A Review of Lightweight Rotor Design and Energy-Efficiency Collaborative Optimization of High-Speed PMSMs for New Energy Vehicles under Multiphysics Coupling

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Abstract: Against the macro-level backdrop of the "dual-carbon" strategy and the ongoing transformation of the energy landscape, new energy vehicle drive systems are rapidly evolving toward higher rotational speeds, greater power density, and deeper system integration. As the pivotal component responsible for both energy conversion and mechanical load bearing, the rotor of the high-speed permanent magnet synchronous motor (PMSM) is confronted with a set of tightly coupled multiphysical challenges, including sharply increased electromagnetic losses, the approach to centrifugal stress limits, and severe thermal management constraints. This paper presents a literature review of rotor lightweight design and coordinated energy-conversion-efficiency optimization for high-speed PMSMs under multiphysics coupling constraints.

The review first elucidates the dynamic mechanisms underlying electromagnetic–thermal–mechanical coupling in high-speed operating conditions, with particular emphasis on the nonlinear effects of windage loss, which scales with the cube of rotational speed, and rotor thermal deformation on air-gap magnetic fields and operational safety. It then synthesizes the principal pathways for rotor lightweight design, including topology optimization, shape optimization, and material substitution, while further examining the synergistic interplay among sleeve materials, soft magnetic materials, and heat-transfer paths. Finally, from the perspectives of control and system-level regulation, the review summarizes representative strategies for enhancing the efficiency of high-speed PMSMs, encompassing intelligent control, harmonic-suppression modulation, and operating-point optimization.

Keywords: High-speed Permanent Magnet Synchronous Motor; Rotor Sleeve; Multiphysics Coupling; Windage Loss; Rotor Eddy-current Loss;Topology Optimization

1. Introduction

1.1 Research Background and Significance

Driven by the dual-carbon goals and the ongoing transformation of the energy structure, the new energy vehicle industry has become a key pathway for carbon reduction in the transportation sector. As the core power unit of electric vehicles, high-speed permanent magnet synchronous motors (PMSMs) play a decisive role in vehicle efficiency and driving range. The drive motor is one of the most critical components in new energy vehicles, and its performance directly affects vehicle dynamics and endurance. Owing to their high efficiency and high power density, PMSMs have become the mainstream traction solution for electric vehicles. Peng et al reported in a study of railway traction systems that, under the same operating conditions[1], simply replacing an induction motor with a PMSM improved the system energy-saving rate by approximately 12.96%, corresponding to a reduction of at least 1.01 kWh in energy consumption per kilometer. Although this result was obtained in the field of rail transit, it still provides useful insight into the potential of PMSMs to alleviate range anxiety in electric vehicles, as it highlights their superior energy efficiency over a wide operating range.

To further meet the dual requirements of rapid acceleration and high-speed cruising, drive motors are developing toward higher speed and higher integration. As the key rotating component of the motor, the rotor plays a central role in this process. Its lightweight level and structural stability are crucial to improving motor power density and ensuring reliable operation, and are therefore of great significance to the high-quality development of the new energy vehicle industry.

Under high-speed operating conditions, the rotor of a high-speed PMSM is subjected to coupled electromagnetic, thermal, and mechanical fields, which can easily lead to structural deformation, magnetic property degradation, and other related problems. As a result, a fundamental conflict arises between lightweight design and structural strength, as well as between efficiency improvement and performance stability. However, most existing studies focus on the optimization of individual performance indicators in isolation, and a systematic understanding of the intrinsic relationship among rotor structure, lightweight design, and energy conversion efficiency under multiphysics coupling is still lacking. This limitation has constrained further performance improvement of high-speed motors.

Therefore, this study focuses on rotor lightweight design and energy conversion efficiency optimization under multiphysics coupling, which is of both theoretical and practical significance. From a theoretical perspective, revealing the influence mechanism of multiphysics coupling on rotor performance and establishing a quantitative structure–performance model can provide support for cross-field collaborative optimization. From a practical perspective, this work can improve motor cyclic reliability and energy efficiency, provide engineering guidance for the design of new energy vehicle motors, promote technological breakthroughs in key components, and support the efficient development of the industry.

1.2 Scope of This Review

This review focuses on rotor lightweight design and energy conversion efficiency optimization under multiphysics coupling conditions in high-speed permanent magnet synchronous motors. Based on a systematic survey of the relevant literature, the review examines this topic from the perspective of coordinated optimization between structural design and operating efficiency. The main contents are summarized as follows:

1.Existing studies on electromagnetic design, thermal analysis, and structural strength of high-speed permanent magnet synchronous motors are first reviewed, and an analytical perspective incorporating electromagnetic–thermal–mechanical coupling is outlined to clarify the combined effects of rotational speed, temperature rise, and stress variation on rotor structural safety and electromagnetic performance.

2.Current lightweight design methods and material application strategies are then summarized to identify rotor lightweight design approaches suitable for high-speed operating conditions. Particular attention is given to how rotor mass distribution optimization, under the constraints of structural strength and operational reliability, affects electromagnetic performance and loss characteristics.

3.In addition, studies on motor efficiency improvement and control strategies are reviewed to analyze how variations in rotor structural parameters influence overall system efficiency from the perspectives of energy flow and loss composition, thereby highlighting the intrinsic relationship between structural design and operating efficiency.

4.Finally, by integrating findings from different research directions, this review attempts to establish a collaborative analytical framework centered on structure, material, and efficiency for high-speed permanent magnet synchronous motors, with the aim of providing useful reference for future research in this field.

1.3 Methodology and Scope of the Review

This review adopts a thematic literature analysis approach to systematically categorize and synthesize previous studies on rotor structural design, material selection, loss analysis, and efficiency optimization of high-speed permanent magnet synchronous motors under multiphysics coupling conditions. Particular attention is given to four closely related aspects, namely the mechanisms of electromagnetic–thermal–mechanical coupling, rotor topology and material characteristics, lightweight design methods, and system-level efficiency optimization strategies.

In selecting the literature, priority is given to studies closely related to high-speed PMSMs, traction motors for electric vehicles, rotor structural design, loss analysis, thermal management, and efficiency optimization. In addition, representative studies from other high-speed electrical machine applications are incorporated where they provide useful methodological insights or transferable design concepts. For literature derived from application scenarios that differ from those of high-speed traction systems for new energy vehicles, the

discussion is limited primarily to their analytical methods, design principles, and optimization approaches, rather than directly extending their conclusions to vehicle operating conditions.
This article is a narrative topical review. Its main purpose is to summarize current research progress from the integrated perspective of structure, material, loss, and efficiency, to analyze the applicable conditions, principal advantages, and inherent limitations of different technical routes, and to provide a problem-oriented analytical framework for future research.

