Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA29303

Analysis of Thermal Management, Material Protection, and Efficient Control Strategies for Permanent Magnet Synchronous Motors

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Abstract. As a core component of new energy vehicle drive systems, the technological breakthroughs in permanent magnet synchronous motors (PMSM) directly determine the energy efficiency, range, and reliability of the entire vehicle. This article systematically reviews key technological advancements in three major areas: thermal management, material protection, and control strategies. First, in terms of thermal management, a composite oil-water cooling + intelligent control system is constructed, employing spiral channel design and phase change microchannel technology to achieve extreme condition temperature control accuracy of ±1.5 ℃. Second, in terms of materials, the coercivity is increased to 180kA/m through rare-earth permanent magnet doping and grain boundary diffusion processes, while also developing non-rare-earth materials to reduce dependence on rare-earth resources. Finally, in terms of control, model predictive control (MPC) is integrated with a sensorless sliding mode observer, reducing the dynamic response time to 2ms and decreasing energy consumption by 21%-23% under WLTC conditions. In the future, digital twin multi-physics simulation and green manufacturing processes are needed to promote the evolution of motors towards full-condition self-adaptation and zero resource consumption.

Keywords: New energy vehicles, permanent magnet synchronous motor, material protection, thermal management

1. Introduction

Driven by the dual forces of global energy structure transformation and the rapid development of the new energy vehicle industry, permanent magnet synchronous motors have become the core component of new energy vehicle drive systems due to their advantages, such as high-power density, high torque density, and high efficiency. Their installed capacity accounts for the majority of the global new energy vehicle motor market [1]. However, with the continuous increase in motor power density, bottleneck problems such as thermal runaway, material corrosion, and insufficient adaptability to extreme operating conditions are becoming increasingly prominent. Firstly, traditional cooling technologies result in excessive temperature differences inside the motor due to long heat dissipation paths and high thermal resistance, causing the peak winding temperature to rise

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DOI: 10.54254/2755-2721/2026.KA29303

to exceed the critical value and accelerating the aging of insulation materials [1]. Secondly, neodymium iron boron permanent magnets have a large annual corrosion thickness and a high magnetic flux loss rate in humid and hot environments [2], and the pitting depth of aluminum alloy housings under Cl^- erosion can reach 30% of the substrate thickness [3]. Finally, the heat dissipation efficiency decreases significantly under high-altitude and low-pressure operating conditions, resulting in large torque fluctuations and increased control overshoot [1,4]. These problems seriously restrict the improvement of motor power density and all-condition reliability, and solutions are urgently needed.

In response to the bottlenecks of thermal runaway, corrosion, and adaptation to extreme operating conditions of permanent magnet synchronous motors, technological progress at home and abroad focuses on three major directions. In the field of thermal management, China has developed oil-water composite cooling + microchannel phase change technology [1], while internationally, dynamic flow optimization is achieved through model predictive control, which reduces energy consumption by 21-23% compared with traditional solutions [4]. Regarding corrosion protection, domestic companies use TiN/Al-PVD multilayer films to reduce the corrosion rate by two orders of magnitude, while international companies improve salt spray resistance to 200 hours by electroless plating Ni-Cu-P alloy [2]. In terms of adapting to extreme operating conditions, China has established a correction model for boiling heat transfer at high altitudes, while internationally, a field-weakening dynamic phase adjustment technology has been proposed to increase the high-temperature demagnetization threshold to 180°C [1].

In response to the above challenges and technologies, this paper will systematically analyze the collaborative innovation path of materials, structures, and control of permanent magnet synchronous motors, discuss thermal management solutions such as oil-water composite cooling, analyze the corrosion mechanism and protection technology of neodymium iron boron, and explore the improvement mechanism of intelligent control strategies on multi-condition adaptability. Through the integration of multidisciplinary technologies, it provides a theoretical basis for more reliable, high-power-density motor design and promotes the sustainable development of the new energy vehicle industry.

