IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 5, Issue 9, March 2025 Impact Factor: 7.67

Optimized Control Techniques For Synchronous Reluctance Motors in Electric Vehicle Applications

J Gowrishankar[1], Chinnapapa Ajay [2], Madhan Teruvai[3], Chandragiri Pravallika[4], Chinthapudi Chenchu Krishnaiah[5], Kogila Gopi[6]
Professor, Department of EEE, Siddharth Institute of Engineering & Technology, Puttur, AP, India[1]
UG Student, Department of EEE, Siddharth Institute of Engineering & Technology, Puttur, AP, India[23456]
sietkrnd@gmail.com[1], 19016ee003@gmail.com[2], Madhanteruvai@gmail.com[3], pravallikareddy9988@gmail.com[4], rockchenchu3@gmail.com[5], kogilagopi883@gmail.com[6].

Abstract*: This project explores the development and optimization of control strategies for a Synchronous Reluctance Motor (SynRM) drive in electric vehicle (EV) applications. A bidirectional DC/DC converter is implemented as an interface between the battery and motor drive, ensuring a well-regulated and boostable DC-link voltage for enhanced performance across a wide speed range. Additionally, the converter facilitates efficient regenerative braking, improving overall energy efficiency by recovering energy back to the battery. The proposed SynRM drive incorporates robust current PWM switching control to mitigate slotting effects, along with a model reference-based speed control strategy. An Adaptive Commutation Scheme (ACS) is introduced to optimize commutation timing, thereby minimizing motor losses. Furthermore, enhanced control techniques such as back-EMF cancellation and tracking error compensation are integrated into the feedback loop to ensure smooth operation and improved torque response. A Proportional-Integral (PI) controller is implemented within a closed-loop control system to regulate motor speed and torque based on real-time sensor feedback. This approach improves accuracy, enhances system robustness against varying load conditions, and optimizes energy efficiency, thereby extending battery range. The proposed control strategies contribute to reliable and efficient EV propulsion, ensuring superior motor performance while maximizing energy utilization.*

Keywords: Synchronous Reluctance Motor (SynRM), Electric Vehicle (EV), Bidirectional DC/DC Converter, Regenerative Braking, PWM Switching Control, Adaptive Commutation Scheme (ACS), Back-EMF Cancellation, Model Reference-Based Speed Control, Proportional-Integral (PI) Controller, Closed-Loop Control, Energy Efficiency, Torque Optimization, DC-Link Voltage Regulation

I. INTRODUCTION

The rapid growth of electric vehicles (EVs) has intensified research into high-efficiency, cost-effective, and sustainable motor drive solutions. Traditionally, Permanent Magnet Synchronous Motors (PMSMs) and Induction Motors (IMs) have dominated EV propulsion due to their superior torque and efficiency characteristics. However, PMSMs rely on rare-earth materials, which suffer from high costs and supply chain constraints [3][5]. Similarly, IMs exhibit high copper and iron losses, leading to reduced energy efficiency, particularly in variable-speed applications [4].

To address these concerns, Synchronous Reluctance Motors (SynRMs) have emerged as a promising alternative. SynRMs eliminate the need for permanent magnets, reducing dependency on rare-earth materials while offering high efficiency, robustness, and improved fault tolerance [1][11]. Moreover, they provide excellent performance under vector control techniques and offer efficient torque generation, making them a viable candidate for EV applications [16]. Despite these advantages, SynRMs face challenges in torque ripple, control complexity, and efficiency optimization, necessitating further advancements in control strategies [10].

Although significant progress has been made in the design and control of SynRM drives, several key challenges remain:

A. Torque Ripple and Slotting Effects:
SynRMs suffer from high torque ripple, leading to vibrations and increased acoustic noise. Traditional control methods struggle to suppress these effects effectively [15][6].

B. Suboptimal Commutation Control:
Existing commutation schemes fail to optimally adjust timing, resulting in increased losses and reduced efficiency [14].

C. Inefficient Regenerative Braking:
While SynRMs support bidirectional power flow, conventional control methods do not fully optimize regenerative energy recovery, limiting efficiency gains [5][19].

