2. Direct torque control strategy

Torque regulation through direct feedback mechanisms and power transistor manipulation offers a simpler approach to controlling output torque compared with indirect torque control methods. The literature has shown that DTC strategies are classified into three categories: DTC, direct instantaneous torque control (DITC), and model predictive torque control (MPTC).

3.1.2.1. Direct torque control and direct instantaneous torque control

Direct torque control strategies have been developed to mitigate torque ripple in SRMs,[29–31] as illustrated in Figure 12. In this approach, the reference current is calculated using look-up tables of stored current profiles, which include the current torque position. The generation of switching signals is accomplished through the current controller, which compares sampled currents with the reference currents.

DITC is an advancement of DTC that has attracted significant attention due to its rapid response to torque errors, facilitating a more effective reduction of torque ripple.[32,33] The DITC block diagram is shown in Figure 13. In DITC, the torque reference is employed directly for control applications without being converted into a current reference. The instantaneous torque is assessed in real time and utilized directly as the control variable, thereby eliminating the need for a current loop. A torque hysteresis controller then generates the requisite switching signals. In a previous study, DITC was further utilized to simultaneously reduce the vibration of SRMs and torque ripple, achieving high performance in automotive applications.[34] Meanwhile, a robust direct torque controller based on a Lyapunov function was proposed to minimize torque ripple.[35] This controller effectively addresses the nonlinear torque-generation mechanism of SRMs and has been validated for robustness against uncertainties in the flux-linkage model.

The integration of pulse-width modulation with predictive control in DITC enables a notable decrease in torque ripple, irrespective of current or flux profiles computed offline.[36] To further enhance performance, several methods have been integrated into DITC. These include the adoption of a distinctive switching approach based on TSF,[37] current control mechanisms,[38] parameter identification techniques that eliminate the need for rotor locking,[39] a speed controller utilizing adaptive terminal sliding mode,[40] and an adaptive dynamic commutation strategy.[41]

3.1.2.2. Model predictive torque control

Model predictive torque control represents a sophisticated control strategy characterized by its inherent simplicity in handling multivariable systems with fast transient response, the ability to accommodate nonlinearities, and the inclusion of simple constraints within the control law. These attributes make it particularly attractive for high-performance motor drive applications. However,

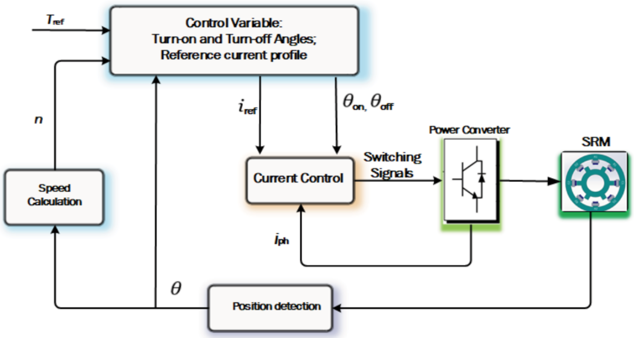


Figure 12. Direct torque control strategy for switched reluctance motors (SRMs). Adapted from Yan et al.[31]

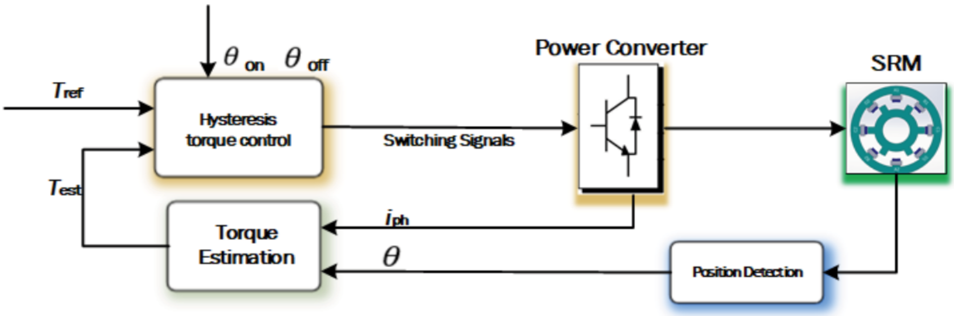


Figure 13. Direct instantaneous torque control strategy for switched reluctance motors (SRMs). Adapted from Klein-Hessling et al.[34]

the strongly nonlinear electromagnetic characteristics of SRMs can lead to reduced control accuracy, prolonged stabilization times of control variables, inadequate dynamic response, and suboptimal performance in torque ripple mitigation. MPTC employs a system model to forecast future output values over a specified time, based on the current state variables. The optimal control output is then determined by formulating a cost function. Through the utilization of feedback information, this strategy enables online correction and rolling optimization of the model.[42,43] Figure 14 presents the conventional block diagram of MPTC.

3.1.3. Artificial intelligence-based control strategy

Recently, an AI-based control strategy was introduced to translate human knowledge into a computationally interpretable format. The implementation of intelligent control enables both offline and online current optimization, thereby enhancing SRM performance and minimizing torque ripple. Such systems demonstrate significant self-learning and adaptive capabilities, integrating methodologies such as fuzzy logic, neural networks, and evolutionary algorithms.[44,45]

3.1.3.1. Fuzzy logic control

Fuzzy logic control is an AI-based control technique with strong self-learning and adaptive capabilities. It enhances performance control, including robustness and flexibility, by using fuzzy condition design and uncertain language. A fuzzy controller typically has three major processes: fuzzification, inference, and defuzzification.[45] Furthermore, the controller's properties can be continuously modified based on the various necessities and aims of the control system.[46] Fuzzy logic control was utilized in previous studies to mitigate torque ripple in SRMs.[47,48] Figure 15 illustrates a block diagram of a fuzzy logic control for SRMs, as proposed in.[47]

The fuzzy inputs are divided based on membership functions to enable SRM operation across the entire positive torque-generating zone, while the outputs are controlled using the center-of-average method during the defuzzification stage. During adaptation, each output's value (weight) is randomly modified and optimized.[49] In a previous study, a fuzzy logic controller could provide smooth torque at rated speed while demonstrating resilience to errors in rotor position.[50] The primary advantage of fuzzy logic controllers is that they do not require an analytical model of the system, making them highly suitable for nonlinear systems and independent of machine