2. New energy vehicle motor introduction

First, there are asynchronous motors, which rely on the interaction between the rotating magnetic field generated by the stator winding and the rotor's induced current to produce torque. The rotor does not require external excitation and is divided into two types: squirrel-cage and wound-rotor. These motors have a simple structure, are easy to maintain, low in cost, and reliable in operation, making them suitable for a wide range of loads. However, they have a low power factor, poor speed regulation performance, and their efficiency is greatly affected by the load. They are commonly used in industrial machinery, household appliances, etc [5,6].

Next are switched reluctance motors, which feature a salient pole structure with concentrated stator windings. The rotor has no permanent magnets or brushes, and torque is generated through changes in reluctance, following the principle of minimum reluctance. These motors have a simple and robust structure, low cost, strong overload capacity, and can operate in all four quadrants, making them suitable for harsh environments. However, they have large torque pulsations, high noise, and complex control, and are mostly used in small electric vehicles such as patrol cars [6].

Finally, there are permanent magnet synchronous motors, which are the focus of this article. Their rotors use permanent magnets (such as NdFeB) to generate a constant magnetic field, while the stator windings carry alternating current to form a rotating magnetic field. The two rotate

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synchronously to achieve energy conversion. These motors have high efficiency, high power density, small size, low noise, and support field weakening for extended speed range, but they rely on rare earth materials, are expensive, and are prone to demagnetization at high temperatures [6]. Fortunately, China is rich in rare earth elements, and permanent magnet synchronous motors are now widely used as motors for new energy vehicles. Therefore, researching the application challenges of permanent magnet synchronous motors and attempting to propose solutions is in line with future development trends.

3. Application challenges of permanent magnet synchronous motors

3.1. Thermal management challenges

3.1.1. Temperature rise characteristic

Permanent magnet synchronous motors have become the core drive unit of new energy vehicles due to their power density advantages. However, the increase in power density directly leads to a surge in heat load during operation. Taking a 200kW peak power motor as an example, under a continuous 3-second peak operating condition, the copper loss of the winding can reach 42.95kW, the iron core loss can reach 18.7kW, and the total heat power density exceeds 12kW/m². This high heat load causes the internal temperature field of the motor to exhibit a significant nonlinear distribution, especially forming local high-temperature zones in the end winding and magnet regions [1,7]. Experimental data shows that under extreme conditions of 620Arms peak current lasting for 20 seconds, the winding rapidly rises from an initial temperature of 70℃ to 167℃, with a temperature rise rate of 4.8℃/s. The highest temperature point appears in the weak insulation area of the winding end. Due to eddy current loss and thermal conduction delay, the magnet temperature can reach 111℃, close to the demagnetization critical temperature (120℃) of NdFeB permanent magnets. The maximum temperature difference between the stator core and the winding reaches 23℃, forming a significant thermal stress concentration area [1]. Although the high power density of PMSM improves energy efficiency, it leads to a sharp increase in heat load. Local high temperatures and thermal stress concentration seriously threaten reliability and lifespan, highlighting the urgency of breakthroughs in thermal management technology.

3.1.2. Cooling demand

In air-cooled systems, the air convection heat transfer coefficient is only 20-30W/(m²·K), which is difficult to meet the demands of high power density. The end winding has a long heat dissipation path and a high thermal resistance of 0.8℃/W, leading to the risk of local overheating. Although direct liquid cooling in liquid-cooled systems can increase the thermal conductivity to 1500W/(m·K), it faces two major contradictions: first, the trade-off between heat dissipation performance and system complexity. Microchannel liquid cooling requires the arrangement of 300-500 internal cooling tubes, with machining accuracy requirements of ±0.05mm, increasing costs by 40%; second, the challenge of temperature uniformity. Traditional liquid cooling solutions have limited capabilities, and the temperature difference between the end winding and the iron core still reaches 15℃, affecting the stability of the permanent magnet [1,8]. Thus, air-cooled systems are limited by low heat transfer efficiency, leading to local overheating of the end winding, while liquid cooling, although improving heat dissipation capacity through microchannels, faces the contradiction of

DOI: 10.54254/2755-2721/2026.KA29303

machining accuracy and temperature uniformity, exacerbating the risk of permanent magnet demagnetization.

