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Review Article

A Comprehensive Review of Recent Developments in Torque Ripple Minimization of Switched Reluctance Motor Drives

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Abstract *- Recent research efforts have increasingly focused on Switched Reluctance Motors (SRMs), with extensive investigations reported for applications ranging from transportation and aerospace to industrial and residential systems. Torque ripple in an SRM is mainly caused by the dependence of electromagnetic torque on rotor position and the discrete nature of phase excitation. Consequently, numerous strategies have been recognized to reduce torque ripples using both direct and indirect approaches. Through the smoothing of the torque output from the motor, these methods aim to lessen vibration and noise. There have been a lot of studies conducted regarding minimizing torque ripple in SRM drives, and various approaches have been presented to address this problem. The objective of this review is to explore the various strategies and techniques developed to reduce torque ripple in SRMs.The goal of the survey is to study the approaches and models that have been established to lower the SRM's ripple torque. The reviews cover the pre-processing techniques to reduce torque ripple, such as changes to the power electronics, controller algorithms, and motor design. It also gives the surveys related to the SRM using current shaping, predictive control, and DTC, respectively. The different metrices used in the works were also exposed in the analysis part of the paper. By examining several methods used in the literature, the work provides a thorough overview of the torque ripple minimization technique in SRM drives and draws attention to the effectiveness, challenges, and future possibilities of this sector.*

Keywords *- Direct Torque Control, Torque Ripple Minimization, Model Predictive Control, Switched Reluctance Motor Drives, Current Shaping.*

1. Introduction

Industrial adoption of Switched Reluctance Motors (SRMs) has expanded significantly due to their simple construction, absence of permanent magnets, mechanical robustness, and inherent fault tolerance [1-5]. These attributes make SRMs particularly attractive for applications requiring high reliability and harsh-environment operation. Nevertheless, torque ripple remains the principal technical barrier restricting their broader deployment in high-performance systems. The doubly salient structure and nonlinear magnetic characteristics of SRMs inherently produce discontinuous torque profiles, resulting in pronounced torque pulsations. Excessive torque ripple directly contributes to acoustic noise, mechanical vibration, increased stress on drivetrain components, and degraded energy efficiency [6-8]. Consequently, effective ripple mitigation is essential for enabling SRMs to meet the performance standards demanded in robotics, precision industrial drives, and electric vehicle propulsion systems [9-15]. From a physical standpoint, SRM torque production is governed by the rotor's tendency to align with the minimum reluctance position. The instantaneous electromagnetic torque is proportional to the derivative of phase inductance with respect to rotor position and to the square of the phase current. Because the inductance profile is highly nonlinear and strongly influenced by magnetic saturation, uniform torque generation requires precise coordination between excitation current and rotor angle. The most critical source of ripple occurs during phase commutation, where torque transfer between outgoing and incoming phases is imperfectly synchronized [16-25]. Insufficient current overlap during this interval produces torque dips, whereas excessive overlap induces torque spikes. At higher speeds, limited demagnetization intervals and elevated back-electromotive force further intensify these effects. Hence, torque ripple suppression is not merely a current regulation problem but a multidisciplinary challenge involving electromagnetic design, converter topology, and advanced control theory. Despite these intrinsic challenges, SRMs remain competitive alternatives [26, 27] to conventional motor technologies across diverse domains, including integrated motor-drive systems [5, 6], aircraft starter–generator platforms [36, 37], electrified transportation [28], renewable energy applications [29-35], and ultrahigh-speed machinery [38, 39]. However, the nonlinear flux–current relationship and doubly salient geometry significantly complicate smooth torque control [41]. Additional limitations include elevated acoustic emission, structural vibration, and the dependence on accurate rotor position information. To address these issues, extensive research efforts have explored both machine-level design optimization, such as pole arc modification, air-gap tailoring, and winding topology refinement, and advanced control methodologies aimed at shaping phase current and improving commutation performance [41-45]. Studies in [45-48] investigate magnetic circuit optimization strategies aimed at improving torque density, reducing torque ripple, and enhancing the scalability of SRM topologies. These works emphasize electromagnetic design refinement, including geometric parameter tuning and structural modification, to improve torque smoothness without compromising power capability. In addition, diverse rotor position sensing techniques- both sensor-based and sensorless have been developed, with intelligent estimation algorithms employed to improve commutation accuracy and operational reliability. Converter topology optimization has also received considerable attention.

The configurations analyzed in [49-51] address switching performance, ripple mitigation, and application-specific adaptability under varying load and speed conditions. Owing to their mechanically robust structure, thermal resilience, and absence of permanent magnets, SRMs maintain stable operation across wide speed and temperature ranges, making them suitable for harsh and variable-speed environments [52, 53]. Nevertheless, inherent structural and electromagnetic characteristics continue to limit SRM performance. The doubly salient geometry produces highly nonlinear flux-current relationships, and imperfect phase commutation introduces significant torque ripple and acoustic noise [54]. Furthermore, conventional control approaches exhibit limited adaptability, as torque regulation accuracy depends strongly on machine parameters, converter dynamics, and feedback precision [55]. Accordingly, recent research has shifted toward advanced control frameworks, including predictive, adaptive, and AI-assisted strategies, to compensate for magnetic nonlinearity and improve phase coordination. These approaches aim to achieve superior ripple suppression, enhanced robustness, and improved dynamic performance, thereby strengthening the practical viability of SRM drives in high-performance electrical applications.

Despite extensive investigations in [1-55], torque ripple minimization in SRM drives remains fragmented across isolated approaches, including DTC-based control, predictive strategies, current profiling, and structural optimization. Most studies evaluate individual techniques under limited operating conditions, without a unified framework for systematic comparison. Consequently, objective benchmarking in terms of ripple reduction effectiveness, computational complexity, hardware requirements, cost impact, and practical feasibility is lacking. Reported ripple reduction levels vary widely due to differences in speed ranges, load conditions, and evaluation metrics, further complicating direct comparison. Although advanced predictive and AI-based methods show promising improvements, their real-time implementation challenges and cost–performance trade-offs are not comprehensively addressed in existing reviews. Therefore, a structured and integrated comparative analysis is necessary. This work bridges that gap by classifying and quantitatively evaluating torque ripple reduction techniques, highlighting their strengths, limitations, and suitability for applications such as electric vehicles and high-performance industrial drives.