D. DC-Link Voltage Regulation Issues:
The DC/DC converter in EVs needs to provide a stable and boostableDC-link voltage to enhance SynRM performance across varying speed ranges. However, maintaining optimal voltage control remains a challenge [13].

E. Lack of Integrated Loss Minimization Strategies:
Existing control approaches do not effectively integrate back-EMF cancellation and tracking error minimization, leading to suboptimal efficiency under varying load conditions [18].

Given the challenges associated with SynRM drives in EVs, there is a need for an optimized control strategy that enhances torque smoothness, regenerative braking efficiency, and energy utilization. An effective closed-loop control system can address these limitations by implementing adaptive commutation schemes, robust DC/DC converter control, and enhanced feedback mechanisms [11][17]. Additionally, incorporating Proportional-Integral (PI) control can significantly improve speed and torque regulation, leading to improved performance and extended battery life in EV applications [10].

The main objectives of this study are:

- To develop an optimized control strategy for SynRM drives in EV applications.
- To implement a bidirectional DC/DC converter for enhanced DC-link voltage regulation and efficient regenerative braking.
- To introduce an Adaptive Commutation Scheme (ACS) for minimizing commutation losses and improving efficiency.
- To integrate back-EMF cancellation and tracking error compensation into the feedback control loop.
- To design and implement a PI-based closed-loop control system for precise speed and torque regulation.

This paper presents the following key contributions:

- A Novel Adaptive Commutation Scheme (ACS) to dynamically adjust commutation timing, minimizing switching losses and enhancing motor efficiency.
- An Improved DC/DC Converter Control Strategy that ensures a boostable and stable DC-link voltage, improving regenerative braking efficiency.
- Advanced Feedback Control Techniques, including back-EMF cancellation and tracking error minimization, to mitigate torque ripple and enhance motor performance.
- Implementation of a PI-Based Closed-Loop Control System for real-time speed and torque regulation, improving robustness and accuracy.
- Comprehensive Performance Evaluation, comparing the proposed method with existing control techniques to demonstrate its superior energy efficiency and torque smoothness.

The remainder of this paper is structured as follows: Section 2 presents a detailed literature review, analyzing previous studies on SynRM control strategies. Section 3 describes the proposed system architecture, including the DC/DC converter, inverter, and control algorithms. Section 4 details the PI-based closed-loop control implementation and feedback mechanisms. Section 5 discusses the experimental setup and simulation results, demonstrating the effectiveness of the proposed approach..Section 6 concludes the paper and outlines future research directions

II. RELATED WORKS

The growing demand for efficient and cost-effective electric propulsion systems has led to increased research on Synchronous Reluctance Motors (SynRM) as a viable alternative to traditional Permanent Magnet (PM) and Induction Motors. This literature survey presents an overview of key contributions in SynRM design, control techniques, and their application in electric vehicle (EV) propulsion.

A. Synchronous Reluctance Motor as an Alternative for EV Drives

Lipo (1991) [1] introduced the potential of SynRM as a competitive AC drive, highlighting its advantages such as reduced cost and improved efficiency. Krause et al. (2013) [2] provided an in-depth analysis of electric machinery, covering mathematical modeling and control strategies applicable to SynRM. Boldea et al. (2014) [3] explored rare-earth-free propulsion systems, emphasizing the benefits of PM-free machine topologies for automotive applications.

B. Design and Optimization of SynRM for Traction Applications

Several studies have focused on the optimization of SynRM design to enhance efficiency and torque density. Matsuo and Lipo (1994) [14] presented rotor design optimization techniques for SynRM, while Vagati et al. (1998) [15] proposed methods for minimizing torque ripple. More recent works by Nardo et al. (2018) [6] and Palmieri et al. (2016) [7] introduced high-speed design methodologies tailored for automotive and aeronautical applications.

C. Control Strategies for Enhanced Performance

Advanced control strategies have been developed to improve the performance of SynRM drives in EVs. Estenlund et al (2016) [4] reviewed PM-less motor topologies, discussing their suitability for EV traction. Taghavi and Pillay (2014) [10] introduced a sizing methodology for SynRM in traction applications. Bianchi et al. (2016) [11] analyzed different control techniques for improving SynRM performance in EV traction, including model reference-based control and adaptive commutation strategies.