3.2. Corrosion and material degradation

3.2.1. NdFeB permanent magnet

NdFeB permanent magnets are prone to hydrogen absorption corrosion in humid and hot environments, and their corrosion process can be divided into three stages. Water molecules in the environment first decompose on the surface of the neodymium-rich phase, and hydrogen atoms diffuse into the interior of the magnet through the grain boundaries. The neodymium-rich phase then reacts with the water film to generate neodymium hydroxide, and the released hydrogen atoms trigger grain boundary corrosion, leading to local expansion and magnetic property degradation. Finally, corrosion products form cracks at the grain boundaries, accelerating magnet pulverization, and the remanence loss can reach 15%-20%. Experimental data show that in a humid and hot environment with a temperature of 40°C and a relative humidity of 90%, the intrinsic coercivity of NdFeB magnets decreases from 180 kA/m to 145 kA/m (a decrease of 19.4%). Calculated based on an annual corrosion thickness of 38.68 μm, the service life of unprotected magnets in coastal areas is less than 3 years [2,9]. The hydrogen absorption failure of NdFeB permanent magnets in humid and hot environments is caused by the preferential corrosion of the neodymium-rich phase at the grain boundaries, resulting in a sharp drop in intrinsic coercivity. The service life of unprotected magnets in coastal areas is extremely short. These problems highlight the fatal threat of humid and hot corrosion to the reliability of high-performance magnetic materials [10,11].

3.2.2. Motor housing

Electrochemical corrosion occurs in motor aluminum alloy housings when the humidity is >60%. The corrosion rate exhibits an exponential relationship with Cl^- concentration, and the activation energy is 0.85 eV with a temperature coefficient α=0.04%/°C. When the relative humidity is >65%, the corrosion rate jumps from 0.12 μm/year to 1.8 μm/year. The corrosion morphology is divided into two types: first, pitting corrosion, where Cl^- is adsorbed at defects in the Al_2O_3 film, forming micro-pits with a diameter of 10-50 μm and a depth of up to 30% of the substrate thickness; second, intergranular corrosion, where corrosion paths distributed along the Mg_2Si phase cause a 40% reduction in the tensile strength of the housing [3]. Electrochemical corrosion initiated in motor aluminum alloy housings under high humidity, and pitting corrosion and intergranular corrosion together lead to catastrophic degradation of the mechanical properties of the housing, highlighting the urgency of corrosion-resistant design in high-humidity environments.

3.3. Impact of extreme operating conditions

3.3.1. Effects of low air pressure in high altitude environments

For every 1000m increase in altitude, air density decreases by 10%, resulting in a roughly 20% reduction in motor heat dissipation capacity. Tests by Lin et al. have shown that the temperature rise of the CR450 traction motor increases by 18K at an altitude of 4000m, and the insulation life is shortened by 30%. The partial discharge inception voltage decreases under low air pressure. Lin et al. reduced the partial discharge quantity to below 5pC by increasing the thickness of the epoxy resin impregnation layer (from 0.5mm to 0.8mm). Under the combined effect of high temperature

DOI: 10.54254/2755-2721/2026.KA29303

(>80 ℃) and high-frequency vibration (>20g), the irreversible demagnetization rate of NdFeB magnets can reach 0.05%/h [1].

3.3.2. Robustness requirements for frequent start-stop operation

The acceleration of subway vehicles reaches 1.2m/s² during starts and stops, causing abrupt torque changes (ΔT=±300Nm). Traditional PID control overshoots by more than 15%, and temperature variations of ±10 ℃ cause inductance parameter fluctuations of ±8%. Huang et al. proposed a disturbance observer-based compensation strategy, which uses a dynamic model to estimate and offset internal and external disturbances in real-time. Positive and negative feedback is used to monitor the motor temperature and make adjustments, reducing the parameter adaptive adjustment time to 0.5s [4].

