A REVIEW ON THE DEVELOPMENT STATUS AND TRENDS OF KEY TECHNOLOGIES FOR HYBRID TRACTORS
/
混合动力拖拉机关键技术发展现状及趋势综述

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ABSTRACT
Driven by global agricultural mechanization and green low-carbon transformation, hybrid tractors have become a key focus in agricultural machinery competition due to fuel economy and operational adaptability. Using literature review and comparative analysis, this paper summarizes global and domestic technological development and characteristics of typical models. It analyzes three core power topological structures, compares energy configurations and management strategies, clarifies applicable scenarios and pros and cons of different routes, and points out bottlenecks in power coupling, energy storage and control, as well as industrial dilemmas like high costs and poor supporting facilities.

摘要
在全球农业机械化与绿色低碳转型的双重驱动下，混合动力拖拉机凭借其燃油经济性与作业适应性优势，成为全球农机技术竞争的焦点。为厘清混合动力拖拉机关键技术的发展现状与现存问题，为该领域技术的进一步优化和规模化推广提供参考，本文采用文献梳理与对比分析的方法，系统归纳了该领域国内外技术发展格局与代表机型技术特征，深入剖析了三类核心动力拓扑结构的工作原理与性能差异，对比了不同能量源配置方案、能量管理策略的应用效果与验证方法。研究明确了各类技术路线的适用场景与优劣势，指出了当前该领域在动力耦合、储能系统、控制策略方面的研发瓶颈，以及成本、配套设施等产业化应用难题。

INTRODUCTION
Currently, global agriculture is transforming toward industrial model upgrading and sustainable development, and the problems of high emissions and high energy consumption commonly existing in traditional agricultural machinery have become increasingly prominent. As the core power equipment in agricultural production, the energy consumption control and emission management of tractors have become critical to industrial development. Pure electric tractors are limited by shortcomings such as insufficient horsepower, short endurance and operating time, and poor environmental adaptability, and it will take time to overcome these problems. Against this background, hybrid tractors, which integrate traditional fuel power and electric power and realize collaborative energy distribution through a power coupling system, have become a key transitional technology. With remarkable effects on energy conservation and emission reduction as well as great potential for improving operational efficiency, they also represent an important direction for the iterative upgrading of agricultural machinery and equipment. Policies from various countries have gradually increased support. China's 14th Five-Year Plan clearly includes high-end intelligent and new energy agricultural machinery in key supported areas, creating a favorable environment for the technical research and development and industrialization of hybrid tractors (*Yin et al., 2025*).

At present, the technology of hybrid tractors has formed a diversified pattern with three mainstream technical routes, namely series hybrid, parallel hybrid and series-parallel hybrid, developing in parallel. Meanwhile, energy management strategies have gradually evolved from rule-based control to optimization algorithms and intelligent strategies, which has become a current research hotspot. Nevertheless, this field still faces core controversial issues and technical bottlenecks as follows: the low collaborative efficiency of the power coupling system restricts the performance improvement of the whole machine.

The excessively high cost of power batteries leads to the high price of the complete machine, affecting its market promotion; energy management strategies are highly complex and difficult to adapt to diverse operating scenarios, and their stability and reliability need to be further enhanced. These problems jointly hinder the industrialization process of hybrid tractors, and further exploration in technological breakthroughs and path optimization is required to realize their large-scale application (*Li, 2026*). Current reviews of hybrid tractors only discuss individual technologies (topology or energy management) without systematic comparisons across the full technical chain: topology, coupling, components, strategies and configurations. Most reviews focus on regional research rather than establishing a global framework covering European, North American and Asian technical routes, and seldom summarize core debates and industrial limitations from practical engineering cases.

This paper reviews global advances in hybrid tractor technologies, compares three typical topologies and various energy management schemes, identifies industrialization barriers and technical disputes, and predicts future trends to offer systematic support for further research and engineering implementation.

The objective of this review is to systematically analyze the technical routes, key bottlenecks, and development trends of hybrid tractors, aiming to provide a reference for their performance optimization and industrial promotion.

Development Background and Driving Forces

Agricultural machinery, as an important part of non-road mobile machinery, has attracted increasing attention concerning its emission problems. Traditional agricultural tractors are usually equipped with oversized diesel engines and emit large quantities of pollutants and carbon dioxide during field operation. Studies have shown that agricultural machinery and equipment are among the major contributors to emissions in the agricultural sector. This situation runs counter to the trend of global sustainable development, prompting various countries to pursue more environmentally friendly power solutions for agricultural applications[Error! Reference source not found.].

