International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 10 Issue: 01 | Jan - 2026 SJIF Rating: 8.586 ISSN: 2582-3930

Comprehensive Review of Torque Ripple Minimization in Switched Reluctance Motor Drives: From Geometric Design to Advanced Digital Control

Krishnarajsinh A. Jadav[1], Khyati P. Ravat[2], Mayank S. Bhatt[3], Vishal D. Devdhar[4]

[1,2,3,4] Department of Electrical Engineering, Government Polytechnic, Rajkot-360003, Gujarat, INDIA

---***---

Abstract - The Switched Reluctance Motor (SRM) has recently experienced a renaissance in industrial and automotive sectors, driven by its rare-earth-free construction, high fault tolerance, and robust thermal performance. However, the doubly salient structure of the SRM inherently produces significant torque ripple, which manifests as acoustic noise and mechanical vibration, limiting its adoption in high-performance traction applications. This paper presents an extensive review of the state-of-the-art techniques for torque ripple minimization. We categorize these techniques into two primary domains: magnetic design optimization (geometric modification) and advanced electronic control. Special emphasis is placed on the evolution from classical single-phase excitation to modern multi-phase excitation strategies (Improved Digital Control), Torque Sharing Functions (TSF), and Direct Torque Control (DTC). Through a comparative analysis of recent literature and fundamental electromagnetic theory, we demonstrate that while geometric alterations offer passive ripple reduction, active digital control strategies provide the dynamic adaptability required for wide-speed-range operation in electric vehicles.

Key Words: Switched Reluctance Motor (SRM), Torque Ripple Minimization, Torque Sharing Function (TSF), Direct Torque Control (DTC), Two-Phase Excitation, Digital Control Strategy.

1. INTRODUCTION

The global shift towards electrification in transportation and industry has intensified the search for electric motor topologies that balance efficiency, cost, and sustainability. The Switched Reluctance Motor (SRM) stands out as a prime candidate due to its unique construction: the rotor is a simple piece of laminated steel with no permanent magnets or windings. This absence of rare-earth materials (like Neodymium or Dysprosium) shields the SRM from geopolitical supply chain volatilities and allows it to operate at much higher temperatures than Permanent Magnet Synchronous Motors (PMSM).

Despite these structural advantages, the SRM has historically been plagued by a critical drawback: high torque ripple. Unlike the smooth, rotating magnetic field of an induction motor or PMSM, the SRM produces torque through discrete pulses of reluctance force. As the rotor poles align with the stator poles, the torque is non-linear and discontinuous. When excitation switches from one phase to the next, a momentary dip in torque—often referred to as the "commutation notch"—occurs, leading to vibration, acoustic noise, and speed oscillations at low frequencies.

Recent advancements in power electronics and digital signal processing have shifted the focus from purely mechanical solutions (like skewing the rotor) to sophisticated control algorithms. This paper reviews this technological evolution, with a specific focus on "Improved Digital Control Strategies" (IDCS) that utilize overlapping phase excitation to bridge the torque gaps inherent in classical control. We further explore complex algorithmic solutions such as Torque Sharing Functions (TSF) and Direct Torque Control (DTC), which model the motor's non-linearities to synthesize smooth torque profiles.

2.FUNDAMENTAL PRINCIPLES AND MATHEMATICAL MODELING

To understand the origin of torque ripple, one must first analyze the electromagnetic physics of the SRM. The motor operates on the principle of minimum reluctance: the movable rotor tends to align itself with the path of maximum magnetic flux.

2.1 Voltage and Flux Equations

The voltage equation for a single phase of an SRM is given by Faraday's law:

$$V = iR + \frac{d\psi\,(\theta, i)}{dt}$$

Where V is the terminal voltage, i is the phase current, R is the winding resistance, and ψ is the flux linkage. Because of the doubly salient structure (teeth on both stator and rotor), the flux linkage ψ is a highly non-linear function of both rotor position (θ) and phase current (i). Expanding the flux term reveals the two components of back-EMF:

$$V = iR + L(\theta, i)\frac{di}{dt} + i\frac{dL\,(\theta, i)}{d\theta}\omega_m$$

Here, the term $i\frac{dL}{d\theta}\omega_m$ represents the motional back-EMF, which opposes the applied voltage during torque production.