2. Theoretical Foundations of Multiphysics Coupling

High-speed electrical machines operate under the combined action of multiple physical fields, including electromagnetic, thermal, and mechanical effects. When the rotor rotates at ultra-high speed, these fields become strongly intertwined, giving rise to phenomena that cannot be adequately captured by single-field analysis alone. As a result, designs that neglect multiphysics coupling often fail to ensure sufficient reliability under practical operating conditions. It is therefore necessary to develop a theoretical understanding of the principal coupling mechanisms in high-speed PMSMs. The following sections introduce the fundamental concepts of electromagnetic coupling, mechanical coupling, and multiphysics numerical simulation methods.
For clarity, multiphysics coupling in this review is divided into three levels. One-way coupling refers to a sequential transfer of results, such as using electromagnetic loss as a heat source for thermal analysis and then applying the resulting temperature field to mechanical stress analysis. Bidirectional coupling further considers the reverse influence of temperature rise or deformation on electromagnetic parameters, material properties, loss distribution, and air-gap characteristics. Closed-loop coupling denotes an iterative framework in which electromagnetic, thermal, and mechanical calculations are repeatedly updated until the main field variables converge, making it more suitable for high-speed PMSMs with strong feedback interactions among loss, temperature rise, deformation, and demagnetization risk.

2.1 Theory of Electromagnetic Field Coupling

An increase in rotational speed fundamentally alters the characteristics of electromagnetic losses in PMSMs. At low and medium speeds, stator copper loss and iron loss are generally the dominant contributors to temperature rise. However, once the machine enters the high-speed regime, windage loss at the rotor surface increases markedly, and its magnitude is commonly approximated as being proportional to the cube of rotational speed $\left(P_{\text{wind}} \propto \omega^3\right)$. Previous studies have shown that, under high-speed operating conditions, windage loss may surpass copper loss and become the primary source of rotor heating [2]. At the same time, the electromagnetic–thermal coupling induced by high-speed operation may trigger a self-reinforcing deterioration process. On the one hand, the magnetic properties of permanent magnets degrade with increasing temperature, and the resulting reduction in magnetic flux leads to a decline in output torque. On the other hand, in order to maintain torque output, the control system often increases current injection, while the enhanced demagnetizing field further aggravates local demagnetization of the permanent magnets. Sain described this demagnetization fault as a chain-reaction mechanism: elevated temperature reduces the intrinsic coercivity of the permanent magnets, and when combined with excessive demagnetizing current, irreversible demagnetization may occur[3]. This demagnetization, in turn, induces current distortion and torque ripple, thereby intensifying motor heating and vibration and eventually giving rise to a vicious cycle involving coupled thermal, magnetic, and electrical fields. In addition, Costin emphasized the importance of data-driven control(DDC)[4].
As shown in Figure 1, by constructing high-efficiency operational datasets for underlying learning, intelligent control systems may bypass complex parameter-based modeling and achieve efficient and stable operation over a wide operating range. This perspective reflects an emerging trend toward the integration of PMSM drive-control modeling with data-driven methods.
These observations suggest that loss generation, temperature rise, and material-property deterioration are strongly coupled under high-speed operating conditions, forming a self-reinforcing degradation loop rather than an isolated single-field response.

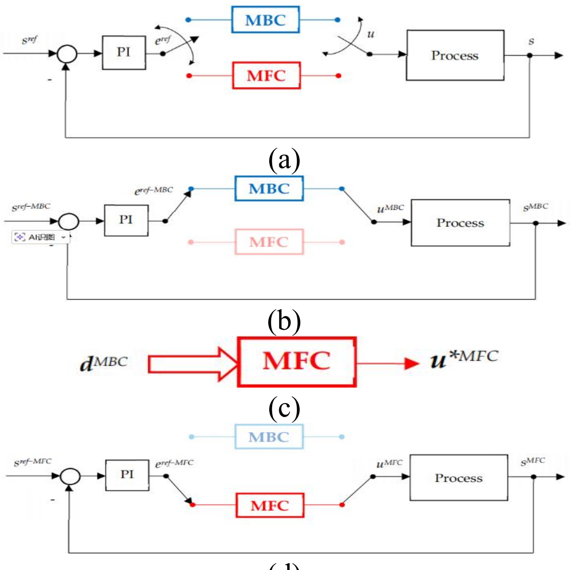


Figure 1. The Transition from MBC to MFC: (a) The Basic Control Scheme (b) Stored Data from MPC Running (c) Designing of MFC Strategy: Training Phase (d) Designing of MFC Strategy: Testing Phase[4]

The corresponding coupling relationship is schematically illustrated in Figure 2.

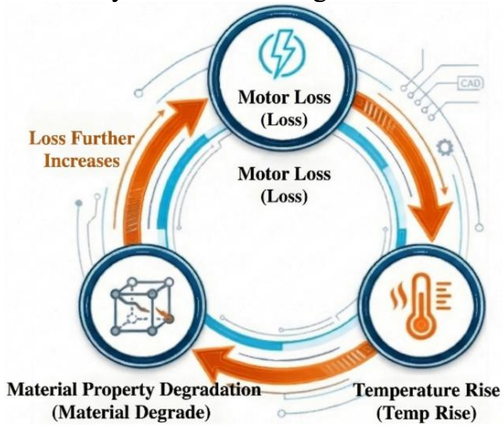


Figure 2. Schematic Illustration of the Coupled Deterioration Loop Among Motor Loss, Temperature Rise, Material Degradation in High-speed PMSMs

2.2 Mechanical Coupling Field Theory

Mechanical coupling effects are primarily reflected in the combined influence of centrifugal force and electromagnetic excitation force on rotor structural performance under high-speed operating conditions. First, with regard to centrifugal loading, surface-mounted rotors usually require high-strength, non-magnetic retaining sleeves to ensure effective constraint of the permanent magnets; sleeve design is therefore a critical factor in maintaining rotor mechanical integrity. However, the interference fit between the sleeve and the permanent magnets must be controlled within an appropriate range. Excessive mechanical preload may damage brittle magnets under stationary or low-speed conditions, whereas insufficient preload may lead to sleeve loosening or even detachment during high-speed operation. Previous studies have shown that this fit relationship requires high dimensional accuracy and must also take into account the influence of differences in the thermal expansion coefficients of different materials over a temperature range from −40 °C to 150 °C, so as to ensure the stable service performance of the magnets under varying temperature and speed conditions. These considerations indicate that rotor mechanical design should not be treated in isolation, but rather integrated with the analysis of material thermal properties to achieve coordinated optimization under multiple constraints.