The contributions of the paper are summarized as follows:

- Analysis of 50+ research publications and different approaches for ripple torque reduction in SRM drives.
- Examination of different pre-processing techniques for reducing torque ripple.
- Address several control schemes and algorithms, including advanced control methods like current shaping, predictive control, and DTC, that are developed for ripple torque lessening in SRMs.
- Evaluation of key performance metrics, such as torque smoothness, efficiency, current waveform quality, and motor performance stability, is used to assess torque ripple minimization.
- To discuss current research gaps and challenges in minimizing torque ripple, including addressing high system complexity, optimizing trade-offs between cost and performance, and ensuring robustness in practical applications. These points are intended to guide future research in improving SRM drive performance.

The organization of this work is listed below: Chapter 1 presents a brief review of techniques for reducing torque ripple in SRM drives; Chapter 2 presents the state-of-the-art procedures for the SRM torque ripple reduction models; Chapter 3 analyzes and discusses existing techniques of the SRM; Chapter 4 identifies research gaps; and Chapter 5 concludes the paper.

2. State-of-the-Art Research

Torque ripple reduction strategies in SRM drives have evolved from conventional Chopping Current Control and fixed commutation angle methods to advanced control frameworks. Techniques such as TSF and ATC improved phase coordination during commutation. With advances in digital processing, DTC and MPC enabled faster dynamic response and enhanced ripple suppression. More recently, AI-based and hybrid control approaches have been introduced to address magnetic nonlinearity and operating variability. Each method involves trade-offs in ripple reduction capability, computational demand, and implementation complexity.

2.1. Pre-Processing Approaches

In SRMs, pre-processing techniques can reduce torque ripple and optimize performance during real-time control execution. It examines several pre-processing strategies for reducing torque ripple, such as modifications to the power electronics, controller algorithms, and motor design. Haque et al. [3] suggested a control strategy to preserve machine performance while lowering the current ripple in the dc-link. This study maintains the performance of the machine by reducing the DC-link ripple current with the use of the control that has been analyzed. The suggested approach separates the ripples of the current of the DC-link, with the use of a high-pass filter. This approach enables inter-phase circulation of residual energy and minimizes energy pulsations from the DC source. Through the broad range of speed, the ripple of the DC-link was lowered for the purpose of allowing the SRM to operate in a dependable and effective manner without the need for any hardware. However, with the speed of 1200 rpm, the torque was transmitted from 50 Nm to 98 Nm in the existing management techniques. As a result, this algorithm presents many possibilities and feasible options, particularly in automotive software. Ling et al. [24] suggested a novel approach based on the improved torque distribution function for suppressing SRM torque ripples. The 4-phase, 8/6-pole SRM electromagnetic representative method is initially created, and each method is then fully acquired with the CMAC.

The torque reference for each phase was first calculated by designing an improved torque distribution function based on the torque model, and then mapped to the reference flux linkage using the inverse torque model. With the use of torque ripple, every phase of reference torque is calculated to improve the distribution of the torque. Lastly, every phase of the voltage PWM duty was given as output with the use of PID control theory. Using this exact model-based planning strategy on the simulation structure decreased the average error to within 1% and the output values of the highest variable torque below 3%. These results were effectively less than the 15% error that would result from using the conventional DTC method. In 2022, Anuchin et al. [25] employed offline analysis of the magnetization surface of SRM in the suggested model predictive control technique. The SRM’s magnetization surface was handled via the suggested model predictive control approach. In the OE mode, this helps in obtaining predefined references of current for every position of the angular rotor and instruction of torque. In online mode, the predictive control method quickly determines the appropriate voltage command of the converter by implementing a present direction using the magnetization field. Modern microcontrollers were used to implement the CCS MPC. A simulation model that successfully stabilized the torque from 0 to the rated speed served as confirmation. In 2015, Zeng et al. [30] presented a new DITC for an 8/6 switching reluctance drive that operates in four phases. A DITC by a distinct switching approach was created based on the characteristics of the ideal TSFs. The testing findings confirm that it can attain the maximum working range by producing a similar phase torque. Based on the ideal TSF that could provide the greatest performing range, the reference phase current was determined. The testing findings confirmed that it could attain the maximum working range by producing the same phase torque as the ideal TSFs.

A simplified ATC approach for electric vehicles was introduced by Hamouda et al. [31] and employed to determine optimal SRM control parameters numerically. The torque ripples were found to be greatly reduced by the current control as contrasted to traditional methods. The suggested control scheme aims to reduce complexity and expense by simplifying the control algorithm. Further, it strives to satisfy the requirements of every vehicle. The most effective excitation settings that can satisfy the vehicle criteria were found using an optimization model. Two terms composed the objective function: efficiency and torque ripple. Reliable operation, MTPA generation, and high-performance control were all achieved by including appropriate limits for different angles. To confirm the insensitivity parameter, quick dynamics, extra torque limitations, and monitoring the torque with high-performance were also included. A precise motor method was produced with the use of flux and torque features that were determined experimentally. Approximately 72.43% was the average torque ripple reduction ratio across the speed range. It also had drawbacks, such as the requirement for meticulous parameter tweaking and possible difficulties in reaching the optimum torque at all working positions. In 2015, Cheng et al. [33] examined SRM’s ATC and instantaneous torque control algorithms to choose the best control mode for use in EVs. The accuracy of the steady-state torque would be increased, and a real-time estimation of the SRM’s average torque would be produced. It might be computationally complex and may encounter difficulties at high speeds, but it provides accurate torque control and less ripple. Even with its simplicity, ATC might have trouble with dynamic responsiveness and may sacrifice overall effectiveness and torque ripple suppression.