4. Key technology advancements

4.1. Helical cooling channel

Traditional liquid cooling pipes have low cooling efficiency. Therefore, based on Lin et al.'s spiral tube heat exchange theory, the oil-water composite cooling system adopts a reverse spiral flow channel design to improve heat exchange efficiency through the following mechanisms: First, centrifugal force enhances heat transfer. The fluid forms a secondary circulation in the spiral flow channel, increasing turbulence intensity by 3.2 times, and the Nusselt number increases from 45 to 53. Second, countercurrent contact is optimized. The countercurrent flow of cold and hot fluids maximizes the temperature difference gradient, increasing the logarithmic mean temperature difference to 18.7K. Third, the microchannel effect is utilized. Spiral threads of 0.1mm are machined on the wall of the spiral flow channel, and the local heat transfer coefficient reaches 2158W/(m²·K), an 18% increase compared to traditional straight pipes [1]. All three mechanisms increase heat dissipation efficiency by indirectly increasing the contact area.

4.2. Corrosion protection technology

Firstly, there's the physical vapor deposition multilayer film technology. TiN/Al_2O_3 multilayer films prepared by magnetron sputtering significantly improve the corrosion resistance of NdFeB. In a 3.5% NaCl solution, the self-corrosion current density is reduced to 1.77×10^{-5} A/cm², with a protection efficiency of 91.9%. An Al_2O_3 buffer layer (800nm thick) inhibits the columnar crystal growth of TiN through lattice distortion, reducing the crack density of the film by 72% [2].

Secondly, the chemical vapor deposition composite coating ZrN/TiN gradient coating (5μm thick) forms a dense transition layer through interface element diffusion. Its tribological properties include a hardness of 18GPa, a friction coefficient of 0.4, and a wear rate reduced to 3.2×10^{-6} mm³/(N·m). A ZrO_2 passivation film (200nm thick) remains stable in an acidic environment of pH=2, inhibiting Cl^- erosion [2, 10]. Regardless of whether physical or chemical deposition methods are used, they protect the permanent magnet and aluminum alloy shell internally, but small molecules can still penetrate and cause corrosion, which does not fundamentally solve the problem.

Finally, there's the heavy rare earth element doping strategy of adding Ho element (mass fraction 0.5-2.0%) to enhance coercivity through grain boundary strengthening. The coercivity Hcj increases from 180 kA/m to 220 kA/m, an increase of 22%, but the remanence Br decreases from 1.32 T to 1.25 T, with a slight decrease in magnetic induction. Ho^{3+} occupies the Nd-rich phase at the grain boundaries, inhibiting abnormal grain growth (average grain size refined from 50μm to 35μm) [2].

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After all, the Ho element is not the first choice for permanent magnet materials, and doping it in will inevitably affect the original performance, requiring strict control of the proportion.

4.3. Intelligent control strategy optimization

Compared to traditional PID on-off control, the MPC strategy reduces pump energy consumption by 18.7% under WLTC conditions, from 2.1kW to 1.68kW, while the maximum winding temperature decreases from 167 ℃ to 142 ℃ [4]. Based on the MPC model predictive control framework, constructing a multi-objective optimization model can reduce winding temperature rise by 14.7% and energy consumption by 18.7% compared to on-off control in MPC control [1,4]. Integrating electromagnetic-thermal-fluid coupling simulation can reduce the prediction error to <0.5 ℃, and dynamically adjust the coolant flow rate according to load mutations (such as sudden vehicle acceleration), reducing the winding temperature fluctuation range to ±1.8℃.

5. Future development trends

5.1. Microchannel phase change cooling technology breakthrough

On the one hand, composite phase change materials are used for microchannels. By compositing n-octadecane (phase change temperature 28°C) with graphene in a certain proportion, the thermal conductivity of n-octadecane can be greatly improved, thereby accelerating heat transfer. On the other hand, the surface microstructure is optimized by etching bionic leaf veins or teardrop-shaped grooves (20μm groove depth) on the inner wall of the microchannel to enhance nucleate boiling heat transfer, increasing the critical heat flux density from 50W/cm² to 85W/cm² [12].

5.2. Collaborative optimization

Firstly, the drive-battery thermal management linkage, through an innovative thermal management system architecture, directs the recovery of waste heat generated during motor operation for battery preheating, significantly enhancing energy efficiency in low-temperature environments. Taking Tesla's Octovalve heat pump technology as an example, its integrated coolant circulation circuit and bidirectional heat exchangers can stably raise the battery compartment temperature to a working range of 15-20 ℃ in -30 ℃ environments, achieving a 26% improvement in energy efficiency compared to traditional PTC heating. This system uses intelligent temperature control algorithms to dynamically regulate coolant flow, prioritizing the use of motor waste heat (up to 80℃) during the drive phase, and coordinating with PTC auxiliary heating to achieve multi-mode synergy, increasing winter range by more than 80 kilometers [4].

Simultaneously, lightweight and highly thermally conductive materials also play an important role in the field of key motor components. Graphene-based copper composite materials (Gr/Cu) have achieved revolutionary breakthroughs through three-dimensional network reinforcement structures. Their unique layered stacking design allows the heat conduction path to extend axially, and with biomimetic blade-shaped reinforcement bodies, forms a directional heat transfer channel, successfully reducing the axial temperature gradient of the winding from 25 ℃/m for traditional materials to 12 ℃/m. Experimental data shows that a permanent magnet synchronous motor using Gr/Cu windings reduces copper loss by 34% and thermal resistance by 41% at 20,000rpm, increasing power density to 8.2kW/kg. This material innovation complements Tesla Model S Plaid's carbon fiber sleeve technology, which eliminates eddy current losses to break rotor speeds of

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24,000rpm, jointly promoting motor thermal management into a new stage of “active cooling + passive heat conduction” collaborative optimization [1,13].

5.3. Extreme environment technology

Addressing the issue of decreased boiling point due to reduced atmospheric pressure in high-altitude regions (boiling point drops to approximately 70°C at an altitude of 4500m), a boiling heat transfer coefficient prediction algorithm for high-altitude environments is established based on Lin et al.'s modified Rohsenow correlation model. An altitude correction factor is introduced to dynamically adjust the latent heat of vaporization and surface tension coefficient, resulting in a prediction error of <8% in the 70-100°C boiling range. COMSOL Multiphysics is integrated to establish a “pressure-temperature-flow” three-field coupling model to simulate the nucleate boiling process of coolant in microchannels, with the predicted critical heat flux density deviating by <5% from experimental data. An LSTM neural network is used to predict altitude change trends and real-time correct the heat transfer coefficient, reducing the temperature fluctuation range of the motor winding to ±1.2°C [1]. This scheme promotes the evolution of high-altitude thermal management from experience-based design to a new generation of technology system driven by mechanism and data through the technology integration of “multi-field coupling + intelligent algorithm + scenario customization,” laying the foundation for improving the reliability of equipment such as high-altitude motors.

Simultaneously, based on Lin et al.'s low-pressure chamber technology scheme, a sealing verification system adapted to an altitude of 4500m can also be constructed. The main sealing layer uses fluorosilicone rubber sealing strips with a compression set rate of ≤18% and a temperature resistance range of -50~200°C. The joints of the cabin are filled with silicone sealant with a tensile strength ≥2.8MPa after curing, and a labyrinth-style diversion groove is used to block sand and dust. A nitrogen charging device is integrated to adjust the gas replenishment rate through a PID algorithm, with cabin pressure fluctuations <±1kPa [1]. This scheme embodies the three major breakthrough directions of high-altitude extreme environment sealing technology: material performance upgrade, structural sand and dust resistance design, and intelligent regulation technology, marking the leap of high-altitude sealing systems from passive protection to adaptive dynamic regulation, providing a new paradigm for the reliability of extreme environment equipment.