In terms of vibration coupling, although rotor lightweighting helps reduce rotational inertia, weight reduction achieved through measures such as shaft thinning or reduced stator core thickness may also weaken the overall structural stiffness of the machine, thereby increasing the likelihood of mechanical resonance during high-speed operation. At the same time, the electromagnetic force in the air gap is not constant but exhibits force-wave characteristics that vary in both time and space under high-frequency electromagnetic excitation. When the frequency of the electromagnetic force wave approaches the natural modal frequency of the rotor or stator, elastic structural vibration may be induced, which in turn can lead to increased noise and additional losses. The demagnetization-related dynamic analysis reported by Sain further indicates that magnetic-state changes can introduce current distortion and torque fluctuation[3], which may serve as additional excitation sources in electromechanical coupling. However, this evidence should be understood as support for the existence of electromagnetic dynamic disturbance, rather than as direct proof of rotor structural resonance suppression. Therefore, the mitigation of vibration and noise in high-speed electrical machines should be based on the coordinated optimization of electromagnetic design, mechanical structural design, and operating-control strategy.

2.3 Multiphysics Coupled Numerical Simulation Methods

Traditional numerical analysis methods usually follow a one-way sequential workflow, in which electromagnetic field analysis is first used to calculate losses, thermal field analysis is then performed to determine temperature rise, and mechanical field analysis is finally employed to evaluate stress and deformation. Although this approach retains a certain degree of engineering applicability under conventional operating conditions, its limitations become increasingly evident for PMSMs operating at high rotational speeds and high power density. These limitations are mainly associated with the insufficient consideration of the temperature dependence of material properties and the feedback interactions among different physical fields. As local rotor temperature rises, the remanence of permanent magnets, the resistivity of windings, and the thermophysical properties of the cooling medium all vary accordingly, which further affects loss distribution, temperature field evolution, and structural stress states, thereby forming a coupled process in which multiple fields interact and mutually reinforce one another.

To address these issues, bidirectional and even multidirectional coupled modeling has gradually become an important development trend in the analysis of high-speed PMSMs. The study by Xu et al. provides quantitative evidence for the importance of bidirectional coupling analysis[29]. Using a 150 kW, 30,000 r/min prototype as the research object, they established a bidirectional iterative magneto-fluid-thermal-stress coupling model that accounts for the dynamic reverse evolution of material properties. Their results showed that, compared with the conventional one-way model, the predicted hotspot temperature increased by 14.19% and the evaluated tangential stress in the permanent magnets increased by 5.28%, while the calculated temperature distribution was also in better agreement with experimental measurements from the test bench. These findings indicate that, in the rotor analysis of high-speed PMSMs, neglecting reverse coupling effects under high-speed operating conditions may lead to an underestimation of the rotor thermal safety margin and structural reliability.

In terms of model implementation, multiphysics coupling analysis can be developed according to a closed-loop procedure consisting of electromagnetic loss calculation, thermal field solution, structural response analysis, and parameter feedback updating. First, heat-source information, including iron loss, copper loss, eddy-current loss, and windage loss, can be obtained through three-dimensional electromagnetic finite-element analysis or loss decomposition models. Second, the temperature distribution can be solved using thermal network models or computational fluid dynamics methods, and the magnetic properties, electrical resistivity, and cooling-related parameters of the materials can then be updated accordingly. Finally, the temperature field is introduced into the mechanical model as a load to analyze rotor stress, deformation, and air-gap variation. When necessary, the structural response can be further fed back into the electromagnetic model, thereby forming an iteratively convergent Multiphysics coupling framework. This sequential-and-feedback workflow is shown in Figure 3.

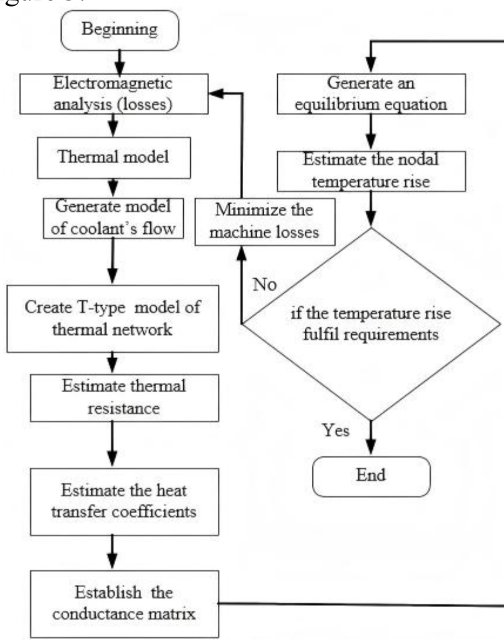


Figure 3. Flow Diagram of the Temperature Rise Estimation Method[2]

For rapid engineering iteration, reduced-order coupled approaches may be adopted to balance computational accuracy and efficiency. For example, the simplified three-dimensional hybrid thermal model proposed by Liang et al. can predict the internal temperature distribution and hotspot locations of segmented permanent magnets with relatively high efficiency[30], thereby providing support for rotor thermal design and the comparison of magnet segmentation schemes. In addition, Song et al.

introduced robust topology optimization for an interior PMSM under current uncertainty[31], showing that uncertainty in current excitation should be considered when reducing torque ripple and improving the stability of optimized motor structures. Overall, future multiphysics coupling analysis for high-speed PMSM rotors should place greater emphasis on achieving a balance among modeling accuracy, computational efficiency, and engineering applicability, so as to support the coordinated development of lightweight design, thermal management optimization, and operational reliability assessment. More broadly, robust design studies of permanent-magnet machines have shown that manufacturing, assembly, and service-related uncertainties can be incorporated directly into the optimization process. For example, Dong et al. introduced quantified constraint satisfaction into the robust design optimization of a permanent magnet linear synchronous motor[27], while Kim et al. used bootstrap-based uncertainty characterization for the robust optimization of a surface-mounted PMSM[28]. These studies indicate that uncertainty factors should be considered during the design stage rather than only being checked after deterministic optimization.