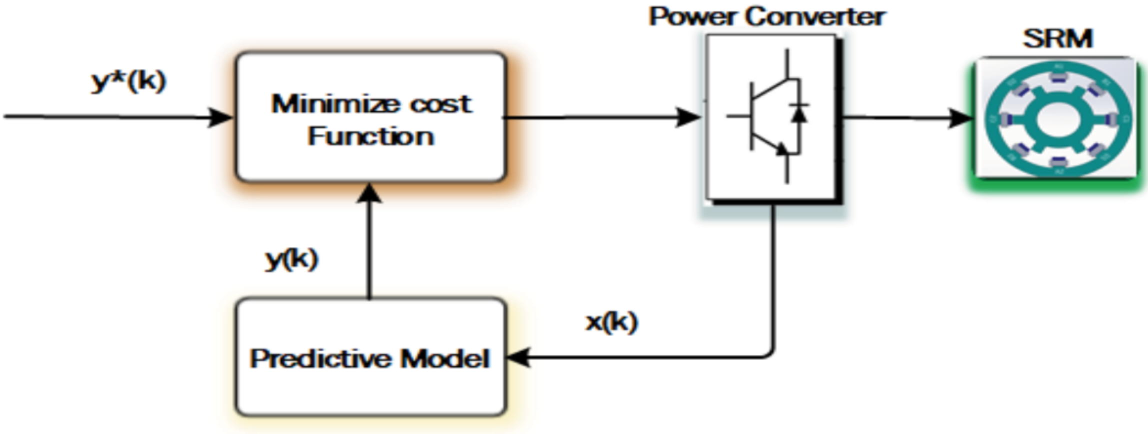


Figure 14. Model predictive torque control strategy for switched reluctance motors (SRMs). Adapted from Ge et al.[42]

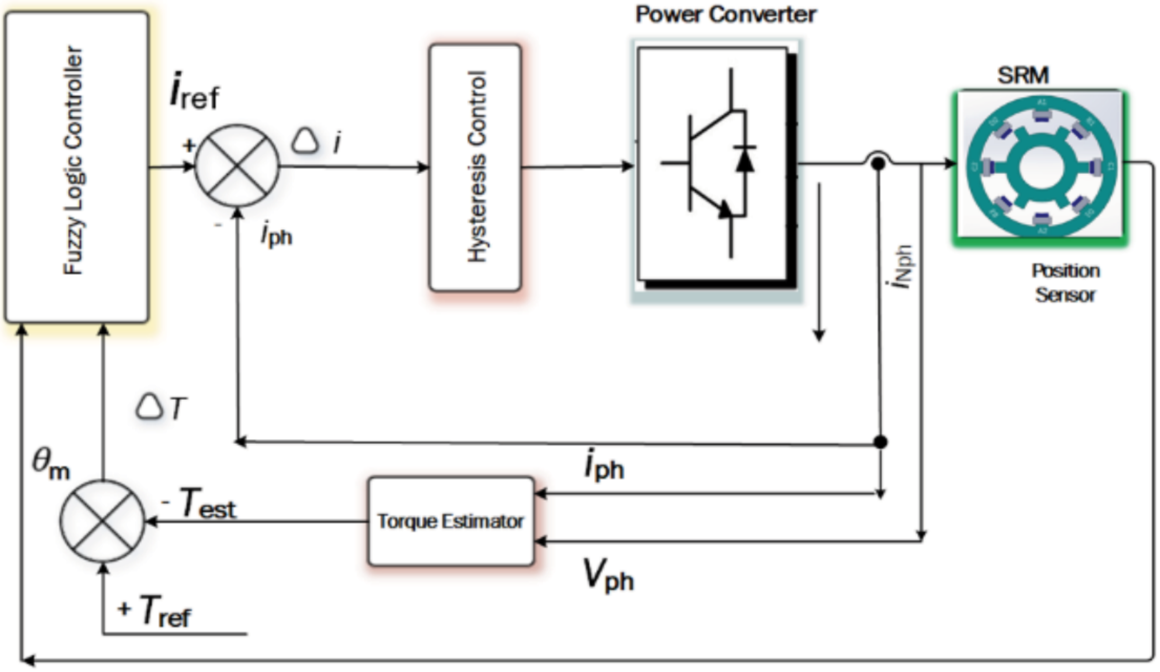


Figure 15. Fuzzy logic control strategy for switched reluctance motors (SRMs). Adapted from Sasidharan and Isha.[47]

parameters. However, their main drawback lies in the complexity of the underlying computational algorithms. In a previous study, a fuzzy logic controller was proposed to minimize torque ripple and enhance SRM performance, with its effectiveness validated against both fuzzy and proportional-integral controllers.[51] To further enhance SRM performance, the adaptive technique's coefficients were tuned online using Lyapunov theory of stability. In another study, a fuzzy controller-based indirect instantaneous torque control strategy was developed for reducing SRM torque ripple.[52]

3.1.3.2. Artificial neural network

Artificial neural network (ANN) models are relatively simple and capable of operating in noisy environments. Moreover, this approach does not require large storage memory to store the magnetic features of SRMs.[53] An ANN-based strategy for reducing torque ripple is presented in a previous study.[54] The typical ANN architecture is illustrated in Figure 16. It consists of four input layers, two hidden layers, and one output layer. The output layer represents torque, while the input layers correspond to speed. The hidden layers function as speed-to-torque converters.

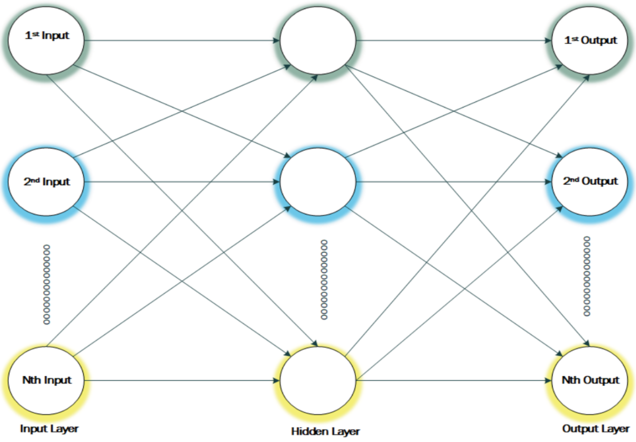


Figure 16. The typical architecture of an artificial neural network. Adapted from Dudak and Bakan.[54]

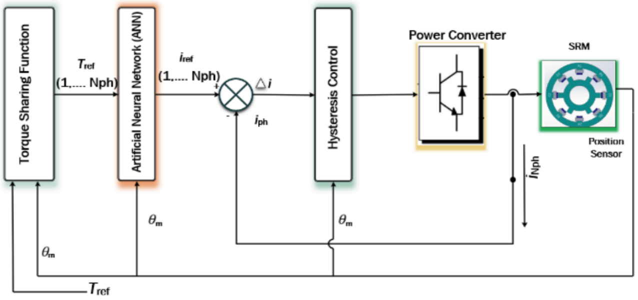


Figure 17. Artificial neural network-based control strategy for switched reluctance motors (SRMs). Adapted from Dudak and Bakan.[54]