In 2020, de Paula et al. [39] offered a method for online turn-off angle variation called MTRPT. The model introduced back-emf cancellation and the Dahlin cruise controllers. The present design profiling method was taken into consideration by the system model. Simulation and experimentation were used to validate the developed model. EUDC and ECE-R15 driving lists confirm a system’s minimum ripple torque tracking capability at wide operating speeds. At the instant of a load change, the convergence time of MTRPT was approximately one second in both simulations and experiments. The controller’s speed tracking feature in simulation yields an RMSE of 0047s for the ECE-R15 driving cycle and 00182rad s for the EUDC driving cycle. The tracking error of speed was 099% and the turn-off angle was fixed at 13414%. The possibility of complicated control algorithms and the requirement for accurate parameter predictions were its main disadvantages, since they might raise the overall complexity and cost of the system. In 2022, Hamouda et al. [41] created the UTC method for SRM to satisfy every vehicle's needs at a variety of speeds. There were two distinct control methods used in the developed UTC. It employed an ATC at high speeds and a DITC strategy at low speeds. The DITC and ATC are chosen depending on their performance in terms of current ratio, efficiency, and ripple torque. Findings demonstrate that the suggested UTC can meet vehicle specifications and obtain an advantage of torque control across the entire speed value. For SRMs, UTC was a control method that sought to provide the best torque management throughout a broad speed range, especially in applications such as electric automobiles. High torque ripple, a major problem with traditional SRM control techniques, particularly at lower speeds, was resolved.

2.2. Various Control Techniques

2.2.1. Direct Torque Control (DTC)

DTC has been extensively adopted in SRM drive systems to mitigate torque ripple. The torque of the motor and flux linkage are directly managed, which enables a faster and accurate torque response than traditional techniques. Other methods that reduce torque ripples in SRM drives include ATC, TSF, and Predictive DTC. However, DTC's primary goals are sensorless control, high efficiency, fast torque response, and accurate control. Robotics, wind turbines, elevators, cranes, industrial drives, and electric cars are examples of prevalent applications. DTC is a widely used technique for SRMs to minimize torque ripple. In 2018, Yan et al. [7] employed a DTC technique to reduce the intrinsic output torque ripple of the SRM.

First, the hysteresis-loop control flux was eliminated. To reduce ripple torque, a novel voltage vector selection strategy was developed. Secondly, due to the inductance profile, the electrically separated sectors are rearranged in their actual positions. Real-time working conditions were used to identify and update the boundaries between certain sectors. Lastly, if any phase was excited, it distinguishes the different voltage vectors for raising or decreasing torque. Thus, the ripple torque is reduced since the output torque precisely mirrors the reference. Based on the real-time turn-off angle, the ampere ratio of torque was raised to prevent the negative torque. The suggested approach reduced the experimental prototype's torque ripple from 38.33% to 16.67% when compared to the conventional DTC method. The model increased the torque-ampere ratio by at least 18.43%. The fact that the constant reference flux ratio was not appropriate for every operating state was one of the disadvantages. In 2018, Sadat et al. [8] suggested a new torque control technique based on DTC-SVM for a 3-phase 6/4 SRM. A certain phase and amplitude, including vector voltage, was determined using FLC to correspond with the intended variations in the flux and motor's torque. Using the SVM algorithm, the estimated voltage vector was inserted into the SRM. It required less than 0.045 seconds for the suggested control system to track flux references. A quick dynamic response could minimize both stator flux and motor torque ripple. In 2018, Han et al. [9] suggested the four-phase SRM using the DTC approach. To establish the switch-on/off state principle, the connection between the voltage vector and space flux vector was examined. Simulink was used to represent the DTC control technique in contrast to the prevalent old strategy known as CCC. In comparison to the conventional approach, according to the simulation, DTC reduced the torque ripple by 73% for a four-phase (8/6) SRM. In 2021, Sun et al. [10] presented a DTC-based NTSMC. Based on unusual perturbation parameters and load disturbance, the NTSMC was able to reduce the torque ripple and disturbance in the system. Consequently, under NTSMC, the SRM's torque ripple was decreased from 53.4% to 31%. This improved SMC's torque ripple reductions (from 60.3% to 37.5%) and PI's (from 65.9% to 44%).

In 2018, Ye et al. [18] assessed a TSF family's maximum qth-power current value to reduce torque ripples in the SRM. In comparison to the sinusoidal, linear, and CCC TSFs, the TSF1 (r = 4) had a reduced peak and phase rms current. Further, the TSF1 (r = 4) showed a commuting TRR in the saturation magnetic domain at 3000 rpm that was one-third lower than that of the conventional TSFs. In 2019, Sheng et al. [20] proposed a novel approach to the DTC algorithm that used model predictive flux control to address the issue of significant torque ripples in an SRM. First, the SRM's discrete time method determines the flux linkage using the following period. Using a torque hysteresis generated in the model, the three potential voltage vectors for the cost function are selected. It also lessens the computational load and improves dynamic response. Implementing and choosing the optimal voltage vector in the system depends on lowering the flux linkage. A nonlinear magnetic property of SRM was well suited to the suggested DTPFC approach, which also performs better in both dynamic and steady-state circumstances than DTC.

2.2.2. Predictive Control

Predictive control algorithms are mostly used to reduce ripple in torque in SRMs by forecasting the motor's future behaviour and optimizing control signals to reduce torque variations. To accomplish this, a model of the SRM is used to predict the torque production for a range of possible control actions. The action that results in the smoothest torque profile is then chosen. In 2022, He et al. [26] proposed a better hybrid control system for the torque drive scheme of a 12/14 bearing less SRM that uses LADRC based on MPTC. The suggested method could improve the anti-disturbance capability and significantly lower the ripple torque. To lessen the ripple torque in the commutation interval, a modified piecewise TSF was first used. Second, to further lessen the ripple torque, the hysteresis control and model predictive control were implemented. Since the TSF determines the value of current using various circumstances of every phase, choosing an ideal weighting factor was avoided, and the cost function could be made easier. To achieve better tracking and anti-disturbance capability, an improved LADRC-based speed controller was developed using an extended state observer with proportional observation error gain and a time-varying function. On the extended-state observer, the observation error and a time-varying function's proportionate gain were examined to perform better tracking using the controller, as well as anti-disturbance ability using an improved LADRC. When compared, the MPTC with cosine TSF and the MPTC with modified MPTC reduce the TRR to 34% and 18%, respectively. The method demonstrated superior results in the model.