D. Energy Efficiency and Loss Minimization

Optimizing energy efficiency is crucial for improving the range and sustainability of EVs. Qu and Hinkkanen (2013) [16] reviewed loss-minimizing control methods, while Hofmann et al. (2004) [17] proposed a stator-flux-oriented vector control strategy for maximizing efficiency. Signal injection techniques for efficiency optimization were investigated by Kim et al. (2010) [18], while Yamamoto et al. (2013) [19] introduced a novel loss minimization controller integrated with an inductance estimator.

E. Regenerative Braking and DC-Link Voltage Control

Efficient bidirectional power flow is essential for energy recovery in EVs. Cabezuelo et al. (2018) [5] reviewed rare-earth-free EV motor drives, discussing inverter and regenerative braking strategies. Ibrahim et al. (2017) [20] emphasized the importance of including saturation and position dependence in SynRM modeling to improve control accuracy, particularly for regenerative braking applications.

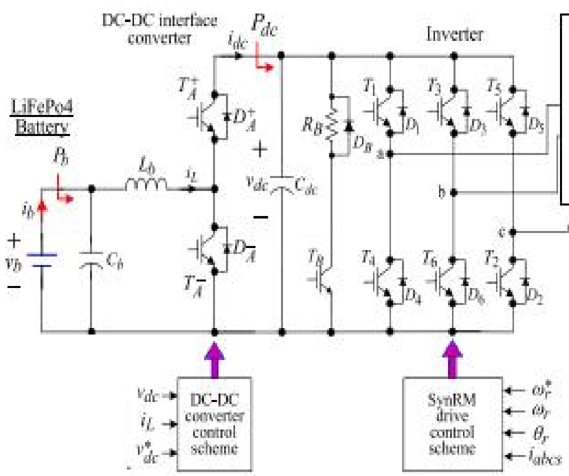
The reviewed literature demonstrates that Synchronous Reluctance Motors offer a promising alternative for electric vehicle applications, with ongoing advancements in design optimization, control techniques, and energy efficiency. Recent research has focused on minimizing torque ripple, improving regenerative braking, and optimizing control strategies to enhance the performance and efficiency of SynRM-based EV drives. Future work will likely explore AI-driven adaptive control methods and further improvements in bidirectional power converters for enhanced EV integration

The proposed method introduces an optimized control strategy for Synchronous Reluctance Motors (SynRMs) in electric vehicle (EV) applications, focusing on improved efficiency, precise torque control, and enhanced regenerative

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429 Volume 5, Issue 9, March 2025 Impact Factor: 7.67

braking. A bidirectional DC/DC converter is integrated between the battery and the motor drive to regulate and boost the DC-link voltage, ensuring stable operation across a wide speed range. This converter also facilitates efficient regenerative braking, allowing energy recovery to the battery, thereby increasing overall energy efficiency. To address the inherent torque ripple and slotting effects in SynRMs, the proposed method incorporates an Adaptive Commutation Scheme (ACS) that dynamically adjusts the commutation timing, minimizing losses and improving performance. Additionally, an advanced closed-loop control system based on a Proportional-Integral (PI) controller is implemented to regulate motor speed and torque in real-time. The feedback system integrates back-EMF cancellation and tracking error minimization, further enhancing stability and reducing performance fluctuations. The proposed system not only ensures robust and precise motor control but also enhances the reliability and efficiency of SynRM drives for EVs, making them a viable alternative to Permanent Magnet Synchronous Motors (PMSMs) without relying on rare-earth materials.

III. PROPOSED CIRCUIT DIAGRAM



Close Loop SRM Motor Control in PI Control

A. Battery Power Supply (LiFePO4):

- The LiFePO4 battery provides the initial DC power (Vb). This power is not directly suitable for driving the SRM.
- The capacitor Cb helps to smooth out any voltage fluctuations from the battery and reduce current ripple.