Many researchers have employed ANNs to derive the command current from the reference torque. This reference torque is generated from the distributed command torque through the TSF, utilizing rotor position information, as illustrated in Figure 17. In other studies, adaptive ANNs have been combined with proportional-integral-derivative (PID) controllers.[55] The key advantages of ANNs include simplicity, high accuracy, and cost-effectiveness. However, several challenges remain, including slow learning speed and the need for offline learning.[56]

The adaptive neuro-fuzzy inference system integrates the advantages of ANNs and fuzzy logic systems.[57] Its learning mechanism increases the independence of the controller from motor characteristics. The initial values of the membership functions and rule base can be defined using information about SRM dynamic behaviors, after which the adaptive neuro-fuzzy inference system optimizes the membership function parameters. The controller is capable of self-adaptation in response to variations in system variables, including load and speed changes. Additionally, the system adjusts the operating point in accordance with control system variables to minimize torque ripples, as illustrated in Figure 18.[58]

Artificial neural networks have proven to be an effective alternative for intelligent control algorithms in SRMs. In addition to nonlinear modeling of SRMs,[59] various ANN-based techniques have also been applied for tasks such as parameter optimization, sensorless control, and controller design. For example, in sensorless position control, a study introduced a minimal neural network architecture that incorporates a preprocessor and excludes hidden layers, thereby achieving accurate position estimation.[60] Furthermore, to achieve precise positioning, an adaptive inverse control mechanism was implemented utilizing basic interval type-2 fuzzy neural networks[61] in conjunction with a back-propagation neural network that employs an improved algorithm.[62]

3.1.3.3. Machine learning

A machine learning system represents an advanced evolution of intelligent control systems, characterized by an enhanced capacity for auto-learning and a streamlined architecture, rendering it suitable for industrial applications.[63] A previous study presented a machine-learning approach that employs two pre-trained ANN models to reduce torque ripple across an extensive speed range

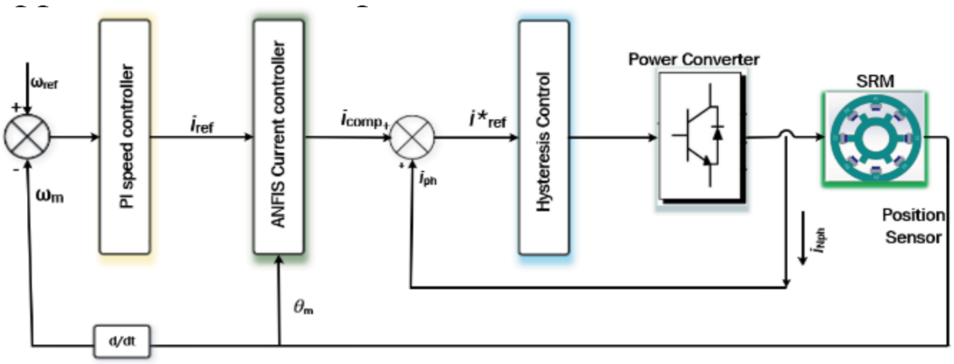


Figure 18. Adaptive neuro-fuzzy inference system (ANFIS) strategy for switched reluctance motors (SRMs). Adapted from Pushparajesh et al.[58]
Abbreviation: PI: Proportional integral.

of SRMs.[64] The proposed pre-trained ANN models were employed to estimate the actual torque using motor current and position data, in addition to calculating the suitable reference currents for each phase to mitigate torque ripple. Meanwhile, a novel intelligent technique was proposed to manage SRM speed, with a focus on minimizing torque ripple.[63] This technique was based on a computational model of the mammalian limbic system and emotional processes—the brain's emotional learning based intelligent controller. This method employs machine learning to achieve simple and effective controls that are fully independent of motor characteristics and eliminate the need for conventional controllers. The proposed technique demonstrated high tracking capability, rapid auto-learning, enhanced speed response, and significant reduction of torque ripple.

3.1.4. Other torque controlling strategies

This section presents a comprehensive overview of various other techniques aimed at reducing torque ripple. For example, a variable structure control technique is employed for SRM to enhance its performance and reduce torque ripple compared with conventional control techniques.[64] However, the effects of phase coupling and magnetic saturation were ignored in this approach.

For SRM current controllers, studies have employed the corresponding sliding mode variable structure control theory.[65] Furthermore, the iterative learning control approach was applied to the SRMs, yielding favorable control effects without the need for measuring the motor's magnetic features or high model precision.[66] Another study proposed a self-learning method that enables online optimal current determination for each phase to fulfill the overall torque command.[67] Meanwhile, voltage feedback was incorporated to enhance bandwidth control.[68] Genetic algorithms have been applied to torque control, utilizing direct flux control rather than relying on phase current or torque control.[69] While this method is well-suited for digital control implementations, it requires precise information regarding the motor's features and rotor position.

The feedback linearization approach employs state feedback to transform the nonlinear system into a linearized closed-loop system,[70] efficiently addressing the nonlinear features of the motor. However, the significant drawbacks of this method include the requirement for an accurate motor model that necessitates large currents while operating at low speeds and the monitoring of state variables (stator currents, position, and velocity). To address these limitations, an adaptive feedback linearization method has been employed, leveraging multi-objective optimization through a genetic algorithm.[71]

3.2. Comparison of the torque control strategies

All the mentioned torque control strategies have the potential to mitigate torque ripple, although their implementation and computing complexity may differ. For example, the average torque control strategy maintains a constant reference phase current during excitation. This approach facilitates ease of implementation and reduces costs, thereby achieving high precision in torque estimation and enabling precise torque control. However, it is associated with notable drawbacks, including the generation of significant speed oscillations and fluctuations at low speeds that arise from torque ripples during the phase commutation process.

The average torque of SRMs is not directly obtained from phase currents. Consequently, an open-loop current control strategy is introduced; however, this technique demonstrates significant sensitivity to variations in the actual motor variables. On the other hand, the TSF control strategy presents several advantages, including simplicity, robustness, widespread acceptance, efficiency, and the capability to deliver smooth torque in low-speed regions. However, its inadequate current response hinders the effective monitoring of torque distribution functions during the commutation process. Consequently, the torque control performance in the medium and high-speed regions decreases, attributable to its limited capability in tracking the reference current. These indirect torque control strategies necessitate the implementation of a current control loop, thereby rendering torque control performance contingent upon the tracking capability of the current controller.

