New Energy Vehicle Mechanical Transmission System and Energy Flow Distribution Optimization

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Abstract. The collaborative optimization of the mechanical transmission system and energy flow in new energy vehicles is a key technology for improving vehicle dynamic performance, transmission efficiency and driving range. This paper systematically reviews the energy transfer paths of two typical configurations: pure electric and hybrid electric. It analyzes the configuration of the mechanical transmission system and clarifies that, as the core carrier of energy flow, its structure, speed ratio and efficiency characteristics directly affect the overall vehicle energy consumption. This review compares the technical characteristics and applicable scenarios of three types of energy flow management strategies: rule-based control, global optimal control, and model predictive control. It briefly analyzes the influence mechanism of transmission forms on energy utilization efficiency, and points out key issues including the nonlinear efficiency of transmission systems and parasitic losses. This paper summarizes mainstream collaborative optimization methods such as multi-parameter joint optimization, dynamic efficiency compensation, and real-time collaborative control, as well as the verification system combining simulation and experimentation. According to the review, the integrated collaborative control of the mechanical transmission system and energy flow represents an important development direction for future energy-saving technologies of new energy vehicles, and can provide a theoretical reference for improving overall vehicle energy efficiency.

1 Introduction

Under the guidance of the "Dual Carbon" goal and the global energy structure transformation, new energy vehicles have become the core direction for the automotive industry to break away from fossil energy dependence and achieve green and low-carbon development. Breakthroughs in their mechanical transmission technology directly determine the progress and quality of industrial upgrading. As the core carrier of power transmission for new energy vehicles, the mechanical transmission system and energy flow distribution, which is the key to achieving efficient energy utilization, are synergistically optimized as a core breakthrough

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to address the insufficient driving range of new energy vehicles and resolve the contradiction between dynamic performance and energy consumption balance.

At present, scholars at home and abroad have conducted extensive research on the mechanical transmission system of new energy vehicles. Ranging from structural innovation and the application of lightweight materials to the precision design of transmission components, intelligent algorithms have been introduced in the field of energy flow distribution. Existing research shows that through the collaborative design of transmission ratio optimization, multi-motor torque distribution, and energy flow regulation of the transmission system, vehicle energy consumption can be effectively reduced. However, most existing studies separate the mechanical transmission system design from the energy flow distribution optimization, lacking an in-depth exploration of their coupling mechanism.

Based on the above analysis, this paper focuses on the collaborative optimization of mechanical transmission systems and energy flow distribution in new energy vehicles. It first examines the structural features of transmission systems and energy flow transfer rules in pure electric and hybrid electric vehicles, and summarizes the key factors affecting transmission losses and energy allocation. Then, investigations are conducted from two aspects: the topological design, parameter matching of mechanical transmission systems, and the intelligent control strategies for energy flow distribution. The study further explores the coupled optimization approach for transmission systems and energy distribution under various driving conditions, with the goal of lowering mechanical and energy conversion losses. Through these efforts, the multi-objective optimization of vehicle dynamic performance, energy economy, and battery service life can be effectively realized.

2 Core components of the mechanical transmission system for new energy vehicles

2.1 System composition and classification

The mechanical transmission system of new energy vehicles takes electric drive as the core, mechanical reduction as the matching mechanism, and differential distribution as the execution. Its overall architecture is greatly simplified compared with traditional fuel vehicles. According to the power source and coupling mode, it can be divided into three categories: pure electric transmission, hybrid electric transmission, and fuel cell electric transmission. The mechanical transmission system must balance power coupling and distribution [1]. The electric drive axle highly integrates the motor, reducer, differential, and parking mechanism, has become the mainstream technical route for most new energy vehicles at present, and achieves the integrated electromechanical-thermal design.

2.2 Core composition of pure electric mechanical transmission system

2.2.1 Drive motor

The drive motor replaces the internal combustion engine as the power source. Permanent magnet synchronous motors are mainstream, featuring high low-speed torque, a wide speed regulation range, and instantaneous response characteristics. The rated speed is 8000–15000 r/min, and the peak speed can reach above 20000 r/min. Peak torque is available at zero speed, which theoretically eliminates the dependence on multi-gear transmission [2]. The motor output shaft is directly and rigidly connected to the input shaft of the reducer, with no idle speed and no power interruption. This significantly reduces mechanical shock loads and improves the service life and reliability of the transmission system.

2.2.2 Speed reducer

The reducer is the only variable-speed and torque-increasing mechanism in pure electric drive systems, and it is classified into four types: single-stage parallel-axis, single-stage planetary gear set, two-speed electronically controlled, and wheel-side/hub reducers. Conventional passenger cars primarily use single-speed fixed-ratio reducers, which feature simple structure, high efficiency and low cost. High-performance vehicles generally adopt two-speed reducers to balance start-up and climbing performance with high-speed energy efficiency. According to the transmission ratio design formula, the required torque at the wheel end and the motor output torque satisfy the following relationship:

$$T_w = T_m \cdot i_0 \cdot \eta_g \qquad (1)$$

Where:T_w— wheel driving torque (N·m);T_m— motor output torque (N·m);i_0 — final drive ratio; η_g— gear transmission efficiency [3].

Relevant experiments show that the overall efficiency of a reducer is the superposition of four types of losses: gear meshing loss, bearing friction loss, oil churning loss, and oil seal loss. A total efficiency model exists accordingly.

$$\eta_{total} = \eta_{gear} \cdot \eta_{bearing} \cdot \eta_{churn} \cdot \eta_{seal} \qquad (2)$$

According to the formula, the high-efficiency range of a single-stage reducer can reach 95%–98%, which is significantly higher than that of conventional AT/DCT transmissions (85%–92%)[4].

2.2.3 Differential and half shafts

The differential enables differential rotation of the left and right drive wheels of the vehicle, effectively eliminating wheel slip and wear during steering and reducing additional internal stress in the transmission system. It is a core component of the vehicle drive axle. According to their structural forms and limited-slip characteristics, differentials are mainly classified into three categories: open differentials, limited-slip differentials and electronic differentials. For vehicles with a distributed drive configuration, the traditional mechanical differential mechanism is eliminated, and electronic differential function is realized through closed-loop control of independent torque from dual motors. Compared with traditional mechanical differentials, its dynamic response speed is improved by an order of magnitude, and the control accuracy and response characteristics are significantly optimized.

2.2.4 Integrated electric drive axle

Integrated electric drive axles combine the motor, reducer, differential, inverter, and thermal management system into one compact unit. With a coaxial or parallel-shaft layout, they eliminate redundant parts such as housings, bearings, and seals, reducing volume by 30% and weight by over 25%. This shortens the transmission chain and lowers mechanical losses. The integrated design also optimizes NVH, structural stiffness, and heat dissipation, making it the mainstream solution for 800V high-voltage electrified platforms.

2.3 Core configuration of hybrid electric powertrain system

A hybrid powertrain system adds an engine-motor coupling mechanism to the basic structure of a pure electric powertrain, and can be divided into four categories according to different configurations. In a series hybrid system, the engine only generates electricity and does not drive the wheels directly, so its transmission structure is basically the same as that of pure electric vehicles. Parallel hybrid adopts coaxial or parallel-axis coupling between the engine and the motor, and realizes power transmission with clutches, couplers, and single-speed or multi-speed gearboxes. Power-split hybrid takes the planetary gear mechanism as the core, which can realize stepless power distribution and speed regulation without traditional gear positions. It mainly consists of planetary carriers, input and output shafts, and braking mechanisms. The P2 coaxial parallel layout places the motor at the input end of the gearbox, supporting multiple working modes including pure electric drive, hybrid drive, and direct engine drive, while the transmission system performs both gear shifting and power coupling functions. In the power-split system, the transmission ratio and torque distribution follow the fundamental characteristics of the planetary gear train. The kinematic relationship can be expressed as:

$$n_s+\alpha n_r-(1+\alpha)n_c=0 \tag{3}$$

where n_s, n_r, and n_c represent the rotational speeds of the sun gear, ring gear, and planet carrier, respectively. $\alpha=z_r/z_s$ denotes the ratio of the number of teeth between the ring gear and the sun gear [5].

3 Optimization theory and control strategy of energy flow distribution

3.1 Energy flow composition and transmission path

The energy flow of new energy vehicles mainly involves three forms: electric energy, mechanical energy and chemical energy. The core transmission paths vary with different power types. For battery electric vehicles, power is transmitted from the power battery to the wheels through the motor controller, drive motor and mechanical transmission system. For hybrid electric vehicles, the engine or motor drives the wheels via the power coupling mechanism and transmission system, and the braking energy can be recovered to the battery through motor generation. For fuel cell vehicles, the fuel cell stack supplies power through a DC/DC converter, motor controller and drive motor, and then transmits power to the wheels via the transmission system. The mechanical transmission system directly affects energy transmission efficiency, loss distribution and dynamic response, serving as a key component for vehicle-level energy flow optimization. Its gear ratio matching, transmission efficiency and characteristics of the coupling mechanism all exert significant impacts on overall vehicle energy consumption.

3.2 Core objectives of energy flow distribution optimization

Optimizing energy flow distribution represents one of the critical challenges in the new energy vehicle industry. Its core objectives include: operating the drive motor and engine within their high-efficiency ranges, with the objective function of minimizing overall energy consumption expressed as $\min E=\int P(t)dt$, where $P(t)$ is the real-time power of the vehicle, thereby reducing energy consumption per kilometer and extending driving range; minimizing transmission losses such as gear meshing loss, bearing friction and churning loss to improve mechanical transmission efficiency; balancing vehicle dynamic performance and energy economy; maximizing braking energy recovery; and avoiding overload and frequent shock of key components to achieve lifespan balance of the motor, battery and transmission system.

3.3 Typical energy flow distribution control

Energy distribution based on preset working condition thresholds is widely adopted in mass-produced vehicles due to its simple structure, easy implementation and high reliability. Under pure electric drive with low speed, low load and sufficient SOC, only the motor operates. Under high-load conditions such as rapid acceleration and climbing, the engine and motor output power together. In charging mode with low SOC and low-speed idle, the engine drives the generator to charge the battery. During deceleration and braking, the motor reverses to recover energy via regenerative braking. Although this strategy can improve energy efficiency, it relies heavily on calibration experience and can hardly achieve the global optimum over all working conditions. With objective functions of minimum energy consumption and minimum transmission loss, global optimal energy distribution can be obtained by dynamic programming when the driving cycle is known. This method achieves collaborative optimization of the power source and transmission system with theoretically optimal efficiency. However, its large computation amount and requirement for prior road information limit its application mainly to simulation and calibration, rather than real-time on-board control.

3.4 Influence mechanism of mechanical transmission system on energy flow

The mechanical transmission system affects energy flow mainly through gear ratio characteristics, nonlinear efficiency, coupling losses and dynamic response. A single-speed reducer features a simple structure and high steady-state efficiency, yet tends to push the motor into low-efficiency regions at high speeds, while multi-speed transmissions can broaden the high-efficiency range but introduce additional shifting losses and control complexity. The efficiency of gears, clutches and differentials varies nonlinearly with torque, speed and temperature, resulting in high friction loss at low load and efficiency degradation at high load. In hybrid configurations, parasitic losses from planetary gears and coupling mechanisms must be considered to avoid control deviations. Moreover, backlash, stiffness and shifting processes lead to extra energy loss from power fluctuation and impact, so the energy flow optimization strategy should take dynamic transmission characteristics into account to improve overall energy efficiency.

4 Collaborative optimization method of mechanical transmission system and energy flow

4.1 Collaborative optimization design principles

The collaborative optimization of the mechanical transmission system and energy flow distribution requires breaking through the traditional independent design of power source and transmission, and establishing an integrated optimization framework of power-transmission-vehicle. Taking transmission efficiency, high-efficiency range of power source and driving conditions as inputs, the multi-objective optimization aims at minimum energy consumption, optimal dynamic performance and good ride comfort, so as to realize global coordination of parameter matching, control logic and operation modes. The ratio scheme and coupling structure are determined in configuration design, while gear decision, torque distribution and braking recovery are coordinated in real-time during control, thus achieving high-efficiency energy transfer throughout the whole vehicle.

4.2 Parameter matching optimization based on transmission efficiency characteristics

The key parameters of the mechanical transmission system directly affect energy flow transmission efficiency, so multi-parameter joint matching should be carried out according to the characteristics of the power source. The optimization variables mainly include the reducer ratio, gear ratios of multi-speed transmissions, shift speed, and mechanical efficiency of the transmission system. By establishing a coupling model combining the motor/engine efficiency MAP and transmission efficiency MAP, and taking energy consumption per 100 km and dynamic response as objective functions, intelligent optimization algorithms such as particle swarm optimization and genetic algorithm are adopted to obtain the optimal ratio combination and transmission component design parameters. Meanwhile, aiming at typical low-efficiency working conditions such as low load and high speed, targeted optimization is performed on transmission stiffness, lubrication scheme and gear parameters to reduce friction and churning losses and improve energy utilization efficiency under full working conditions [6].

4.3 Real-Time energy flow – transmission system coordinated control

During vehicle operation, the energy management strategy and transmission control must be determined synchronously. Based on driving condition identification and vehicle speed prediction, the controller outputs three core control variables in real time: torque distribution of the power source, transmission gear command, and regenerative braking intensity [7]. Under acceleration conditions, the power source is preferentially adjusted to its high-efficiency region with the optimal gear ratio. During cruising, transmission ratio regulation prevents the power source from over-speeding. In braking conditions, the maximum recyclable generation torque is determined according to the reverse transmission efficiency to avoid secondary energy losses during transfer. The coordinated control effectively alleviates the problems in traditional control, such as rough power switching, unsynchronized gear shifting and torque distribution, and low utilization of high-efficiency regions.

4.4 Energy correction mechanism considering dynamic losses

Traditional energy flow distribution models usually treat transmission efficiency as a fixed value, which has an obvious deviation from actual working conditions. To improve control accuracy, a dynamic efficiency correction module should be introduced to incorporate factors such as torque, rotational speed, oil temperature, and gear shifting process into real-time calculation. During dynamic processes like gear shifting, mode switching, and sudden torque changes, compensation is made for clutch slip loss, gear meshing impact loss, and torque response lag loss to correct energy distribution commands. Through dynamic efficiency closed-loop correction, the error of the vehicle energy consumption model can be controlled within a smaller range, providing more accurate model support for optimal control strategies and model predictive control.

4.5 Multi-domain simulation and bench test verification method

The synergy optimization effect of the mechanical transmission system and energy flow must be verified through multi-physics domain co-simulation and bench tests. A motor-engine-transmission-vehicle simulation platform is established using AVL Cruise, Matlab/Simulink, AMESim and other software. Multi-cycle operating conditions such as NEDC, WLTC and CLTC are simulated to verify indicators including energy consumption, recovery rate and dynamic performance [8]. On this basis, gear losses, coupling mechanism losses and shift quality are measured via powertrain test benches and transmission efficiency test rigs, so as to calibrate the simulation model and control parameters. The combination of simulation and experiment ensures the reliability and engineering feasibility of the optimization scheme in real vehicle applications.

5 Conclusion

This paper systematically reviews the optimization of mechanical transmission systems and energy flow distribution for new energy vehicles. The energy flow transmission paths of three typical configurations, namely battery electric, hybrid electric and fuel cell vehicles, are clarified, and the core role of the mechanical transmission system in energy conversion, transmission and loss is revealed. Studies show that the ratio arrangement, transmission efficiency, power coupling characteristics and dynamic response of the mechanical transmission system are key factors restricting the overall vehicle energy efficiency. Only by integrating its loss and operating characteristics into the energy flow distribution control model can the optimal energy efficiency under full operating conditions be achieved.

For energy flow distribution optimization, rule-based control, global optimal control and model predictive control have respective advantages in engineering application and theoretical optimization. Among them, model predictive control achieves a good balance between real-time performance and optimization accuracy, making it suitable for energy management under complex road conditions. Energy flow optimization should target five objectives: operation in high-efficiency regions, minimum transmission loss, balance between dynamic performance and economy, maximized braking energy recovery and balanced component life. Through hierarchical control architecture and multi-objective optimization algorithms, the integrated coordinated control of power sources, power batteries and mechanical transmission systems is realized.

Mechanical transmission parameter matching, real-time coordinated control, dynamic efficiency correction and multi-domain simulation verification can effectively reduce energy loss in the transmission process, expand the high-efficiency range of power sources, and improve vehicle energy economy and braking energy recovery rate. This provides theoretical basis and technical support for the optimal design of powertrains and the development of energy management strategies for new energy vehicles.

Future optimization of mechanical transmission systems and energy flow distribution for new energy vehicles will evolve toward high efficiency, integration, intelligence, and coordination. As electric drive assemblies develop toward multi-speed, coaxial integration, and high-speed operation, the efficiency, dynamic loss, and shift quality of transmission systems will become key focuses in energy flow optimization. With the maturity of road condition prediction, driving pattern recognition, and AI algorithms such as reinforcement learning, energy flow distribution will achieve self-learning, adaptive, and real-time online optimization. Meanwhile, the rapid development of fuel cell and distributed-drive electric vehicles will make coordinated energy distribution and torque control of multiple power sources new research hotspots. The deep integration of transmission systems and vehicle energy management will effectively enhance the driving range, energy efficiency, reliability, and ride quality of new energy vehicles, supporting the technological upgrading of the industry.

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