B. DC-DC Boost Conversion:

- Purpose: To step up the battery voltage (Vb) to a higher DC voltage (Vdc) required by the inverter and SRM.
- The DC-DC converter uses a boost converter topology.
- The switching transistor T+A is turned ON, allowing current to flow from the battery through the inductor Lb, storing energy in the inductor's magnetic field.
- When T+A is turned OFF, the inductor's magnetic field collapses, inducing a voltage that adds to the battery voltage. This combined voltage is then delivered to the DC link capacitor Cdc through the diode DA.
- The switching of T+A is controlled by the DC-DC converter control scheme.
- The control scheme monitors the DC link voltage (Vdc) and the inductor current (iL).
- It compares the actual Vdc to the desired V*dc.
- Based on the error, it adjusts the duty cycle (ON/OFF time ratio) of T+A to maintain the desired Vdc.
- Result: A stable DC link voltage (Vdc) is achieved, higher than the battery voltage.

C. DC Link Stabilization:

- The DC link capacitor Cdc acts as a large energy reservoir.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 9, March 2025
Impact Factor: 7.67

- It smooths out any voltage fluctuations from the boost converter and provides a stable DC voltage to the inverter.
- It also supplies the instantaneous current demands of the inverter and SRM.

D. Inverter Operation:
- To convert the DC voltage (Vdc) to a three-phase AC voltage with variable frequency and amplitude, suitable for driving the SRM.
- The inverter uses a three-phase bridge configuration with six switching transistors (T1-T6).
- The switching of these transistors is controlled by the SynRM drive control scheme.
- By selectively switching the transistors ON and OFF, the inverter generates a three-phase AC voltage with a specific pattern.
- The frequency of the AC voltage determines the speed of the SRM.
- The amplitude of the AC voltage determines the torque of the SRM.
- The diodes D1-D6 provide freewheeling paths for the inductive current of the SRM windings when the transistors are switched off.

E. Switched Reluctance Motor (SRM) Drive:
- The three-phase AC voltage from the inverter is applied to the windings of the SRM.
- The SRM's rotor aligns with the stator poles based on the magnetic field created by the energized windings.
- By sequentially energizing the stator windings, the rotor is made to rotate.
- The speed and torque of the SRM are controlled by adjusting the frequency and amplitude of the AC voltage from the inverter.

F. Closed-Loop Control (SynRM Drive):
Purpose: To maintain the desired speed (ω*) of the SRM.
Operation:
- The SynRM drive control scheme receives feedback signals:
- Actual rotor speed (ωr)
- Rotor position (θr)
- Phase currents (iabcs)
- It compares the actual speed (ωr) to the desired speed (ω*).
- Based on the error, it calculates the required voltage and current for the SRM windings.
- It then generates the appropriate switching signals for the inverter transistors (T1-T6).
- This control scheme often involves complex algorithms like current profiling and torque control to optimize the SRM's performance.

G. Feedback and Regulation:
- The entire system operates in a closed-loop fashion.
- The DC-DC converter control scheme regulates the DC link voltage (Vdc).
- The SynRM drive control scheme regulates the SRM's speed (ωr).
- This closed-loop operation ensures accurate and stable performance of the SRM drive system.
- Key Aspects of the Operation:
- Energy Conversion: The system efficiently converts the battery's DC power to the AC power required by the SRM.
- Voltage Regulation: The DC-DC boost converter ensures a stable DC link voltage.

IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429 Volume 5, Issue 9, March 2025 Impact Factor: 7.67

- Speed and Torque Control: The inverter and SynRM drive control scheme provide precise control over the SRM's speed and torque.
- Feedback Mechanism: The closed-loop control system uses feedback signals to ensure accurate and stable operation.
- In essence, this circuit efficiently manages the power flow from a battery to an SRM, enabling precise control of the motor's speed and torque through a combination of DC-DC conversion and inverter operation, all within a closed-loop control framework.

H. Implimentation

Power Stage:

- LiFePO4 Battery: Provides DC power.
- Boost Converter: Steps up battery voltage to a stable DC link voltage.
- Inverter: Converts DC link voltage to variable AC for the SRM.

Control System:

- DC-DC Control: PI controller regulates DC link voltage using inductor current feedback.
- SRM Drive Control: Complex algorithm (likely PI-based) regulates SRM speed using speed, position, and current feedback.