On the other hand, DTC, DITC, and MPTC are direct torque control strategies. In these strategies, torque control performance is directly related to the control method. The selection of appropriate switching angles in the DITC method enables smooth torque production up to the rated speed while reducing copper losses through optimized commutation intervals. In contrast, the presence of an additional flux-linkage loop in the DTC strategy imposes constraints on torque ripple-free operation and overall effectiveness. Compared to DTC, MPTC demonstrates superior torque ripple suppression capabilities and optimizes multiple objectives via a simple scalar cost function, eliminating the necessity for varying switching angles across different operating conditions. However, MPTC is hindered by high computational complexity and notable negative torque at high speeds.

In this context, artificial intelligence-based control strategies are recognized as a viable solution for torque ripple reduction in SRMs. These methods offer several advantages, including nonlinear and self-learning capabilities, as well as adaptive functionality. However, these techniques require significant computational time for algorithm execution and introduce high algorithmic complexity.

Figure 19 illustrates that, upon comparison of all the discussed control strategies for SRMs, the DITC strategy demonstrates superior overall efficiency in minimizing torque ripple. Its implementation is simple, while offering flexibility across a broad torque and speed range. The minimization of root mean square current, and consequently the reduction of losses, can be accomplished through adjusting the turn-on/off angles. Finally, a key advantage of DITC is that it treats total torque as the primary control parameter, rather than individual torques (as in TSF) or currents (as in current profiling). Table 2 presents the quantitative comparison between DITC and TSF.

4. Power converters of switched reluctance motors

Converter design represents a fundamental aspect of SRM research, as both the performance and cost of the drive are significantly influenced by the characteristics of the converter. Numerous converters have been developed to reduce the number of switches and enhance commutation times. Each SRM converter presents distinct advantages and disadvantages. Common disadvantages include low efficiency, high voltage ratings, multiple switches, complex control schemes, and the need for auxiliary windings. Consequently, converter design always involves a trade-off between performance and cost.

This section presents an analysis of SRM power converter topologies in recent research studies. A distinction is made between hard-switching and soft-switching converters, highlighting the notable advantages and disadvantages of each topology. This analysis aims to support the selection of the most suitable power converter topology for EV applications.

4.1. Requirements for switched reluctance motor power converters

A converter must satisfy multiple criteria to enhance SRM performance.[72] The basic requirements for supplying power to SRMs include the following:

- Each SRM phase should be capable of operating independently from the other phases.
- The converter must ensure phase demagnetization prior to its transition into the generating region when the machine functions as a motor. Conversely, it must excite the phase before entering the generating region when operating as a generator.

4.2. Classification of switched reluctance motor power converters

Most power converters are selected based on their intended application. For low-performance applications, low-cost converters are suitable, as precise torque control is not necessary. Conversely, a high-performance converter with rapid phase demagnetization is required for applications requiring accurate torque control and efficiency.

Table 2. Quantitative comparison of direct instantaneous torque control (DITC) and torque sharing function (TSF) control strategies[23–26, 32–35]

Metric	DITC	TSF (linear/sinusoidal)
Torque ripple reduction	∼70–90%	∼50–70%
Average torque	Higher (5–10% improvement)	Lower (5–15% drop)
Computational load	Higher (real-time control)	Lower (predefined functions)
Dynamic response	Faster	Slower

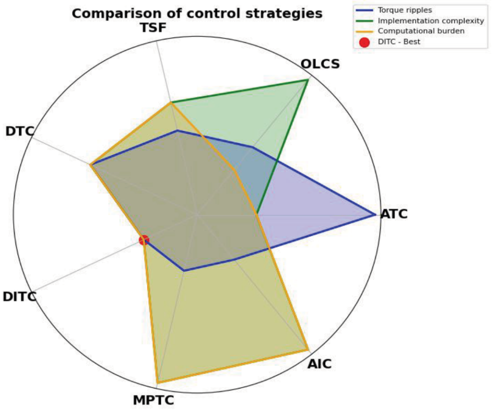


Figure 19. Comparison of the switched reluctance motor torque control strategies. Figure created by the authors using Python software
Abbreviations: AIC: Artificial intelligence-based control; ATC: Average torque control; DITC: Direct instantaneous torque control; DTC: Direct torque control; MPTC: Model predictive torque control; OLCS: Open-loop current sharing; TSF: Torque sharing function.

Converters with a lesser number of switches typically exhibit lower fault tolerance, which is a primary concern for drive reliability. Meanwhile, converters with only one device drop per phase are preferred for low-voltage applications. Other aspects to consider when selecting a converter for a drive include performance, control complexity, cost, and the number of passive elements.

The converter of SRMs is typically categorized according to two primary criteria: the quantity of switching devices and the commutation method employed.[73] Figure 20 illustrates the classification of SRM power converter topologies, which are classified into two primary groups: hard-switching converters and soft-switching converters.

4.2.1. Soft-switching converter

The implementation of soft-switching converters can significantly reduce switching losses by using resonant circuits, enabling zero-voltage or zero-current switching mechanisms.[74] In contrast to hard-switching converters, the voltage stresses on the devices must be elevated to several times their nominal values, leading to a substantial increase in the volt–ampere rating of the converter.[75] It has been shown that, in the context of EV application, the energy savings achieved through soft-switching converter implementation are insufficient to justify their adoption.[76, 77] Soft-switching converters are generally classified under a single subgroup: self-commutating converters.

4.2.2. Hard-switching converter

The majority of SRM converters are hard-switching converters, as they require less circuitry and are easier to implement than soft-switching converters. Hard-switching converters are generally classified into five subgroups: single converters, magnetic converters, dissipative converters, capacitive converters, and bridge converters.

4.3. Comparison of switched reluctance motor power converters

This section presents a comparative analysis of the recent power converter topologies used by researchers to identify the optimal converter for EV applications. The topology types and the number of switches, diodes, and capacitors used per phase, as well as the advantages and disadvantages of these power converter topologies, are compared in Table **??**. The topology diagrams are illustrated in Figures 21–25.

