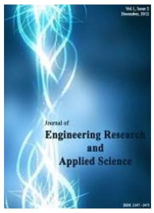
Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 15 (1), June 2026, pp 39-51
ISSN 2147-3471 © 2026



Electromechanical Evaluation and Performance Metrics of Next-Generation EV Motors: A Comparative Study on Traction Technologies

Emin Alkoç[1,*], Ünal Kurt[2]

[1]Renewable Energy and Applications, Amasya University, Amasya, Turkey
[2]Electrical and Electronics Engineering, Amasya University, Amasya, Turkey

Accepted 27 May 2026

Abstract
Driven by the urgent global imperative to curb carbon emissions and address the dwindling reserves of fossil fuels, the automotive world is currently navigating a major transition toward electrified propulsion. In this new era, the real-world performance of a New Energy Vehicle (NEV) is no longer just about the battery; it is defined by the complex electromechanical interplay between energy storage and the specific behaviour of its traction motor. This research offers an in-depth electromechanical assessment and a side-by-side comparison of the core motor topologies dominating today's market: AC Induction Motors (ACIM), Permanent Magnet Synchronous Motors (PMSM), Brushed and Brushless DC (BLDC) units, Switched Reluctance Motors (SRM), and the emerging Axial Flux architectures. Rather than just listing features, this study interrogates each design through the lens of critical metrics, including power-to-weight ratios, thermal endurance, and the hard realities of manufacturing costs. While PMSMs remain the industry's "gold standard" for high-end efficiency, our analysis uncovers a strategic move toward magnet-free alternatives, specifically SRMs and ACIMs, as manufacturers seek to escape the volatile supply chains of rare-earth elements. Beyond the hardware, we examine how sophisticated control frameworks, such as Field-Oriented Control (FOC) and Model Predictive Control (MPC), act as the "brain" of the drivetrain to refine dynamic response and energy recovery. By merging structural insights with operational realities, this work provides a practical roadmap for identifying the right traction solutions to meet the diverse demands of future e-mobility.

Keywords: *Electric Vehicle (EV), Traction Motors, Electromechanical Evaluation, PMSM, Switched Reluctance Motors, Axial Flux Technology, Performance Metrics.*

1. Introduction
The contemporary automotive landscape is currently witnessing a transformative era, primarily catalyzed by the urgent global imperative to mitigate the environmental degradation and energy inefficiencies inherent in internal combustion engine (ICE) vehicles. This transition toward alternative and clean energy sources has redefined the historical development of electric vehicles (EVs), placing the evolution of propulsion motor technologies at the very core of this industrial revolution. While early-stage mobility solutions favored simple brushed Direct Current (DC) architectures for their straightforward control mechanisms, the subsequent leap in power electronics and semiconductor technologies has paved the way for more sophisticated topologies. Today, the electromechanical evaluation of a vehicle's traction system, encompassing everything from torque-to-volume ratios to advanced control paradigms, serves as the definitive metric for operational success in the next generation of e-mobility.

The environmental degradation and energy inefficiency caused by vehicles with traditional internal combustion engines (ICE) have directed the automotive industry toward alternative and clean energy sources [1]. In the historical development of electric vehicles (EVs), the evolution of the motor technologies comprising the propulsion system has played a critical role. In early electric vehicle projects, traditional brushed Direct Current (DC) motors were preferred because speed and torque control could be achieved in an extremely simple and low-cost manner without the need for power electronics [2]. However, the mechanical brush and commutator systems inherent in the structure of brushed DC motors led to energy losses due to continuous friction, overheating, low power density, and the necessity of regular maintenance [3].

*Corresponding author: eminalkoc@gmail.com

The rapid advancements in power electronics, semiconductor technologies, and microcontrollers since the late 1990s have been a turning point for the automotive industry. This technological leap made it possible to replace the function of mechanical brushes with electronic drives (inverters), leading to the complete obsolescence of brushed DC motors in the industry [1]. Today, the propulsion systems that act as the heart of modern electric vehicles are shaped around AC Induction Motors (ACIM), Brushless DC Motors (BLDC), and Permanent Magnet Synchronous Motors (PMSM), which offer high efficiency, zero maintenance requirements, and superior performance across wide speed ranges [4]. These new-generation motors are expected to respond rapidly to instantaneous power demands and maintain their reliability under harsh operating conditions. To meet these requirements, various motor and battery architectures with different characteristics are utilized in the industry.

2. Motor Technologies Used in Electric Vehicles

Traditionally, electric motors are fundamentally divided into two main categories: alternating current (AC) and direct current (DC) motors. However, traditional brushed DC motors are no longer utilized in contemporary electric vehicles due to limiting factors such as low power density, high maintenance costs stemming from the brush-commutator system, overheating issues, and overall inefficiency. In this context, moving beyond classical classifications, the subsequent sections of this study will examine in detail the advanced motor topologies actively preferred in modern electric vehicles, which address the contemporary performance and range demands of the automotive industry.

2.1. Synchronous Motors

Figure 1 presents the internal structure of a synchronous motor. The stator houses three-phase AC windings that generate the rotating magnetic field, whereas the rotor carries the field-producing element, shown here as DC excitation windings supplied through the slip-ring and brush assembly at the front. In permanent magnet variants (PMSM), these windings are replaced by rotor-mounted magnets, which removes the need for brushes. This arrangement produces the zero-slip synchronous rotation described below, in which the rotor locks to the stator flux and pushes efficiency above 95%.

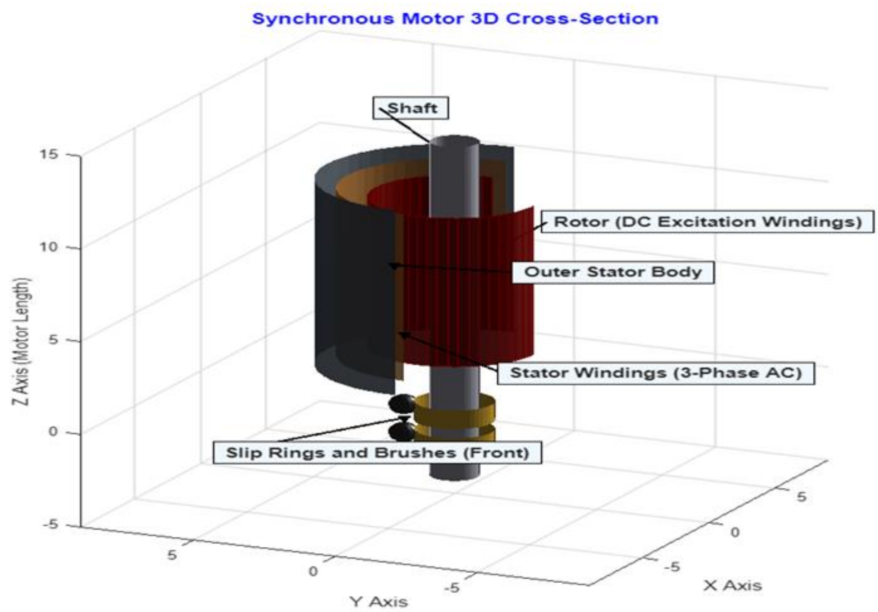


Figure 1. Three-dimensional cross-sectional view of a synchronous motor, showing the shaft, the rotor carrying DC excitation windings, the outer stator body, the three-phase AC stator windings, and the front slip-ring and brush assembly. [**Source:** Generated by the author using MATLAB].

The classification of permanent magnet motors encompasses various subcategories, with Permanent Magnet Synchronous Motors (PMSM) increasingly dominating the landscape of next-generation vehicle propulsion. Among these configurations, Interior Permanent Magnet (IPM) structures have emerged as the industry standard for traction applications. This preference is driven by their superior reluctance torque, high power factor, and exceptional efficiency, complemented by a compact design that minimizes both heat generation and acoustic noise. Furthermore, their fully enclosed, maintenance-free architecture effectively reduces windage losses and aerodynamic interference. Synthesizing these performance metrics,

[5] emphasize that the IPM-configured PMSM represents the most optimized solution for New Energy Vehicle (NEV) traction motors, balancing efficiency and power density requirements.

The evolution of electric mobility necessitates traction solutions that combine high-tier performance with operational economy. Consequently, Permanent Magnet Synchronous Motors (PMSM) have become a pivotal element in contemporary electric propulsion frameworks, attributed to their exceptional power density and torque-to-volume ratios. The absence of slip rings in their architecture facilitates more streamlined control strategies, which inherently boosts the overall effectiveness of the energy conversion processs [6]. In comparison to conventional brushed DC machines, PMSMs exhibit superior characteristics such as enhanced power-to-mass ratios, quieter operation, and significantly lower maintenance demands. Moreover, these motors ensure the high-degree dynamic response and stringent speed regulation essential for handling the complexities of varying driving profiles [7, 8].

The architectural development of these motors is fundamentally driven by the global imperative to phase out internal combustion engines and curtail environmental degradation. Such designs are intricately linked to specific vehicle dynamics, including mass, dimensions, and necessary tractive effort. Consequently, achieving a synergy between high load-bearing capacity and energy economy necessitates a rigorous, cyclical optimization framework. This iterative approach, which involves the constant refinement of design variables, is vital for ensuring that motor outputs are maximized within predefined operational constraints [5, 9, 10, 11].

2.1.1. Synchronous Motors: Structure, Operating Principle, and Automotive Applications

As electromechanical conversion units, synchronous motors are characterized by their outstanding efficiency and power-to-volume ratios, operating on the principle that the rotor's rotational velocity precisely aligns with the stator's revolving magnetic field [3]. Within the evolving electric vehicle sector, these machines are a cornerstone of propulsion technology. Specifically, Permanent Magnet Synchronous Motors (PMSM) have long been the industry's primary choice, while Externally Excited Synchronous Motors (EESM) have gained significant traction in recent years as a prominent alternative for delivering main drive power.

2.1.2. Structural Characteristics

Much like their induction counterparts, the stationary component (stator) in synchronous machines features a multiphase winding configuration driven by alternating current (AC). However, the primary anatomical distinction lies within the rotor design. Within PMSM topologies, the requisite magnetic flux is supplied by high-density rare-earth elements (REEs), predominantly Neodymium-Iron-Boron (NdFeB) magnets, which are either integrated directly into the rotor core or affixed to its surface [4]. Conversely, EESM architectures substitute these permanent magnets with copper coil windings. To establish the essential magnetic field in these systems, direct current (DC) must be delivered to the rotor coils through external mechanisms, employing either traditional brush-and-slip-ring assemblies or contactless inductive transfer techniques.

2.1.3. Operating Principle and Magnetic Locking

The fundamental operating principle of synchronous motors is based on the interlocking of two independent magnetic fields. The multiphase AC current applied to the stator windings creates a magnetic field rotating at a specific frequency within the air gap. Simultaneously, the permanent magnets (or excitation windings) located on the rotor produce a constant magnetic field.

Fundamentally, the propulsion mechanism relies on the continuous electromagnetic engagement between the stator's revolving magnetic field and the rotor's opposing poles. This dynamic attraction establishes a robust 'magnetic lock,' compelling the rotor to revolve at a velocity strictly synchronized with the stator's flux [2]. Consequently, any discrepancy between the actual rotor speed (N_r) and the synchronous speed (N_s) is entirely eliminated. By operating with absolute zero slip, a stark functional contrast to the inherent mechanics of induction motors, this seamless synchronization significantly curtails energy dissipation, thereby pushing peak operational efficiency well above 95%.

2.1.4. Role in Electric Vehicles and Control Strategies

Permanent Magnet Synchronous Motors (PMSM), attributed to their exceptionally high torque production capacity relative to their low volume and weight, are currently the primary choice of manufacturers such as Tesla (Model 3 and Y), Porsche (Taycan), and Volkswagen (MEB platform), and stand as the "gold standard" of the industry [1]. However, the control of PMSMs is complex; advanced vector control algorithms such as Field Weakening are required, especially at high highway speeds, to prevent the motor's back electromotive force (back-EMF) from exceeding the battery voltage [12].

Furthermore, the supply chain risks and high costs associated with the rare-earth elements in PMSMs, along with the danger of the magnets losing their magnetism (demagnetization) in the event of overheating, have prompted the search for new alternatives in the automotive sector. In this context, Externally Excited Synchronous Motors (EESM), which do not contain rare-earth elements and wherein the magnetic field in the rotor can be dynamically controlled via current, are actively used today by manufacturers such as BMW (5th Generation eDrive) and Renault, forming a strong alternative to PMSMs.

2.2. Asynchronous (Induction) Motors (ACIM)

The squirrel-cage induction motor in Figure 2 has no windings, magnets, or brushes on the rotor. Conductive bars embedded in the laminated rotor core are short-circuited at both ends by end rings, forming the squirrel cage visible in the figure. When the three-phase stator windings energise the air gap, the rotating flux induces currents in these bars, and the resulting rotor field interacts with the stator field to produce torque. The absence of a permanent rotor field allows the motor to be de-energised without generating drag torque, a property that makes it well suited as a secondary machine in dual-motor architectures.

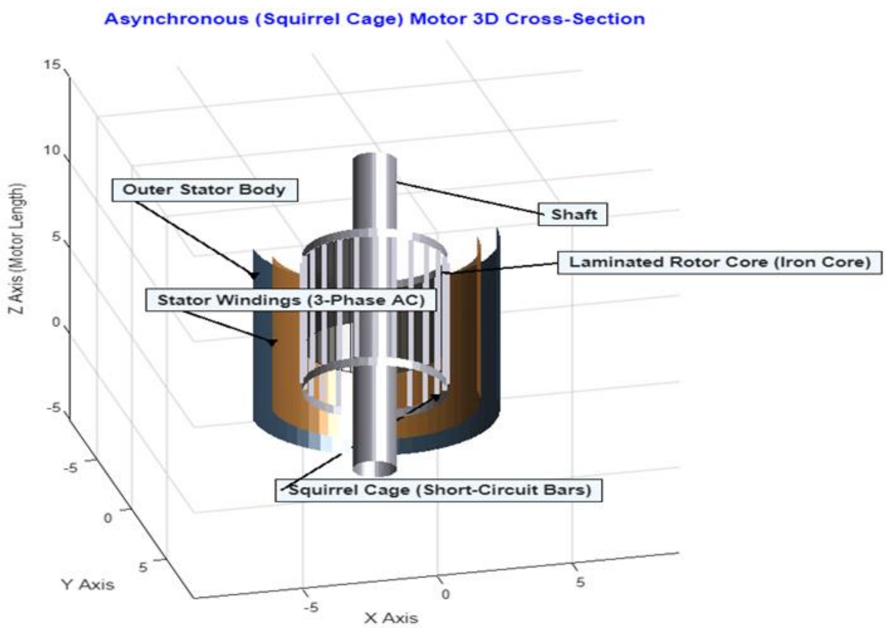


Figure 2. Three-dimensional cross-sectional view of a squirrel-cage induction (asynchronous) motor, showing the shaft, the outer stator body with three-phase AC windings, the laminated rotor core, and the squirrel-cage short-circuit bars. [**Source:** Generated by the author using MATLAB]

Induction machines have historically maintained a significant presence in the electric vehicle sector, largely facilitated by their robust squirrel-cage topologies. These systems offer inherent benefits, including structural simplicity, exceptional reliability, cost-effectiveness, and minimized torque ripple within a maintenance-free framework. Furthermore, they excel in sustaining a broad constant power region, seamlessly achieving rotational velocities more than 15,000 rpm. Nevertheless, despite these operational merits, the global market footprint of asynchronous motors is progressively contracting. This decline is primarily attributed to the intricate nature of their control algorithms, coupled with inferior efficiency and power density metrics when benchmarked against permanent magnet alternatives [5].

2.2.1. Asynchronous (Induction) Motors: Structure, Operating Principle, and Automotive Applications

Asynchronous motors (AM), or induction motors as they are otherwise known in the literature, are electromechanical energy conversion systems widely used in industrial applications and electric vehicle (EV) propulsion systems ascribed to their rugged construction, low costs, and high reliability [13]. Unlike permanent magnet motors, they do not require permanent magnets to generate a magnetic field in the rotor; this frees them from dependence on rare-earth elements (REE), placing them in a strategic position in terms of supply chain and cost [14].

2.2.2. Structural Characteristics

Fundamentally, the anatomical framework of an induction motor relies on a stationary stator housing AC-excited multiphase coils, paired with a rotating inner core. Within the realm of electric mobility, the 'squirrel-cage' rotor topology has emerged as the prevailing standard. This specific architecture is characterized by conductive aluminium or copper bars seamlessly integrated into laminated steel punching, which are then electrically short-circuited at both extremities via terminal rings [2]. By deliberately omitting friction-dependent current transfer mechanisms, namely brushes, slip rings, and commutators, this robust configuration dramatically curtails mechanical degradation, thereby yielding a highly durable and virtually maintenance-free operational lifespan.

2.2.3. Operating Principle and the Phenomenon of Slip

At its core, the electromechanical energy conversion in induction machines is strictly governed by Faraday's Law of Electromagnetic Induction. The excitation of the stator coils with a multiphase alternating current establishes a revolving magnetic flux across the air gap, which propagates at the synchronous velocity (N_s). As this dynamic field sweeps across the resting rotor bars, it electromagnetically induces an electromotive force (EMF), and consequently, a localized current, within the rotor circuit [1].

The circulation of this localized current subsequently generates a secondary magnetic flux within the rotor. The dynamic interplay between this newly formed rotor flux and the primary revolving field of the stator yields the mechanical torque required to drive the shaft. Crucially, sustained torque generation relies on the persistent relative motion between the stator's flux and the rotor conductors. Consequently, the rotor's actual velocity (N_s) is fundamentally precluded from ever matching the synchronous speed (N_r). This inherent velocity gap, universally termed 'slip,' dictates the core operational behavior of induction machines [13].

2.2.4. Role in Electric Vehicles and Control Strategies

In early modern electric vehicles (e.g., the first-generation Tesla Model S), asynchronous motors proved their competence by being utilized as the main propulsion unit. Although their volumetric power density and efficiency, particularly at low speeds, are lower compared to permanent magnet synchronous motors (PMSM), they can currently exhibit a dynamic performance very close to that of PMSMs thanks to advanced power electronics and vector control (Field-Oriented Control - FOC) algorithms [2].

Furthermore, since there is no permanent magnetic field in the rotor when the current to the stator is cut off, asynchronous motors do not generate mechanical drag (drag torque). This characteristic feature makes them an ideal option, especially as a "secondary motor" in dual-motor all-wheel-drive (AWD) electric vehicle architectures; when the vehicle is cruising at a constant speed on the highway, the asynchronous motor can be completely shut down to achieve energy savings [1].

2.3. Brushed Direct Current (DC) Motors

Figure 3 shows the components that account for both the strengths and the weaknesses of the brushed DC motor. Direct current reaches the rotating armature windings through the carbon brushes and the segmented commutator, an arrangement that enables simple and low-cost speed control. This same sliding contact is a continuous source of friction, wear, and sparking, which explains the maintenance requirement and the reduced high-speed efficiency that have removed the topology from the main propulsion of modern vehicles.

In the nascent stages of electric mobility, direct current (DC) motors saw widespread adoption, primarily facilitated by their straightforward speed regulation mechanisms. Nevertheless, inherent structural limitations, namely sub-optimal efficiency, excessive mass, and the mechanical vulnerabilities associated with brush-and-commutator assemblies, render them inadequate for the rigorous demands of contemporary high-speed New Energy Vehicles (NEVs). Consequently, their modern application spectrum has been largely relegated to niche sectors, such as intralogistics and low-velocity utility transport [5].

2.3.1. Operating Principle and Advantages

Brushed direct current (DC) motors enable continuous, smooth, and precise control of speed and torque, thereby allowing vehicles to respond instantaneously to acceleration and deceleration conditions [15].

2.3.2. Limitations

Despite their simple construction, they require frequent maintenance due to brush wear; their efficiency decreases at high speeds, and the use of a mechanical commutator exacerbates friction and wear [15].

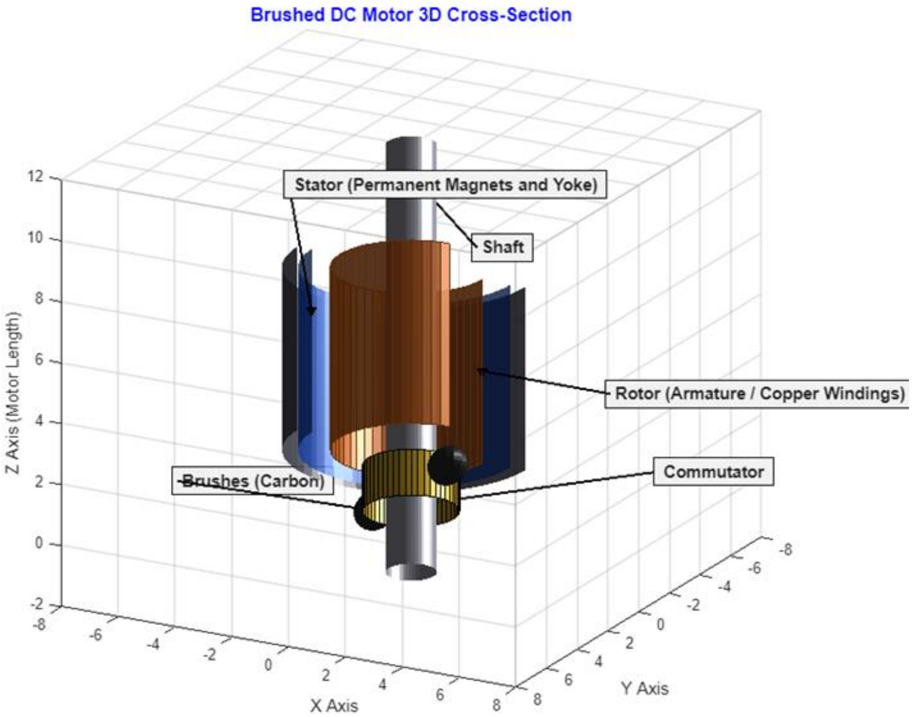


Figure 3. Three-dimensional cross-sectional view of a brushed DC motor, showing the shaft, the stator formed by permanent magnets and yoke, the rotor armature with copper windings, the carbon brushes, and the mechanical commutator. [**Source:** Generated by the author using MATLAB]

2.4. Brushless Direct Current (BLDC) Motors

In the BLDC motor shown in Figure 4, the permanent magnets sit on the rotor and the windings are fixed to the stator, which is the reverse of the brushed arrangement in Figure 3. With no brushes or commutator, the switching that a mechanical commutator once performed is handled electronically, typically using rotor-position feedback from Hall-effect sensors. This eliminates the friction and wear of the brushed design and raises efficiency to roughly 85 to 90%, at the cost of a more complex electronic controller and a tendency toward torque ripple.

Against the backdrop of depleting fossil fuel reserves and escalating greenhouse gas emissions, the integration of photovoltaic (PV) systems into electric vehicles has gained considerable traction, with Brushless Direct Current (BLDC) motors being identified as a highly compatible propulsion technology. Within the broader e-mobility sector, these architectures have emerged as a favoured choice for light-to-moderate power applications, fundamentally driven by their exceptional torque delivery, minimized electromagnetic footprint (EMI), and highly cost-effective lifecycle management. The structural elimination of brushes significantly mitigates both eddy current and copper losses, thereby sustaining high operational efficiency alongside minimal maintenance demands. Furthermore, utilizing permanent magnets for excitation inherently prevents field winding losses, pushing the overall system efficiency to its optimal limits. When benchmarked across comprehensive technological metrics, BLDC motors demonstrate a clear performance superiority over conventional DC, asynchronous, and switched reluctance alternatives [16].

Although Brushless DC (BLDC) machines are widely recognized for their formidable power-to-weight ratios and torque capabilities, their practical deployment is frequently constrained by inherent regulatory complexities. Chief among these operational hurdles are pronounced torque pulsations, susceptibility to electromagnetic interference (EMI), and a diminished capacity for fault resilience. To effectively suppress this torque ripple phenomenon and thereby refine the dynamic response of electric propulsion systems, contemporary designs necessitate highly sophisticated regulatory paradigms. To this end, researchers and engineers increasingly rely on advanced algorithmic frameworks, predominantly utilizing Direct Torque Control (DTC), Field-Oriented Control (FOC), and Model Predictive Control (MPC) architectures to optimize driving performance [17].

BLDC motors are systems in which the mechanical brush and commutator structure found in traditional DC motors is replaced by electronic control circuits.