In 2019, Ding et al. [27] suggested a novel hybrid control approach that integrates vector control with continuous current conduction to increase HESRM's efficiency. The HESRM controller was made simpler, and torque ripple was decreased by redefining vector control, which was commonly used in AC machines, based on static torque characteristics. However, the torque ripple reduction effect worsens, thus the current tracking accuracy declines with high speed and heavy load operation. Vector control was used in conjunction with continuous current conduction to maintain smooth torque ripple and increase the precision of current tracking. For HESRM, power typically decreases almost proportionately to the square of speed in the baseline; moreover, the conventional control methods were sustaining a limited range of constant power. Since the HESRM under investigation possessed a very low base speed, the hybrid control method increases the constant-power range. This strategy reduced torque ripple and expanded the constant-power area for every SRM, including dissimilar nominal power and speed.

In 2024, Al Quraan et al. [28] proposed an improved TSF-based indirect ITC to reduce torque ripple for SRM drives that are operating at greater speeds. To lessen the torque ripple, the TSF was improved depending on forecasting the departing phase torque through the demagnetizing phase. Also, to achieve even greater benefits and increased speed, the control angles were adjusted using straightforward analytical methods. Depending on the static magnetic properties calculated by the finite element examination, a precise nonlinear motor model was produced.

As speed increases, the technique provides a torque ripple mitigation, effectively reducing it by 10% to 45%. Also, the regulator increases efficiency as well as the torque/current ratio, and decreases the copper losses. In 2023, Al Quraan et al. [29] presented a technique that used DITC and an adjustable turn-on angle to enhance torque ripple performance in SRM-based electric vehicle drives. Similarly, the DITC was passed into the minimum phase induction part, and the receiving and the departing phases were altered to track the necessary torques in the model. However, the receiving phase was exiting its least inductance zone when the departing phase was demagnetized. Thus, for tracking, the incoming phase state was altered. Also, as the stator and rotor poles are ready to intersect, closed-loop regulators were used to manage the turn-on angle to obtain its initial peak, hence enhancing the motor's efficiency. The classic DITC and conventional DITC had maximum and lowest torque error thresholds of 0.4 and 0.2, respectively.

2.2.3. Current Shaping

The SRM control approach uses current shaping to control the current waveform phase and reduce torque ripple effectively. To reduce pulsations and enhance the smoothness of torque delivery, the current profile must be optimized. Control algorithms can reduce torque ripple and enhance the SRM's overall performance by accurately regulating the current. In 2021, Li et al. [32] suggested an indirect control strategy with high performance for the SRM drive system that minimizes ripple in torque. With lower copper losses, this could reduce torque ripple. In this model, the generated copper loss P_{loss} was 5.43, and the stator phase current reached 7.8 A. It was computed using the copper loss P_{loss} of 5.92 and the peak current of 7.5 A. However, the stator's highest phase current was 7.9 A, while the copper loss was 6.37. As a result, the current tracking performance was good for the robust current controller. Its drawbacks included digital delays, model insecurity, parameter mismatches, and external disruptions.

In 2021, Ren et al. [34] explored a new control technique to decrease the ripple in the torque of an SRM that was dependent on MPC and TSF. The torque ripple coefficient of DITC exceeded 50% at various speeds, whereas MPTC maintained it at approximately 38%. In 2023, Omar et al. [36] demonstrated the use of a BPNN to map out the geometrical characteristics of the SRM. The ideal design lowers torque ripples by around 24% and increases average torque by about 2%. In 2019, Huang et al. [37] proposed a current profiling method for improving torque density in SRMs. Comparing the suggested technique to the traditional SRM excitation, the recommended approach could increase the torque density by 15% under rated conditions and by 20% under light load conditions.

In 2021, Das et al. [49] suggested a modification to the stator's structural design that would improve the structure's stiffness using mass proportion. "In this case, a 24-slot/16-pole SRM designed for NVH optimization using stator pole bridges at various target operating points achieved a noise reduction of 12.52 dBA compared to the baseline SRM, specifically through the stator pole bridge approach. In 2015, Kiyota et al. [50] suggested a cylindrical outer shape rotor in an SRM to decrease acoustic noise and windage loss at high rotational speeds. With 7500 r/min, including 2768 r/min, the estimated rotors produced an overall efficiency of 3.9% and 1.7%, which was less than the current model. As an actual suggested rotor had less windage loss, the effectiveness of the rotor drops at 7500 r/min and lower to 2768 r/min.

In 2023, Juarez-Leon et al. [51] presented various structural design strategies to lower an 8/6 SRM's acoustic noise, preserving its electromagnetic performance. A multiphysics Finite Element Analysis (FEA) was conducted to evaluate system performance for each technique. Acoustic noise data from a four-phase 8/6 SRM were used to confirm the multiphysics accuracy experimentally. In the 8/6 SRM, several structural approaches had been studied, and it also falls into two primary categories: rotor and stator-housing changes. For a stator and rotor structural changes, the final design reduces the total SPL by 19.48% while increasing the total mass by 2.63% and increasing the phase current's RMS value by less than 3% for the same electromagnetic torque.

In 2019, Zhang et al. [52] suggested a novel control technique to enhance SRMs' acoustic and vibratory performance. The traditional SRM control approach, ATC, was supplemented with two new control blocks: DFC and RCA. DFC was used for regulating the radiating force in the stator's teeth. The inherent trade-off observed between a DFC and ATC strategies was suggested to be handled by RCA.

To automatically adjust the reference current based on the control necessity, it generates an auto-tuning current reference. An auto-tuning current adaptor was used for balancing the trade-off, reducing the oscillation of DFC, and minimizing the TRR of ATC. Similarly, upto 17.9dB of vibration reduction was achieved near the natural frequency without compromising efficiency or significantly penalizing torque ripple. The maximum SPL was reduced by up to 13.7 dB near the natural frequency.