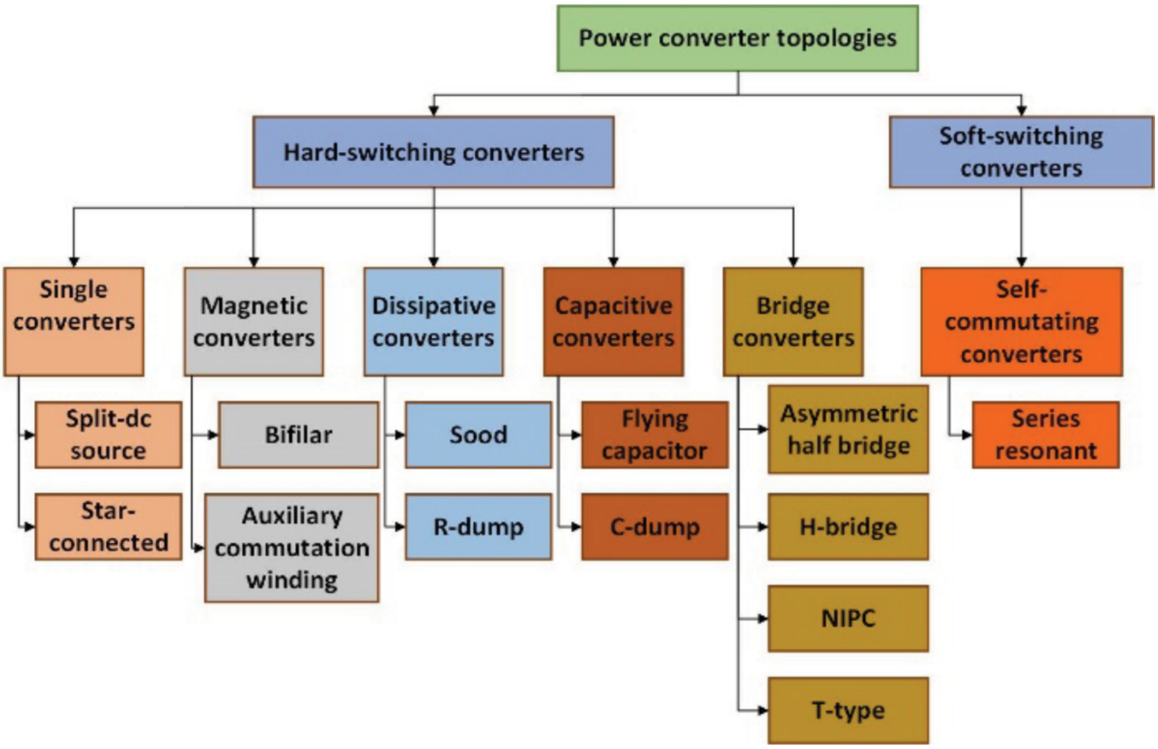


Figure 20. Classification of switched reluctance motor power converters. Figure created by the authors using Microsoft Visio software
Abbreviations: DC: Direct current; NIPC: Novel integrated power converter.

Table 3. Comparative analysis of hard-switching converter topologies[75, 78–94]

Type of Topology	**No. of switches per phase**	**No. of diodes and capacitors per phase**	**Advantages**	**Disadvantages**
Split DC source (Figure 21A)	1	1, 2	• Fast demagnetization • No additional passive components • Improved voltage utilization • Reduced voltage stress • Compact design • Better control of phase currents • Regenerative braking support • Cost-effective and reduced electromagnetic interference	• High switching frequency losses • Low dynamic response • Reducing speed capability • Increased complexity in DC source management • Limited fault tolerance • Complex thermal management • Power loss in source switching
Star connected (Figure 21B)	2	2, 1	• Reduced harmonics and higher efficiency • Simplicity in control and compact design • Better voltage utilization • Improved fault tolerance • Lower manufacturing and maintenance costs due to simpler design and fewer components • Enhanced reliability • Regenerative braking support	• Limited power density • Increased phase voltage stress • Complex phase current control • Star configuration may result in reduced torque production • Failure in one phase can affect the operation of the entire system, especially in the case of unbalanced load conditions • Cooling challenges • Reduced scalability

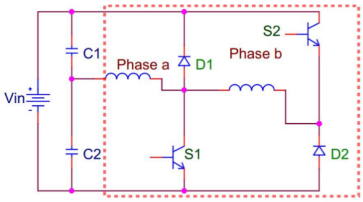
Type of Topology	**No. of switches per phase**	**No. of diodes and capacitors per phase**	**Advantages**	**Disadvantages**
Bifilar (Figure 22A)	1	1	• Fewer power switches and fast demagnetization • Compact design • Better magnetic utilization • Improved control and lower electromagnetic interference • Improved system reliability • Cost-effective for high power	• Low power density and high torque ripple • High stress one the switching elements and low efficiency • Complex in snubber circuits • Greater space requirement for windings • Increased manufacturing complexity
Auxiliary commutation winding (Figure 22B)	4	4, 1 shared capacitor for the entire system, not per phase	• Reduced torque ripple • Improved efficiency • Enhanced motor performance • Lower voltage stress • Better fault handling • Regenerative braking support can be adapted for various power and performance levels in EV applications	• Increased complexity • Additional components and manufacturing complexity raise production costs • Requires more physical space for the auxiliary windings, which may challenge compact designs • Need more sophisticated control algorithms for managing auxiliary windings effectively • Higher maintenance • Energy loss in auxiliary windings • Integration issues • Adds extra weight due to additional windings • Scalability limitations
Sood (Figure 23A)	1	1, 1	• Fewer power switches • Four modes of operation • Reduce fault tolerance and increase high efficiency • Reduced electromagnetic interference • Improved torque control and compact design • Enhanced thermal management • Regenerative braking support	• Complex control • High losses in the energy recovery circuit • Higher voltage stress • Limited scalability • Higher initial cost

Type of Topology	No. of switches per phase	No. of diodes and capacitors per phase	Advantages	Disadvantages
R-dump (Figure 23B)	2	2, 1	• Fewer power switches • Simple structure and low cost • Reduced torque ripple • Improved efficiency • Better control of phase currents • Lower electromagnetic interference • Improve the fault tolerance of the motor system • Reduced mechanical stress due to the damping action	• Large voltage variation • No zero-voltage state during conduction • The additional resistive damping element can increase overall losses, reducing system efficiency • Incorporating the R-dump winding requires a more complex design and integration with the motor • The added resistance can cause higher local heating, increasing thermal management challenges • May not be suitable for high-power • The damping resistance may reduce the overall power density • Potential for voltage stress • Slower response due to damping
Flying capacitor (Figure 24A)	4	4, 2	• Improved voltage balancing, reducing the risk of overvoltage • Reduce harmonics leading to smoother operation • Better efficiency • Compact design reduced stress on switches • Enhanced regenerative capability • Higher reliability	• Complex control needs sophisticated algorithms • Capacitor voltage ripple requires additional control • Higher component count • Additional capacitors increase the overall cost • Lower power density • Multiple capacitors increase the size and weight
C-dump (Figure 24B)	2	2, 1	• Independent phase control • Fewer power switches • Improved torque ripple control • Simpler structure • Cost-effective • Support for regenerative braking • Reliable operation	• Low efficiency • Energy recovery circuit losses • Higher voltage stress • Limited scalability • Energy loss in dumping the capacitor • Reduced fault tolerance • Thermal management challenges