Policy-driven support serves as a critical impetus for the development of hybrid tractors. The key special project on Key Technologies for Factory Agriculture and Intelligent Agricultural Machinery Equipment implemented under China's 14th Five-Year Plan has accelerated the research, development and industrial application of high-end intelligent agricultural power equipment. The Agricultural Mechanization Station of the Ministry of Agriculture and Rural Affairs has provided clear directional guidance for the industry by organizing technical seminars on the test and appraisal of power machinery, focusing on technological innovation and test certification of new energy agricultural machinery and equipment. The field trials and verification of new energy and high-end intelligent tractors carried out in Tacheng, Xinjiang in 2025 systematically assessed key indicators including product reliability and operating efficiency, providing an important basis for technological optimization and industrialization of such equipment [Error! Reference source not found.].

Market demand is also a key factor in the development of hybrid tractors. With the increase in the number of large-scale farms, the demand for hybrid tractors—agricultural machinery featuring high efficiency and low operating costs—is growing steadily, as shown in Figure 1 and Figure 2.

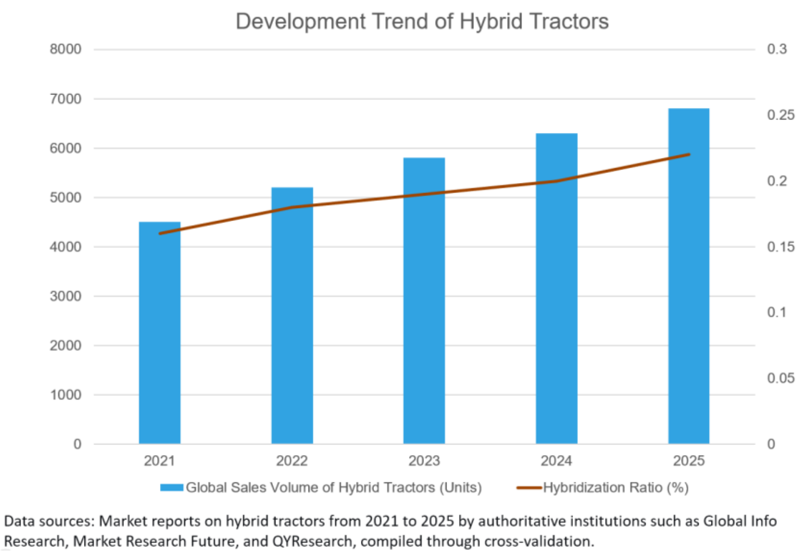
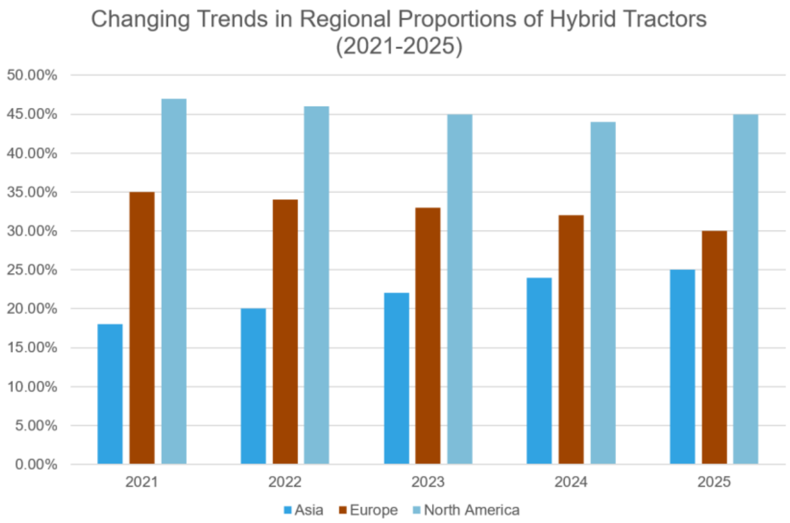


Fig. 1 - Development Trends of Hybrid Tractors



Data sources: 2021–2025 hybrid tractor market reports from authoritative institutions including Global Info Research, Market Research Future, and QYResearch, collated through cross-validation.

Fig. 2 - Trend of Regional Proportion Change of Hybrid Tractors

Taking the world's largest hybrid wheeled tractor launched by Zoomlion as an example, it is specially designed for high-intensity and high-efficiency operations in ultra-large-scale farms. It can achieve a continuous operating area of 7,200 mu within 12 hours, with a 15% improvement in operating efficiency and a 10% reduction in fuel consumption. Such remarkable performance advantages endow it with strong competitiveness in the international market. This high-quality agricultural machinery equipped with cutting-edge technology can effectively solve the pain points of modern agriculture (*Han, 2023*).