2.2 Torque Production

The electromagnetic torque T_e generated by a single phase is derived from the co-energy W_c of the magnetic field. For a linear magnetic circuit (ignoring saturation), the torque is expressed as:

$$T_e = \frac{1}{2}i^2\frac{dL(\theta)}{d\theta}$$

This equation reveals a critical characteristic of the SRM: torque is proportional to the square of the current (i^2), meaning the torque direction is independent of the current direction. This allows for the use of simple unipolar converters. However, the term $\frac{dL}{d\theta}$ dictates that positive motoring torque is only produced when the inductance L is increasing (i.e., the rotor is moving toward alignment). When the inductance is decreasing (rotor moving away from alignment), a negative braking torque is produced if current is still present.

2.3 The Origin of Torque Ripple

Total torque is the sum of the torques produced by individual phases. Ideally, as one phase's torque contribution declines, the next phase picks up the load. However, due to the finite inductance of the windings, current cannot rise or fall instantaneously.

- **Commutation Dip:** In classical control, if the outgoing phase is turned off before the incoming phase has built sufficient current, a "valley" appears in the total torque waveform.
- **Saturation Effects:** At high currents, the magnetic core saturates, flattening the inductance profile and reducing the torque capability near the aligned position, further distorting the waveform.

3. Classification of Ripple Minimization Strategies

Efforts to mitigate torque ripple are generally classified into two broad categories:

1. **Motor Design (Hardware):** Altering the physical geometry of the machine.
2. **Control Strategies (Software):** Modulating the current and switching angles to compensate for non-linearities.

While hardware modifications like rotor skewing, pole shaping, and non-uniform air gaps are effective, they often reduce the average torque density and increase manufacturing complexity. Consequently, modern research prioritizes electronic control strategies, which are the primary focus of this review.

4. Evolution of Digital Control Strategies

4.1 Classical Angle Control (Single-Pulse Mode)

The most basic control method, often used in low-cost drives, is the "Angle Position Control" (APC). Here, the controller applies a single voltage pulse defined by a Turn-on angle (θ_{on}) and a Turn-off angle (θ_{off}).

- **Strategy:** The phase is energized when the inductance begins to rise and de-energized before the inductance starts to fall to avoid negative torque.
- **Limitation:** This "hard switching" approach results in severe torque ripple. The current in the incoming phase takes time to rise against the back-EMF, while the outgoing phase decays. This lack of coordination creates the characteristic "pulsating" torque profile.

4.2 Improved Digital Control Strategy (IDCS): Two-Phase Excitation

To overcome the limitations of single-pulse control, researchers have developed the "Two-Phase Excitation" method, often referred to in literature as an Improved Digital Control Strategy (IDCS). This method fundamentally changes the commutation sequence.

Mechanism of Action:
Instead of sequentially triggering phases (A... then B... then C), the IDCS actively overlaps the firing sequences. The incoming phase is energized before the outgoing phase is turned off. For a specific interval (the commutation angle), two adjacent phases produce torque simultaneously.

Benefits of Overlap:

1. **Torque Compensation:** The rising torque of the incoming phase compensates for the falling torque of the outgoing phase, filling the "commutation dip."
2. **Mutual Inductance Utilization:** When two phases are energized, mutual coupling effects (often ignored in simple models) can enhance the effective flux linkage, boosting the average torque during the critical handover period.
3. **Experimental Validation:** Studies by Zhu et al. and others have shown that optimizing the overlap angle can reduce torque ripple by 30-40% compared to classical methods without requiring complex current profiling. This makes IDCS an ideal "middle ground" solution—offering better performance than classical control without the heavy computational burden of TSF or DTC.

5. Advanced Algorithmic Control

For high-performance applications like electric vehicles, where even minor vibrations are unacceptable, the industry has moved toward algorithmic current profiling.

