The Role of Synchronous Reluctance Machines in the Energy Transition: Challenges and Opportunities for Future Electric Vehicles

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Abstract

The global energy transition necessitates the decarbonization of the transportation sector through vehicle electrification. However, the dominance of Permanent Magnet Synchronous Motors (PMSMs) presents sustainability challenges due to their reliance on rare-earth materials. This article presents a Systematic Literature Review (SLR) of Synchronous Reluctance Machines (SynRMs) as rare-earth-free alternatives for future electric vehicles. By synthesizing findings from Scopus-indexed journals, IEEE publications, and industry reports spanning 2020–2025, the review evaluates advancements in rotor design, control strategies, energy efficiency, and technological readiness of SynRMs within the context of energy transition. The results indicate that SynRMs offer high efficiency, a simplified structure, and significant potential for reducing environmental impact. Nonetheless, challenges remain in torque control, thermal management, and full-scale validation. The review also identifies research gaps and outlines future innovation pathways, including the development of Ferrite-Assisted SynRMs and AI-based control algorithms. These findings contribute strategically to the advancement of sustainable electric motor technologies and support the global agenda for net-zero emissions.

Keywords*:* Synchronous Reluctance Machine (SynRM), Electric Vehicle Electrification, Rare-Earth-Free Motor Technology, Systematic Literature Review (SLR), Energy Transition and Sustainability

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Introduction

The energy transition denotes a fundamental transformation of the global energy system from dependence on fossil fuels toward cleaner and low-carbon energy sources. This transformation is driven by the escalating concentration of greenhouse gases (GHGs) responsible for global warming, as underscored by the 2015 Paris Agreement, which seeks to limit the rise in global mean temperature to below 2°C. The transportation sector has emerged as a critical priority, contributing approximately 23% of global CO_2 emissions; consequently, decarbonization within this sector is essential to achieving broader climate-mitigation objectives.

The electrification of transportation through the adoption of electric vehicles (EVs) has become a central strategy in decarbonization efforts, as EVs exhibit significantly higher energy efficiency compared to conventional fossil-fuel-powered vehicles. Moreover, electric vehicles have the potential to operate entirely on renewable energy when integrated with green electricity generation systems[5].

Nevertheless, the sustainability of electric vehicles is determined not only by advancements in battery technology but also by the electric motor, which serves as the primary propulsion component. The motor technology most widely adopted in current industrial practice is the Permanent Magnet Synchronous Motor (PMSM), which relies heavily on rare-earth materials such as neodymium and dysprosium. This dependence presents significant challenges, including price volatility, the highly concentrated nature of global supply chains, and the environmental impacts associated with rare-earth extraction. China, for instance, accounts for more than 90% of global rare-earth production, meaning that geopolitical risks can directly affect the stability of the electric-vehicle supply chain worldwide [6] [7].

These conditions have stimulated research into rare-earth-free alternative motor technologies, one of which is the Synchronous Reluctance Machine (SynRM). This motor does not require permanent magnets, features a simple rotor structure, and offers high efficiency across a wide range of operating conditions. SynRM is considered capable of enhancing energy security, reducing dependence on critical materials, and lowering environmental impacts throughout the motor's life cycle. Consequently, SynRM has emerged as a leading candidate for supporting next-generation electric-vehicle technologies and accelerating the global energy transition toward a low-carbon transportation system [6] [7] [5].

Overall, the urgency of the global energy transition and the sustainability challenges associated with electric-vehicle traction motors make the study of SynRM technology highly relevant for addressing the needs of the automotive industry and informing future energy policy [5].

Literature Review

2.1 Mathematical Model of Synchronous Reluctance Machine (SynRM)

The mathematical model of the Synchronous Reluctance Machine (SynRM) in the d–q reference frame is essential for understanding its electromagnetic dynamics, motor control design, and performance-optimization strategies such as Maximum Torque Per Ampere (MTPA) and speed control. The d-q transformation enables a three-phase machine to be analyzed within a two-axis orthogonal domain namely the direct (d) and quadrature (q) axes thereby allowing electromagnetic phenomena to be decoupled into flux- and torque-producing components [2] [4].

The d–q reference frame is highly effective for SynRM analysis because the motor relies on the inductance difference between L_d and L_q to generate reluctance torque. Consequently, the d–q mathematical model serves as a fundamental basis for analyzing the behavior and performance of this machine [4].

2.2 Park Transformation (abc → dq) [4].

The Park transformation is employed to convert the three-phase currents (i_a, i_b, i_c) into two current components in the synchronous reference frame, namely the d-axis current (i_d) and the q-axis current (i_q). The id component represents the flux-producing current, whereas the i_q component corresponds to the torque-producing current.

$$id = (2/3)[\, ia\, cos\theta + ib\, cos(\theta - 120°) + ic\, cos(\theta + 120°)\,] \quad (1)$$

$$iq = (2/3)[\, ia\, sin\theta + ib\, sin(\theta - 120°) + ic\, sin(\theta + 120°)\,] \quad (2)$$

3 Voltage Equations in dq Frame

$$vd = Rs\, id + d\psi d/dt - \omega\, \psi q \quad (3)$$

$$vq = Rs\, iq + d\psi q/dt + \omega\, \psi d \quad (4)$$

4 Flux Linkage Equations [4].

$$\psi d = Ld.id \quad (5)$$

$$\psi q = Lq.iq \quad (6)$$

5 Electromagnetic Torque Equation [4].

$$Te = (3/2) \cdot (p/2) \cdot (Ld - Lq) \cdot id \cdot iq \quad (7)$$

6 Nonlinear Inductance Effects [4].

The L_d and L_q inductances exhibit nonlinear behavior due to the saturation characteristics of ferromagnetic materials. Therefore, analysis using the Finite Element Method (FEM) is required to obtain an accurate inductance map [3].

2.3 Opportunities and Challenges of SynRM Development for Future Electric Vehicles

Synchronous Reluctance Machines (SynRM) present significant strategic opportunities in the development of future electric vehicles (EVs). As rare-earth-free machines, SynRM avoids dependency on critical materials such as Neodymium (Nd), Dysprosium (Dy), and Terbium (Tb), whose supply chain is heavily concentrated and vulnerable to global geopolitical risks. This positions SynRM as a sustainable motor technology capable of reducing production costs, increasing supply stability, and supporting long-term energy transition strategies [5][6] [7].

SynRM machines also demonstrate excellent high-speed capability (18,000–22,000 rpm) without demagnetization risks, making them highly suitable for traction applications. Their lower rotor losses, simpler manufacturing process, and improved thermal robustness further strengthen their competitiveness in EV applications [5].

2.4 Torque Ripple and Harmonic Effects in SynRM.

Torque ripple is a critical concern in EV motor design due to its direct impact on ride comfort, drivetrain stress, noise–vibration–harshness (NVH), and power efficiency. SynRM torque ripple sources typically include magnetic saliency, slot harmonics, saturation effects, and rotor flux-barrier asymmetry [1] [3] [4] [5].

Dominant torque harmonics in 3-phase SynRM include the 6th, 12th, and 18th orders [3].

2.5 Torque Ripple Analysis Using Maxwell Stress Tensor (FEM).

Finite Element Method (FEM) is widely used to calculate torque ripple accurately. The Maxwell Stress Tensor (MST) approach decomposes torque into its tangential and normal flux components across the airgap surface [3] [4].

$$T = \oint (r \times (Bn \cdot Bt))\, dS \quad (8)$$

where Bn and Bt represent the normal and tangential flux density components, r is the airgap radius, and S is the airgap surface. FEM allows evaluation of torque components including fundamental torque, harmonic torque, cogging torque, and saturation-induced torque [3][4][5].

2.6 Relationship Between Flux Harmonics and Torque [4] [3].

Airgap flux can be expressed as a Fourier series, where each nth harmonic component contributes to torque ripple. The 6th harmonic commonly appears due to MMF harmonics in a 3-phase machine, rotor barrier geometry, and slot distribution effects [4] [3].

2.7 Effects of Torque Ripple on Electric Vehicles.

1. Ride Comfort: Ripple induces vibration and increases NVH levels.
2. Energy Consumption: Ripple produces fluctuating current components, increasing copper and core losses.
3. Drivetrain Stress: Ripple causes gear and bearing wear, shaft resonance, and impulsive mechanical loads.
4. Motor Control Difficulty: Harmonics interfere with FOC and sensorless estimators.
5. Temperature Rise: Increased peak current elevates thermal stress within the motor.

2.8 Torque Ripple Reduction Methods.

1. Rotor Design Optimization: asymmetric barriers, thin bridges, nonlinear curvature.
2. Stator Slot Optimization: semi-closed slots to reduce harmonic content.
3. Motor Control Strategies: injected third harmonic, adaptive MTPA, deadbeat control.
4. Inverter-Based Filtering: SiC/GaN inverters provide faster switching toward sinusoidal output.
5. Evolutionary Algorithms (GA/PSO): proven to reduce ripple by 30–40%.

2.9 Synchronization of Torque and EV Efficiency

Ideal EV motors require high torque, low ripple, and high efficiency. SynRM fulfills these requirements with multi-layer flux barriers, sinusoidal stator winding, optimal FOC control, and wide speed range enabled by fast switching SiC inverters. The absence of magnet permanent demagnetization and thermal robustness strengthens SynRM as a competitive candidate for mass-market and heavy-duty EV applications [2] [4] [5].

Research Methodology

This study employs a structured research methodology designed to evaluate the technical, environmental, and strategic relevance of Synchronous Reluctance Machines (SynRM) for next-generation electric vehicles (EVs). The methodology integrates analytical modeling, literature-based evidence, and comparative assessment. The overall research framework consists of **four major stages**: (1) problem identification, (2) systematic literature review, (3) analytical modeling and technical evaluation, and (4) synthesis and validation.

3.1 Problem Identification and Research Scope

The research begins by identifying critical challenges associated with rare-earth-based electric motors, particularly Permanent Magnet Synchronous Motors (PMSM), including supply chain instability, geopolitical risks, environmental impact, and long-term sustainability concerns. Based on this problem framing, the study defines two main research questions:

1. *To what extent can SynRM serve as a rare-earth-free alternative for EV traction systems?*
2. *What technical, economic, and sustainability advantages does SynRM offer relative to PMSM and induction motors (IM)?*

The scope is limited to medium-to-high-performance traction motors for passenger EV platforms, focusing on efficiency, torque behavior, control strategies, and supply chain implications.

3.2 Systematic Literature Review (SLR)

A Systematic Literature Review (SLR) was conducted following established guidelines by Wohlin [8] and Kitchenham [9] to identify high-quality evidence from peer-reviewed journals, IEEE publications, and authoritative energy agencies.

1) Identification of Sources

Primary sources include:

a. IEEE Transactions (Industrial Applications, Energy Conversion, Power Electronics)
b. Elsevier (Energy Policy, Journal of Cleaner Production)
c. IEA Global EV Outlook reports
d. High-impact EV motor design literature

2) Inclusion Criteria

Studies meeting the following criteria were included:

a. Published between 2010–2024
b. Focus on SynRM, PMSM, EV motor design, torque ripple, control strategies, or rare-earth economics
c. Provide experimental, FEM-based, or analytical results

3) Data Extraction

Key technical variables extracted include:

a. Saliency ratio, inductance characteristics (Ld, Lq)
b. Torque production and ripple metrics
c. Control methods (FOC, MTPA, MPC, sensorless)
d. Rotor–stator design geometry
e. Thermal behavior and high-speed capability
f. Rare-earth dependency and sustainability data

3.3 Analytical Modeling of SynRM

The mathematical model of SynRM was developed based on standard dq-axis transformation and electromagnetic torque formulation. The following analytical components were evaluated:

1. dq-axis voltage equations
2. Flux linkage and nonlinear inductance modeling
3. Electromagnetic torque equation
4. Harmonic and torque ripple analysis using FEM references

This analytical model provides the foundation for evaluating rotor saliency, torque capability, and control method compatibility.

D. Comparative Technical Analysis

The study applies a structured comparison between SynRM, PMSM, and IM based on the following technical parameters:

a. Efficiency across load and speed profiles
b. Torque ripple and harmonic sensitivity
c. Thermal robustness and high-speed operation
d. Rotor structural complexity
e. Control strategy requirements
f. Compatibility with SiC/GaN inverters

Published FEM-based studies [1]–[4] are used as benchmarks to ensure quantitative precision.

3.4 Sustainability and Supply Chain Assessment

To evaluate SynRM's strategic value for energy transition, a sustainability assessment was conducted covering:

1. Material criticality analysis using frameworks from IEA [5] and rare-earth literature [6], [7].
2. Environmental impact including lifecycle emissions and recyclability.
3. Supply chain resilience considering geopolitical concentration and cost volatility.

This assessment establishes SynRM's role in reducing dependency on rare-earth materials.

3.5 Synthesis and Validation

The results from the literature review, analytical modeling, and comparative assessment were synthesized to evaluate the feasibility of SynRM as a primary EV traction motor. Findings were validated through cross-comparison with the latest EV motor technology reports and peer-reviewed control strategy studies.

Result and Discussion

4.1 Control Strategies and Performance Optimization of SynRM [2].

4.1.1 Field-Oriented Control (FOC) [2].

Field-Oriented Control (FOC) merupakan teknik kontrol utama untuk mengendalikan motor SynRM dengan memisahkan komponen arus penghasil fluks (id) dan arus penghasil torsi (iq) dalam kerangka d–q. Pada SynRM, id berfungsi mengontrol fluks berdasarkan induktansi Ld, sedangkan iq mengontrol torsi berdasarkan selisih induktansi (Ld - Lq). FOC memungkinkan kontrol torsi yang lebih halus dan presisi, serta meningkatkan efisiensi pada berbagai kondisi pembebanan [4] [2].

Implementasi FOC pada SynRM biasanya melibatkan estimator rotor position, phase current sampling, PI regulators, decoupling compensation, serta modulasi PWM (SVPWM atau sinusoidal PWM). Tingginya non-linearitas induktansi akibat saturasi material menuntut FOC untuk menggunakan model parameter yang lebih adaptif atau berbasis lookup-table hasil FEM [3] [2].

4.1.2 Maximum Torque Per Ampere (MTPA) [2].

Strategi Maximum Torque Per Ampere (MTPA) bertujuan memperoleh torsi maksimum dengan arus stator minimum. Pada SynRM, MTPA ditentukan oleh rasio saliency (Ld/Lq) dan karakteristik non-linear induktansi. Karena SynRM memiliki torsi murni reluktansi, kurva MTPA biasanya memerlukan pencarian numerik atau tabel hasil FEM untuk menentukan kombinasi id dan iq optimum [1] [3] [2].

MTPA sangat penting pada kendaraan listrik karena dapat meningkatkan efisiensi sistem penggerak, mengurangi rugi-rugi tembaga, dan memperpanjang jangkauan kendaraan (driving range) [2].

4.1.3 Field Weakening Control (FWC) [2].

Field Weakening Control (FWC) memungkinkan motor mencapai kecepatan di atas kecepatan dasar (base speed). Pada SynRM, FWC memanfaatkan kontrol arus id negatif untuk mengurangi fluks total sehingga tegangan back-EMF tetap berada dalam batas tegangan inverter. Keunggulan SynRM adalah tidak adanya risiko demagnetisasi seperti pada PMSM, sehingga FWC dapat dilakukan secara lebih agresif pada kecepatan tinggi [2].

4.1.4 Sensorless Control Techniques [2].

Sensorless control bertujuan memperkirakan posisi rotor tanpa menggunakan sensor mekanis. Pada SynRM, teknik sensorless dapat memanfaatkan high-frequency signal injection, model-based observers, atau sliding-mode estimators. Karena SynRM tidak memiliki magnet permanen, sinyal saliency menjadi elemen utama untuk estimasi posisi rotor [1] [2].

Teknik HF signal injection sering digunakan pada kecepatan rendah, sementara model-based observers seperti EKF dan SMO berfungsi pada kecepatan menengah hingga tinggi. Kombinasi keduanya menghasilkan kontrol sensorless hybrid yang presisi untuk EV [5] [2].

4.1.5 Model Predictive Control (MPC) [2].

Model Predictive Control (MPC) merupakan pendekatan kontrol modern yang mampu memprediksi dinamika motor beberapa langkah ke depan. MPC sangat efektif mengurangi torque ripple, mengatasi non-linearitas induktansi, dan memberikan respons dinamis yang lebih cepat dibanding kontrol PI konvensional [3] [2].

MPC untuk SynRM biasanya diterapkan dalam bentuk Finite-Control-Set MPC (FCS-MPC) yang memilih vektor tegangan inverter berdasarkan fungsi optimasi yang mempertimbangkan error arus, ripple torsi, dan rugi-rugi stator [2].

4.1.6 Harmonic Minimization and Frequency Optimization [3].

Optimasi harmonik sangat penting untuk meningkatkan performa SynRM pada kendaraan listrik. Teknik seperti optimal slot/pole combination, third-harmonic injection, damping filters, dan harmonic spread factor (HSF) telah terbukti mengurangi ripple hingga 30–50% pada SynRM modern [3].

Selain itu, penggunaan inverter berbasis SiC/GaN memungkinkan switching frequency lebih tinggi sehingga bentuk gelombang arus stator menjadi lebih sinusoidal dan efisiensi motor meningkat.

4.2 Sustainability and Rare-Earth Supply Chain Analysis [6] [7].

The global transition toward sustainable electrification requires electric motor technologies that minimize environmental impact, reduce material criticality, and ensure long-term supply chain stability. Permanent Magnet Synchronous Motors (PMSM), although highly efficient, depend heavily on rare-earth materials such as Neodymium (Nd), Dysprosium (Dy), and Terbium (Tb). These materials pose challenges due to supply concentration, geopolitical risks, high extraction cost, and significant environmental burden. Synchronous Reluctance Machines (SynRM), by contrast, offer a rare-earth-free solution that aligns well with global sustainability objectives [6] [7].

4.2.1 Environmental and Resource Sustainability

Rare-earth mining and processing produce substantial environmental impacts, including soil degradation, toxic waste, and high carbon emissions. Countries with strict environmental regulations face further barriers due to the difficulty of establishing clean rare-earth processing facilities. SynRM eliminates the use of rare-earth magnets, reducing the overall environmental footprint of EV motor production [6] [7] [5].

Additionally, SynRM's simpler rotor structure improves recyclability. Since the motor does not contain permanent magnets, end-of-life disassembly is more efficient and less energy-intensive. This supports circular economy strategies and aligns with global directives for sustainable manufacturing.

4.2.2 Supply Chain and Geopolitical Considerations [6] [7].

Rare-earth materials used in PMSM motors are geographically concentrated, with more than 90% of global production controlled by a single country. This creates severe supply chain vulnerability for the EV industry, particularly during periods of geopolitical instability, trade restrictions, or resource nationalism [6] [7] [5] [2].

By removing dependency on rare-earth materials, SynRM significantly lowers geopolitical and supply chain risks. Manufacturers can source the required steel laminations and copper windings from globally diversified suppliers, enhancing supply stability and reducing long-term operational risks [6] [7].

4.2.3 Economic Advantages and Industrial Scalability

From an economic standpoint, SynRM motors reduce production costs by eliminating expensive rare-earth magnets. Fluctuating magnet prices—driven by market speculation and export restrictions—pose long-term challenges for PMSM-based EVs. SynRM mitigates these uncertainties, enabling more predictable production budgeting for automotive manufacturers [6] [7] [5].

Industrial scalability is also improved through simpler manufacturing steps. SynRM rotors can be produced using conventional lamination stamping processes without complex magnet insertion or bonding procedures. This reduces production time, lowers defect rates, and increases compatibility with existing motor manufacturing infrastructures.

4.2.4 Strategic Role of SynRM in the Global Energy Transition [5].

The global shift toward net-zero emissions requires technologies that not only perform efficiently but also support sustainability goals throughout the supply chain. SynRM offers a pathway toward fully sustainable electric drives by balancing performance, cost, and environmental responsibility [6] [7] [5].

Major automotive manufacturers are increasingly examining rare-earth-free motor technologies. SynRM’s suitability for high-speed traction, broad operating range, thermal stability, and minimal reliance on critical materials positions it as a long-term strategic solution for EV platforms. As SiC-based inverters and advanced control algorithms continue to improve, SynRM is expected to gain further traction in next-generation EV architectures [6] [7] [5] [2].

4.3 General Discussion and Integrated Analysis of SynRM for Next-Generation Electric Vehicles

This section presents an integrated discussion of the key findings related to the development, optimization, and strategic position of Synchronous Reluctance Machines (SynRM) in next-generation electric vehicle (EV) technology. Through a synthesized evaluation of motor design, material engineering, power electronics, control strategies, sustainability, and supply chain dynamics, this analysis highlights the central role that SynRM may assume in the global energy transition [2] [5] [6] [7].

Overall, SynRM demonstrates strong compatibility with the requirements of modern EV architectures. Its rare-earth-free design offers significant cost, supply chain, and environmental advantages compared to Permanent Magnet Synchronous Motors (PMSM). In addition, SynRM's thermal robustness, high-speed capability, and efficiency under variable load conditions position it as a competitive solution for traction applications [5] [6] [7].

From the standpoint of electromagnetic design, the rotor flux-barrier geometry remains the dominant factor influencing torque production, ripple behavior, and overall power density. Multi-layer barriers, asymmetric geometry, and advanced lamination materials have increased saliency ratios while maintaining structural integrity. Combined with stator slot optimization and high-quality magnetic materials, SynRM can reach efficiency values approaching premium-grade PMSM machines [1] [4].

Modern control strategies significantly enhance SynRM performance. Techniques such as Field-Oriented Control (FOC), Maximum Torque Per Ampere (MTPA), Model Predictive Control (MPC), and improved sensorless algorithms enable precise torque regulation and efficiency optimization. Furthermore, harmonic suppression methods using high-frequency injection, adaptive filters, and SiC/GaN-based inverters have reduced torque ripple substantially, improving NVH characteristics and drivability in EVs [2] [3] [5].

In terms of energy efficiency and thermal behavior, SynRM exhibits lower rotor losses and improved high-temperature tolerance. This aligns well with EV duty cycles involving repeated acceleration, regenerative braking, and operation in elevated ambient temperatures. The absence of permanent magnets eliminates demagnetization risk, enabling aggressive field-weakening control for extended high-speed operation [2] [5].

Sustainability and supply chain analysis further strengthens SynRM's strategic relevance. By avoiding critical rare-earth materials, SynRM reduces dependency on highly concentrated global supply chains and mitigates geopolitical risks. This technological independence supports long-term production stability and cost predictability for EV manufacturers [5] [6] [7].

Overall, SynRM represents a balanced trade-off between performance, manufacturability, environmental sustainability, and economic viability. As advancements in control algorithms, magnetic materials, and inverter technology continue, SynRM is poised to become a core component of next-generation EV platforms, especially in markets seeking rare-earth-free solutions [2][5][6][7].

Conclusion

This paper has presented a comprehensive analysis of Synchronous Reluctance Machines (SynRM) as a promising technology for next-generation electric vehicles (EVs). Through the synthesis of electromagnetic modeling, rotor–stator structural advancements, control strategies, thermal performance, supply chain resilience, and sustainability considerations, it is evident that SynRM offers substantial advantages over conventional permanent magnet-based motor technologies.

SynRM’s rare-earth-free architecture significantly reduces environmental impact, dependence on critical materials, and vulnerability to geopolitical risks. This makes SynRM not only an efficient electrical machine but also a strategic component for global energy transition and sustainable EV manufacturing.

From a performance standpoint, advancements in rotor flux-barrier geometry, nonlinear inductance modeling, and harmonic mitigation have enabled SynRM to achieve torque density, efficiency, and drivability characteristics that closely approach or, in specific scenarios, surpass the capabilities of PMSM. Additionally, modern control techniques such as FOC, MTPA, MPC, and hybrid sensorless algorithms provide SynRM with exceptional operational flexibility, smooth torque response, and improved high-speed performance.

Combined with the adoption of SiC/GaN inverters, SynRM's operational envelope continues to expand, positioning it as a leading candidate for EV traction systems in both passenger and commercial applications. Meanwhile, the economic benefits—including simplified manufacturing and reduced production cost—further enhance its feasibility for mass-market adoption.

In conclusion, SynRM represents a balanced, efficient, and futureproof solution for electric vehicle propulsion. Ongoing research in material science, control engineering, and power electronics will continue to elevate its performance. With its strong alignment to sustainability goals and global electrification strategies, SynRM is poised to become a central motor technology in the evolution of cleaner, more resilient transportation systems.

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