3. Motor Rotor Structure Analysis

The rotor, as the rotating part of the motor, is not only central to power transmission, but also represents the primary region where multiple physical-field interactions converge. In high-speed PMSMs, even minor changes in rotor structure can lead to pronounced variations in electromagnetic, mechanical, and thermal performance. A systematic review of existing rotor configurations, together with their respective advantages and limitations, is therefore necessary, particularly when material characteristics and thermal behavior are taken into account. Accordingly, the following section discusses high-speed PMSM rotors from three aspects: rotor topology, material properties, and thermal distribution.

3.1 Rotor Structure Types

At present, the rotor topology design of high-speed PMSMs is showing an increasingly diversified development trend. Conventional rotor structures mainly include surface-mounted permanent magnet (SPM) and interior permanent magnet (IPM) configurations, each of which exhibits distinct characteristics in terms of mechanical strength, leakage flux control, flux-weakening capability, and manufacturing complexity. With the continuous expansion of application requirements, a variety of novel topologies have been proposed on this basis. Öğülmüş designed a three-degree-of-freedom spherical motor capable of decoupled multidimensional torque output[7]. To address the space constraints of in-wheel motors, Cabuk optimized key structural parameters by combining radar-chart-based evaluation with the quality function deployment method[8]. Jena proposed an air-core PMSM scheme[9], in which the conventional iron core was eliminated, and a high-frequency Buck converter drive was employed to enable ultra-high-speed operation under iron-loss-free conditions. Overall, exploration topologies such as spherical motors, in-wheel motors, and air-core PMSMs have broadened the scope of structural design research for high-speed electrical machines. However, their application backgrounds differ to some extent from those of high-speed traction motors for new energy vehicles. For this reason, the subsequent discussion in this review remains focused primarily on SPM and IPM rotor topologies intended for high-speed traction applications, with particular emphasis on the coordinated design of the retaining sleeve, permanent magnets, and rotor shaft.

3.2 Rotor Material Properties

Material selection largely determines the upper limits of the “magnetic performance–mechanical strength–loss–thermal path” trade-off in high-speed rotors. For power density enhancement, one approach is to employ soft magnetic materials with high saturation flux density, such as Fe–Co-based alloys, so that the magnetic circuit cross-section and core volume can be reduced under the same flux requirement, thereby creating additional design space for lightweighting. Relevant studies have identified the combination of lightweight structures and high-performance soft magnetic alloys as an important route toward higher power density[26]. In addition, high-specific-power aerospace PMSM design for more electric aircraft also indicates that high-temperature permanent magnets and high-performance soft magnetic alloys can be combined to improve power-density-oriented motor design[10]. Another, and in many cases more decisive, engineering pathway lies in the selection of the retaining sleeve material system, including titanium alloys, non-magnetic high-strength alloys, and carbon-fiber-reinforced polymers (CFRPs). The sleeve thickness and electrical conductivity directly affect eddy-current loss and the effective air gap, whereas its thermal conductivity governs the distribution of rotor thermal resistance, hotspot formation, and demagnetization margin. The retaining sleeve should therefore be regarded as a typical multiphysics design variable rather than merely a mechanical reinforcement component [32].

As motor speed exceeds the conventional operating range and approaches extreme rotational conditions, such as 30,000 rpm, the permanent magnets located at the outer periphery of surface-mounted rotors are subjected to severe centrifugal peeling forces. The semi-embedded magnet and carbon-fiber sleeve configuration is shown in Figure 4.

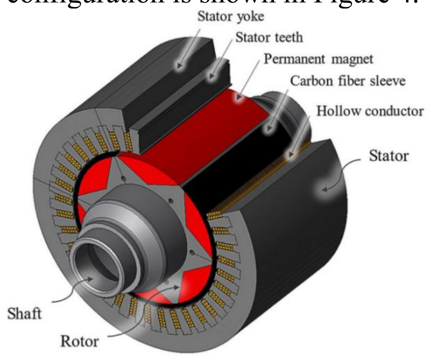


Figure 4. Partial Cut of the Designed PMSM with a Carbon Fiber Sleeve and Semi-embedded Permanent Magnets[33]

Under such conditions, the use of CFRPs, which possess exceptionally high specific strength and very low density, together with novel rotor pole geometries, has become a promising option for achieving extreme physical load reduction in the rotor. The detailed rotor layout and axial cooling channel arrangement are further shown in Figure 5.

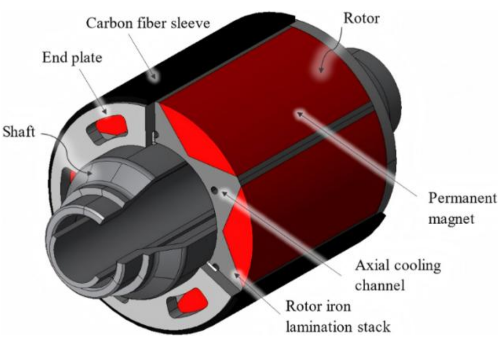


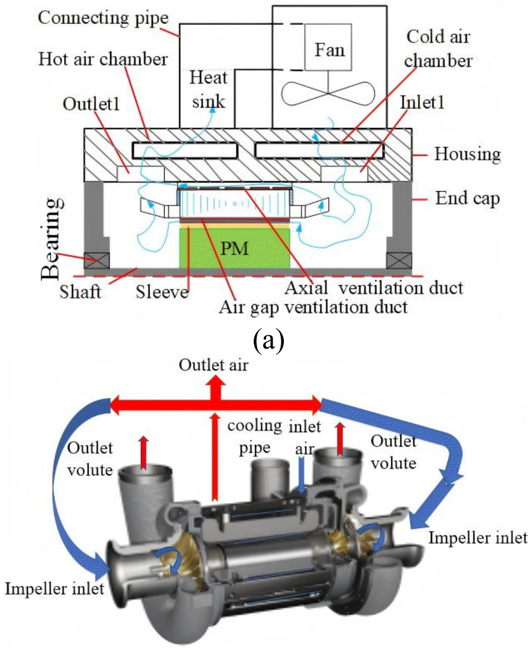
Figure 5. Perspective Partial Section View of the Designed Rotor[33]

However, because CFRPs exhibit very low radial thermal conductivity, they effectively form a dense thermal barrier around the rotor air-gap periphery, severely impeding the outward heat-transfer path for high-frequency loss-generated heat. To resolve this multiphysics design paradox, advanced rotor designs must move beyond passive cooling and instead incorporate more integrated thermal management solutions, such as internal forced stator oil cooling, in order to achieve a better balance between extreme lightweighting and thermal stability [33].