Key Measurements:

- DC Link Voltage (Vdc): Feedback for DC-DC control.
- Inductor Current (iL): Feedback for DC-DC control.
- SRM Speed (ωr): Feedback for SRM control.
- Rotor Position (θr): Feedback for SRM control.
- Phase Currents (iabcs): Feedback for SRM control.

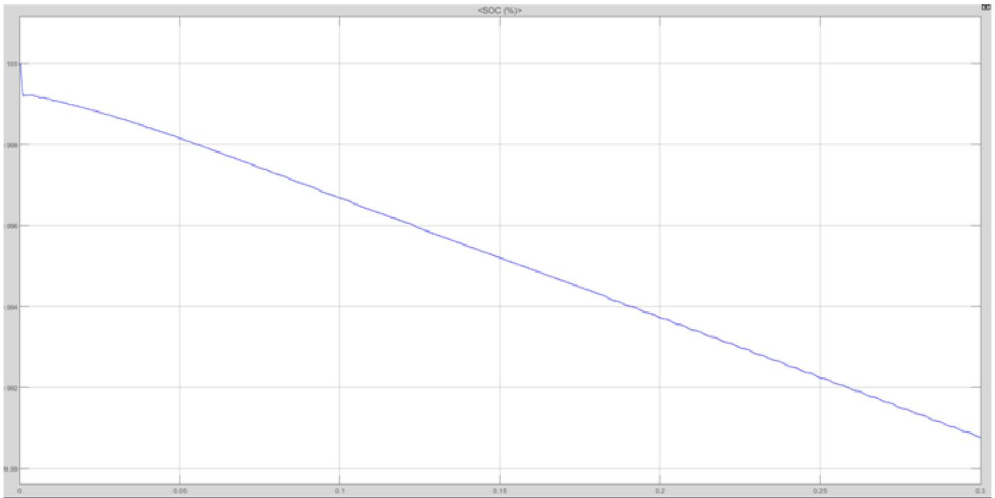
Process:

- Battery supplies DC.
- Boost converter raises voltage.
- Inverter creates AC for SRM.
- Controllers adjust switching based on feedback to maintain desired voltage and speed.

IV. SIMULATION RESULTS

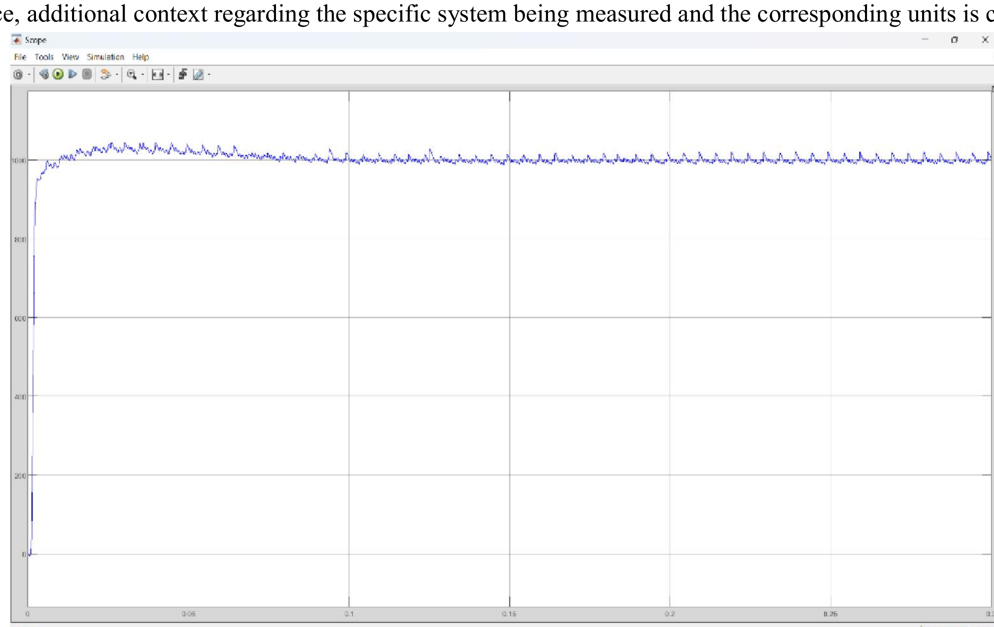
The provided SOC (State of Charge) graph depicts a linear discharge pattern over a short time interval. Beginning slightly below 100%, the battery's SOC steadily declines to approximately 98.8% within 0.3 units of time, suggesting a consistent current draw during this period. The calculated discharge rate of roughly 3.33% SOC per unit time indicates a relatively rapid depletion, though the overall 1% drop might seem minor. This behavior could be attributed to a constant load, a high current pulse, or an initial transient phase of a longer operation. However, without additional context such as the time unit, battery capacity, and load information, a precise interpretation remains challenging. To gain a comprehensive understanding of the battery's performance, further data encompassing a longer operational timeframe and detailed load specifications are necessary.

