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State-of-the-Art, Challenges, and Future Trends in Hub Motor Technology for New Energy Electric Vehicles

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Abstract:

Growing global energy and environmental concerns have positioned new energy electric vehicles (NEVs) as a strategic direction in automotive development. As a core technology in NEVs, hub motor systems offer distinct advantages including simplified powertrain architecture and direct torque control. However, technical challenges remain in areas such as thermal management, energy efficiency, and system integration. This paper provides a comprehensive review of key hub motor technologies, analyzing the current research landscape, comparative characteristics of different motor types, innovation bottlenecks, and technological evolution trends. By systematically evaluating domestic and international advancements, this study aims to establish a theoretical framework for future research directions and practical applications in hub motor technology optimization.

Keywords: New Energy Electric Vehicles (NEVs), Hub Motor Systems, Key Technologies, Future Trends

1. Source of the Research Project and Research Objectives

With the continuous increase in global vehicle population, conventional fuel-powered automobiles have not only exacerbated environmental pollution but also intensified energy security concerns. To address these challenges, promoting new energy vehicles has become imperative, with drive motor technology emerging as a critical component requiring significant advancements. Hub motor drive systems, which integrate the drive motor directly into the wheel assembly, are revolutionizing electric vehicle development by offering innovative solutions in vehicle kinematic control and structural layout optimization. These systems demonstrate notable advantages including simplified powertrain architecture, precise torque vectoring capabilities, and weight distribution improvements, thereby attracting extensive research attention in both academia and industry.[1-3].

2. Research Progress at Home and Abroad

2.1 Research Progress Abroad: Evolutionary Trajectories and Milestones

In foreign countries, research on hub motors was initiated earlier. In the 1950s, American inventor Robert first created a hub device integrating motor, reduction gear, and braking systems. Subsequently, in 1968, General Electric applied this technology to heavy-duty mining vehicles, marking the first practical application of hub motor technology in engineering projects. Since 1991, Professor Hiroshi Shima's research team at Keio University achieved significant accomplishments in electric vehicle development, successfully developing experimental vehicles including IZA, Eco, KAZ, and Eliica, particularly the Eliica electric vehicle, which accumulated important experience for subsequent research through its application of hub motor technology. By 2003, Bridgestone exhibited its self-developed hub motor at the Tokyo Motor Show, combining it with specially designed tires to form an electric wheel with dynamic shock absorption functionality, featuring an outer-rotor permanent magnet synchronous motor (OPMSM) internally, demonstrating innovative integration of hub motor and tire technologies. In the same year, General Motors successfully implanted hub motor technology into the Chevrolet S-10 pickup trucks, significantly enhancing vehicle torque performance and verifying the substantial application prospects of hub motors in light-duty commercial vehicles.

French company TM4's outer-rotor permanent magnet motor (OPMM) has been integrated into hub motor designs. Under standard operating conditions, this motor achieves an average efficiency of 96.3%, demonstrating its technical advantage in motor efficiency optimization [4].At the 2009 Frankfurt Motor Show, Audi unveiled its all-electric sports car e-tron equipped with four independent hub motors for four-wheel-drive capability, demonstrating the significant potential of hub motors in high-end electric vehicles. British company Protean Electrics' shock absorber spring-integrated ProteanDriveTM hub motor and Michelin's Active Wheel System also achieved notable advancements in hub motor technology, promoting diversified development in this field[5].

2.2 Domestic Research Progress

China's research on hub motors started relatively late, gradually unfolding after the national promotion of the "863 Program." Tongji University achieved notable accomplishments in hub motor technology, with its "Chunhui" electric vehicles (2002, 2003, and 2004) employing low-speed permanent magnet brushless DC (PMBLDC) hub motors, providing practical experience for domestic research in this field[6].

In 2004, Tsinghua University developed an all-electric sedan named "Hali," equipped with four 2 kW hub motors. This vehicle achieved a top speed of 80 km/h and a range of 100 km, representing a valid exploration of all-electric vehicle performance. During the same year, BYD unveiled the "ET" concept car at the Beijing Auto Show, featuring four 25 kW wheel-mounted hub motors enabling individual wheel torque control. The vehicle achieved a maximum speed of 165 km/h and a range of 350 km, demonstrating domestic innovation in hub motor technology. In 2011, Chery introduced the Riichi X1 series range-extended pure electric sedan at the Shanghai International Automobile Exhibition, showcasing a novel "hub-type" electric vehicle design that contributed new ideas to China's new energy vehicle market[7-9].Although there are existing gaps in hub motor technology between China and foreign countries, recent years have witnessed rapid development driven by national policy support and increased corporate R&D investment.

3. Hub Motor Types and Characteristics

3.1 Direct Current Motor (DC Motor)

During the initial phase of new energy vehicle technology development, DC motor drive and control technology served as one of the core propulsion methods. Characterized by user-friendly operation, DC motors enable precise regulation of speed and torque by simply adjusting the armature voltage or current, delivering fast response times to instantly match power output requirements for vehicle start-stop, rapid acceleration, or braking scenarios. Composed of stator, rotor, brushes, and commutator, DC motors feature easy maintenance and low repair costs, making them irreplaceable in environments requiring frequent start-stop operations and precise speed control requirements[10].

DC motors exhibit significant disadvantages due to their mechanical commutation mechanism. The operation relies on brush-commutator contact, causing friction between brushes and commutator during rotation, which accelerates brush wear and necessitates frequent replacements, thereby increasing operational costs and maintenance burdens. Spark generation during commutation not only damages internal insulation but also induces electromagnetic interference (EMI), restricting high-speed operation capabilities. Additionally, DC motors possess large physical dimensions, posing spatial challenges in vehicle applications, along with higher manufacturing costs, collectively limiting their adoption in new energy vehicles.

3.2 Alternating Current Induction Motor (ACIM)

With technological advancements, the new energy vehicle sector is progressively transitioning from traditional DC motors to AC induction motors. These motors operate based on electromagnetic induction principles: when

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three-phase alternating current (AC) is applied to the stator windings, a rotating magnetic field is generated. The rotor, positioned within this field, experiences electromagnetic interaction, inducing eddy currents and producing torque to drive the vehicle. This mechanism eliminates mechanical commutation components, offering advantages such as improved energy efficiency, reduced maintenance requirements, and enhanced operational reliability compared to DC motors[11-12].AC induction motors feature structurally simple and robust designs with squirrel cage rotors, eliminating brushes and commutators to reduce maintenance costs and failure risks. They achieve high energy conversion efficiency under rated operating conditions, providing sustained vehicle propulsion. Their strong environmental adaptability ensures stable operation in extreme conditions (high temperature, humidity, altitude), covering diverse vehicle applications including passenger cars, buses, and trucks for both urban and long-distance travel[13].

AC induction motors exhibit inherent limitations in precision speed control, particularly during fine adjustments during vehicle operation. Under specific working conditions such as low-speed, light-load scenarios, their energy efficiency becomes suboptimal with elevated power consumption. Additionally, torque ripple generated during operation can compromise vehicle ride comfort by affecting driving smoothness. These drawbacks collectively restrict their applicability in scenarios demanding high-precision control and energy efficiency[14].

3.3 Permanent Magnet Motor (PMM)

Permanent magnet drive motors occupy a significant position in new energy vehicle hub motor applications, primarily including two categories: permanent magnet brushless DC motors (PMBLDC) and permanent magnet synchronous motors (PMSM).The permanent magnet brushless DC motor replaces the mechanical commutator of traditional DC motors with an electronic commutation system, effectively reducing brush wear and spark generation risks, thereby ensuring more stable motor operation and simplified maintenance. Due to the absence of excitation losses, the PMBLDC motor achieves high efficiency and power density, enabling substantial torque output within a compact and lightweight design [15].Due to these advantages, the PMBLDC motor has increasingly become a preferred choice for electric vehicle hub motor applications.

Structurally similar to the PMBLDC motor, the PMSM employs sinusoidal wave driving. Compared to brushless DC motors, it exhibits superior noise reduction performance, effectively minimizing vehicle operating noise and enhancing cabin quietness. Renowned for its high power density, low rotational inertia, and exceptional control precision, the PMSM enables precise torque adjustments to improve vehicle handling. It also supports field-weakening speed regulation, expanding the constant power operating range and making it an ideal choice for electric vehicle hub motors. Due to its inherent magnetic field characteristics, the PMSM demonstrates a linear torque-speed relationship, rapid response, and outstanding efficiency, which reduces energy losses, extends driving range, prolongs battery life, decreases charging frequency, and optimizes driving experience. However, its complex mathematical model and intricate control strategies demand high-performance controllers, increasing system development complexity and costs[16].

Permanent magnet synchronous motors are primarily categorized into three types: transverse flux, radial flux, and axial flux, each exhibiting distinct advantages and disadvantages[17-19].Transverse flux motors are favored for their high torque density but face challenges in complex manufacturing processes and elevated costs. Radial flux motors feature compact structures and broad applicability, yet exhibit limitations in torque density enhancement. Axial flux motors, with their flat configurations, are suitable for space-constrained applications but require sophisticated magnetic circuit design capabilities[20].