In addition, Hsiao et al in their study of reaction-wheel motors for satellite attitude control, pointed out that the application of high-permeability and low-loss materials is important for reducing stator core loss and rotor eddy-current loss[11]. Their results showed that material optimization can effectively reduce total motor loss and improve overall system efficiency. Although their study did not focus on high-speed traction motors for electric vehicles, the conclusions regarding the relationship between material properties and loss distribution still provide useful insight for material selection in high-speed PMSMs. Overall, advances in materials science have provided important support for performance improvement in high-speed PMSMs. In future design practice, material density, mechanical strength, thermal conductivity, and magnetic properties should be comprehensively balanced according to specific application requirements, so that materials such as high-strength aluminum alloys, CFRPs, and high-performance soft magnetic alloys can be selected appropriately to achieve an optimized balance among mass, strength, and electromagnetic performance.

3.3 Rotor Thermal Distribution Analysis

Thermal management has long been one of the major challenges in the design of high-speed rotors. Because the rotor is enclosed by the stator and usually lacks a direct cooling path, it tends to form a confined “thermal island” under high-speed operation, making heat dissipation particularly difficult. Abubakar established a lumped-parameter thermal network (LPTN) model to simulate the temperature-rise process of a 225-kW high-speed PMSM[2], and the corresponding two-dimensional and three-dimensional cooling passages are shown in Figure 6.



(a)

(b)

Figure 6. Structure of 225 kW HSPMSM with FACAVS: (a) 2D Cut View with Two Parallel Ventilations Ducts (b) 3D Cut view of the Machine with Air Cooling's Passage[2]

On this basis, Abubakar showed that, in the absence of effective cooling, the temperature of the rotor permanent magnets can rapidly exceed the safe operating limit, for example 150 °C. Existing studies have further indicated that the temperature distribution within high-speed rotors is typically characterized by pronounced spatial non-uniformity [32], with hotspots often concentrated in regions where the heat-dissipation path is relatively long and the loss density is relatively high. Such non-uniform temperature rise not only aggravates the risk of local demagnetization, but may also induce thermal stress concentration and compromise rotor service reliability [32][33]. It is therefore necessary to adopt dedicated cooling measures for high-speed rotors. Current technical approaches mainly include axial oil cooling, in which oil channels are integrated into the rotor shaft and cooling oil is pumped through them to remove heat; forced end-wind cooling, in which built-in fans introduce cool air into the cavities at both rotor ends to enhance heat transfer; and heat-pipe-based cooling, in which phase-change heat pipes are embedded within the rotor to conduct heat outward.

Beyond the design of heat-dissipation paths within the rotor itself, thermal management in high-speed PMSMs must also be considered in coordination with inverter efficiency control and vehicle-level thermal management. The variable DC-bus voltage control (VVC) strategy proposed by Yang et al. [22] showed that adjusting the DC-bus voltage according to real-time operating conditions can reduce inverter switching loss under certain operating states, thereby indirectly alleviating the thermal load of the motor. Estima et al. , from the perspective of overall efficiency in the battery–inverter–motor system, further demonstrated the importance of system-level optimization for total energy consumption and thermal-load allocation[23]. When these findings are considered together with the studies of Du et al. [32] and Clauer et al. [33] on retaining sleeves and cooling paths, it becomes clear that the thermal issue in high-speed PMSMs is not merely a matter of selecting a single cooling method, but is closely related to loss distribution, sleeve thermal resistance, hotspot location, and operating-point control at the system level. Overall, thermal management of high-speed rotors should be addressed through coordinated optimization across structural design, material selection, and system control.

4. Rotor Lightweight Design Methods

Rotor lightweighting is one of the primary approaches to improving the performance of high-speed electrical machines. However, lightweighting should not be understood simply as weight reduction; rather, it aims to remove ineffective mass as far as possible while satisfying strength and stiffness constraints, so that the required electromagnetic forces can be sustained with minimum structural cost. At present, rotor lightweight design mainly relies on three categories of approaches, namely topology optimization, shape optimization, and material substitution. The principles and representative applications of these methods are introduced in the following sections.

4.1 Topology Optimization

Topology optimization is an effective approach for rotor lightweighting, as it identifies the optimal structural distribution through mathematical optimization. Zhang et al were among the first to introduce topology optimization into the design of high-speed PMSM rotors and proposed a bionic supporting topology featuring a hollow shaft and spoke-like structure. In their approach[13], the rotor core was modeled as a cantilever beam subjected to the combined action of centrifugal force and electromagnetic force. Their analysis showed that rotor mass exhibits a minimum with respect to the length-to-diameter ratio (L/D). On this basis, most of the internal “dead-zone” material that does not participate in magnetic flux conduction was removed while maintaining rotor stiffness above the safety threshold, thereby achieving substantial weight reduction. Compared with the conventional solid cylindrical rotor, this topology significantly reduced rotor inertia and improved motor acceleration performance, while introducing almost no adverse effect on electromagnetic performance.

These findings demonstrate that topology optimization can establish a new balance between structural strength and electromagnetic performance. In addition to the bionic configuration described above, topology optimization has also been applied to the design of lightweight rotor structures with H-shaped slots, hollow ribs, and other unconventional features, thereby continually extending rotor design beyond the limitations of empirical approaches. It should be noted, however, that topology-optimized geometries are often highly complex, and their practical implementation still requires careful consideration of manufacturability and stress concentration. Nevertheless, with the continued development of additive manufacturing and related technologies, such complex topologies are expected to become increasingly feasible for practical high-speed electrical machines.

However, as demands for extreme speed and ultra-high power density continue to increase, it is becoming difficult to achieve further breakthroughs solely through topology reduction based on a single ferromagnetic material. Recent interdisciplinary research at the interface of computational mathematics and electromagnetics has therefore turned to multi-material generative topology optimization (MMTO)[34]. This method introduces a high-dimensional multi-material level-set algorithm based on the topological derivative and establishes, at the mathematical level, a strongly coupled model incorporating both magnetostatic approximation and steady-state heat conduction. Under the strict constraint of a fixed permanent-magnet volume, the algorithm enables global optimization of the average electromagnetic torque with respect to the distribution of multiple materials within the rotor domain, while simultaneously satisfying hard constraints on maximum temperature rise and peak mechanical stress. These developments indicate that multi-material topology optimization is driving rotor lightweight design away from traditional experience-based approaches and toward multi-constraint, multi-objective collaborative optimization, thereby opening a new avenue for future high-speed PMSM rotor design. The representative lightweight structure is shown in Figure 7.

