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Applications and Challenges of Electromechanical Integrated Transmission Systems in Intelligent Vehicles

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Abstract. With the rapid development of intelligent vehicles and the global push for carbon neutrality, Electromechanical Transmission (EMT) systems have attracted wide attention for their unique benefits. This paper provides an in-depth analysis of the three primary EMT architectures—series, parallel, and series-parallel hybrid configurations—highlighting their structural characteristics and operational principles. The study identifies key research directions focusing on enhancing energy utilization efficiency, improving drivability, and reducing system costs. Furthermore, it examines the current applications of EMT systems in intelligent vehicles, delineates the challenges encountered, and explores critical technologies such as lightweight design, hybrid power cooperative drive, and intelligent control strategies. The paper also evaluates various methodologies and algorithms employed within these technologies, assessing their respective advantages and limitations. Looking ahead, EMT systems are poised to play an increasingly pivotal role across multiple domains. However, to fully realize their potential, it is imperative to address prevailing issues related to system reliability, cost-effectiveness, and the integration of advanced intelligent control mechanisms, thereby contributing to the sustainable development of the automotive industry.

Keywords: Electromechanical Transmission Systems, Hybrid Electric Vehicles, Energy Management Strategies, Control Strategies, Lightweight Design

1. Introduction

Following the establishment of China's "dual carbon" objectives—aiming to peak carbon emissions by 2030 and achieve carbon neutrality by 2060—the automotive industry has been identified as a critical sector for emission reductions. The "New Energy Vehicle Industry Development Plan (2021–2035)" delineates strategic targets, including achieving a 20% share of new energy vehicles (NEVs) in total vehicle sales by 2025, with battery electric vehicles (BEVs) becoming predominant by 2035 . Given the limited energy capacity of electric vehicle batteries, enhancing energy efficiency is essential to extend driving range, reduce charging frequency, and improve overall user convenience. Consequently, the development of high-efficiency powertrain systems has become increasingly vital.

Electromechanical Transmission (EMT)[1], as a power-split hybrid system, employs dual pathways—mechanical and electrical—to transmit power. This configuration not only optimizes

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engine operation but also leverages the advantages of the mechanical power path, thereby significantly enhancing both energy efficiency and dynamic performance[2]. Compared to conventional mechanical transmissions and purely electric drives, Electromechanical Transmission (EMT) systems offer advantages such as compact architecture and flexible torque distribution. These attributes enhance their competitiveness in terms of energy utilization, power output, and adaptability to complex operating conditions[3].However, the structural complexity inherent in Electromechanical Transmission (EMT) systems introduces significant challenges, including increased control difficulty, elevated manufacturing costs, and reliability constraints. These issues are particularly pronounced under harsh operating conditions and high dynamic load environments, where EMT systems are subjected to severe mechanical stresses and vibrations, potentially leading to fatigue failures and reduced operational lifespan. Consequently, enhancing the reliability of EMT systems, optimizing their control strategies, and reducing production costs have become central research objectives. Moreover, the complex application scenarios of intelligent vehicles impose higher demands on the adaptability and intelligent control capabilities of EMT systems. Improving the performance of EMT systems across diverse scenarios and operating conditions remains a critical direction for future research.

In recent years, to address these challenges, researchers have focused on optimizing powertrain system architectures, enhancing energy management strategies, and integrating advanced control algorithms. For example, implementing more efficient energy recuperation mechanisms[4], refining vehicle energy management strategies[5], optimizing gear-shifting logic[6], and employing advanced control techniques such as dynamic programming[7] and deep learning algorithms[8] for real-time regulation can collectively enhance the overall performance of Electromechanical Transmission (EMT) systems. These approaches contribute to improved energy efficiency, adaptability to varying driving conditions, and enhanced system responsiveness.

In the future, with advancements in new energy technologies, intelligent control systems, and advanced materials, Electromechanical Transmission (EMT) systems are poised to play a more significant role in military, special-purpose, and intelligent electric vehicles. This paper will discuss the structural design, control strategies, energy management, and future development trends of EMT systems, exploring the current research status, technical challenges, and future application prospects of electromechanical hybrid transmission systems. Such discussions aim to inspire researchers in the field of electromechanical hybrid transmission systems and promote innovative development.

2. Challenges and research status of electromechanical hybrid transmission systems

Electromechanical hybrid transmission (EMT) systems can be classified into three configurations based on the coupling form of vehicle drive power sources: series, parallel, and series-parallel[9]. As shown in Figure 1, in a series EMT system, the electric motor directly drives the vehicle, while the internal combustion engine (ICE) functions solely as a generator to supply power to the motor. Conversely, in a parallel EMT system, the vehicle can be driven either by the electric motor, the ICE, or both simultaneously. The series-parallel EMT system integrates the advantages of both configurations, enabling flexible power distribution and enhancing overall performance.

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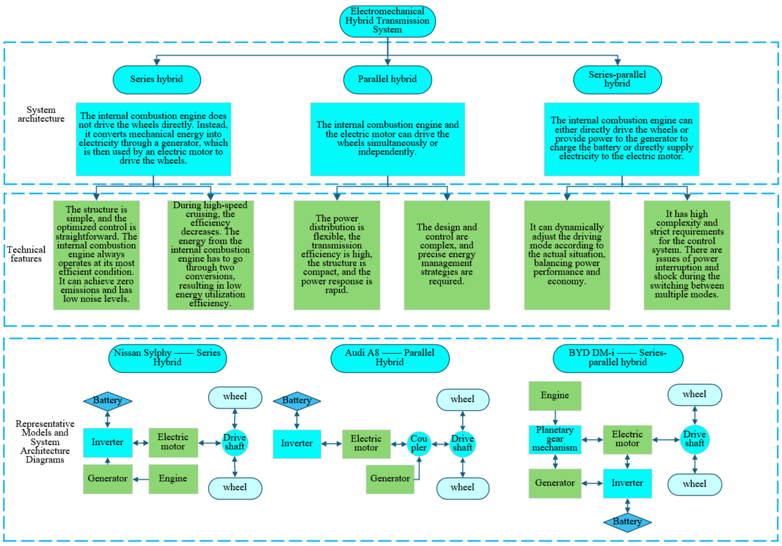

Figure 1: Schematic diagrams of different electromechanical hybrid transmission system architectures

Enhancing energy utilization efficiency and ensuring smooth power delivery remain pivotal challenges in the development of Electromechanical Transmission (EMT) systems. Current research focuses on optimizing Energy Management Systems (EMS) and achieving dynamic coordination among multiple power sources. Strategies to improve energy efficiency encompass enhancing engine combustion efficiency, minimizing thermal and chemical losses in batteries, and optimizing regenerative braking systems.Enhancing the smoothness of power delivery in Electromechanical Transmission (EMT) systems necessitates the optimization of mode transition logic. According to Ref. [10] , an energy management system (EMS) based on Model Predictive Control (MPC) was developed to enhance powertrain efficiency. By forecasting future system states and control inputs over a defined time horizon, this approach optimizes the control sequence and determines an optimal operating point trajectory. Consequently, the internal combustion engine (ICE) operates along this trajectory during steady-state conditions, minimizing the duration spent at inefficient operating points and thereby improving combustion efficiency. However, under dynamic conditions, the engine's operating point may deviate from the optimal efficiency curve. To address this issue, Refs. [10] propose the use of the battery to buffer transient variations in engine output. This strategy enables the operating point to remain close to the optimal efficiency trajectory, reducing energy losses during power transitions and further enhancing overall system energy efficiency.

Traditional EMS architectures often neglect the influence of driver behavior on vehicle operation. Ref. [11]addresses this gap by integrating a driver behavior model based on a Markov chain into the MPC framework. A stochastic model predictive control and learning-based predictive vehicle control approach is proposed, which improves the adaptability and robustness of the system. Additionally, this method offers significantly reduced computational complexity compared to conventional stochastic dynamic programming, making it more suitable for real-time applications.Ref. [12] introduces a dual fuzzy logic control strategy that dynamically adjusts the clutch hydraulic pressure in response to driver intent and vehicle state. This approach enables precise torque control of the clutch, significantly mitigating torque fluctuations and vehicle jolts during mode transitions. As a result, it optimizes shift logic and improves vehicle ride comfort.

Reducing the manufacturing cost of electromechanical transmission (EMT) systems while improving fuel economy has emerged as one of the key research focuses in the field. EMT systems

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in power-split hybrids can be categorized primarily into two technological pathways: series-parallel and power-split configurations.The Honda i-MMD system adopts a series-parallel architecture utilizing a P1+P3 dual-motor layout, wherein both the generator and traction motor are integrated into the transmission. This integration minimizes additional mechanical components and system complexity, thereby reducing production costs. The Toyota Hybrid System (THS), representing a power-split configuration, employs a planetary gear set to allocate and couple power from the internal combustion engine (ICE) and electric motor. By optimizing the connection between the traction motor and planetary gear set, the system increases the gear ratio from the traction motor to the wheels, effectively reducing motor torque requirements while increasing operational speed. This not only improves drivetrain efficiency but also contributes to cost reduction. Similarly, BYD’s DM-i system utilizes the P1+P3 dual-motor configuration akin to the Honda i-MMD, but it differentiates itself through strong hybrid control strategies that decouple engine speed from vehicle speed. Additionally, it employs a high-capacity battery pack for dynamic energy management. This configuration enables the engine to operate along a single-efficiency curve rather than across a wide operating range, allowing it to function within its optimal efficiency region under approximately 70% of driving conditions. As a result, the DM-i system significantly enhances engine thermal efficiency and fuel economy.

The continuous refinement and innovation of these technologies have laid a solid foundation for the advancement of series-parallel hybrid systems. Looking forward, with further technological breakthroughs and ongoing reductions in production costs, series-parallel hybrid vehicles are expected to play an increasingly prominent role in the global automotive market, contributing to the industry's transition toward green and sustainable development.

3. Key technologies of electromechanical transmission systems in intelligent vehicles

3.1. Lightweight design and high-efficiency energy conversion

Lightweight vehicle design and enhanced energy conversion efficiency represent pivotal technologies in electromechanical transmission systems, exerting a significant influence on key performance metrics such as fuel economy, all-electric driving range, and maximum operational range.

The primary approach to lightweight design is the use of lightweight materials. Hybrid electric vehicles (HEVs) predominantly utilize lightweight materials such as light alloys (e.g., aluminum, magnesium, and titanium alloys), high-strength steels (HSS and AHSS), and composite materials[13]. The density of aluminum alloys is approximately one-third that of steel, significantly reducing vehicle weight, thereby improving fuel efficiency, acceleration performance, braking performance, and handling characteristics[14]. Replacing low-carbon steel with High Strength Steel (HSS) and Advanced High Strength Steel (AHSS) can significantly reduce the thickness of the front body panels with the same or greater energy absorption capacity, thereby achieving impact protection. This enables the use of thinner structures while ensuring safety, contributing to lightweight design. HSS and AHSS are widely applied in various vehicle components, including the body shell, crash zones, roof and pillars, chassis parts, seat frames, doors and door beams, cross members, and longitudinal beams[15]. For example, the roof arches and pillars of the Volvo XC90 and the body of the General Motors Cadillac ATS. Depending on the type of reinforcing materials used, composite materials can achieve weight reductions ranging from 15% to 40% in the automotive industry. Additionally, they offer a range of superior properties, including high specific strength, excellent corrosion resistance, design flexibility, and low thermal conductivity. For

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example, in the Volvo XC90, most of the polymer composites (approximately 65%) are used in the vehicle's exterior and interior components, while the remainder is utilized in structural and powertrain systems. One of the most promising composite materials is carbon fiber reinforced plastic (CFRP), which offers extremely high specific strength and specific stiffness, significantly reducing vehicle weight and improving fuel efficiency and overall vehicle performance[16]. For instance, the body of the BMW i3 utilizes CFRP, resulting in a 50% reduction in body weight compared to traditional steel bodies, while maintaining high strength and excellent crash resistance.

The primary approaches to enhancing energy conversion efficiency encompass improving engine thermal efficiency, implementing regenerative braking systems for energy recovery, and reducing thermal and chemical losses in battery energy.

Enhancing engine thermal efficiency can be achieved by optimizing the combustion process through lean-burn techniques and rapid combustion technologies. For instance, the Toyota Prius hybrid vehicle has realized over 45% thermal efficiency by employing such advanced combustion strategies. Reducing friction losses is another effective method to improve engine thermal efficiency. The BYD DM5.0 utilizes ultra-low friction coatings, 0W-20 low-viscosity engine oil, low-tension piston rings, and diamond-like carbon (DLC) coatings to significantly decrease mechanical friction, thereby enhancing engine thermal efficiency. Hybrid Electric Vehicles (HEVs) can recover braking energy through regenerative braking systems, storing it in the battery to improve overall energy utilization. Research indicates that regenerative braking contributes approximately 35% to the total energy efficiency improvement in the Toyota Prius hybrid vehicle, substantially enhancing fuel efficiency[4].

Reducing energy losses in batteries can be approached by minimizing both chemical and thermal losses. The primary method for reducing thermal losses in batteries involves real-time estimation of the battery's state of charge (SOC), state of health (SOH), and other parameters through a Battery Management System (BMS). A typical Battery Management System (BMS) utilizes an equivalent circuit model[17]. However, such models often neglect the mass transfer limitations caused by solid-phase diffusion, leading to prediction errors when used across a wide operating range. Reference [18] discusses that the Battery Management System (BMS) for Hybrid Electric Vehicles (HEV) should utilize a physics-based electrochemical model rather than an equivalent circuit model, which has played a crucial role in advancing BMS design. Choosing battery materials with good thermal stability is also a method for reducing thermal energy loss in batteries. For example, selecting battery materials such as lithium iron phosphate ($LiFePO_4$), which exhibit lower thermal decomposition temperatures and better thermal stability at high temperatures. Reducing battery chemical loss can be achieved by limiting the charge and discharge currents to avoid energy waste or damage to the battery caused by overcharging or overdischarging.

3.2. Hybrid powertrain synergy technology

The hybrid powertrain synergy technology of electromechanical composite transmission systems is predicated on the coupling of electromechanical drive mechanisms. Central to this technology are Dynamic Coordinated Control Strategies (DCCS) [19] and Energy Management Strategies (EMS) [20]. These strategies facilitate efficient propulsion through the deep integration of mechanical and electronic control systems.

The steady-state control of electromechanical composite transmission systems, specifically Energy Management Strategies (EMS), primarily manages the torque distribution between the motor and the engine, as well as the power balance of the battery [20]. Existing strategies are often based on deterministic rules (such as threshold control), global optimization algorithms (e.g., dynamic

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programming DP), or instantaneous optimization algorithms (e.g., Equivalent Consumption Minimization Strategy ECMS). To improve the energy utilization efficiency of the EMS system, QI, YUNLONG et al. [21] employed a Model Predictive Control (MPC)-based coordination controller for power-split HEVs. By linearizing the nonlinear components in the transmission model and applying a rapid MPC approach to reduce the online computational workload, simulation and experimental results demonstrated that this method effectively enhanced fuel economy and driving performance.

However, these strategies are typically based on single operating condition assumptions, neglecting the dynamic characteristics of transmission components such as clutches and planetary gears (e.g., clutch slip loss, gear coupling inertia). This leads to difficulties in balancing energy distribution and component life optimization under real-world complex operating conditions, requiring the intervention of a multi-power source dynamic coordination control system (DCCS) when operating conditions change. When these power sources are coupled through devices such as clutches and planetary gears, asynchronous response results in torque fluctuations at the wheel end, causing longitudinal shocks to the vehicle body, resonance in the drivetrain, and even power interruption [22]. Therefore, the goal of DCCS is not to achieve rapid tracking by a single power source, but to minimize the composite torque fluctuations during the switching process. HONG JINLONG et al. [23] proposed a three-step nonlinear method to improve engine speed tracking accuracy based on the above concept, integrating steady-state, reference trajectory dynamics, and tracking error information. At the cost of sacrificing intake manifold pressure tracking performance, this approach ensures the asymptotic convergence of engine speed tracking errors, reduces shift time, and improves vehicle acceleration. SHI, DH et al. [22] addressed the issue of multi-clutch power-split HEV mode switching control by constructing a matrix-type powertrain model and analyzing the effects of clutch engagement timing and slip duration on switching characteristics. LIN, YP et al. [24] proposed a coordinated control strategy between clutch pressure, motor torque, and engine torque, and the results demonstrated that the variation rates of determined clutch pressure, motor torque, and engine torque can be effectively coordinated to meet the vehicle’s performance requirements during engine startup.

In summary, the hybrid powertrain collaborative drive technology enhances the energy utilization efficiency and overall performance of electromechanical composite transmission systems under complex operating conditions through the coupling of electromechanical composite transmission mechanisms and the integration of multi-power source dynamic coordination control with energy management strategies.

3.3. Intelligent control technology

Optimizing the control strategy of electromechanical composite transmission systems is crucial for improving the energy utilization efficiency of hybrid electric vehicles (HEVs). The control strategies for electromechanical composite transmission systems can be categorized into rule-based control strategies, Equivalent Consumption Minimization Strategy (ECMS), Dynamic Programming (DP), Model Predictive Control (MPC), Reinforcement Learning (RL), and Deep Reinforcement Learning (DRL), among others.

Rule-based control strategies are among the earliest developed and applied control methods for hybrid power systems. These strategies manage the vehicle's various operating modes through a set of predefined rules. They offer significant advantages in terms of computational speed and ease of establishment; however, the fixed rules often do not provide the optimal control solution and require integration with other algorithms for optimization [25, 26] to achieve better control performance.