In 2021, Sadeghi et al. [53] employed an SRM drive system to balance vibration amplitude and torque profile. In this system, a single-phase Vienna rectifier was employed for SRM's front-end converter to enable rapid demagnetization and power factor adjustment. In demagnetization, the three-level Vienna rectifier was used to increase the negative voltage; however, it might reduce the current head and speed up demagnetization. During demagnetization, the voltage was improved by a detrimental effect on the amplitude of oscillation in the demagnetization area.

This control algorithm was developed by reducing the minimum rate of change within the linear average range during the demagnetization interval. The initialization of demagnetization was used for the purpose of performing the negative voltage modulation applied to the motor phase. The nominal voltage of the rectifier was mentioned as half of the DC-link voltage. The ACM technique was used by this SRM drive system to decrease THD at the AC side and achieve a unity power factor.

In 2023, Reis et al. [54] explored the use of the GA technique of a 2 kW 8/6 SRM to minimize torque ripples and improve the commutation angles. The main objective was to lessen the torque ripple. Using lookup tables derived from FEM simulations, the mechanism was first exhibited in MATLAB/Simulink. The ideal phase commutation angles were determined by using GA for the purpose of reducing the ripple factor of torque. However, the performance of the torque was impacted by the commutation angles for the search for the best solution. Then, using an asymmetric bridge converter and a built drive platform with DSP-based control, the GA output for its operation was confirmed. For one of the operating points under evaluation, the method employed proved appropriate for reducing the torque ripple by almost 50%. In 2023, Jing et al. [55] proposed an RTNN to lower torque ripple through online reference torque adjustment. First, the TSF approach forms the foundation of the RTNN. Furthermore, the RTNN was intended to be a single-input, single-output network. In RTNN, the first node parameter of the implicit function was the rotor angle, and it represented the periodic relationship of the ripple torque and angle of the rotor. As a result, reference torque could be effectively restrained by one-step RTNN modification. Finally, the torque ripple was decreased by modifying the RTNN's environments based on the torque inaccuracy. This work compares and tests the PD compensation, RTNN approaches, and fuzzy compensation. The suggested RTNN reduces a torque ripple by 77% and 25%, while the PD compensation, RTNN algorithms, and fuzzy compensation yield torque ripples of 51.7%, 15.7%, and 11.8%, respectively. When speed and load torque were increased, the survey reported that the TRR was lowered for varying degrees.

Table 1 summarizes the selected pre-processing techniques for SRM torque ripple reduction projects. Several ideas from the existing work on single-tooth winding topology, online average torque management, torque sharing functions, etc., were employed in this survey paper with a motor design approach. The torque ripples were significantly reduced by 30 to 50 percent. Several techniques from the existing work, including DTC, ACMC, and current shaping, MPC, and MPTC, are explained. It also presents articles based on controller algorithm approaches. It exhibited a 40-70% potential for reducing ripples. The PM, SST-SRM, and other techniques from previous papers were analysed in this paper on power electronics approaches. It experienced a moderate decline of 20 to 40% decline. However, the overall insight shows that minimizing torque ripple in SRM drives is most effective. The power electronics enhancements are most practical for existing systems, and the motor design optimization is best for new designs.

Table 1. Summary of selected control approaches for SRM torque ripple minimization

Control Techniques	Techniques	Impact	Advantages	Limitations
Motor Design Approaches [1, 4, 13, 23]	Single-Tooth Winding Topology, online Average Torque Control, and torque sharing functions.	Permanent reduction in torque ripple by 30–50%.	No control overhead; stable performance.	Not adjustable post-manufacturing; complex and costly redesign.
Controller Algorithm Approaches [2, 3]	DTC, ACMC, And Current Shaping, MPC, MPT	High ripple reduction potential of 40–70%.	Real-time adaptability; optimal under varying load/speed.	Computationally intensive; requires high-speed processors.
Power Electronics Approaches [5, 6, 24, 42-46]	Permanent Magnets, the Slotted Stator Tooth Switched Reluctance Motor (SST-SRM)	Moderate reduction by 20–40%.	Can retrofit existing systems; does not require motor redesign.	Adds cost, complexity, and thermal management needs.

2.3. Controller Algorithm

Due to the nature of torque output and the doubly salient structure, the SRMs are affected by the torque ripple problem. Numerous algorithms and control systems have been created to lessen this ripple. In 2022, Kimpara et al. [14] suggested a two-step method for reducing vibration and torque ripple in drives that use SRMs. This technique reduces torque pulsation and acoustic noise in SRM. It also provided a practical step toward the widespread usage of SRM in a variety of applications. A two-step method was suggested to achieve this goal. Secondly, the radial vibration was actively cancelled by applying the optimal current potential to the SRM using an adaptive hysteresis band controller. The investigation revealed that the suggested excitation causes a higher vibration, and it was reduced. The suggested technique employed an optimization process depending on the non-derivative optimization method and FRM to determine the ideal current profile, which reduces the torque pulsation. By using a hybrid technique with a standard square wave excitation, the stator vibration was reduced by 22% and the torque ripple was decreased by 42.6%.

In 2023, Sheng et al. [19] presented a DPTC technique to lower the SRM torque ripple and copper loss. Similarly, the DPTC process provides the commutation optimization. Initially, the line between two continuous phases was altered, and the achievable phase torque range was forecasted. A suppression of torque ripple was made simple by immediately splitting the range of the torque for producing a torque allocation set. Second, a cost function solely associated with the phase current was produced because of the problem of optimization during commutation. Additionally, the cost function could be solved for minimizing copper loss, eliminating the need for weight parameter selection. This approach uses a DPTC algorithm to optimize commutation. With torque ripples of 22.4%, 3.2%, and 39.4%, respectively, the DPTC approach was less disruptive than the MPTC method. This indicates that the technique decreases the TRR by 30.02%, 30.54%, and 45.63%, respectively, and that it corresponds adequately with the simulation findings.