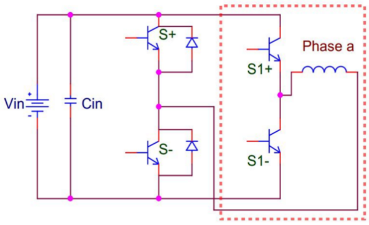
Type of Topology	No. of switches per phase	No. of diodes and capacitors per phase	Advantages	Disadvantages
AHB (Figure 25A)	2	2, 1	• Flexible control • Good fault-tolerant capability • Regenerative braking capability • Fast demagnetization • Simpler design • High efficiency • Improved torque control • Cost-effective • Easier thermal management • Regenerative braking support • Reduced electromagnetic interference	• More power switches and diodes • High losses • Lower power capability • Higher current ripple • Voltage stress on components. • Reduced scalability
H-bridge (Figure 25B)	2	2, 1	• Low switch losses • Suitable for modular design • Simple and robust design • Bidirectional power flow • Efficient torque control • High efficiency • Scalability • Compact design • Improved thermal performance • Flexibility • Enhanced reliability	• Underutilization of power switches • Extra power switches and gate drivers • Complexity in commutation • Switching losses • Higher voltage stress • Limited fault tolerance • Reduced efficiency at low load • Electromagnetic interference
NIPC (Figure 25C)	2	2, 1	• High efficiency • Simplified design eliminates the need for additional inverters • Cost-effective, reduces component count and system complexity • Enhanced reliability • Improved torque ripple reduction • Compact size and optimized design • Efficiently handles regenerative braking, enhancing energy recovery in EVs	• Limited fault tolerance • Can generate higher electromagnetic interference and noise • High switching losses • Adapting NIPC with existing SRM designs and EV systems can be challenging

Type of Topology	No. of switches per phase	No. of diodes and capacitors per phase	Advantages	Disadvantages
T-type (Figure 25D)	3	2, 1	• Reduced switching losses and conduction losses enhance overall system efficiency • Reduced torque ripple • Compact design requires fewer components, resulting in a lightweight design • Supports better utilization of the DC bus voltage, enhancing motor speed and performance • Cost-effective • Effectively supports energy recovery during braking • Lower power losses result in reduced heat generation, simplifying cooling requirements. • Reliable operation • Suitable for various power levels, making it adaptable for different EV applications	• Switching complexity • High-speed switching may generate significant electromagnetic interference, requiring additional filtering • Concentration of power handling in specific components may lead to localized heating issues

Abbreviations: AHB: Asymmetric half bridge; DC: Direct current; EV: Electric vehicle; NIPC: Novel integrated power converter; SRM: Switched reluctance motor.



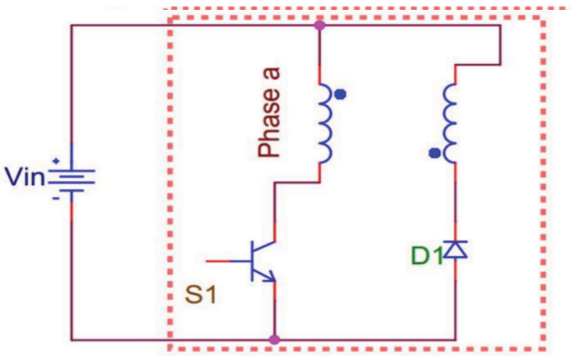
a) Split DC Source



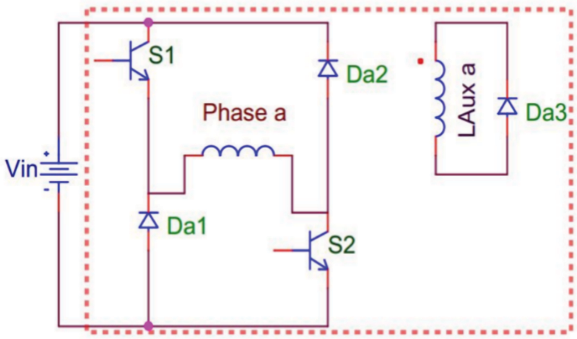
b) Star Connected

Figure 21. Types of single power converters. (A) Split direct current source. (B) Star connected. Adapted from Deepak et al.[79]

Based on an extensive literature review (Table 3), three converter topologies have emerged as the most suitable for SRM applications: the asymmetric half-bridge (AHB),[89] novel integrated power converter (NIPC),[87] and T-type converter.[88] Each of these configurations demonstrates a unique combination of efficiency, control flexibility, reliability, power productivity, and cost-effectiveness, making them highly compatible with the performance demands of modern

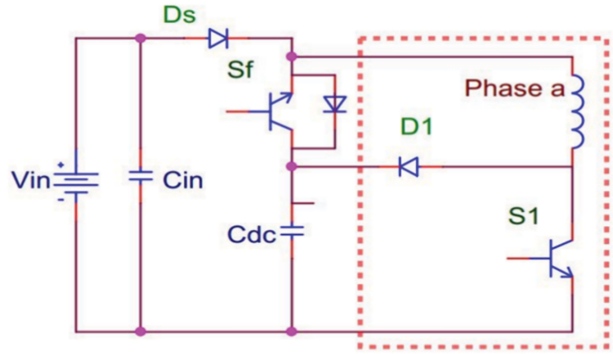


a) Bifilar

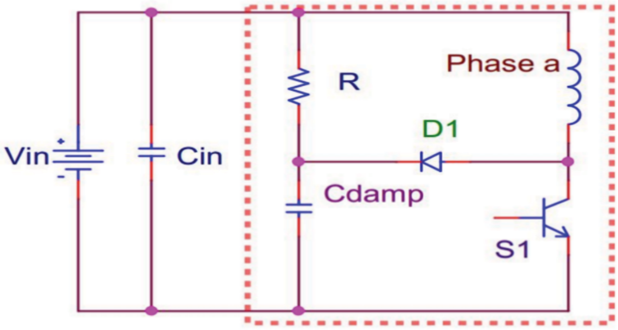


b) Auxiliary Commutation Winding

Figure 22. Types of magnetic power converters. (A) Bifilar. (B) Auxiliary commutation winding. Adapted from Deepak et al.[79]