3.4 Switched Reluctance Motor (SRM)

Switched reluctance motors have emerged as a developing motor type in the hub motor field. In terms of energy conversion efficiency, while slightly inferior to permanent magnet synchronous motors (PMSM efficiency ≈95% vs. SRM ≈90%), SRMs still demonstrate commendable efficiency. Their response speed generally surpasses PMSMs, enabling rapid adjustment of reluctance angles to provide instant responses to control signals, thereby meeting dynamic power output demands in complex vehicle operating environments. SRMs exhibit greater control flexibility through reluctance angle and supply voltage modulation, whereas PMSMs primarily rely on frequency and voltage adjustments. However, SRMs suffer from inherent drawbacks such as severe current fluctuations, leading to noise and vibration that degrade ride comfort and NVH performance. These issues stem from the motor's double salient pole structure and are challenging to eliminate, requiring additional current and position sensors to monitor and suppress fluctuations and vibrations, which increases system complexity and costs.

4.Challenges in Hub Motor Development

4.1 Suspension System Compatibility Issues

The integration of hub motors within wheels significantly increases the unsprung mass, altering the dynamic response characteristics of vehicle suspension systems. This elevated mass amplifies sensitivity to road irregularities, degrading ride comfort and handling stability. When traversing rough terrain, impact forces are transmitted more directly to the vehicle body, inducing pronounced vibrations and oscillations that compromise passenger comfort. Traditional suspension systems, originally designed for conventional powertrain layouts, prove inadequate for hub motor-driven vehicles due to fundamental differences in load distribution and dynamic behavior. This necessitates comprehensive redesign and parameter optimization of suspension architectures to accommodate hub motor-induced changes. However, current research in this domain remains at an early stage of technological maturity, with persistent challenges in identifying optimal suspension configurations that balance performance, durability, and cost-effectiveness[21].

4.2 Thermal Dissipation Challenges

The hub motor in electric vehicles is situated within the compact wheel space, where thermal dissipation conditions are constrained. During operation, the motor continuously generates heat, but rotational airflow disturbances caused by wheel motion hinder effective heat dissipation. During braking, additional heat transfers to the motor, further elevating its temperature. If permanent magnet materials exceed 140°C, demagnetization may occur, degrading motor performance and potentially leading to motor failure, thereby negatively impacting overall vehicle performance. Current cooling systems for hub motors remain underdeveloped, with traditional methods such as air cooling, water cooling, or oil cooling struggling with uneven cooling distribution and low efficiency. These approaches fail to meet the thermal management demands of hub motors under variable driving conditions.

4.3 Maintenance Cost Escalation

Hub motors integrated within wheels are prone to damage due to persistent impacts from road debris. Combining functions such as power output and braking systems, their complex structures make repairs technically demanding. Maintenance requires specialized equipment and technicians, often involving wheel and component disassembly, which increases time and costs. As an emerging drive technology, hub motors face limited availability of repair parts in the market, coupled with high prices. This creates challenges in sourcing components and sustaining elevated repair costs, hindering the large-scale adoption of hub motor drive systems[22].

4.4 Reliability Standard Compliance

The stability of wheel hub motors is crucial for vehicle driving safety. In complex driving environments, hub motors must endure vibrations, impacts, temperature fluctuations, and other harsh operational conditions, demanding exceptionally high reliability. As hub motor technology remains in its developmental stage, the quality and reliability of certain critical components still require improvement. Issues persist in areas such as the motor's sealing performance and bearing durability, which may lead to operational failures, disrupt normal vehicle operation, and even pose safety hazards.

5. Targeted Technical Solutions for Existing Challenges

5.1 Suspension Geometry Optimization

The adoption of lightweight hub motors significantly reduces unsprung mass , thereby minimizing dynamic disturbances to the suspension system. Utilizing advanced materials and precision engineering, the motor structure is optimized to achieve weight reduction while maintaining power output performance.

Customized damping configurations are tailored for hub motor-equipped chassis. By calibrating key parameters such as spring stiffness and damper damping in alignment with hub motor dynamics and driving requirements, the suspension system enhances adaptability to complex road surfaces while improving ride comfort and handling precision.

Strategic weight redistribution increases the sprung-to-unsprung mass ratio through rational vehicle mass allocation, effectively reducing wheel-induced impacts on the body. During the initial vehicle design phase, structural and layout optimizations elevate the mass above the suspension while ensuring balanced overall vehicle performance[23].

5.2 Advanced Thermal Management Solutions

The adoption of lightweight hub motors significantly reduces the unsprung mass of tires, thereby minimizing dynamic interference with the suspension system. By utilizing advanced materials and technologies, the motor structure undergoes refined design to achieve optimal weight reduction while ensuring performance output. Customized damping settings for the chassis suspension are tailored specifically for hub motors. Combined with the characteristics of hub motors and vehicle driving requirements, key parameters such as spring stiffness and damper damping of the suspension system are precisely adjusted to enhance adaptability to complex road surfaces and optimize ride comfort and handling performance. By increasing the weight above the suspension and rationally redistributing vehicle mass, the ratio of unsprung mass to sprung mass is effectively reduced, mitigating the impact

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of wheel oscillations on the vehicle body. During the initial vehicle design phase, the structural layout is optimized to increase the mass above the suspension while ensuring balanced overall vehicle performance[24].Hub motors are equipped with diversified cooling systems such as water cooling, air cooling, or oil cooling, with the optimal cooling method or combination selected based on actual operating conditions. For example, during low-speed driving, air cooling can be utilized for heat dissipation, while water cooling or oil cooling systems are activated during high-speed driving or heavy-load conditions. This ensures effective cooling of the motor across various operational states.

5.3 Lifecycle Cost Reduction Strategies

Research and develop cutting-edge hub-driven motors to enhance operational stability and extend service life, thereby reducing failure rates. Through optimized structural design, selection of higher-quality materials and components, and refined production processes, comprehensively improve motor performance metrics and reliability, minimizing maintenance frequency.

Establish a comprehensive hub motor maintenance service network and cultivate technically skilled maintenance personnel. Expand service center coverage to ensure users receive prompt professional assistance when motor issues arise. Strengthen technical training programs for maintenance teams to enhance diagnostic proficiency, enabling rapid fault localization and efficient repair solutions.By advancing the standardization and mass production of hub motor maintenance components, part costs can be reduced. Through establishing unified component standards, interchangeability across manufacturers is enhanced, production scale is expanded, and manufacturing costs are lowered, thereby decreasing component procurement expenses during maintenance.

5.4 Fault-Tolerant System Integration

By deeply revising stator and rotor parameters to enhance the operational characteristics of permanent magnets, accurately grasping the functionality of magnetic steel and the electromagnetic properties of the motor, the reliability and stability of the motor are improved. During the design and manufacturing stages, meticulous optimization and adjustments are made to the specifications, materials, magnetic steel geometry, and layout based on specific application scenarios, ensuring stable motor performance across diverse operating environments.

In the development and production of hub motors, quality control for core components is strengthened. Critical parts such as bearings, sealing elements, and coils undergo rigorous quality inspections and screening to select superior products, guaranteeing overall motor quality and reliability.

Advanced fault diagnosis and early warning technologies are introduced to monitor the operational status of hub motors in real time. Sensors embedded within the motor collect data on temperature, current, rotational speed, and vibration. Leveraging data analytics and diagnostic algorithms, potential faults are identified proactively, enabling timely maintenance interventions to prevent failure escalation[25].

6.Hub Motor Technology Development Trends

Hub motor technology will advance in multiple dimensions. For durability, research will focus on developing stronger housing materials and advanced sealing technologies to resist external impacts and prevent contaminant ingress, while optimizing internal structures to enhance the reliability of critical components. In lightweight design, hub motor technology will evolve through size and structural optimization. Additionally, advancements in durability will include the creation of more robust housing materials and sophisticated sealing systems to withstand external shocks and block impurities, alongside refining internal architectures to improve the dependability of key parts[26].In lightweight design, system weight is reduced through dimensional and structural optimization as well as the adoption of new materials, enhancing vehicle energy efficiency. Regarding cost competitiveness, continuous technological advancements and large-scale mass production significantly lower raw material and manufacturing costs, thereby boosting corporate market competitiveness.

Integration efforts involv wheels, motors, and other components, optimizing chassis design to improve overall vehicle performance. Innovations +++++++++++++++ +++++++++++++++++in thermal management include high-efficiency cooling systems that precisely control motor temperature rise to prevent permanent magnet demagnetization.

Upgrades to permanent magnet materials focus on developing impact- and vibration-resistant alloys to suppress demagnetization. Torque ripple suppression technology will delve into multi-physics coupling mechanisms, enabling precise motor parameter control to enhance speed and torque accuracy.

Breakthroughs in electronic differential control surpass the limitations of traditional mechanical differentials, achieving superior performance. Sensorless control technology leverages optimized algorithms and intelligent systems, eliminating reliance on mechanical sensors to reduce costs and complexity.

Coordinated control ensures precise synchronization of multiple motors, enhancing vehicle stability and durability. In intelligent development, smart connectivity integrates hub motor systems with other vehicle subsystems, advancing toward autonomous “wheeled mobile robots” that elevate traffic efficiency and user experience[27-29].

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