6. Conclusion

This article addresses the core challenges of permanent magnet synchronous motors in new energy vehicles regarding thermal management, material protection, and adaptability to extreme operating conditions, constructing systematic solutions through technological innovation. Although PMSMs have become core drive units due to their high efficiency and power density, they face bottlenecks such as uncontrolled temperature rise, corrosion of permanent magnets and their housings, and demagnetization under extreme conditions. The study breaks through the thermal-magnetic-mechanical coupling constraints through spiral oil-water composite cooling channels, physical vapor deposition multilayer films, model predictive control, and heavy rare earth doping/graphene-based composite materials. However, the processing accuracy and cost of complex cooling systems, the long-term durability of corrosion protection, the dependence on rare earth materials, and the risk of high-temperature demagnetization still need to be verified. Its technological impact is significant: cross-system thermal management linkage increases winter range by 80 kilometers, microchannel phase change cooling technology breaks through traditional heat dissipation bottlenecks, and

DOI: 10.54254/2755-2721/2026.KA29303

material innovation promotes the synergistic optimization of “active cooling + passive heat conduction.”This not only strengthens the transformation of China's rare earth resource advantages, but also helps to synergistically improve range, lifespan, and environmental adaptability. The research starts with performance shortcomings, forms technical solutions through multi-disciplinary collaboration, and ultimately aims at large-scale application, laying the theoretical and engineering foundation for achieving the “dual carbon” goals.

References

[1] Deng, W., Wang, P., Qi, L., et al. (2020). Research progress on corrosion mechanism and protection of NdFeB permanent magnetic materials. Vacuum, 57(05), 45-51.
[2] Fang, M. (2024). Analysis of the structural principles of three-phase asynchronous motors for new energy vehicles. Internal Combustion Engine and Accessories, (15), 43-45.
[3] Gao, Y., Xu, X., Li, M., et al. (2024). Research on modelling and control strategy of motor thermal management system for pure electric vehicles. In Proceedings of the 43rd Chinese Control Conference (11) (pp. 495-500). Technical Committee on Control Theory, Chinese Association of Automation.
[4] Hu, Z., Wang, K., Gan, H., et al. (2023). Current status and analysis of electric vehicle battery thermal management system. Agricultural Equipment and Vehicle Engineering, 61(01), 69-74.
[5] Huang, K. (2025). Research on efficient control strategies for permanent magnet synchronous motors in new energy vehicles. Popular Automobile, (02), 34-36.
[6] Jiang, C., Zheng, S., Peng, J., et al. (2021). A brief discussion on the common drive motor types and principles used in new energy vehicles. Internal Combustion Engine and Accessories, (01), 73-76.
[7] Kovačič, P. T., Kovačević, N., & Milošev, I. (2025). Corrosion of sintered NdFeB permanent magnets. Journal of The Electrochemical Society, 172(7), 071501.
[8] Wan, J. (2025). Research on temperature rise characteristics and thermal management strategies of permanent magnet synchronous motors under multiple operating conditions. Small & Miniature Motors, 53(05), 13-20.
[9] Soo, H. Y., Yu, H. K., & Ismail, A. M. (2025). Heat transfer enhancement of microchannel heat sink with water-droplet grooves: Geometrical and grooves arrangement effects. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 47(11), 568.
[10] Song, J. (2025). The cooling secrets of the “heart” of new energy vehicles: A comprehensive disclosure of high-efficiency cooling technology for drive motors. China Automobile Market, (02), 107-110.
[11] Wang, Q., Sun, H., Wang, Y. Y., et al. (2025). Preparation and thermal conductivity study of graphene/hexadecane composite phase change material. Journal of Metrology, 46(04), 511-517.
[12] Yang, X., Dai, T., Zhao, J., et al. (2022). Simulation study on atmospheric corrosion and protection of aluminum alloy enclosure for electric vehicle motors. Journal of Beijing Institute of Chemical Technology, 30(04), 25-30 + 41.
[13] Zheng, H., Zheng, G., & Ma, C. (2002). Research on chemical nickel-palladium alloy plating process and its application in anti-corrosion of NdFeB permanent magnets. Surface Technology, (02), 42-45.