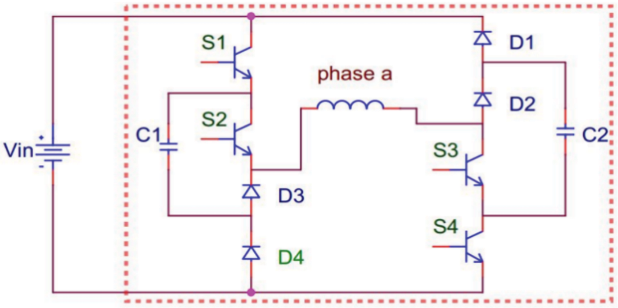


a) Sood

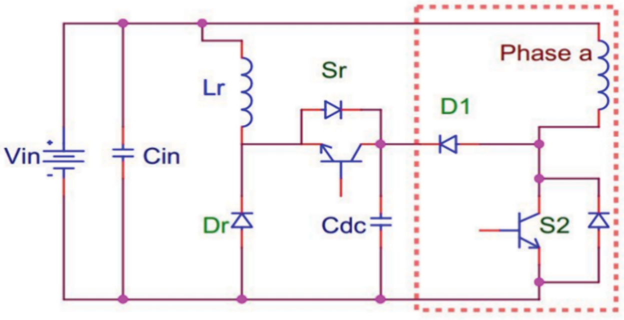


b) R-Dump

Figure 23. Types of dissipative power converters. (A) Sood. (B) R-dump. Adapted from Damarla et al.[80]

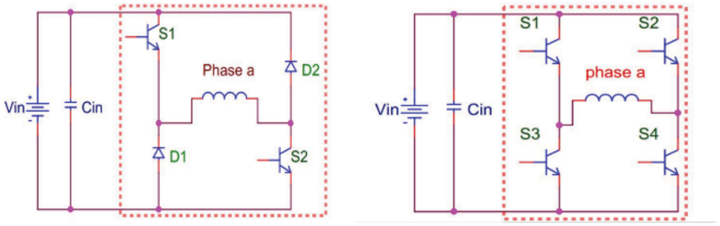


a) Flying Capacitor



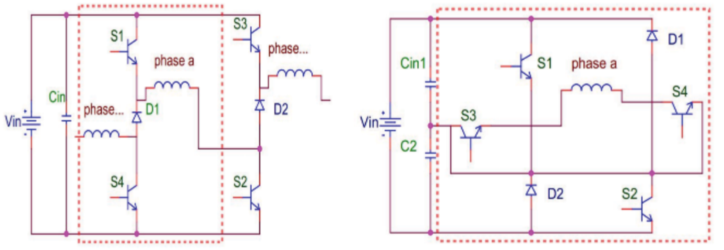
b) C-Dump

Figure 24. Types of capacitive power converters. (A) Flying capacitor. (B) C-dump. Adapted from Yamada and Hoshi.[81]



a) Asymmetric Half Bridge (ASHB)

b) H-bridge



c) Novel integrated power converter (NIPC)

d) T-Type

Figure 25. Types of bridge converters. (A) Asymmetric half-bridge. (B) H-bridge. (C) Novel integrated power converter. (D) T-type. Adapted from Gaafar et al.[88]

EVs. The selection of these three topologies is grounded in their proven performance across multiple studies and real-world applications: the AHB topology is widely recognized for its reliability and control precision, the NIPC is valued for its integrated design and reduced component count, and the T-type converter is lauded for its efficiency in specific operating ranges. While these characteristics have established their suitability, the detailed operating principles and implementation considerations of each topology are discussed in subsequent sections.

4.3.1. Asymmetric half-bridge

The AHB topology, widely recognized for its robustness and simplicity, provides excellent control over phase currents and offers high reliability under varying load conditions. However, its inherent requirement for a greater number of switching devices per phase increases cost and complexity, particularly in high-power applications. The AHB converter is widely implemented with several control schemes.[90] Figure 25A depicts the topology of AHB. The AHB architecture offers significant advantages due to its inherent flexibility in selecting control strategies. However, using a greater number of switching devices increases the cost.

4.3.2. Novel integrated power converter

The NIPC topology integrates functionalities to reduce the number of active components while maintaining adequate performance, thereby achieving a favorable balance between efficiency and cost. Despite its integration advantages, NIPC may face limitations in scalability and thermal management in larger SRM systems. NIPC lowers the costs by requiring fewer devices and enhancing the reliability of switch reluctance drive (SRD) systems. Studies indicate that all power devices are susceptible to faults, and the impact of these faults on the operation of NIPC differs. A short circuit in the capacitor and diodes would lead to a short circuit of the power source, resulting in complete power converter failure. Additionally, an open-circuit fault in the diodes would interrupt the release path of stored energy, causing overvoltage that can damage the power devices; hence, the system cannot continue operating under the faulty diode. In contrast, when a battery is chosen as the power source, the response speed of the DC link is lowered under the open-circuit fault of the capacitor; however, the NIPC can still operate.[87] The NIPC topology is illustrated in Figure 25C.

4.3.3. T-type converter

The T-type converter delivers a compelling compromise with reduced conduction losses and improved efficiency in medium-voltage ranges, positioning it as a strong candidate for EV applications. However, its control complexity and sensitivity to parameter variations necessitate the use of advanced control strategies for optimal operation. The T-type converter demonstrates a significant ability to mitigate torque ripple by enabling simultaneous magnetization and regenerative demagnetization between two phases. Nonetheless, its potential for enhancing power productivity remains limited due to the limitations imposed by magnetization voltage and regenerative demagnetization. Besides, it also offers fault-tolerance capability. The T-type converter topology is illustrated in Figure 25D.

When comparing the AHB, NIPC, and T-type converter topologies, the most suitable choice depends on specific design priorities, such as cost, efficiency, fault tolerance, thermal management, implementation complexity, and space constraints. As shown in Figure 26, the T-type converter demonstrates superior overall suitability for SRMs in EV applications.

5. Conclusion

This paper provides a comprehensive review of the state-of-the-art control strategies and power converter topologies for SRMs in EV applications. Through a detailed examination of torque control techniques, including indirect torque control, DTC, and AI-based control strategies, this study highlights their effectiveness in mitigating the drawbacks of SRMs, particularly torque ripple and acoustic noise. Each strategy presents distinct advantages and disadvantages, and the choice of technique depends on the desired application requirements. However, for EV applications, the DITC strategy demonstrates superior efficiency in mitigating torque ripple, offering both ease of implementation and flexibility across a broad range of torque and speed conditions.

In addition to control techniques, this study also explored several power converter topologies commonly employed in SRM drives, summarizing their major advantages and drawbacks. Among the various topologies, surveys revealed that the fault tolerance, rapid demagnetization, and regenerative braking capabilities of the AHB, NIPC, and T-type converters make them particularly suitable for EV applications. The AHB and NIPC converters offer a favorable cost profile while providing high efficiency and a significant capacity for torque ripple reduction. However, their ability to enhance power productivity remains comparatively limited. In contrast, the T-type converter represents a superior conversion mechanism, providing redundant switching states that enable both magnetization and regenerative demagnetization. When paired with a four-phase SRM, this topology emerges as the most optimal configuration due to its ability to handle high switching frequencies and reduce switching losses, while maintaining excellent fault tolerance and reliability.

By synthesizing the available research, this study identifies a four-phase SRM coupled with a T-type converter and controlled via DITC as the most promising configuration for EV applications, as shown in Figure 27.

A four-phase SRM is considered, with phases designated as a, b, c, and d, all of which are energized in succession. Shared switches allow the energization of non-consecutive phases, specifically, phases a and c, while additional shared switches energize the remaining non-consecutive phases, namely phases b and d, achieving a high level

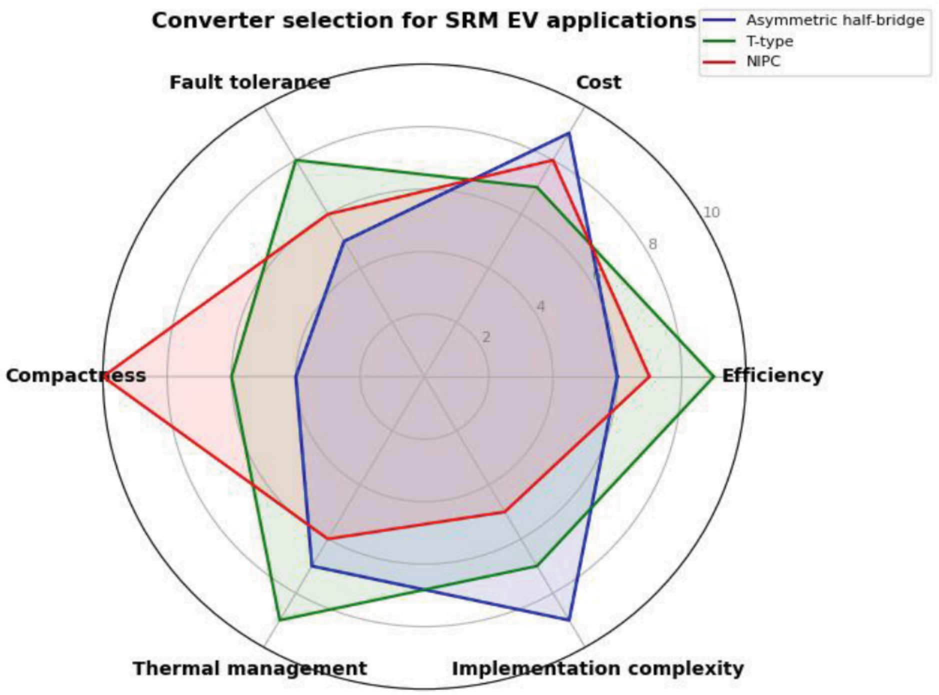


Figure 26. Comparison analysis of the asymmetric half-bridge, novel integrated power converter, and T-type converter topologies. Figure created by the authors using Python software
Abbreviations: EV: Electric vehicle; SRM: Switched reluctance motor.

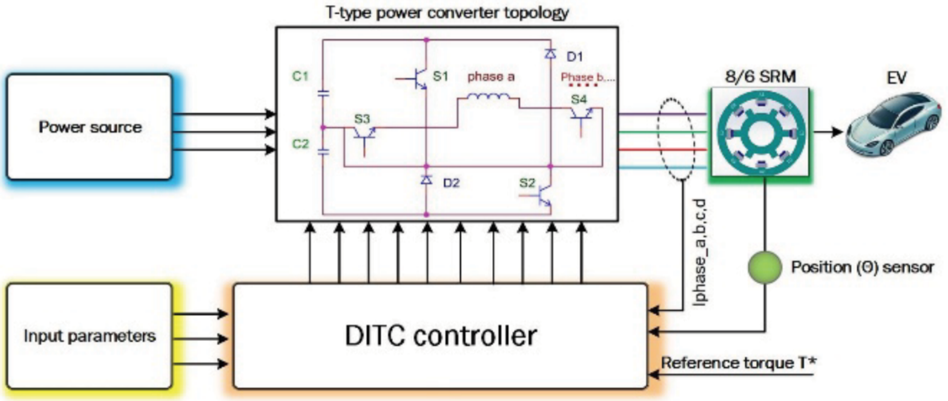


Figure 27. Proposed SRM drive for EV applications. Figure created by the authors using Microsoft Visio software
Abbreviations: DITC: Direct instantaneous torque control; EV: Electric vehicle; SRM: Switched reluctance motor.

of converter switch utilization. When coupled to a T-type converter, this four-phase SRM configuration offers several advantages, particularly in efficiency, reliability, and performance. The extra phase in the motor reduces torque ripple, ensuring smoother operation, while the T-type converter minimizes losses and electromagnetic interference through its advanced three-level design. This setup also enhances fault tolerance, allowing the motor to continue operating even if one phase fails. Additionally, the system distributes power more evenly, improving thermal management and extending the lifespan of components. Overall, this configuration provides a balanced trade-off among motor performance, cost, and system complexity, making it particularly advantageous for EV applications that demand cost-effective, reliable, and high-performance solutions. These features ensure smooth operation and high reliability, both of which are critical for EVs.

Future research should focus on enhancing the adaptability of SRM drives to varying operating conditions, improving efficiency across a broader range of speeds and loads, and minimizing the impact of torque ripple under dynamic conditions. Furthermore, incorporating advanced AI techniques, such as machine learning for adaptive control and fault detection, can enhance the real-time performance of SRMs, enabling them to respond more effectively to varying driving conditions in EVs. Additionally, the development of more efficient power converters and their integration with SRM drives remains a key area for innovation, particularly in reducing losses and improving overall system efficiency. Recent developments in lightweight materials, such as amorphous alloys, along with optimized motor topologies, including axial-flux designs and integrated ripple-suppression controls, are essential for addressing the weight and size constraints of SRMs in compact EVs. Overcoming these challenges will allow SRMs to compete effectively in space-constrained, high-efficiency EV applications.

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Conflict of interest

The authors declare that they have no conflict of interest regarding the publication of this article.

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Availability of data

Not applicable.

AI tools statement

All authors confirm that no AI tools were used in the preparation of this manuscript.

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