In 2018, Li et al. [21] suggested FS-PTC, an enhanced finite-state predictive torque control, to decrease the SRM drive's torque ripples. First, a discrete-time model was developed for forecasting the upcoming states of the SRM drive model that also used an accurate analytical method. Second, the sector partition technique was used to lessen the computational load by introducing a novel switching table for the predictive controller.

Furthermore, the model could also evaluate the average switching frequency, copper losses, and torque ripple. Consequently, the suggested FS-PTC approach may effectively decrease the average switching frequency and copper losses for minimizing ripple in torque. Lastly, using the suggested control algorithm, the experimental findings were conducted for a three-phase, 12/8 pole, 1.5 kW SRM. The outcomes were contrasted with those of the traditional DITC technique. Comparing the control technique to the traditional DITC approach, the copper losses P_{loss} were reduced by 4.8, 6.5, and 3.7%.

In 2022, Shen et al. [22] proposed a predictive PCC technique for an SRM that was dependent on a local linear phase voltage approach. The PCC was simple to use and did not require a previous understanding of the motor's properties. In a short period of time, a linear model was suggested to estimate the association between the current and voltage slope. From a prior control cycle, the slope and intercept of the model were found by utilizing the current and voltage slope data. Thus, the obtained data was then utilized to forecast the average voltage to precisely track its reference within the subsequent PWM cycle. However, the phase voltage changed the DC link voltage to positive or negative values from zero. An experiment was conducted to confirm the efficiency of the suggested PCC. The findings showed that, by comparison of hysteresis control at a similar sampling rate, the suggested control system may greatly minimize the current and torque ripples. For pursuing a specific current profile, a PCC was comparatively appropriate. One of its disadvantages was that it required more current sensors.

In 2017, Jamil et al. [23] suggested an SRM online ATC for LEV applications. The ATC's function was stabilizing the dynamics of the system by regulating the average torque in the innermost control loop. This was done by calculating the average torque at each instant in time while considering the motor's primary parameters, such as speed, phase currents, and rotor position. The suggested ATC was made for modifying the switching angles and reference current to attain a necessary average torque at the operating speed, as well as to obtain the controller efficiency for traction control across a wide speed range. To achieve precise torque and estimated results, this research also suggested a torque approximation technique with a Fourier series approximation and the inductance profile. The effectiveness of the suggested approach was demonstrated through the simulation of a 3kW, 6/4SRM for LEV use. By applying the methodology for LEV applications, the exact torque estimation and average torque control were achieved.

In 2021, Gupta et al. [13] suggested several design techniques that were examined to enhance the radial flux performance. Depending on the rotor segment's pole arc equations, the collection of stator slots/rotor segments selection was examined. Further, the impact of winding polarity on DSSRM's output torque and core loss was examined. Lastly, as the rotor structure design was modified, the torque ripple was reduced.

It also suggested the angular shift in the alternate rotor segments in the direction of rotation. Using the ANSYS/MAXWELL software, the 3-phase 12/10/12 pole radial flux DSSRM-based finite-element model was created. It also displayed the simulation results to examine the efficacy of the suggested design modification. DSSRMs had a single-tooth winding setup. With the specified motor, the model obtained a reduced torque ripple of 40%. By increasing the incoming phase's torque-generating capacity in the commutation zone, the design could lessen the torque dip, and, in turn, the torque ripple was reduced.

In 2022, Al-Amyal et al. [35] offered a better DITC for SRMs. This method significantly improves the efficiency and torque of the system by adjusting the turn-on and turn-off angles. Thus, the torque of the system was significantly improved by the DITC strategy for reducing the torque ripple. An enhanced DITC for SRMs was presented in the study. Here, the revolutionary adaptive real-time commuting mechanism was incorporated.

The suggested approach could efficiently increase the efficiency by appropriately adjusting the turn-off and turn-on angles within the actual period. To attain the maximum torque generation capability, initially, a primary value of the turn-on angle was chosen. The immediate mistake could then be further adjusted in real-time using the pre-selected initial angle. As a result, the torque was reduced. The outcomes of the torque ripple minimization method were more apparent in the simulation results. This study presents a sophisticated optimization technique for serving the stand-in model, which uses dynamic as well as static properties of the model with the help of a learning technique. The average and ripple torque were mapped out in this work using a BPNN.

It was measured from the arc angles of the stator and rotor pole, the geometrical parameters of SRM, and the measures of dynamic performance of the model. To collect the training data and also examine the dynamic as well as static properties of the motor, the MATLAB and FEA models were used. The BPNN was trained via the Levenberg-Marquardt technique. The ideal design lowers torque ripples around 24% and increases average torque by about 2%.

In 2019, Sun et al. [38] developed a new HIL-based MEC for 16/10 SSRM simulation in real time. The iron core of the SSRM, air gap, and slot leakage were all hurdles in the suggested real-time MEC. A ten-cross-ten matrix scheme was created in MEC to accelerate the emulation process. The matrix system was solved using a new algorithm that cuts down on computing time. The HIL was used to conduct the experiment. It offered an accurate and up-to-date condition for the new method.

An operational platform for achieving the MEC model's real-time simulation on the test bench was provided by the field programmable gate array. As confirmed, the suggested real-time MEC model enhances the SSRM's performance assessment and real-time emulation. This model effectively replicated a novel 16/10 SSRM's performance. To estimate the motor performance without a prototype, the model could achieve precise and real-time emulation. It reduces the motor's improvement period, respectively. In 2021, De Paula et al. [40] presented a design strategy for a model that employs sliding mode as a cruise controller and a direct instantaneous torque controller as a component of the controlled plant.

By altering the reference torque with a generated approach, a back-electromotive force cancellation was also included. The sharpest descent MPPT model was adapted to suggest an MTRPT that operates over the turn-off angle. For improving torque regulation, this angle was also regulated. The cruise controller could reject load disturbances, which were robust to parameter changes and Lyapunov stable.

According to experimental findings, the MTRPT convergence time for a step of load was 25 s, and for a step of speed, it was approximately 1625 s. Regarding the driving schedules for EUDC and ECE-R15, the suggested system's speed tracking capacity provides an MAE of 09223% and 10884%, respectively. The torque ripple was decreased by 101% at high speeds (EUDC) and 146% at low speeds (ECE-R15) due to the MTRPT.