Development History

Since the 19th century, the development of hybrid tractors has gradually realized the leap from conceptual prototype to commercial explosion, as shown in Table 1. From the hybrid system combining steam and internal combustion engines, to the research and development of modern hybrid technologies, and then to the formation of a multi-architecture product matrix, it indicates that hybrid power technology has become increasingly mature (*Niu, 2025; Wen et al., 2025*).

Table 1

The Development History of Hybrid Tractors

Stage	Time Range	Core Progress	Representative Events
Technical Embryonic Stage	1970s–1999	Integration of steam and internal combustion engines, accumulation of hydraulic transmission technology.	1970s: US initiated research on hybrid power for construction and agricultural machinery; 1997: John Deere launched the world's first hybrid tractor prototype.
Exploration Stage	2000-2016	European and American enterprises launched research and development of modern hybrid power technology.	India's ITL launched commercial prototypes.
Independent Innovation Stage	2017-2024	Domestic enterprises broke through core technologies and broke the foreign monopoly.	Yuchai IE-POWER powertrain was implemented; LiuGong 350 hp-class hybrid models were mass-produced.
Commercial Explosion Stage	From 2025	Formation of a multi-architecture product matrix and implementation of policy subsidies.	Zoomlion series-parallel hybrid models were mass-produced; special subsidies were implemented in Jiangsu and other regions.

Stage Achievements

A number of iconic prototype models have emerged in the field of hybrid tractors at present, with major breakthroughs achieved in core performance. A collaborative development pattern of multiple configurations has been formed, and a complete industrial ecosystem centered on "configuration innovation — control optimization — independent component development — standard support" has been gradually built, driving the industry to achieve leapfrog development.

Hybrid configurations have become the mainstream direction for heavy-duty hybrid tractor models. The hydraulic-electric hybrid configuration based on HMCVT (Hydromechanical Continuously Variable Transmission) enables efficient power transmission. HMCVT transmits power in parallel through dual flows, namely the hydraulic branch and the mechanical branch, and its overall efficiency depends on the synergistic cooperation between the two branches. The hydraulic branch, i.e., the pump-motor system, features relatively low efficiency (generally 60% to 80%), while the mechanical branch boasts high efficiency (up to over 95%). The overall transmission efficiency of the system is improved by optimizing the power split ratio between the two branches *(Wang, 2018; Xu et al., 2012*).

Currently, a virtuous cycle has taken shape among policy subsidies, technological R&D, production and manufacturing, and market application, laying a solid foundation for the sustainable development of the hybrid tractor industry. It has driven the sector to achieve leapfrog development, gradually shifting from "foreign technological monopoly" to "domestic independent innovation" and from "single-point demonstration application" to "full scenario coverage".

Research Progress Abroad

Research progress on hybrid tractors varies in different regions abroad, with characteristic technical routes formed in accordance with local farming scenarios, accompanied by high technical maturity and industrialization levels.

North America focuses on high-horsepower models, with power-split hybrid technology as the core, featuring mature commercialization and comprehensive experimental data, which are suitable for large-scale farming. As shown in Figure 3(a), studies on the American John Deere 8R 410 Hybrid series-parallel power-split tractor demonstrate that control strategies such as MPC are adopted to improve energy efficiency. The Case NH Puma Hybrid series has a rated power of 250 kW and a comprehensive fuel-saving rate of 24%, and has been put into large-scale batch production (*Zhou et al., 2024; Wang et al., 2025*).

In Europe, plug-in hybrid technology serves as the core, with emphasis on multi-energy coupling to adapt to diverse low-carbon operating scenarios. As shown in Figure 3(b), the Italian Antonio Carraro SRX Hybrid, a parallel-torque-coupled hybrid tractor, integrates a 55 kW Stage 5 internal combustion engine and a 20 kW electric motor. It supports multiple operating modes including pure electric, hybrid, energy recovery, and power assist, and features a compact articulated narrow body for flexible orchard operations. It combines the advantages of fuel saving and low emissions, and is also integrated with an Industry 4.0 intelligent control system to achieve high efficiency, environmental protection, and operational stability. In 2019, Germany's Fendt launched the X concept series, a series hybrid tractor without energy storage devices, as illustrated in Figure 3(c). Figure 3(d) presents the series-parallel hybrid topology adopted by Austria's STEYR, with a peak power of 250 kW. This model achieves a maximum gradeability of 35° and a fuel saving rate of 25% in tests conducted in the Alpine region. Relevant studies also indicate that control strategies such as MPC are employed (*Wang, 2024; