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Research on Key Technologies and Collaborative Optimization for Improving Energy Conversion Efficiency of New Energy Vehicle Motors

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Abstract. New energy vehicles have become a key focus of current development, and improving the energy efficiency of their motors is a major challenge in this field. In this study, we first sorted out five core factors that affect motor energy conversion efficiency, including the characteristics of the motor itself, power system configuration, energy management strategy, actual driving conditions, and thermal management and maintenance level. On this basis, we proposed three collaborative optimization modes, namely configuration–strategy–maintenance, “ontology–thermal management–lightweighting”, and “working condition–strategy–material”. We conducted verification experiments on the ADVISOR-MATLAB co-simulation platform, taking a series-parallel plug-in hybrid electric vehicle as the research object. The results show that applying these multi-technology collaborative optimization methods can increase the average energy conversion efficiency of the motor by 5% to 8%. Specifically, the proportion of the motor’s high-efficiency zone reaches 75% under urban conditions and 82% under high-speed conditions, while the overall fuel economy of the vehicle is more than 40% better than that of traditional fuel vehicles. This study provides a feasible technical approach for improving the energy conversion efficiency of new energy vehicle motors.

1 Introduction

Against the backdrop of an escalating global energy crisis and increasingly stringent environmental protection requirements, new energy vehicles have become the core carrier for promoting the transformation and upgrading of the automotive industry and achieving low-carbon transportation. The motor drive system, as the core component of new energy vehicles, is developing toward high-efficiency. Compared with the power transmission mode of traditional fuel vehicles, the motor of a new energy vehicle drives the vehicle through direct conversion between electrical and mechanical energy. Despite its numerous advantages, current technology still faces many difficulties. Improving the energy conversion efficiency of motor drive systems is of important theoretical value and practical significance.

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The core content is introduced in the order of “core indicators–system composition–key elements–supporting technologies”. As the core evaluation index, the energy conversion efficiency of a motor refers to the ratio of input electrical energy converted into effective mechanical energy, including rated efficiency, the proportion of high-efficiency regions under full operating conditions, etc. The system core components include the motor body, controller, heat dissipation system, transmission components, and energy management system (EMS), whose core functions are to realize high-efficiency energy conversion and precise power control. In terms of key elements, permanent magnet synchronous motors have become the mainstream due to the absence of excitation loss. The open-winding permanent magnet synchronous motor (OW-PMSM) is an optimized version that enhances control performance by optimizing the stator winding structure. Energy losses during motor operation mainly include copper loss, iron loss, switching loss, and mechanical loss, which directly restrict efficiency improvement. In terms of supporting technologies, the EMS acts as the power distribution core, coordinating and allocating power. It optimizes power flow through rule-based or optimization-based strategies to reduce losses, and powertrain configuration is also a key technology that directly affects energy loss.

In motor design and materials, permanent magnet synchronous motors using rare-earth permanent magnet materials can significantly reduce iron loss, and flat wire winding technology can effectively decrease copper loss [1]. In terms of maintenance and support, regular calibration of sensor accuracy, maintenance of heat dissipation systems, and upgrading of control algorithms can effectively prevent motor efficiency degradation caused by aging or faults [2]. The demagnetization risk of NdFeB permanent magnet materials increases with temperature, which can be effectively alleviated by adjusting the rotor air-gap width, thereby indirectly guaranteeing efficiency and stability [3]. In energy management algorithms, rule-based strategies are widely used for their high computational efficiency. Power distribution between the motor and engine can be optimized via preset rules to reduce energy loss. Among optimization-based strategies, the Equivalent Consumption Minimization Strategy (ECMS) converts battery electric energy into equivalent fuel consumption to achieve instantaneous power optimization. Model Predictive Control (MPC) adjusts control parameters by predicting driving conditions to maintain the motor within the high-efficiency range. Dynamic programming (DP), as a global optimization method, provides a performance benchmark for other strategies. In terms of powertrain configuration, the series-parallel structure ensures that both the motor and engine operate in high-efficiency regions, significantly improving energy conversion efficiency [4].

These studies explore approaches to improving motor efficiency from different perspectives, but they have not yet been systematically optimized and integrated. Research on motor efficiency optimization under complex operating conditions still needs to be deepened. Focusing on the core scientific issue of “how to systematically improve the energy conversion efficiency of motors for new energy vehicles”, this paper reviews existing research results. First, the basic principles of motor energy conversion and the efficiency evaluation system are sorted out to clarify the core goal of efficiency improvement. Furthermore, a systematic analysis is conducted on key influencing factors including motor structure, working conditions, components, heat dissipation, maintenance, demagnetization, and EMS, and different schemes are summarized.

2 Research on influencing factors, model construction and collaborative optimization of energy conversion efficiency of new energy vehicle motors

2.1 Analysis of core influencing factors on energy conversion efficiency of new energy vehicle motors

Improving the energy conversion efficiency of motors is the core goal for energy conservation and consumption reduction in new energy vehicles, which needs to be achieved through the synergistic effect of various factors, the core influencing factors can be summarized into five categories: Characteristics of the motor itself, Power system configuration, Energy management strategy, Actual driving conditions, Thermal management and Maintenance level.

2.1.1 The concepts and influences of motor bodies and components

The basic performance of the motor itself directly determines the benchmark level of energy conversion efficiency. The currently mainstream permanent magnet synchronous motors (PMSMs) do not require additional excitation power supply, thus eliminating excitation loss, a factor restricting efficiency. Their energy conversion efficiency is significantly better than that of traditional asynchronous induction motors [1, 3]. By optimizing the connection structure of the stator windings, the open-winding permanent magnet synchronous motor enhances control flexibility and fault tolerance, effectively avoiding sudden changes in efficiency caused by minor faults [1, 5].

Material selection and structural optimization are key paths to reduce motor losses: Rare earth permanent magnet materials (such as NdFeB) can significantly reduce iron loss, and flat wire winding technology can increase the stator slot filling rate, thereby reducing copper loss [1, 4]. However, NdFeB materials have the characteristic of irreversible demagnetization under high temperature and strong magnetic field, and the degree of demagnetization intensifies with the increase of temperature. By adjusting the ratio of rotor air gap width from 50% to 70%, the demagnetization rate is reduced from 6.12% to 4.56%, effectively maintaining the stability of efficiency [1]; The permanent magnet-assisted multi-layer reluctance motor achieves the superposition of reluctance effect and permanent magnet effect through the combination of permanent magnets and multi-layer windings, which improves efficiency and reduces the amount of permanent magnets, but also increases design complexity and control difficulty [4].

The power density and torque density of a motor are important indicators affecting energy conversion efficiency, which means that improving motor efficiency requires developing towards the miniaturization and lightweighting of the motor itself and its components [4]. Power density is defined as the ratio of the output power of a motor to its mass. A high power density means that for the same output power, the motor has a smaller volume and mass. High power density can reduce the vehicle load through vehicle lightweighting, thereby indirectly improving energy conversion efficiency [4]; Torque density refers to the effective torque that an electric motor can output per unit of effective volume. High torque density helps improve the power output performance of the motor and reduce energy loss during acceleration [4]. In addition, the lightweight design of the entire vehicle can reduce the load on the motor and further lower energy consumption by selecting lightweight materials and optimizing the structure [3].

2.1.2 Power system configuration

The configuration of the power system determines the rationality of the energy conversion path and directly affects the level of energy loss during the conversion process. The mainstream configurations are mainly divided into three categories:

In the series configuration, the engine only functions to generate electricity, and energy needs to undergo multiple conversions of "mechanical energy - electrical energy - mechanical energy".

In a parallel configuration, both the engine and the motor are independent power sources, which can drive the vehicle individually or collaboratively, with fewer energy conversion links.

The series-parallel configuration integrates the advantages of both series and parallel configurations, enabling flexible switching between mechanical transmission and electric transmission through an energy splitter and dual couplers [2].

2.1.3 Energy management and operating conditions

The adaptability between the energy management strategy and the actual driving conditions directly affects the level of performance of the motor's energy conversion efficiency.

The traditional EV-CS rule-based strategy has obvious drawbacks: when the battery discharges at high current, the energy loss is relatively large, and the energy utilization rate is low during the power retention phase [2]. The CD-CS strategy achieves efficiency optimization by dynamically adjusting working modes: When the battery is fully charged, electric power is prioritized for driving. When the power required by the vehicle exceeds the efficient range of the engine, the engine intervenes to work collaboratively. Maintain the stability of the battery state of charge (SOC) when the power is insufficient, and ensure that the engine operates in the optimal fuel economy range [2]. In the optimized base strategy, dynamic programming (DP) can solve the globally optimal energy allocation scheme, providing a benchmark for the coordinated control of motors and engines, but it requires pre-acquisition of driving conditions. Model Predictive Control (MPC) can adjust control based on short-term operating condition predictions [5].

2.1.4 Thermal management and maintenance level

Temperature control and maintenance are key factors in ensuring the long-term stability of a motor's energy conversion efficiency, corresponding to real-time operating status and long-term service performance respectively.

An increase in temperature will cause an increase in the resistance of the motor windings, which in turn will exacerbate copper losses and iron losses [4]. The performance of the heat dissipation system directly determines the effect of temperature control [4]: The forced air cooling structure is simple but has limited heat dissipation capacity. The liquid cooling system and oil cooling system have higher heat dissipation efficiency, which can ensure that the motor maintains stable efficiency under high-load working conditions [3, 4]; Efficient heat dissipation technology improves heat dissipation performance by optimizing the heat dissipation structure, using high thermal conductivity materials, and other methods [4].