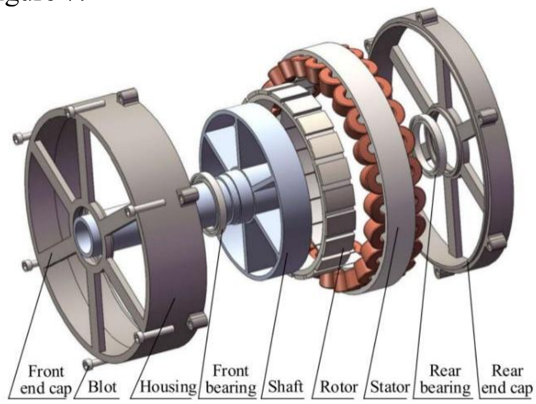


Figure 7. Diagram of Motor Lightweight Structure[13]

4.2 Shape Optimization

Shape optimization is performed on the premise that the overall topology has already been determined, and seeks to further reduce mass and improve overall performance by refining local geometric dimensions and structural details. Compared with topology-level reconstruction, shape optimization places greater emphasis on exploiting the residual potential of an existing structure and can therefore be particularly effective in applications with stringent requirements on both weight and performance.

A representative example is the study by Ma et al. on PMSMs[14]. To achieve a higher degree of lightweighting, their design eliminated the conventional stator housing and, in combination with robust optimization, refined the stator tooth structure by removing non-essential core material and retaining only the basic framework required for magnetic flux conduction. In addition, prestressed aluminum windings were adopted, whereby lower-density aluminum partially replaced conventional copper conductors. This substantially reduced the machine mass, although at the expense of a moderate decrease in structural stiffness. The resulting prototype achieved an output torque density exceeding 6 Nm/kg, which is significantly higher than that of conventional motors. These results indicate that the potential of lightweight design can be effectively exploited through the coordinated optimization of geometric design and material selection.

Beyond weight reduction, shape optimization can also enhance performance and enable functional integration through structural reconfiguration. Luu proposed an axially asymmetric rotor overhang structure[6], in which the magnetic pole at one end of the rotor was extended in the axial direction so as to utilize axial leakage flux that would otherwise remain underexploited, thereby increasing the output torque. At the same time, this protruding structure provided additional space for the integration of components such as position and speed sensors, allowing the motor to achieve improved performance together with enhanced integration capability. This study demonstrates that shape optimization can improve not only electromagnetic performance but also structural layout and system integration, reflecting a high degree of design flexibility.

Overall, within a given topological framework, shape optimization represents an important route for further weight reduction, torque enhancement, and functional extension by adjusting geometric parameters or introducing local structural modifications, such as thinning, slotting, and hollowing. For high-speed electrical machines pursuing high power density, high torque density, and high integration, shape optimization therefore has considerable engineering value.

4.3 Material Substitution Optimization

Material substitution represents another important route toward lightweight design, whereby conventional materials are replaced with alternatives possessing higher specific strength, superior magnetic properties, or more favorable thermal characteristics. In high-speed PMSM rotors, such substitutions must be evaluated under coupled constraints of centrifugal strength, stiffness, thermal conductivity, magnetic saturation, eddy-current loss, and manufacturability, rather than being understood as a simple reduction in material density. A representative example was reported by Fang et al. [26]. They found that although the density of the 1J22 soft magnetic alloy (approximately 8.2 g/cm^3) is slightly higher than that of silicon steel, its exceptionally high saturation capability allows for a substantial reduction in core volume, leading to a significant decrease in the total motor mass. The authors described this counterintuitive effect as “achieving lightweighting through heavier materials,” meaning that a material with higher density but superior performance can ultimately reduce the overall structural weight. This finding highlights the dominant role of material properties in design, as selecting a denser yet higher-performing material may, in some cases, enable substantial system-level mass reduction.

In addition, Erni et al.[15], in their study of an integrated power electronic converter design, likewise demonstrated the value of material and topology substitution. By directly integrating inverter power devices into the motor stator structure, they reduced the mass of independently mounted passive components, such as heat sinks and housings, thereby achieving lightweighting of the overall drive system. It should be noted that such studies do not directly constitute core evidence for rotor lightweighting itself; however, they are instructive for understanding the relationship between component-level and system-level weight reduction. In other words, lightweight design in high-speed electrical machines should not be confined to the rotor core alone, but should also take into account the structural redundancy and integration potential of the entire drive system.

Overall, material substitution provides a multidimensional pathway for lightweight design in high-speed electrical machines. With continued advances in materials science, emerging materials such as nanocrystalline alloys, advanced composites, and even superconducting materials may offer further opportunities for high-speed PMSMs in the future.

5. Energy Conversion Efficiency Optimization Strategies

The energy conversion efficiency of high-speed PMSMs depends not only on rotor structure and material parameters, but also closely on control strategies, parameter matching, and system-level thermal management. Under high-speed and high-power-density operating conditions, structural optimization of the motor itself alone is often insufficient to simultaneously achieve high efficiency, thermal safety, and operational stability. It is therefore necessary to examine the efficiency optimization pathways of high-speed PMSMs from the perspective of coordinated control and system-level design. In recent years, substantial progress has been made in areas such as advanced control algorithms, motor parameter optimization, and thermal management strategies. The following sections review three major categories of efficiency optimization approaches.

5.1 Control Strategy Optimization

The control of high-speed PMSMs becomes increasingly challenging as operating conditions deteriorate, and conventional PI regulation often finds it difficult to maintain both dynamic performance and steady-state accuracy when motor parameters exhibit pronounced nonlinear variation. For this reason, intelligent control methods incorporating artificial intelligence algorithms have attracted growing attention. Hu et al. applied the twin delayed deep deterministic policy gradient (TD3) algorithm from deep reinforcement learning to PMSM speed control[16]. Before the recent expansion of data-driven control, self-controlled PMSM drive strategies for light electric vehicles and PMSM controller designs for electric vehicles had already shown that the control architecture should be matched with vehicle operating conditions and efficiency requirements[5][12]. The dual closed-loop structure is illustrated in Figure 8.

Compared with conventional linear active disturbance rejection control (LADRC), the TD3-based controller demonstrated markedly stronger robustness.

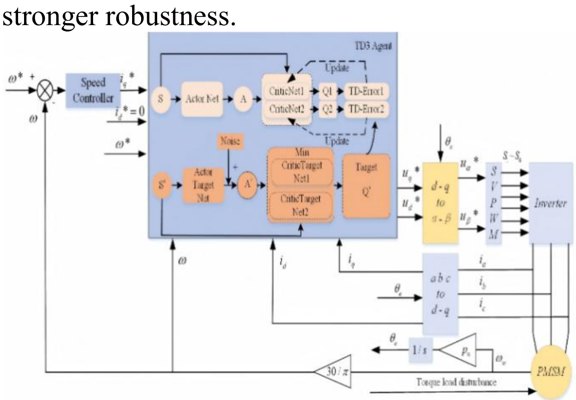


Figure 8. The Dual Closed-loop Control Structure of PMSM Speed and Current Based on TD3[16]

The reported results showed superior performance in speed tracking, q-axis current regulation, and robustness relative to the benchmark methods, indicating the potential of data-driven control under conditions of parameter variation and nonlinearity. It should be noted, however, that current evidence from this type of study is still focused mainly on improvements in control performance and energy-consumption indicators. The specific mechanisms by which such methods reduce copper loss, inverter switching loss, and rotor additional loss remain to be further verified through loss decomposition analysis and experimental testing.

With regard to loss reduction, Lian et al. proposed a current harmonic minimization PWM (CHMPWM) strategy, which reduced the current harmonic content by more than 40% in a 1 MW high-speed PMSM for flywheel energy storage through modulation waveform optimization. The reduction in harmonic current not only improved current waveform quality, but more importantly decreased rotor eddy-current loss induced by harmonics, thereby enhancing motor efficiency at its source.

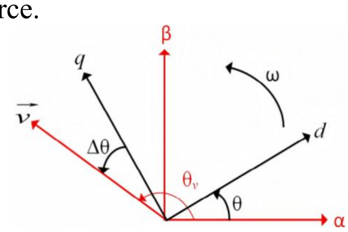


Figure 9. The mapping of the Applied Voltage Vector with Respect to the Stationary and the Synchronous Reference Frame[18]

In addition, Elhaj et al. proposed a current-loop-free direct voltage maximum torque-per-ampere (MTPA) control strategy[18]. The voltage-vector mapping used in this direct-voltage control method is shown in Figure 9.

By omitting the current inner loop used in conventional vector control and directly employing voltage commands to achieve optimal current allocation, this method simplified the control structure and improved dynamic response speed. Their results showed that it could effectively increase output torque in the high-speed flux-weakening region, thereby providing a new approach for transient performance enhancement in high-speed electrical machines. Overall, the application of advanced control strategies has further expanded the scope for improving the efficiency and performance of high-speed PMSMs[17]. With the continued development of artificial intelligence and modern control theory, more intelligent and adaptive control algorithms are expected to enable dynamic optimization of loss allocation and performance output under different operating conditions, thereby further unlocking the operating potential of high-speed PMSMs.

From the perspective of efficiency-oriented control, the optimal current command is no longer strictly identical to the conventional torque-maximizing trajectory when additional losses are considered.

As illustrated in Figure 10, once iron loss is incorporated into the optimization objective, the optimal current trajectory deviates from the conventional MTPA locus.

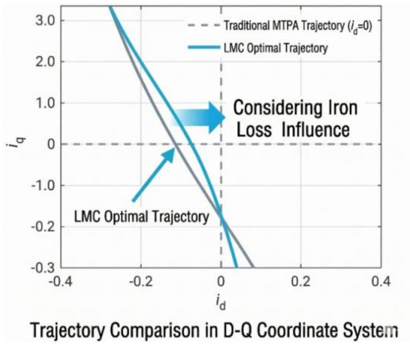


Figure 10. Conceptual Comparison of the Conventional MTPA Trajectory and the Optimal Trajectory Considering Iron-loss Effects in the D–Q Coordinate System (Schematic Illustration)

5.2 Optimization of Motor Parameter Matching

Motor internal parameters, such as winding turns and the degree of magnetic circuit saturation, are usually fixed once the machine is designed. However, given the markedly different operating requirements of low-speed urban driving and high-speed cruising, a single parameter set can hardly ensure optimal efficiency under both conditions. To address this issue, schemes that allow motor parameters to vary with operating conditions have been proposed. A representative example is the tap-change winding technique introduced by Lim et al. [19]. In this approach, taps are reserved in the winding so that the motor can operate with the full number of turns, corresponding to a higher back-EMF constant, under low-speed and high-torque conditions to reduce copper loss, while switching to a lower number of turns at high speed to decrease the back-EMF constant and thereby reduce flux-weakening current loss. Reported results showed that this "reconfigurable" strategy, which dynamically adjusts the equivalent winding turns according to operating conditions, reduced the overall energy consumption of the vehicle by approximately 1.65% under standard driving cycles.

Similarly, Chu et al. investigated the potential of dual-inverter open-winding PMSM systems for efficiency optimization[20]. The drive topology is shown in Figure 11.

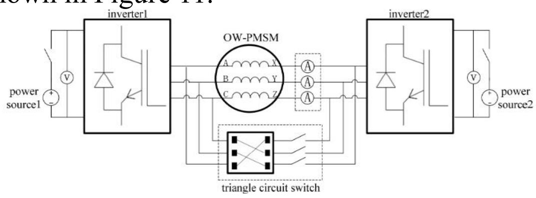


Figure 11. Structure of OW-PMSM Drive System[20]

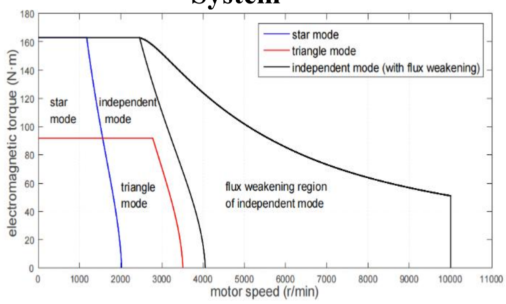


Figure 12. External Characteristic Curves of Each Winding Mode[20]

By coordinately controlling the voltage vector combinations of two inverters, this system enables more flexible regulation of motor operating states and thereby extends the high-efficiency operating region. The external characteristic curves of the different winding modes are shown in Figure 12.

Their study showed that, under medium-speed conditions, the dual-inverter configuration can effectively suppress zero-sequence circulating current, resulting in a more favorable distribution of copper loss and iron loss and allowing the motor to maintain relatively high efficiency over a wider operating range. These findings suggest that dual-inverter drive systems have considerable engineering value for improving the wide-range efficiency performance of high-speed electrical machines.

A further step in this direction was taken by Valladolid et al., who introduced metaheuristic algorithms to optimize the torque–speed allocation strategy of the motor[21]. For a given driving cycle, algorithms such as particle swarm optimization were employed to determine the optimal torque output distribution across different speed ranges, so that the motor could operate as close as possible to its highest overall efficiency state. Simulation results reported in the literature showed that this intelligent optimization strategy significantly reduced energy consumption per unit distance compared with conventional empirical allocation methods.

However, as modern electric passenger vehicles and commercial vehicles continue to impose higher requirements on both dynamic performance and driving range, it is becoming increasingly difficult to sustain further gains in efficiency and performance solely through hardware–software trade-off optimization at the level of a single motor. Han et al. therefore carried out a collaborative optimization study on parameter design and energy management for a dual-motor drive system[35]. Although this work was mainly aimed at improving the efficiency of the vehicle powertrain at the system level and did not directly address the structural design of a single high-speed PMSM rotor, its methodological implications remain highly relevant. More specifically, once motor-level parameter optimization approaches its performance boundary, further efficiency improvement often requires the introduction of system-level power allocation optimization and coordinated operating-point control, so that the motor can be maintained within high-efficiency regions over a broader operating range, thereby enabling sustained improvement in overall vehicle energy efficiency.

Taken together, the existing studies indicate that coordinated optimization of operating parameters and control strategies at the system level can, to some extent, compensate for the limitations imposed by hardware design constraints and further exploit the energy-saving potential of high-speed PMSMs under complex operating conditions.

5.3 Thermal Management System Optimization

The thermal management system is closely related not only to motor safety, but also to energy efficiency. Efficient heat dissipation can reduce the temperatures of the windings and permanent magnets, thereby lowering resistive loss and preventing magnetic property degradation, which is particularly critical for high-speed PMSMs. In recent years, several emerging thermal management strategies have been proposed. These issues, however, should not be understood merely as a matter of selecting a particular cooling technology; rather, they need to be addressed from two interrelated perspectives, namely rotor hotspot control and system-level loss management. On the one hand, hotspot distribution within the rotor can be improved by optimizing retaining sleeve materials, suppressing rotor eddy-current loss, and refining axial oil-cooling or forced end-cooling paths [32-33]. On the other hand, from the perspective of coordinated optimization between power electronics and the motor, Yang et al. proposed a variable DC-bus voltage control (VVC) strategy[22].

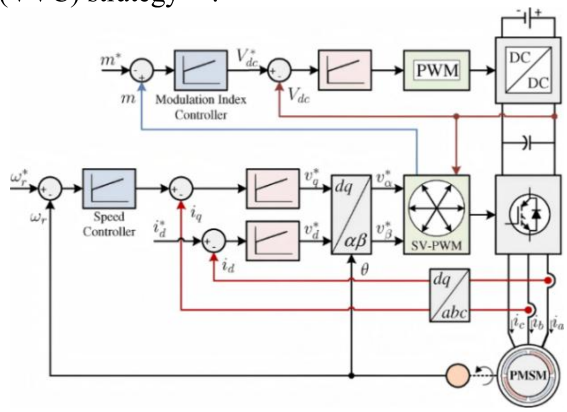


Figure 13. Block Diagram of the Control Strategy for Topology T2[23]

In conventional inverter systems, the DC-bus voltage is generally fixed, whereas this strategy introduces a DC/DC converter between the battery and the motor so that the bus voltage can be dynamically adjusted according to real-time operating conditions. For comparison at the system-topology level, Figure 13 presents the control block diagram of topology T2 reported in [23].

For example, under the low-speed and light-load conditions commonly encountered in electric vehicles, the bus voltage can be reduced to decrease inverter switching loss, whereas under high-speed and heavy-load conditions, the voltage can be increased to ensure sufficient power output. Simulation results showed that the VVC strategy could improve inverter efficiency by up to 12.8% under low-load conditions [22]. This finding indicates that thermal optimization and loss reduction should not be confined to the motor body alone, but instead should be considered from the perspective of energy flow throughout the entire drive system and realized through coordinated optimization of system-level topology and control. For instance, the earlier work of Estima et al. demonstrated that analyzing the efficiencies of different components from the integrated perspective of the battery–inverter–motor system is of considerable value for system optimization[23]. Accordingly, future improvements in energy efficiency should rely on the joint development of hardware and software, as well as the coordinated optimization of devices and systems, so that the efficiency of each energy-conversion stage can be enhanced and the thermal interaction among these stages can be properly managed, ultimately maximizing overall energy utilization. System-efficiency improvement control for PMSM direct-drive systems and energy-balance-based efficiency optimization further support this view by treating motor loss, inverter loss, and energy-flow allocation as coordinated optimization objects [24-25].

6.Conclusion and Outlook

This review has summarized recent progress in the lightweight design and energy-efficiency co-optimization of high-speed permanent magnet synchronous motor (PMSM) rotors for new energy vehicle applications under multiphysics coupling constraints. Overall, current research is shifting from isolated optimization of individual performance indices toward integrated design frameworks that simultaneously consider structural integrity, material behavior, loss mechanisms, thermal safety, and control requirements.

Available studies consistently indicate that multiphysics coupling is no longer a secondary consideration, but a fundamental basis for rotor design and performance evaluation in high-speed PMSMs. As rotational speed and power density increase, the interactions among electromagnetic loss, temperature rise, demagnetization risk, and centrifugal stress become increasingly pronounced, making conventional sequential analysis insufficient for accurately representing actual operating conditions. In parallel, lightweight design is evolving from simple mass reduction toward comprehensive optimization under coupled structural, thermal, electromagnetic, and manufacturing constraints. Likewise, efficiency improvement is extending beyond motor-level design to coordinated optimization involving control strategies, power electronics, and thermal management. Emerging intelligent methods, including data-driven control, robust optimization, generative design, have further expanded the methodological landscape, although their engineering value still requires stronger experimental and system-level validation.

In this context, future research should place greater emphasis on high-fidelity and computationally robust multiphysics modeling, manufacturable lightweight rotor design, system-level loss co-optimization, and the practical integration of intelligent methods with design and operation assessment. Further strengthening the closed-loop connection among theoretical analysis, numerical simulation, and experimental validation will be essential for advancing high-speed PMSMs toward higher power density, improved energy efficiency, and greater operational reliability.

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