

Research Status and Future Trends of Energy-saving Technologies for Permanent Magnet Synchronous Motors in New Energy Vehicles

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ABSTRACT

In the context of the global energy structure transformation and the deep advancement of the "dual carbon" strategy, energy conservation and emission reduction in the transportation sector have become a key link in achieving the carbon peak target, and the energy efficiency level of the drive system of new energy vehicles plays a decisive role in the energy consumption of the entire vehicle. Permanent magnet synchronous motors, with advantages such as high efficiency and high power density, have become the mainstream drive motors for new energy vehicles, and the research on their energy-saving technologies has become a research hotspot in the industry. This paper uses the methods of systematic literature review, comparative study and econometric analysis to systematically review the current research status of energy-saving technologies of permanent magnet synchronous motors for new energy vehicles from four dimensions: material system, structural design, control strategy and thermal management system, and deeply analyze the existing technical bottlenecks such as insufficient energy efficiency stability under extreme conditions and high cost of high-performance materials. And further predict the future development trends of technologies such as material diversification, structural integration, control intelligence and energy interconnection. Research shows that breakthroughs in permanent magnet synchronous motor energy-saving technology require collaborative innovation in multiple fields such as materials, structures, and control, and system-level energy-saving collaboration will become the core direction of future research. This paper provides theoretical and engineering references for the research and development of permanent magnet synchronous motor energy-saving technology and the energy-saving upgrade of the new energy vehicle industry.

KEYWORDS

New energy vehicles; Permanent magnet synchronous motors; Energy-saving technology; Research status; Trends

1 Introduction

The global energy crisis and environmental pollution problems have driven the rapid development of the new energy vehicle industry. As the core power unit, the drive motor has become the key to improving vehicle energy efficiency and range. Permanent magnet synchronous motors, with advantages such as 95-97% peak efficiency, low loss, and high torque density, are gradually replacing traditional motors like induction motors and becoming the preferred choice for new energy vehicle drive systems^[1].

At present, scholars and enterprises at home and abroad have conducted extensive research on energy-saving technologies of permanent magnet synchronous motors, resulting in research achievements in areas such as material modification, structural optimization, and control algorithm improvement. However, the existing research is mostly scattered in a single technical field, and there is a lack of systematic integration and comprehensive analysis of multi-dimensional energy-saving technologies, as well as a lack of forward-looking judgment of technological development trends in combination with industrial demands.

This paper first reviews the current research status of permanent magnet synchronous motor energy-saving technology from four core dimensions: material system, structural design, control strategy, and thermal management system, and clarifies the technical maturity and application effects in each field; Secondly, it conducts an in-depth analysis of the key technical bottlenecks currently faced in the industrial application of permanent magnet synchronous motor energy-saving technology; Finally, in combination with the laws of technological evolution and the orientation of industrial policies, predict the future development trends of the technology. This study employed methods such as systematic literature review, comparative study, and quantitative analysis to construct a multi-dimensional technology benchmarking system for a comprehensive and in-depth analysis of energy-saving technologies for permanent magnet synchronous motors.

The research results can fill the gap in the existing research system integration of permanent magnet synchronous motor energy-saving technology, provide a clear technical direction for research institutions to conduct in-depth research, offer practical references for enterprise product upgrading and technological transformation, and are of great significance for promoting the high-quality development of the new energy vehicle industry and achieving the "dual carbon" strategy.

2 Current Status of Research on Energy-saving Technologies of Permanent Magnet Synchronous Motors for New Energy Vehicles

2.1 Material System: Optimization of Energy-Saving Compatibility between Magnetic Materials and Auxiliary Materials

The performance of magnetic materials is the basis for energy conservation of permanent magnet synchronous motors. Rare earth permanent magnet materials represented by neodymium iron boron have become the mainstream choice for permanent magnet synchronous motors due to their high coercive force and high magnetic energy product characteristics ^[2]. Research on rare earth permanent magnetic materials at home and abroad mainly focuses on the reduction of heavy rare earths (dysprosium, terbium), and grain refinement processes have been successfully applied to improve the magnetic energy product and thermal stability of neodymium iron boron materials, which can reduce material costs by 15-20% while maintaining motor energy efficiency of more than 96%. For non-rare earth permanent magnetic materials, researchers have made technological breakthroughs in high magnetic energy product ferrites and neodymium-iron-nitrogen composite magnets, which have significant cost advantages and are feasible for substitution in mid-to-low-end vehicle models and specific operating conditions. In addition, the upgrading of auxiliary materials also plays an important supporting role in reducing motor losses: high-temperature insulating varnish can effectively suppress copper loss in windings, and high thermal conductivity and heat dissipation materials can improve motor heat transfer efficiency and avoid energy efficiency degradation caused by high temperatures.