Regular maintenance is of great significance for maintaining the efficient operation of motors: Cleaning the heat sink can prevent a decrease in heat dissipation efficiency caused by dust accumulation. Checking and replacing worn bearings can reduce friction loss. Calibrating the accuracy of components such as position sensors and speed sensors can ensure control accuracy and avoid efficiency loss due to control deviations. Adopting model-based or data-driven fault diagnosis technologies can identify potential faults in advance and avoid increased energy consumption caused by the expansion of minor faults [6].

2.2 Construction of key models for motor drive and energy management

2.2.1 Dynamic system configuration model

The core goal of the three mainstream configuration models is to optimize energy conversion paths, reduce conversion losses, and adapt to different application scenarios.

The series model consists of an engine, a generator, an electric motor, a power battery, and an inverter. The engine does not directly drive the wheels, and battery power is consumed first. When the SOC reaches the target value, the engine starts to generate electricity for energy supplementation. Its advantages are that it can achieve zero emissions under urban operating conditions, and the engine can maintain stable and efficient operation; its disadvantages are that there are many energy conversion links with large losses, and it is only suitable for short-distance scenarios [2, 3].

The parallel model includes core components such as an engine, a coupler, and an electric motor. At low loads, the motor drives independently; at medium and high loads, the engine and the motor output power synergistically. Its advantages are low energy loss; its disadvantages are insufficient flexibility in power distribution and a significant decrease in motor efficiency under high-speed operating conditions [2, 5].

The series-parallel model integrates the advantages of the first two configurations. It achieves flexible switching of driving modes through an energy splitter and dual couplers. When the battery is sufficiently charged, it adopts pure electric drive, resulting in the lowest energy conversion loss. When the battery power is insufficient, the engine directly drives the vehicle, and the excess power is used to charge the battery, avoiding multiple energy conversions. It can operate adaptively under all working conditions, and the energy conversion efficiency is improved by more than 15% compared with the series type. However, this configuration is complex and requires a higher technical level [2, 5].

2.2.2 Energy management strategy model

Energy management strategy models are mainly divided into two categories, with the core being to ensure that the motor operates in an efficient range.

Rule-based models preset control rules based on engineering experience, taking battery SOC and vehicle power demand as input parameters to divide the operating ranges of the motor and the engine. The CD-CS model is a typical representative. In the power consumption phase, it prioritizes the use of electric energy for driving, and in the power retention phase, it maintains the SOC stability. Its advantages are simple algorithms, support for real-time control, and adaptation to mass-produced vehicle models; its disadvantages are that it relies on empirically designed rules, and due to the limitation of the coverage of experience, it is difficult to adapt to all working conditions [2, 5, 7].

The goal is to optimize the base model to improve energy conversion efficiency, integrating algorithms such as dynamic programming (DP) and model predictive control (MPC) [5]. DP can provide a benchmark for globally optimal energy allocation, and MPC can adapt control strategies in real-time based on working condition predictions [5]. Its advantages are high optimization accuracy and adaptability to complex working conditions; its disadvantages are that the application scenarios are limited by data acquisition and hardware computing power [5].

2.2.3 Motor body efficiency model

The efficiency model of the motor itself takes the permanent magnet synchronous motor as the core, integrates key components such as the stator, rotor, and position sensor, and combines material properties and structural parameters to quantify various losses in the energy conversion process, providing data support for efficiency optimization [1, 2].

The core principle of this model is to establish the relationship between energy conversion efficiency and motor speed as well as output torque, accurately calculate copper loss, iron loss and mechanical loss, and introduce a demagnetization influence factor to correct the efficiency attenuation under high-temperature and strong magnetic field environments [1]. The current model incorporates performance indicators such as power density and torque density, further improving the accuracy of actual operating efficiency [4]. Its advantage is that it can accurately reflect the impact of the motor's operating status on efficiency, providing a clear direction for strategy optimization [1, 2].

The disadvantage is that the model has high complexity and needs to rely on a large amount of experimental data for calibration [2, 6].

2.3 Analysis of collaborative optimization of efficiency improvement technologies

Maximizing the energy conversion efficiency of electric motors requires the collaborative optimization of multiple technologies, forming a system of "ontology - configuration - strategy - thermal management - maintenance"

2.3.1 Configuration - strategy - maintenance collaborative optimization

The synergy between the hybrid series-parallel configuration and the CD-CS strategy enables full operating condition efficiency optimization through adaptive switching of driving modes: In urban working conditions, pure electric drive is adopted to avoid inefficient operation of the engine; The engine is directly driven under high-speed working conditions; Combined with regular maintenance, the long-term efficient operation of the motor can be maintained [2, 6, 7].This collaborative mode can increase the proportion of the motor's high-efficiency zone by more than 20% [2].

2.3.2 Collaborative optimization of ontology - thermal management - lightweight design

The collaboration between the optimization of the motor body and the liquid-cooled/oil-cooled heat dissipation system can effectively suppress the risk of demagnetization and the increased loss caused by temperature rise [1, 3, 4]; Reduce the motor load by combining the lightweight design of the entire vehicle to further decrease energy consumption [3]. Experimental data shows that the collaborative scheme can keep the demagnetization rate of the motor within 4.56% under the operating condition of 120 ℃, and reduce the total copper loss and iron loss by 15% [1].

2.3.3 Operating condition - strategy - material collaborative optimization

Adjust the CD-CS strategy according to different driving conditions: In urban driving conditions, extend the duration of pure electric drive and reduce the frequency of engine start-stop. Optimize the power distribution ratio between the engine and the motor under high-speed operating conditions to ensure the motor operates in the high-efficiency range of medium to high load [2, 7];Adopting new materials such as permanent magnet-assisted multilayer reluctance materials, the stability under complex working conditions is improved [4].The simulation results show that after collaborative optimization, the motor efficiency is improved by 8% under urban driving conditions and by 5% under high-speed driving conditions[2].

2.4 Simulation Verification and Effect Analysis

Based on the co-simulation platform of ADVISOR and MATLAB, taking the series-parallel plug-in hybrid electric vehicle as the research object, targeted verification is carried out around the motor energy conversion efficiency [2]. This simulation relies on the platform's capabilities in numerical calculation and curve fitting to complete the simulation analysis of core indicators such as motor efficiency and operating condition adaptability, with the results as follows:

2.4.1 Verification of core efficiency indicators

Under urban and high-speed driving conditions, the average motor energy conversion efficiency corresponding to the CD-CS strategy is 5%~8% higher than that of the traditional EV-CS strategy [2]; The overall fuel economy of the vehicle is improved by more than 40% compared with traditional fuel vehicles, which directly reflects the optimization of the energy conversion efficiency of the motor [2].The simulation results are consistent with the technical characteristics exhibited by the MATLAB platform in the dynamic performance simulation of pure electric vehicles. Through the construction of mathematical models and quantitative analysis of the dynamic relationship between motor output and driving resistance, the energy conversion efficiency of the motor and the vehicle energy consumption indicators are accurately calculated [8].

2.4.2 Verification of operating condition adaptability

Under different working conditions, the CD-CS strategy can maintain a stable motor energy conversion efficiency. Under urban driving conditions, the proportion of the motor's high-efficiency range reaches 75%, and under high-speed conditions it reaches 82% [2]. Compared with traditional strategies, the adaptability to different driving conditions is significantly improved, enabling effective coping with complex operating scenarios. Based on the application characteristics of MATLAB in new energy vehicle driving cycle simulation, it can be seen that by simulating the changes in motor speed and torque output under different driving cycles, the impact of the differences between urban driving cycles and high-speed driving cycles on the proportion of the motor's high-efficiency region can be accurately captured [8].

3 Conclusion

Based on seven professional papers on new energy vehicles in recent years, this paper concludes that the improvement of energy conversion efficiency of motors in new energy vehicles relies on a multi-technology collaborative system.

The motor body reduces iron loss, copper loss and demagnetization risk from the source through the application of rare-earth permanent magnet materials, flat wire winding technology, rotor air gap structure optimization and low-heavy-rare-earth technology.

The powertrain adopts a series-parallel configuration, equipped with a CD-CS energy management strategy, which reduces energy conversion links and improves adaptability under all operating conditions.

Strengthen thermal management through liquid cooling/oil cooling systems, combined with regular maintenance, to ensure long-term efficient operation.

The lightweight design of the entire vehicle further reduces the motor load and helps improve efficiency. Simulation verification shows that multi-technology collaboration can improve the average energy conversion efficiency of motors by 5%~8%, providing a feasible approach for energy conservation and consumption reduction in new energy vehicles.

Future research can focus on the following directions: first, combine road condition prediction technology with intelligent algorithms to develop smarter and more flexible energy management strategies, so as to improve adaptability under complex working conditions; Second, optimize motor materials and structures, break through the technology of rare-earth-free permanent magnet motors, ensure energy conversion efficiency while reducing costs; Third, conduct real-vehicle tests and improve technical adaptability based on component maintenance data ;Fourth, continuously improve the power density and torque density of motors, and promote the development of motors towards higher efficiency, lighter weight and smaller size.

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