ISSN: 2581-9429
Impact Factor: 7.67



Battery SOC

The provided output waveform exhibits a characteristic pattern of a stable DC signal superimposed with a consistent ripple. Following an initial transient phase where the signal rapidly ascends from near zero to approximately 1000, it maintains a steady average value around this level for the duration of the 0.3-unit time frame. The presence of a periodic ripple, characterized by a constant frequency and amplitude, suggests the influence of switching noise, commonly observed in power electronic systems utilizing semiconductor devices. Despite this ripple, the overall stability of the signal is evident, indicating a steady-state operation. However, the absence of explicit units for both the Y-axis (magnitude) and X-axis (time) limits a more precise interpretation. To fully comprehend the waveform's significance, additional context regarding the specific system being measured and the corresponding units is crucial.



Output Waveform

V. CONCLUSION AND FUTURE SCOPE

The analysis of the provided output waveform reveals a stable DC signal with a superimposed, consistent ripple, indicative of a system operating in a steady-state condition within a short time frame. This pattern is commonly associated with power electronic systems, where switching noise from semiconductor devices introduces periodic

IJARSCT

International Journal of Advanced Research in Science, Communication and Technology

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429 Volume 5, Issue 9, March 2025 Impact Factor: 7.67

fluctuations. While the waveform demonstrates stability, the lack of explicit units for both the magnitude and time scale necessitates further context for a complete understanding. Overall, the system appears to have reached a stable operating point after an initial transient, suggesting effective control and regulation.

To build upon this analysis and enhance the system's performance, the following future scope considerations are recommended: Filtering: Implement appropriate filtering techniques (e.g., LC filters) to reduce the ripple and improve the signal quality. This is crucial for sensitive applications requiring a smooth DC output. Optimized Switching Strategies: Explore advanced switching techniques (e.g., soft switching, space vector modulation) to minimize switching losses and reduce ripple generation

REFERENCES

[1]. T. A. Lipo, "Synchronous reluctance machine—A viable alternative for AC drive," Electric Mach. Power Syst., vol. 19, no. 6, pp. 659–671, 1991.

[2]. P. Krause, O. Wasynczuk, S. Sudhoff, and S. Pekarek, Analysis of electric machinery and drive systems, Hoboken, NJ, USA: Wiley, 2013.

[3]. Boldea; L. N. Tutelea, L. Parsa, and D. Dorrell, "Automotive electric propulsion systems with reduced or no permanent magnets: An overview," IEEE Trans. Ind. Electron., vol. 61, no. 10, pp. 5696–5711, Oct. 2014.

[4]. S. Estenlund, M. Alakula, and A. Reinap, "PM-less machine topologies for EV traction: A literature review," in Proc. IEEE Int. Conf. Elect. Syst. Aircr., Railway, Ship Propulsion Road Vehicles Int. Transp. Electrific. Conf., 2016, pp. 1–6.

[5]. D. Cabezuelo, E. Ibarra, E. Planas, I. Kortabarria, and J. I. Garate, "Rareearth free EV and HEV motor drives: State of the art," in Proc. Int. Exhib. Conf. Power Electron., Intell. Motion, Renewable Energy Energy Manage., 2018, pp. 1376–1383.