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The ECMS is a rule-based approach that achieves real-time solutions by transforming a global optimization problem into a local cost function. This method has a significantly lower computational cost compared to DP, but since it uses single-step optimization, its solution is only locally optimal, and its control performance is inferior to that of DP. Extensive and in-depth research has been conducted on ECMS [27]. DP is a model-based algorithm capable of providing a global optimal solution. However, it requires the construction of a discrete-time dynamic system and a cost function, resulting in high computational demands. Moreover, since DP requires predefined speed curves, it is difficult to apply in real-time applications [7]. DP is widely used in the development of EMS for HEVs [28]. MPC is a control strategy that uses multi-step optimization. It excels in real-time optimization but is model-dependent, necessitating the use of reduced-order models in analysis, which prevents it from achieving a global optimal solution [29]. Therefore, it requires proper integration with algorithms such as DP or DRL to improve control accuracy [30].

RL methods are developed based on the Markov Decision Process (MDP), which assumes that the future state is influenced only by the current state and not by any preceding states. Similar to humans, RL agents interact directly with the surrounding environment, exchanging information about states, rewards, and actions during the interaction process. The agent uses this exchanged information to learn decision-making, aiming to maximize long-term cumulative rewards, and approximates global optimization using the Bellman equation. In Energy Management Systems (EMS), control algorithms based on reinforcement learning offer specific advantages over traditional techniques: they provide more accurate results compared to rule-based control strategies [31]; they significantly reduce computational time and cost compared to dynamic programming techniques [32], and can operate in real time; their model-free operation eliminates the dependency on reduced-order models in the ECMS and MPC, thus approximating global optimal results and exhibiting optimality similar to dynamic programming [33]. However, this method also faces challenges such as long learning times, which affect practical deployment efficiency, and insufficient adaptability. Therefore, it requires integration with technologies such as MPC and EMS frameworks to reduce learning time and improve robustness [34]. DRL combines Deep Learning (DL) and RL by using Deep Neural Networks (DNNs) to approximate value functions or policy functions, thereby overcoming the limitations of table-based methods in traditional reinforcement learning. DRL can handle more complex systems and larger datasets. The core idea of DRL is to leverage the powerful representation capabilities of deep learning to process high-dimensional state and action spaces, providing significant advantages in terms of real-time performance, model complexity, and optimality. The application of DRL in hybrid power systems has garnered widespread attention in recent years. For example, the framework developed in [35] based on deep reinforcement learning improved the fuel economy of HEVs by 7.1% compared to deep Q-learning. The double deep Q-learning method in [36] achieved fuel economy close to the global optimal DP in hybrid tracked vehicles, with only a 3.5% decrease, significantly reducing computational costs while ensuring control effectiveness, thereby improving real-time performance.

4. Conclusion

This paper conducts an in-depth study on the application of electromechanical composite transmission (EMT) systems in intelligent vehicles. Against the backdrop of the "dual carbon" goals and the development of intelligent vehicle technologies, the paper systematically analyzes the architectural characteristics, current applications, key technologies, and challenges of EMT systems. The main contributions of the work are as follows:

(1) A detailed discussion of the technical characteristics and application scenarios of three EMT system architectures: series, parallel, and hybrid configurations. It is pointed out that hybrid configurations have become mainstream due to their high efficiency and flexibility (e.g., Toyota THS, BYD DM-i), although their structural complexity presents challenges in control and cost. The core research directions are identified as improving energy utilization efficiency, smoothness, and reducing costs.

(2) A review of the technological progress in lightweight materials (such as aluminum-magnesium alloys, carbon fiber), hybrid powertrain coordination control (multi-power source dynamic coordination and energy management), and intelligent control algorithms (such as MPC, reinforcement learning), providing pathways for system performance optimization.

(3) Identification of the core challenges of EMT systems in terms of reliability, cost control, and intelligent control. A solution that integrates material innovation, structural optimization, and algorithmic coordination is proposed, along with an outlook on its potential applications in military, special vehicles, and intelligent electric vehicles.

In summary, electromechanical composite transmission systems have made significant progress in the field of intelligent vehicles but still face numerous critical challenges. In terms of reliability, harsh operating conditions and high dynamic loads have a significant impact on system reliability. Future research should focus on studying the failure modes of the system in complex environments, utilizing advanced materials and manufacturing processes to enhance the performance of key components, and introducing intelligent monitoring and fault diagnosis technologies to enable early fault warning and precise localization, ensuring stable system operation. In cost control, the complex structure of hybrid systems results in high costs. Subsequent research should focus on simplifying system structures, optimizing component designs and integration, reducing costs through mass production, and exploring new low-cost materials and technologies to reduce manufacturing costs without compromising performance. In the field of intelligent control, existing control strategies each have their strengths and weaknesses. Future research should integrate multiple control algorithms to fully exploit the advantages of different algorithms, creating a more intelligent and adaptive control system. In-depth studies on the effects of driver behavior, road conditions, and other factors on the system are needed, so that control strategies can more accurately match actual driving scenarios, thereby improving the system's overall performance.

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