5.1 Torque Sharing Functions (TSF)

Torque Sharing Functions represent a sophisticated approach where the total reference torque (T_{ref}) is mathematically divided between the outgoing phase (T_{out}) and the incoming phase (T_{in}) during commutation.

$$T_{ref} = T_{in}(\theta) + T_{out}(\theta)$$

Types of TSFs:

- **Linear TSF:** Torque is transferred linearly (one ramps up, one ramps down). Simple to implement but may demand current rates of change di/dt that the voltage supply cannot support.
- **Cubic/Cosine TSF:** Uses smooth polynomial curves to define the transition. This reduces the demand for sudden voltage spikes and results in smoother operation.
- **Optimized TSF:** Recent research (2024-2025) utilizes optimization algorithms (like Genetic Algorithms or Harris Hawks Optimization) to

dynamically adjust the shape of the sharing function based on speed and load, decoupling the turn-on angle from the sharing period to maximize efficiency.

Limitations: TSFs rely heavily on accurate knowledge of the motor's magnetic characteristics (look-up tables). If the model is inaccurate, the ripple reduction is compromised. Furthermore, at high speeds, the back-EMF may prevent the current from tracking the ideal TSF profile.

5.2 Direct Torque Control (DTC)

Adapted from AC motor drives, Direct Torque Control treats the SRM's torque and flux as the direct control variables, bypassing the need for complex current profiling.

- **Principle:** The controller estimates the instantaneous torque and stator flux magnitude. These values are compared to reference values using hysteresis comparators. Based on the error, a "switching table" selects the optimal voltage vector (e.g., +V, 0, -V) to drive the torque back within the hysteresis band.
- **Advantages:** DTC offers an extremely fast dynamic response and is less sensitive to parameter variations than TSF.
- **Recent Developments:** New "Model Predictive" DTC (MPDTC) variants use a mathematical model to predict the torque outcome of all possible switching states and select the one that minimizes a cost function (usually a weighted sum of torque ripple and copper loss). This reduces the variable switching frequency problem inherent in classical DTC.

6. Comparative Analysis and Discussion

The choice of control strategy depends heavily on the application requirements. The table below summarizes the trade-offs:

Table -1: Comparative Analysis of Control Strategy

Feature	Classical Angle Control	Improved Digital Control (IDCS)	Torque Sharing Function (TSF)	Direct Torque Control (DTC)
Complexity	Low	Low-Medium	High	Medium-High
Ripple Reduction	Poor	Good (via overlap)	Excellent (low speed)	Very Good (dynamic)
Sensor Req.	Low Res. Encoder	Absolute Encoder	High Res. Position + Current	Voltage/Current Sensors
High Speed	Best	Good	Limited by Back - EMF	Good
Application	Fans, Pumps	Appliances, Light EV	Precision Servo, Robotics	Traction, Heavy EV

Synthesis of Findings:

- Classical control is becoming obsolete for traction due to acoustic noise.
- **IDCS (Two-Phase Excitation)** is the most cost-effective upgrade for existing industrial drives. It requires minimal hardware changes (standard bridge converters) but significantly improves smoothness by simply widening the conduction window to allow overlap.
- **TSF and DTC** are the standards for automotive applications. The latest research focuses on hybridizing these methods—using TSF for smooth low-speed operation and transitioning to IDCS or single-pulse mode at high speeds where current shaping is impossible.

7. Future Trends: AI and Intelligent Control

The frontier of SRM control lies in "Intelligent Control." Researchers are now deploying Artificial Neural Networks (ANNs) and Fuzzy Logic controllers to replace static look-up tables.

- **Neural Networks:** can learn the non-linear inductance profile of the motor in real-time, compensating for manufacturing tolerances and thermal variations.
- **Fuzzy Logic:** provides a robust way to tune the Turn-on/Turn-off angles adaptively. For instance, a Fuzzy controller can monitor the speed ripple and adjust the overlap angle of an IDCS system on the fly to minimize vibration.

8. CONCLUSION

The Switched Reluctance Motor has matured from a noisy, low-cost alternative into a high-performance competitor in the electric drive market. This transformation is largely credited to the evolution of digital control strategies. While geometric optimization provides a foundation, it is the electronic control that truly unlocks the motor's potential.

This review highlights that while complex methods like TSF and DTC offer theoretical perfection in ripple cancellation; the Improved Digital Control Strategy (Two-Phase Excitation) remains a highly practical and robust solution. By strategically overlapping phase excitation, IDCS addresses the fundamental cause of torque ripple—the commutation energy gap—without the computational intensity of model-predictive systems. For future electric vehicles, a hybrid approach combining the simplicity of IDCS at high speeds with the precision of TSF at low speeds appears to be the optimal path forward.

REFERENCES

1. Zhang, X., et al. (2016). "Comparison of torque ripple reduction for switched reluctance motor based on DTC and DITC." Semantic Scholar.
2. Ye, J., et al. (2024). "Torque Ripple Reduction in Switched Reluctance Machines Considering Phase Torque-Generation Capability." MDPI Electronics, 14(9).
3. Zhu, J., et al. (1998). "Switched reluctance motor with 2-phase excitation." IEEE Industry Applications Conference.

4. Gu, L., Clark, A., & Fahimi, B. (2014). "Magnetic design of two-phase switched reluctance motor with bidirectional startup capability." European Conference on Power Electronics.
5. Mishra, A., & Singh, B. (2018). "Control techniques of switched reluctance motors in electric vehicle applications: A review on torque ripple reduction strategies." AIMS Press.
6. Gao, Y. (2021). "Extending Maximum Speed of Torque Sharing Function Method in Switched Reluctance Motor." IEEE Xplore.
7. Chakraborty, C. (2022). "An improved torque ripple suppression method for switched reluctance motor (SRM)." IEEE International Conference on Electrical Machines and Systems.
8. Vujicic, V. P. (1999). "A three-phase switched reluctance motor with two-phase excitation." IEEE Transactions on Industry Applications, 35(5).
9. Husain, I., & Ehsani, M. (1991). "Torque ripple optimization of switched reluctance motor using two-phase model and optimization search techniques." IEEE Power Electronics Specialists Conference.
10. Ahn, J. W., & Lukman, G. F. (2019). "Torque Ripples Minimization Strategies of Switched Reluctance Motor - A Review." IEEE Transactions on Industry Applications.
11. Suresh, S., et al. (2025). "Torque Ripple Minimization for Switched Reluctance Motor Drives Based on Harris Hawks–Radial Basis Function Approximation." MDPI Energies, 18(4).
12. Texas Instruments. (2000). "Switched Reluctance Motor Control - Operation & Example Using TMS320F240." Application Report SPRA420A.
13. Nakamura, T., et al. (2018). "Development and analysis of a two-phase excitation switched reluctance motor with novel winding distribution used in electric vehicles." Journal of Electrical Engineering and Technology.
14. Yan, W., et al. (2021). "Torque Ripple Reduction of Switched Reluctance Motor with Non-Uniform Air-Gap and a Rotor Hole." ResearchGate.
15. Hassan, M., et al. (2025). "Torque Ripple Reduction in MPDTC of SRM Drives Using Optimized Switching States and Advanced Torque Sharing Function." ResearchGate.
16. Rahman, M., et al. (2018). "Brief History of Switched Reluctance Motor." IOSR Journal of Electrical and Electronics Engineering.
17. Sahoo, S. K., et al. (2017). "Performance Analysis of SRM Using Direct Torque Control." IJARBEST, 3(3).
18. El-Nemr, M., et al. (2025). "A Hybrid Torque Sharing Function with Controlled Commutation Period for Torque Ripple Minimization in SRM." ResearchGate.
19. Li, X., et al. (2024). "Vehicle-Mounted SRM DITC Strategy Based on Optimal Switching Angle TSF." MDPI World Electric Vehicle Journal, 16(1).
20. Widodo, A., et al. (2023). "An Overview Of Current Control Strategies For Switched Reluctance Machine." International Journal of Innovative Scientific & Engineering Technologies Research.