3. Analysis and Discussions

The performance of research papers is analysed and discussed in this context, along with the findings that emphasize the relevance of various implementation technologies for SRMs. To minimize torque ripple, the study focuses on current study gaps and challenges. These include addressing high system complexity, improving cost-performance trade-offs, and guaranteeing robustness in real-world applications. These concepts aim to guide further research for improving the SRM drive's performance.

3.1. Analysis of Performance Strategies of Torque Ripple Reduction Techniques for SRM Drives

In SRM drives, ripple reduction for torque is essential for boosting overall motor efficiency and dependability, reducing noise and oscillation, and also improving effectiveness. By examining various papers, the survey mentioned the maximum ripple reduction, higher complexity, and cost impact, which are represented in Table 2.

Significant torque ripple reduction is achieved when control strategies explicitly account for the nonlinear torque–position–current characteristics of the SRM. Conventional methods, such as CCC and fixed commutation angle control, lack adaptability to speed and load variations, leading to torque dips during commutation.

Advanced approaches, including DTC and predictive control, improve ripple suppression through optimized voltage selection and torque forecasting, while AI-based methods enhance real-time adaptability. However, these techniques require higher computational resources and hardware capability. Therefore, their practical adoption depends on achieving an appropriate balance between performance improvement and implementation feasibility.

Table 2. Analyzing the performance of SRM torque ripple reduction models

Citation	Ripple Reduction	Complexity	Cost Impact
[15, 20, 28, 36, 43, 46, 49, 50, 52]	Moderate	Low–Medium	High
[10, 14, 31, 55]	High	High	Medium
[39]	Very High	High	Medium

3.2. Ensuring Robustness in Practical Applications

Ensuring robustness in real-world torque ripple reduction utilization for SRMs is intended to enhance the motor's performance and dependability under a range of operating circumstances, especially when faced with unexpected interruptions or changes. The motor may operate more efficiently, with less noise and vibration, and maintain steady performance even when the load or speed changes by lowering torque ripple. Table 3 shows the various SRM drives used in the model to decrease torque ripple.

Table 3. Analysis of SRM drives used in the model

Citation	SRM Drives used in the Model
[1, 9, 14, 24, 29, 30, 51, 53, 54]	Virtual 4-phase 8/6 SRM
[3, 44]	3-phase SRM
[13]	3-phase 12/10/12 pole radial flux DSSRM
[5]	4-phase 16/10 pole SRM prototype.
[6, 20, 19, 21]	3-phase 12/8 poles SRM
[8, 12, 23, 37]	3-phase 6/4 SRM
[10]	6-phase 12/10 SRM
[11]	SSRM
[17]	6-Phase SRM
[32, 34, 35, 55]	12/8 pole SRM
[36]	6/14 SRM
[38]	16/10 SSRM
[42]	16/6 SST-SRM
[45, 48]	18/12 pole SRMs
[47]	4-phase 16/20 SRM
[49]	24s/16p SRM
[46]	Double Salient Structured SRM
[43]	HESRMs
[40]	DITC-SRM
[14]	8/6 SRM

3.3. Analysis of Metrices

Table 4 shows the speed variations of the SRM systems from the research papers for analyzing the performance of the systems. In this table, 10% of the research possesses 1000rpm-2000rpm speed values, and 80% of papers possess 2000rpm-3000rpm speed values. However, the remaining 10% research possesses a very high-speed rate of >3000rpm, respectively.

Table 4. Speed variation analysis

Citation	Speed of the SRM
[19, 32, 54, 55]	1000rpm-2000rpm
[1, 5, 24, 28, 37, 49, 16, 20, 21, 35, 50, 53, 12, 18]	2000rpm-3000rpm
[3, 14, 11, 43, 46]	>3000rpm

Table 5 shows the torque ripple reduction value obtained by the SRM systems. In this table, 50% of the research possesses a 1% - 30% torque ripple reduction rate, 35% of papers possess 31%-50% of torque ripple reduction rate, and 10% of papers possess 51%-80% torque ripple reduction values. However, the remaining 5% research possesses a very high torque ripple reduction rate of 80%-90%, respectively.

Table 5. Torque ripple reduction value analysis

Citation	Torque Ripple Reduction
[15, 20, 28, 36, 43, 46, 49, 50, 52, 55]	1% - 30%
[11, 12, 16, 17, 19, 28, 54]	31%-50%
[10, 14, 31, 55]	51%-80%
[39]	80%-90%

4. Research Gaps and Future Directions

One major issue that impacts the overall performance of SRM drive systems is torque ripples. Due to this difficulty, the system lags in creating smooth torque output with SRMs due to their nonlinear magnetic properties and discontinuous rotor locations. As the motor performs under different load settings, this problem gets exacerbated. The challenge of achieving a satisfactory compromise between reducing torque ripple and preserving system efficiency, control complexity, and cost endures despite a lot of work in this direction. Torque ripple can be reduced by several methods, including complex control schemes, rotor design changes, and advanced power electronics. However, the cost-effectiveness and usability of these approaches frequently prevent their widespread use.

4.1. Pre-processing Approach

4.1.1. Shortcomings

To address the shortcomings of SRM through pre-processing, it is important to identify the key limitations of SRM.

- The proposed UTC demonstrates performance with a moderately complex control algorithm [41].
- The model needs additional reductions of torque ripples [31].
- The settling time was constrained by the supply voltage and phase inductance [25].

4.1.2. Future Works

The future work related to pre-processing of SRM, focusing on emerging challenges, potential innovations, and areas that need further research, is as follows:

- The practical implementation and verification of the control strategies will be validated.
- Additional torque ripple reduction can be achieved by compensating the reference current through control and/or AI techniques based on measured machine characteristics.
- Future work includes experimental validation of the control systems, considering measurement errors and time delays.

4.2. Direct Torque Control (DTC)

4.2.1. Shortcomings

A main drawback of DTC in SRMs to minimize the ripple in torque is given below,

- NTSMC exhibits superior anti-disturbance performance under the same load disturbance and parameter variations [10].
- A single current sensor is installed on each phase line [18].

4.2.2. Future Works

Future studies can concentrate on several encouraging avenues to improve torque ripple reduction to overcome the present drawbacks of DTC when used with SRMs.

- The multistep predictive control will be used to improve steady-state performance.

4.3. Predictive Control strategies

4.3.1. Shortcomings

The primary drawbacks of predictive control for decreasing the torque ripples in SRMs are given below,

- In the initial stage, it has a shorter dynamic response time without overshoot [26].
- Because of the hysteresis current band and limited sampling frequency, the experimental results show current waveform burrs and slightly higher torque ripple compared to the simulation.[27].
- Three phases may overlap simultaneously, at very high speed [28].

4.3.2. Future Work

Future studies on predictive control for SRM torque ripple reduction are given below,

- Future investigations may focus on an in-depth trade-off analysis to offer deeper insights into the sensitivity of SRM performance.

4.4. Current Shaping Methods

4.4.1. Shortcomings

The current shaping has several drawbacks that limit its ultimate efficacy for torque ripple reduction, which are given below,

- It might require complex control algorithms and computationally intensive calculations, leading to potential issues with implementation and real-time performance [32].
- It should be noted that the current control, rather than voltage control, was required to generate the optimal current profile [37].

4.4.2. Future Works

Future research on current shaping in SRMs is given below,

- Future research directions can study the audio noise and shaking. Moreover, it will extend to consider other geometrical parameters such as the pole heights and taper angles.
- Improvements in the acoustic noise performance of the stator pole bridge model will be considered.

5. Conclusion

This review has presented a structured and comprehensive assessment of torque ripple minimization strategies in Switched Reluctance Motor (SRM) drives. By systematically analyzing more than fifty research contributions, the study integrated developments across motor design optimization, converter topology enhancement, pre-processing techniques, and advanced control methodologies. The findings confirm that effective ripple suppression requires coordinated consideration of nonlinear magnetic behavior, phase commutation dynamics, and converter–controller interaction. Pre-processing and structural design modifications offer permanent improvements in torque smoothness but are typically associated with higher redesign cost and limited flexibility after manufacturing. In contrast, control-oriented approaches, including TSF, ATC, DTC, predictive control, and AI-assisted frameworks, provide adaptive ripple mitigation across varying operating conditions. Predictive and intelligent techniques demonstrate superior ripple attenuation; however, they introduce increased computational complexity and hardware requirements.

A comparative evaluation based on key performance indicators, including torque ripple reduction ratio, dynamic response, speed operating range, current waveform quality, efficiency, computational burden, system complexity, and cost impact, reveals substantial variation across reported studies. While some methods achieve ripple reductions exceeding 50%, trade-offs in implementation feasibility, processor dependency, and economic viability remain significant challenges. The absence of a unified benchmarking methodology further complicates objective comparison among approaches.

Future research should focus on developing computationally efficient hybrid control architectures, experimentally validated under realistic load and speed variations, while ensuring robustness and cost-effectiveness. Particular emphasis should be placed on scalable solutions for electric vehicle propulsion and high-performance industrial drive systems, where torque smoothness, reliability, and energy efficiency are critical performance requirements. In summary, this work establishes an integrated comparative framework grounded in quantitative performance indicators, clarifies existing research gaps, and provides strategic guidance for advancing SRM drive technology toward high-efficiency, robust, and application-oriented motor systems.

Nomenclature

ADSMO	:	Anti-Disturbance Sliding Mode Observer
DTC	:	Direct Torque Control
EV’s	:	Electric Vehicles
PWM	:	Pulse Width Modulation
ATC	:	Average Torque Control
DSSRMs	:	Double-Stator Switched Reluctance Motors
MPTC	:	Model Predictive Torque Control
DPTC	:	Direct Predictive Torque Control
DE	:	Differential Evolution
PMs	:	Permanent Magnets
FEM	:	Finite-Element Method
SRM	:	Switched Reluctance Motor
MPC	:	Model Predictive Control
SST-SRM	:	Slotted Stator Tooth Switched Reluctance Motor
DFC	:	Direct Force Control
TRR	:	Torque Ripple Ratio
DTC-SVM	:	Direct Torque Control Via Space Vector Modulation
CCC	:	Chopping Current Control
TSF	:	Torque Sharing Function
NTSMC	:	Non-singular Terminal Sliding Mode Controller
PCC	:	Phase Current Control
HESRM	:	Hybrid-Excitation Switched Reluctance Motor
MTRPT	:	Minimum Torque Ripple Point Tracking
BPNN	:	Back-Propagation Neural Network
HIL	:	Hardware-In-The-Loop
MEC	:	Magnetic Equivalent Circuit
SSRM	:	Segmented-Rotor Switched Reluctance Motor
CCS MPC	:	Continuous Control Set Model Predictive Control
UTC	:	Universal Torque Control
NVH	:	Noise, vibration, and harshness
ACMC	:	Average Current Mode Control
GA	:	Genetic Algorithm
RTNN	:	Reference Torque Neural Network
ACM	:	Average Current Mode
AI	:	Artificial Intelligence
ML	:	Machine Learning
PI	:	Proportional-Integral Controller
RMS	:	Root Mean Square
CMAC	:	Cerebellar Model Articulation Controller
SST-SRM	:	Slotted Stator Tooth Switched Reluctance Motor
PID	:	Proportional-Integral-Derivative
DITC	:	Direct Instantaneous Torque Control
MTPA	:	Maximum Torque Per Ampere
FLC	:	Fuzzy Logic Control
CCC	:	Current Chopper Control
DTPFC	:	Direct Torque and Predictive Flux Control
LADRC	:	Linear Active Disturbance Rejection Control
ITC	:	Instantaneous Torque Control
SMSC	:	Sliding Mode Speed Controller
RCA	:	Reference Current Adapter
DSP	:	Digital Signal Processor
FRM	:	Field Reconstruction Method
FS-PTC	:	Finite-State Predictive Torque Control
FEA	:	Finite Element Analysis
LEV	:	Light Electric Vehicle

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