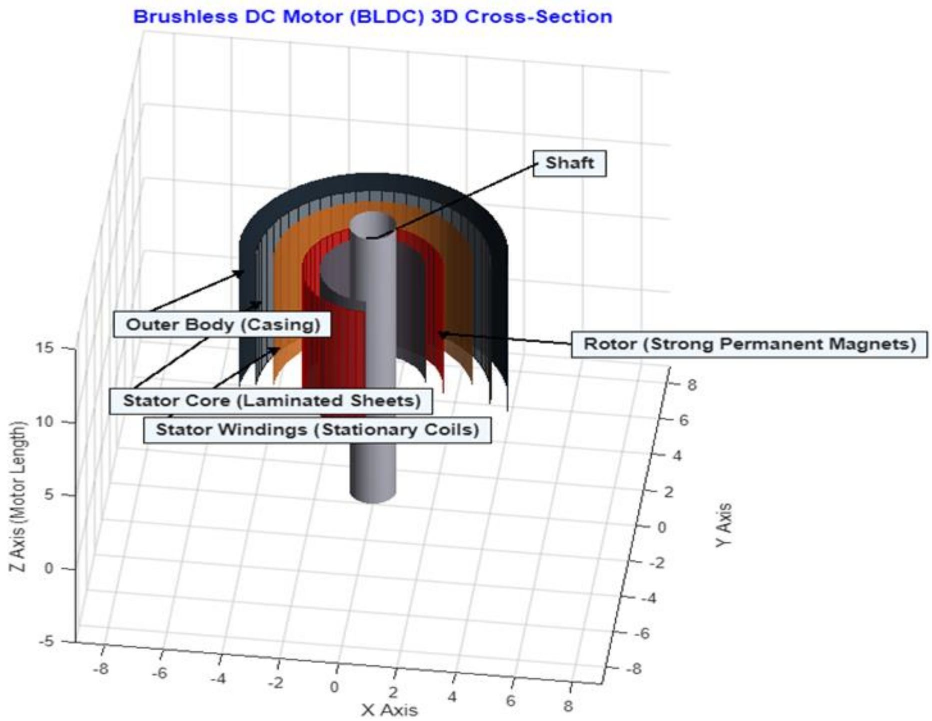


Figure 4. Three-dimensional cross-sectional view of a brushless DC (BLDC) motor, showing the shaft, the outer casing, the rotor with permanent magnets, the laminated stator core, and the stationary stator windings. [**Source:** Generated by the author using MATLAB]

2.4.1. Structure and Operating Principle

Architecturally, these machines feature a magnetic field established by permanent magnets integrated into the rotating core, complemented by stationary armature coils on the stator. Their operational synchrony relies strictly on Hall Effect sensors, which deliver real-time angular feedback regarding the rotor's exact spatial coordinates. By leveraging this continuous telemetry, the excitation sequence within the stator is electronically commutated, thereby sustaining a seamless electromechanical rotation [2].

Unlike traditional brushed architectures, BLDC motors utilize an electronic controller and permanent magnets on the rotor; consequently, friction is eliminated, rendering the motors significantly more durable, quiet, and long-lasting [15].

2.4.2. Evaluation

The absence of mechanical friction increases efficiency and eliminates the need for maintenance. However, torque ripples, which become pronounced at high speeds, can lead to vibration. They are generally used in light electric vehicles and in-wheel (hub) applications.

A standout feature of modern electric propulsion is the implementation of regenerative braking systems, which significantly enhance vehicle range by 8-25% by repurposing the electric motor as a generator during deceleration. This mechanism allows kinetic energy to be harvested and stored rather than being dissipated as thermal waste through conventional friction brakes, offering superior efficiency particularly in urban stop-and-go driving cycles. Furthermore, the use of advanced regenerative controllers, especially when integrated into Brushless DC (BLDC) drives to capture residual coasting energy, provides greater control over braking modulation, reduces the wear on mechanical components, and can boost total system effectiveness by as much as 24% [18].

2.4.3. Limitations

The requirement for complex electronic controllers and generally sensors for the operation of these motors increases design costs, while performance issues such as torque losses at low speeds and overheating under heavy loads may arise [15].

2.5. Switched Reluctance Motors (SRM)

The doubly salient geometry that defines the switched reluctance motor is visible in Figure 5, with prominent poles on both the stator and the rotor. The rotor carries no windings, magnets, or slip rings and consists only of stacked ferromagnetic laminations, which is the origin of the topology's robustness and its independence from rare-earth materials. Torque is produced as the stator phases are excited in sequence and the rotor moves toward the position of lowest magnetic reluctance. This discontinuous, pole-by-pole excitation also produces the pronounced torque ripple and acoustic noise that currently limit the use of SRMs in passenger vehicles.

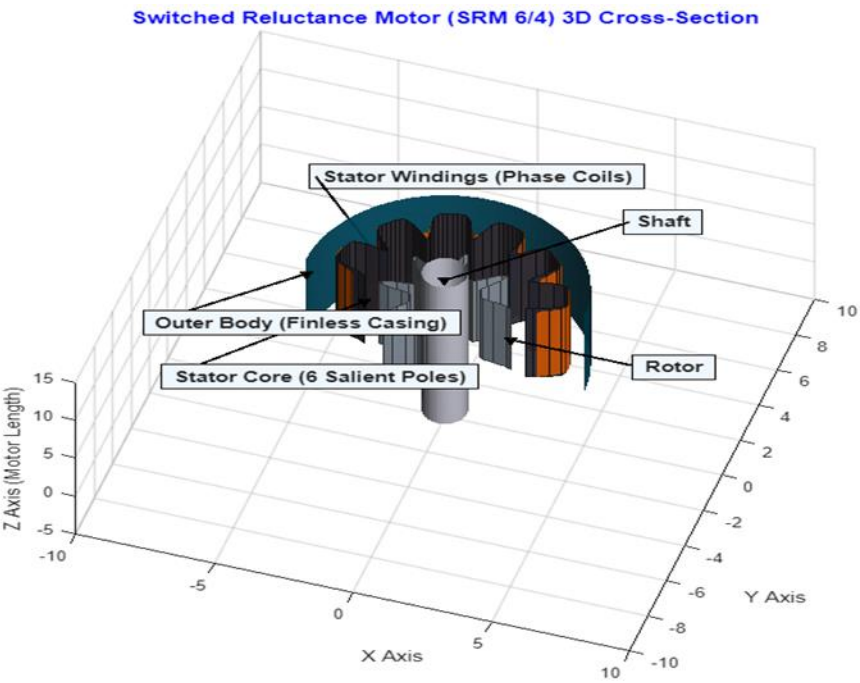


Figure 5. Three-dimensional cross-sectional view of a 6/4 switched reluctance motor (SRM), showing the shaft, the outer casing, the stator core with six salient poles carrying the phase coils, and the salient-pole rotor. [**Source:** Generated by the author using MATLAB]

Switched Reluctance Motors (SRMs) are distinguished by an exceptionally resilient and minimalist architecture, characterized by a rotor assembly completely devoid of windings, permanent magnets, or slip rings. While this streamlined design facilitates high-speed operational capabilities alongside cost-effectiveness, optimal efficiency, and straightforward regulatory mechanisms, their broader implementation is substantially hindered by inherent mechanical drawbacks. Specifically, the generation of pronounced torque pulsations, coupled with excessive acoustic emissions and mechanical vibrations, heavily constrains their integration into mainstream electric vehicle drivetrains [5].