2.2 Structural Design: Tapping into the Energy-saving Potential of Electromagnetic Topology and System Integration

In terms of the optimization of the motor body structure, research has mainly focused on the design of stator slot and rotor magnetic circuit arrangement ^[3]. The application of pear-shaped slots and semi-closed slots can reduce stator iron loss. Flat wire windings and hairpin windings instead of traditional distributed windings can reduce end leakage flux and copper loss, and increase winding utilization by more than 10%. The V-shaped, U-shaped and claw-pole rotor magnetic circuit arrangement can enhance the sinusoidal degree of the air-gap magnetic field, reduce torque ripple and harmonic loss, and effectively expand the high-efficiency operating range of the motor. In terms of electric drive system integration, the "motor + reducer + inverter" integrated solution is gradually replacing the split solution, which can reduce transmission losses by 5-8% and improve system volumetric energy efficiency. High-speed rotor technology research shows that carbon fiber sheath reinforcement can effectively increase motor power density, and the corresponding loss control technology can prevent the surge of mechanical losses at high speeds.

2.3 Control Strategy: Algorithm-based Full-condition Energy Efficiency Improvement

The basic energy-saving control algorithm has been widely applied in the control of permanent magnet synchronous motors. Among them, the maximum torque-to-current ratio (MTPA) control can dynamically optimize current distribution under different loads, achieving the maximum torque output per unit current and reducing copper loss by approximately 10% ^[4]. The demagnetization speed-boosting control technology can expand the high-speed and high-efficiency operating range without increasing the inverter capacity, effectively reducing the iron loss in high-speed conditions. Brake energy recovery control technology becomes standard in new energy vehicles, precisely matching motor power generation conditions with battery charging requirements, and the maximum energy recovery efficiency can increase vehicle range by 15-20%. For advanced intelligent algorithms, model predictive control (MPC), adaptive control, and sensorless control based on sliding mode observer and extended Kalman filter optimize sensor wear and improve motor reliability while ensuring control accuracy. In addition, research on the synergy of silicon carbide (SiC) inverters with control algorithms has become a new hotspot. Combining the high-frequency switching characteristics of SiC inverters with control algorithms can suppress motor losses and increase the overall efficiency of the drive system by 3 to 5 percent.

2.4 Thermal Management System: Maintenance of Energy Efficiency Stability based on Temperature Control

The temperature of permanent magnet synchronous motors is a significant factor affecting their energy efficiency and service life. Existing thermal management solutions mainly include water cooling, oil cooling, and forced air cooling. Forced air cooling is often used for small power motors due to its simple structure and low cost, but its heat dissipation efficiency is limited; Water cooling is the mainstream thermal management solution for medium and high-power permanent magnet synchronous motors, which can keep the motor operating temperature within a reasonable range

under normal conditions. Oil cooling technology, especially splash and immersion oil cooling, has become a research hotspot in recent years. It has a good control effect on the hot spot temperature of high-power-density motors and can effectively avoid the demagnetization of magnets and the increase of copper loss caused by high temperature. The research on the thermally electromagnetic coupling design technology has deepened. The thermal circuit model constructed based on the motor loss distribution can achieve precise control of the temperature of the winding and permanent magnet, maintaining the efficient operation of the motor under complex conditions ^[5].

3 Technical Bottlenecks for the Industrial Application of Permanent Magnet Synchronous Motor Energy-saving Technology

3.1 Insufficient Energy Efficiency Stability under Extreme Conditions

Permanent magnet synchronous motors face harsh working environments in new energy vehicle applications, and there are obvious deficiencies in energy efficiency stability under extreme conditions. In high-temperature environments (above 105 °C), permanent magnets are prone to demagnetization, resulting in a decrease in motor torque and energy efficiency; At high speed and high load conditions, the iron loss and mechanical loss of the motor increase sharply, narrowing the high-efficiency operating range of the motor and affecting the overall energy-saving effect of the vehicle. Existing material modification and thermal management technologies cannot completely solve the problem of energy efficiency degradation under extreme conditions, and there is still a lack of research on material, structure, and control matching design for extreme conditions.