[6]. M. D. Nardo, G. L. Calzo, M. Galea and C. Gerada, "Design optimization of a high-speed synchronous reluctance machine," IEEE Trans. Ind. Appl., vol. 54, no. 1, pp. 233–243, Jan./Feb. 2018

[7]. M. Palmieri, M. Perta, and F. Cupertino, "Design of a 50.000-r/min synchronous reluctance machine for an aeronautic diesel engine compressor," IEEE Trans. Ind. Appl., vol. 52, no. 5, pp. 3831–3838, Sep./Oct. 2016.

[8]. K. Lang, A. Muetze, R. Bauer, and W. Rossegger, "Design of PM-free AC machine-based actuators for elevated-temperature environments," IEEE Trans. Ind. Appl., vol. 52, no. 3, pp. 2241–2252, May/Jun. 2016.

[9]. Y. H. Kim and J. H. Lee, "Optimum design of ALA-SynRM for direct drive electric valve actuator," IEEE Trans. Magn., vol. 53, no. 4, Apr. 2017, Art. no. 8200804.

[10]. S. Taghavi and P. PillayA, "Sizing methodology of the synchronous reluctance motor for traction applications," IEEE J. Emerg. Sel. Topics Power Electron., vol. 2, no. 2, pp. 329–340, Jun. 2014.

[11]. N. Bianchi, S. Bolognani, E. Carraro, M. Castiello, and E. Fornasiero, "Electric vehicle traction based on synchronous reluctance motors," IEEE Trans. Ind. Appl., vol. 52, no. 6, pp. 4762–4769, Nov./Dec. 2016.

[12]. F. N. Jurca, M. Ruba, and C. Mar¸ti¸s, "Design and control of synchronous reluctances motors for electric traction vehicle," in Proc. IEEE Int. Symp. Power Electron., Elect. Drives, Autom. Motion, 2016, pp. 1144–1148.

[13]. D. B. Herrera, E. Galvan, and J. M. Carrasco, "Synchronous reluctance motor design based EV powertrain with inverter integrated with redundant topology," in Proc. 41st Annu. Conf. IEEE Ind. Electron. Soc., 2015, pp. 003851–003856.

[14]. T. Matsuo and T. A. Lipo, "Rotor design optimization of synchronous reluctance machine," IEEE Trans. Energy Convers., vol. 9, no. 2, pp. 359–365, Jun. 1994.

[15]. A.Vagati, M. Pastorelli, G. Francheschini, and S. C. Petrache, "Design of low-torque-ripple synchronous reluctance motors," IEEE Trans. Ind. Appl., vol. 34, no. 4, pp. 758–765, Jul./Aug. 1998.

[16]. Z. Qu and M. Hinkkanen, "Loss-minimzing control of synchronous reluctance motors–A review," in Proc. IEEE Int. Conf. Ind. Technol., 2013, pp. 350–355.

IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 9, March 2025
Impact Factor: 7.67

[17]. H. F. Hofmann, S. R. Sanders, and A. EL-Antably, "Stator-flux- oriented vector control of synchronous reluctance machines with maximized efficiency," IEEE Trans. Ind. Electron., vol. 51, no. 5, pp. 1066–1072, Oct. 2004.

[18]. S. Kim, S. K. Sul, K. Ide, and S. Morimoto, "Maximum efficiency operation of synchronous reluctance machine using signal injection," in Proc. IEEE Int. Power Electron. Conf., 2010, pp. 2000–2004.

[19]. S. Yamamoto, H. Hirahara, J. B. Adawey, T. Ara, and K. Matsuse, "Maximum efficiency drives of synchronous reluctance motors by novel loss minimization controller with inductance estimator," IEEE Trans. Ind. Appl., vol. 49, no. 6, pp. 2543–2551, Nov./Dec. 2013.

[20]. M. N. Ibrahim, P. Sergeant, and E. M. Rashad, "Relevance of including saturation and position dependence in the inductances for accurate dynamic modeling and control of SynRMs," IEEE Trans. Ind. Appl., vol. 53, no. 1, pp. 151–160, Jan./Feb. 2017..