Thanks to their extremely robust structures that eliminate the need for permanent magnets, they represent a highly suitable motor topology for applications due to their high fault tolerance in harsh operating environments. The high-noise operation of these motor types is the primary challenge in their applications. An additional structural drawback stems from the requirement of a customized inverter topology, coupled with an increased volume of power cabling necessary to feed the isolated stator phase windings. Furthermore, their inherent reliance on a discontinuous current operation profile renders these machines significantly more susceptible to mechanical deformation and vibratory stress when juxtaposed with Permanent Magnet Synchronous Motors (PMSM). Nevertheless, to maximize performance throughout the entire torque-velocity spectrum, system efficiency can be successfully elevated to the 95% threshold through the precise modulation of phase excitation parameters. Specifically, by rigorously regulating the commutation onset (turn-on) and extinction (turn-off) angles alongside phase current magnitudes, the operational efficacy of SRMs can be highly optimized [12].

SRMs are one of the simplest motor types, operating on the principle that magnetic flux always tends to follow the path of least magnetic resistance (reluctance) [19].

2.5.1. Structure and Operating Principle

From a structural standpoint, these machines are characterized by a doubly salient geometry, meaning prominent poles are present on both the stationary and rotating components. The rotor itself is remarkably minimalist, constructed exclusively from stacked ferromagnetic laminations without the inclusion of any conductive coils or permanent magnets. The fundamental propulsion mechanism relies entirely on the principle of magnetic resistance; as the stator phases are subjected to sequential excitation, the rotor is continuously compelled to shift toward a positional configuration that offers the lowest possible reluctance. This relentless mechanical pursuit to align with the activated stator poles generates the requisite driving torque for continuous rotation [19].

2.5.2. Evaluation

Their lack of reliance on rare-earth elements and their exceptional durability are their greatest advantages. However, issues of acoustic noise and high torque ripple limit their use in passenger vehicles. They hold a critical potential for the future electrification of heavy-duty vehicles [19].

2.6. Axial Flux Motors

Figure 6 illustrates the planar, disk-shaped construction that sets the axial flux motor apart from conventional radial machines. Two rotor disks carrying permanent magnets sit on either side of a central stator disk, so the magnetic flux travels along the axis of the shaft rather than radially outward. Positioning the magnets on the outer perimeter of the disks yields a gravimetric torque density roughly 30 to 40% higher than a radial motor of comparable power, and up to about four times higher in yokeless designs. The compact axial length is offset by two practical difficulties visible in the layout, namely the strong axial attraction that must be balanced across a millimetre-scale air gap and the difficulty of cooling the enclosed central stator.

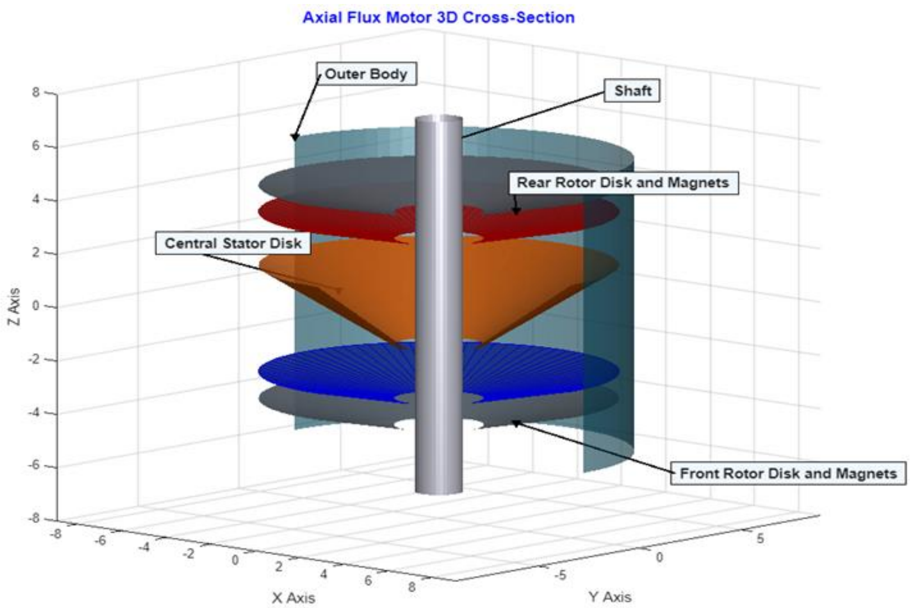


Figure 6. Three-dimensional cross-sectional view of a dual-rotor axial flux motor (AFM), showing the shaft, the outer body, the central stator disk, and the front and rear rotor disks carrying the permanent magnets. [**Source:** Generated by the author using MATLAB].

While magnetic flux radiates outward from the center in traditional radial flux motors, in axial flux motors, the flux travels along a straight axis between the rotor and stator disks [20]. From a mechanical engineering perspective, Yokeless and Segmented Armature (YASA) AFM designs are cited among the most promising types of this technology [21]. Furthermore, to optimize the performance of permanent magnet (PM) motors, brushless dual-rotor motors with axial magnetic field modulation are also examined in the literature, and the specific design conditions required to avoid axial tilting moments in these structures are investigated [5].

The advantage of axial flux motors is that, thanks to the magnets placed on the outer perimeters of the disk, a gravimetric torque density 30-40% higher than that of a radial motor of similar power, and even up to four times higher in yokeless designs, can be achieved [22]. Researchers utilize collaborative optimization systems such as fuzzy logic control and sliding mode control (SMC) in axial flux Permanent Magnet Synchronous Motors (PMSM) to mitigate torque ripple and enhance dynamic motor performance [5].

A disadvantage that complicates the use of axial flux motors is that the strong axial magnetic attractive forces between the rotor and stator make it difficult to maintain the air gap with millimetric precision [20]. The "sandwich-like" structure of axial flux motors (especially dual-rotor or dual-stator designs) makes it difficult to cool the centrally located stator [22]. The greatest potential for axial flux motors lies in new energy vehicles (NEVs) and the aerospace sector [5, 21].

2.6.1. Operating Principle and Advantages

These motors, which have a shorter axial length and a larger diameter compared to traditional radial flux motors, stand out for hybrid electric vehicles (HEVs) due to the high torque density and excellent cooling characteristics they offer despite their compact structures [15].

2.6.2. Limitations

Their initial costs are quite high due to the requirement for the use of advanced materials and high manufacturing precision, the management of rotor dynamics, and the complexity of the manufacturing process [23].

Table 1. Comprehensive architectural and operational comparison of prominent electric propulsion system

Motor Type	Basic Operating Principle	Advantages	Disadvantages	Typical Industry Applications
Asynchronous (Induction) Motor (ACIM)	Propulsion is achieved via electromagnetic induction; specifically, alternating current excites the stator to produce a revolving flux that subsequently induces a reactive field within the rotor core.	Delivers exceptional operational dependability and cost-efficient manufacturing; its structurally resilient framework completely circumvents any reliance on rare-earth materials.	Characterized by sub-optimal energy conversion at reduced velocities, an inherently bulky physical footprint, and the absolute necessity for sophisticated thermal dissipation frameworks.	Particularly preferred in older Tesla Model S and Model X vehicles.
Permanent Magnet Synchronous Motor (PMSM)	Propulsion relies on the strict synchronous engagement between the stator's revolving electromagnetic flux and the permanent field emitted by rotor-embedded rare-earth magnets.	Very high efficiency, high power density, compact dimensions, excellent torque control.	High cost due to rare-earth elements, risk of magnet demagnetization at high temperatures.	Currently the most popular type (e.g., Tesla Model 3/Y, Porsche Taycan, Nissan Leaf).
Brushed Direct Current Motor (Brushed DC)	Operates with direct current transmitted to the rotor via brushes and a mechanical commutator within the stator's magnetic field.	Extremely simple and inexpensive control system, provides high torque at low speeds, highly mature technology.	Requires regular mechanical maintenance due to brush wear, low efficiency, risk of sparking/arcing, low power density.	Early-generation electric vehicles, forklifts, golf carts. No longer used in the main propulsion of modern vehicles.
Brushless Direct Current Motor (BLDC)	Uses electronic commutation instead of brushes/commutators. Similar to PMSM but with a different waveform (square wave).	High starting torque, maintenance-free structure, good speed-torque characteristics, efficiency between 85-90%.	Complex electronic control unit, narrow constant power region at high speeds, susceptible to torque ripple.	Light electric vehicles, e-bikes, e-scooters, and certain hybrid vehicles.
Switched Reluctance Motor (SRM)	Utilizing a purely passive rotor devoid of coils or permanent magnets, rotational torque is generated as the ferromagnetic core continuously aligns itself to the path of least magnetic resistance.	Very low cost, magnet-free, resistant to high temperatures, high fault tolerance.	Subjected to significant harmonic distortion leading to pronounced acoustic emissions and structural oscillations, alongside inherent torque pulsations that necessitate the implementation of sophisticated regulatory control paradigms.	Heavy-duty vehicles, industrial traction systems, and new-generation applications where the use of rare elements is to be avoided.
Axial Flux Motor (AFM)	Characterized by a planar configuration wherein the electromagnetic flux traverses longitudinally alongside the rotational shaft, employing flattened, disc-oriented stators and rotors to achieve an ultra-slim profile.	Immense power and torque density, very thin (short axial length) and lightweight structure, better cooling capacity.	Very difficult to manufacture and assemble (due to millimetric air gap tolerances), considerably high cost.	High-performance sports/supercars and in-wheel applications.

Source: Synthesized by the author based on the technical literature reviewed in this study

3. Conclusions

In the electric vehicle ecosystem, the design of an optimal powertrain varies depending on the usage scenario. While high-performance requirements bring Permanent Magnet Synchronous Motors (PMSM) to the forefront, increasing safety demands and supply chain constraints are driving the industry toward Asynchronous Motors (ACIM) and brushless, magnet-free designs (SRM) [24, 25, 26].

Table 1 presents a synthesized electromechanical evaluation of diverse traction motor topologies, contrasting their operational strengths and inherent design limitations within the modern electric vehicle ecosystem.

Table 2 complements the descriptive overview in Table 1 by rating each topology across the principal electromechanical and economic metrics, which allows the trade-offs to be compared at a glance. The ratings reinforce the central tension of the field. Permanent magnet and axial flux machines lead on efficiency and power density yet depend on rare-earth magnets, whereas induction and switched reluctance machines accept a modest efficiency penalty in exchange for lower cost and independence from rare-earth supply chains.

Table 2. Metric-based comparison of electric vehicle traction motor topologies

Metric	ACIM	PMSM	Brushed DC	BLDC	SRM	AFM
Efficiency	Moderate (lower at low speed)	Very high (>95%)	Low	High (85 to 90%)	High (up to 95%)	Very high
Power / torque density	Moderate	Very high	Low	High	Moderate	Very high (30 to 40% > radial)
Manufacturing cost	Low	High	Very low	Moderate	Very low	Very high
Torque ripple	Low	Low	Moderate	Moderate to high	Very high	Moderate
Rare-earth dependency	None	High	Low / none	High	None	High
Thermal tolerance	Moderate (needs cooling)	Moderate (damage risk)	Moderate	Moderate	High	High (central stator hard to cool)
Control complexity	High (FOC)	High (FOC + field weakening)	Very low	High (electronic commutation)	High (dedicated inverter)	High
Technology maturity	Very high (declining share)	Very high	Very high (legacy)	High	Emerging	Emerging

Note. Comparative ratings were synthesized by the authors from the literature reviewed in this study. Reported efficiency reaches approximately 95% for switched reluctance motors under optimized phase-excitation control [12], 85 to 90% for brushless DC motors, and above 95% for permanent magnet synchronous motors. The axial flux gravimetric torque density is reported as 30 to 40% higher than a comparable radial machine, and up to four times higher in yokeless designs [22]. Induction motors sustain a wide constant-power region at speeds above 15,000 rpm while showing lower efficiency and power density than permanent magnet machines [5]. Switched reluctance and induction motors avoid rare-earth materials, whereas permanent magnet synchronous, brushless DC, and axial flux machines rely on rare-earth magnets and carry a demagnetization risk at elevated temperatures [1, 5, 14].

The technical landscape of electric vehicle propulsion demonstrates that an "optimal" motor design is not a static concept but rather a dynamic trade-off between performance, cost, and resource sustainability. While Permanent Magnet Synchronous Motors (PMSM) currently serve as the industry's "gold standard" due to their peak energy conversion rates and compact power density, the growing concerns regarding the rare-earth element supply chain are driving a significant shift toward magnet-free alternatives. Asynchronous Motors (ACIM) maintain a strategic role, particularly in dual-motor configurations, where their ability to eliminate mechanical drag when de-energized provides a crucial advantage for highway cruising efficiency. Simultaneously, the emergence of Switched Reluctance Motors (SRM) and Axial Flux Motors (AFM) represents the future frontier of electrification. While SRMs offer an ultrarobust, cost-effective solution for heavy-duty applications by bypassing magnet dependency, AFMs provide unprecedented torque-to-weight ratios that are set to redefine high-performance and aerospace propulsion. Ultimately, the evolution of the EV ecosystem will be defined by the successful integration of these diverse hardware topologies with increasingly sophisticated regulatory frameworks. Specifically, the implementation of advanced Field-Oriented Control (FOC) and Model Predictive Control (MPC) architectures will be essential to optimize driving dynamics and ensure maximum operational efficacy within the stringent constraints of energy economy.