3.2 The Cost of High-performance Materials and Devices Remains High

The application of high-performance materials and devices is an important way to improve the energy efficiency of permanent magnet synchronous motors, but their high cost restricts their large-scale popularization in the mid-to-low-end new energy vehicle market. High-performance neodymium iron boron permanent magnet materials containing heavy rare earths have high raw material and processing costs, and the price fluctuations of rare earth resources also increase the production cost risk for enterprises. Wide bandgap semiconductor devices such as silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors have a significant advantage in reducing inverter switching losses, but they are 3 to 5 times more expensive than traditional silicon devices, significantly increasing the overall cost of the drive system. In addition, the research and development and production costs of high-precision control components are also relatively high, further raising the threshold for the application of energy-saving technologies for high-end permanent magnet synchronous motors.

3.3 Insufficient Research on Loss Mechanism and Precise Modeling

The losses of permanent magnet synchronous motors include copper loss, iron loss, mechanical loss, harmonic loss and stray loss, and the loss mechanisms are complex and coupled with each other. At present, the research on copper loss and iron loss is relatively in-depth and the corresponding suppression measures are relatively mature, but the research on harmonic loss and stray loss is not in-depth enough and there is a lack of precise modeling methods. The existing loss models cannot accurately predict the loss variations of motors under complex conditions, resulting in insufficient optimization effects of energy-saving control algorithms based on loss models. In addition, there is a lack of research on the coupling relationship between each loss, and a single loss suppression measure may lead to an increase in other losses, affecting the overall energy-saving effect of the motor.

3.4 The Core Control Algorithm is Low in Intelligence and Lacks Coordination

Although significant progress has been made in the core control algorithms of permanent magnet synchronous motors, the level of intelligence is still low and difficult to adapt to the complex and changeable working conditions of new energy vehicles. Most of the existing control algorithms use fixed parameter Settings and cannot achieve real-time dynamic adjustment based on parameters such as vehicle speed, load, and temperature. The application of artificial intelligence adaptive energy-saving control technology is relatively limited, and the research on loss prediction and early regulation based on artificial intelligence algorithms is still in the experimental stage. In addition, there is insufficient synergy between the motor control algorithm and the vehicle system, and the motor energy-saving control is not closely integrated with the battery management system and the vehicle control system, resulting in unsatisfactory system-level energy efficiency optimization.

4 Future Development Trends of Permanent Magnet Synchronous Motor Energy-saving Technology for New Energy Vehicles

4.1 Material Diversification: Breaking the Reliance on the Rare Earth Supply Chain

Material diversification will become the core development direction of energy-saving technologies for permanent magnet synchronous motors, with a focus on high-performance and low-cost mass production technologies for non-rare earth permanent magnet materials and recycling technologies for permanent magnet materials. On the one hand, researchers will continue to study the modification of high magnetic energy product ferrites and neodymium iron-nitrogen composite magnets to enhance their temperature adaptability and power density and achieve their large-scale application in mid-to-low-end new energy vehicles; On the other hand, research on the reduction of heavy rare earths in neodymium-iron-boron materials will be further deepened, and technologies for heavy rare earth-free permanent magnets will be developed to reduce reliance on rare earth resources ^[6]. In addition, research and application of permanent magnet material recycling and reuse technologies will be accelerated, which can both reduce production costs and minimize environmental impact, forming a green and sustainable material supply chain.

4.2 Structural Integration: Achieving High Efficiency and Miniaturization of Electric Drive Systems

Structural integration will develop towards a deep integration of "multi-in-one", and the research and application of new topological structures will be accelerated ^[7], further enhancing the power density and spatial energy efficiency of motors. The electric drive system will achieve deep integration of "motor + reducer + inverter + charger + DC/DC", which can further reduce system transmission loss and volume and improve the overall energy efficiency of the drive system. Axial flux motors, coreless motors and other new topologies will enter the engineering application stage, which have the advantages of high power density, small size and high efficiency, and can better adapt to the limited installation space of new energy vehicles. In addition, the design of lightweight motors will be further deepened, and the application of high-strength lightweight alloy and composite materials will be expanded to reduce the mass of motors and improve the power-to-mass ratio.

4.3 Intelligent Control: Achieving Dynamic Energy Savings Across All Operating Conditions

Intelligent control will be the key to improving the energy efficiency stability of permanent magnet synchronous motors under complex conditions, relying on the integration of Internet of Vehicles, big data and artificial intelligence technologies. Big data-based adaptive control technology will be widely applied, which can collect vehicle driving data in real time and dynamically adjust motor control parameters according to changes in operating conditions to achieve real-time optimization of energy efficiency. The loss prediction and pre-regulation technology based on artificial intelligence algorithms will mature ^[8], which can predict motor loss changes based on historical data and real-time parameters, take pre-control measures, and avoid energy efficiency degradation caused by parameter fluctuations. In addition, sensorless control technology will be further optimized to improve control accuracy and reliability through the fusion of multiple algorithms and achieve efficient and stable operation of motors across the full speed range.

4.4 Energy Interconnection: Achieving Full-chain Energy Efficiency Optimization for the Entire Vehicle

Energy interconnection will focus on the coordinated control of the motor and the vehicle's energy system, build a multi-component coordinated energy-saving system, and achieve energy efficiency optimization throughout the "charging - driving - energy recovery" chain. The motor control system will be deeply integrated with the battery management system to optimize battery charging and discharging strategies based on motor conditions and improve battery energy utilization efficiency; To achieve coordinated control of motors with new energy systems such as photovoltaic energy replenishment systems, to make full use of renewable energy and reduce reliance on grid power. In addition, combining vehicle-to-grid (V2G) technology with motor energy-saving control enables the motor to act as a mobile energy storage unit, allowing for bidirectional energy flow between the vehicle and the grid, further enhancing the overall energy utilization efficiency of the transportation system.

5 Conclusion

This paper systematically reviews the current research status of energy-saving technologies for permanent magnet synchronous motors in new energy vehicles from four dimensions: material system, structural design, control strategy, and thermal management system, deeply analyzes the key technical bottlenecks in their industrial application, and

predicts the future development trends of material diversification, structural integration, control intelligence, and energy interconnection. The research found that the current energy-saving technology of permanent magnet synchronous motors has achieved rich research results in various fields: the modification technology of rare earth permanent magnet materials has improved material performance and reduced cost; the structural optimization technology has effectively expanded the high-efficiency operating range of the motor; the optimization of the control algorithm has improved energy efficiency under different operating conditions; and the thermal management technology has ensured the energy efficiency stability of the motor under normal operating conditions. However, the technology still faces multiple bottlenecks such as insufficient energy efficiency stability under extreme conditions, high cost of high-performance materials, lack of in-depth research on loss mechanisms, and low intelligence of control algorithms.

The breakthrough of permanent magnet synchronous motor energy-saving technology requires collaborative innovation in multiple fields such as materials, structure, control, and thermal management. Material diversification will break the reliance on the rare earth supply chain, structural integration will achieve high efficiency and miniaturization of the electric drive system, intelligent control will achieve dynamic energy saving in all operating conditions, and energy interconnection will achieve energy efficiency optimization throughout the entire vehicle chain. System-level coordinated energy-saving design of motors with batteries, inverters and vehicle control systems will become the core direction of future research, which can achieve overall optimization of energy efficiency of drive systems and further enhance the energy-saving level of new energy vehicles.

This research is mainly based on literature review and comparative analysis. The experimental verification of technical performance is insufficient. In the future, an experimental platform can be built to carry out multi-dimensional experimental research on the integration of energy-saving technologies, and the technical performance can be verified through bench tests and vehicle tests. The economic benefit assessment of permanent magnet synchronous motor energy-saving technology is insufficient. Subsequently, an economic benefit assessment model can be constructed to analyze the cost-effectiveness of different energy-saving technologies and provide more practical references for the industrial application of the technology. At the same time, research on the application of permanent magnet synchronous motor energy-saving technology in different types of new energy vehicles such as pure electric, hybrid and fuel cell vehicles can be further expanded to achieve customized design of energy-saving technology for different vehicle models.

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