References

[1]. Ehsani, M., Gao, Y., Longo, S., & Ebrahimi, K. (2018). *Modern electric, hybrid electric, and fuel cell vehicles* (3rd ed.). CRC Press. https://doi.org/10.1201/9780429504884

[2]. Chau, K. T. (2015). *Electric vehicle machines and drives: Design, analysis and application*. John Wiley & Sons. http://doi.org/10.1002/9781118752555

[3]. Zhu, Z. Q., & Howe, D. (2007). Electrical machines and drives for electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE*, *95*(4), 746–765. https://doi.org/10.1109/JPROC.2006.892482

[4]. Yong, J. Y., Ramachandaramurthy, V. K., Tan, K. M., & Mithulananthan, N. (2015). A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. *Renewable and Sustainable Energy Reviews*, *49*, 365–385. https://doi.org/10.1016/j.rser.2015.04.130

[5]. Cai, W., Wu, X., & Zhou, M. (2021). Review and development of electric motor systems and electric powertrains for new energy vehicles. *Automotive Innovation*, *4*(1), 3–22. https://doi.org/10.1007/s42154-021-00139-z

[6]. Özçiflikçi, O. E., Koç, M., & Bahçeci, S. (2023). Overview of PMSM control strategies in electric vehicles: A review. *International Journal of Dynamics and Control*, 984–994. https://doi.org/10.1007/s40435-023-01314-2

[7]. Liao, G., Zhang, W., & Cai, C. (2021). Research on a PMSM control strategy for electric vehicles. *Advances in Mechanical Engineering*, *13*(12). https://doi.org/10.1177/16878140211051462

[8]. Wu, J., Wang, J., Gan, C., Sun, Q., & Kong, W. (2018). Efficiency optimization of PMSM drives using field-circuit coupled FEM for EV/HEV applications. *IEEE Access*, *6*, 15192–15201. https://doi.org/10.1109/ACCESS.2018.2813987

[9]. Aung, E., Tun, N. L., & Tin, T. (2014). Design of conventional permanent magnet synchronous motor used in electric vehicle. *International Journal of Scientific Engineering and Technology Research*, *3*(16), 3289–3293. http://ijsetr.com/uploads/532146IJSETR1700-564.pdf

[10]. Levent, A. H., Lordoglu, A., & Aydeniz, M. G. (2020). Design and optimization of permanent magnet synchronous motor for electric vehicle applications. *2020 2nd Global Power, Energy and Communication Conference (GPECOM)*, 148–151. https://doi.org/10.1109/GPECOM49333.2020.9247885

[11]. Park, C.-B., & Jeong, G. (2017). Design and analysis of magnetic-geared permanent magnet synchronous motor for driving electric vehicles. *2017 20th International Conference on Electrical Machines and Systems (ICEMS)*, 1–5. https://doi.org/10.1109/ICEMS.2017.8056127

[12]. Yang, Z., Shang, F., Brown, I. P., & Krishnamurthy, M. (2015). Comparative study of interior permanent magnet, induction, and switched reluctance motor drives for EV and HEV applications. *IEEE Transactions on Transportation Electrification*, *1*(3), 245–254. https://doi.org/10.1109/TTE.2015.2470092

[13]. Bose, B. K. (2002). *Modern power electronics and AC drives*. Prentice Hall.

[14]. Pellegrino, G., Vagati, A., Boazzo, B., & Guglielmi, P. (2012). Comparison of induction and PM synchronous motor drives for EV application including design examples. *IEEE Transactions on Industry Applications*, *48*(6), 2322–2332. https://doi.org/10.1109/TIA.2012.2227092

[15]. Shahakar, D. A., & Shahakar, Y. D. (2025). Review of traction motors for electric vehicle application. *EPJ Web of Conferences*, *341*, 01019. https://doi.org/10.1051/epjconf/202534101019

[16]. Prakash, S., & Boopathy, K. (2024). High speed BLDC motor for grid tied PV based EV system using hybrid PSO-spotted hyena optimized PI controller. *International Journal of Applied Power Engineering (IJAPE)*, *13*(3), 768–782. https://doi.org/10.11591/ijape.v13.i3.pp768-782

[17]. Tabassum, A. A., Cho, H. M., & Mahmud, M. I. (2024). Essential features and torque minimization techniques for brushless direct current motor controllers in electric vehicles. *Energies*, *17*(18), 4562. https://doi.org/10.3390/en17184562

[18]. Palanisamy, R., Sahasrabuddhe, R., Hiteshkumar, M. K., & Puranik, J. A. (2021). A new energy regeneration system for a BLDC motor driven electric vehicle. *International Journal of Electrical and Computer Engineering (IJECE)*, *11*(4), 2986–2993. https://doi.org/10.11591/ijece.v11i4.pp2986-2993

[19]. Miller, T. J. E. (2001). *Electronic control of switched reluctance machines*. Newnes.

[20]. Hao, Z., Ma, Y., Wang, P., Luo, G., & Chen, Y. (2022). A review of axial-flux permanent-magnet motors: Topological structures, design, optimization and control techniques. *Machines*, *10*(12), 1178. https://doi.org/10.3390/machines10121178

[21]. PsPowers. (2024). *Axial flux vs in-wheel motors: Which is better for EV?* https://pspowers.com/axial-flux-vs-in-wheel-motors-which-is-better-for-ev/

[22]. Brogen EV Solution. (2024, 27 Şubat). *Axial flux motor for electric vehicles: A comprehensive overview*. https://brogenevsolution.com/axial-flux-motor-for-electric-vehicles-brief-explanation/

[23]. Future Market Insights. (2024). *Switched reluctance motors market: Demand & growth analysis (2025–2035)*. https://www.futuremarketinsights.com/reports/switched-reluctance-motors-market

[24]. Konda, M., Hofman, T., & Salazar, M. (2022). Energy-optimal design and control of electric powertrains under motor thermal constraints. *2022 European Control Conference (ECC)*, 461-466. https://doi.org/10.23919/ECC55457.2022.9838244

[25]. Darwish, A., Elgenedy, M. A., & Williams, B. W. (2024). A review of modular electrical sub-systems of electric vehicles. *Energies*, *17*(14), 3474. https://doi.org/10.3390/en17143474

[26]. KPMG. (2025). *Securing the supply chain: Preparing for the electric vehicle raw material challenge*.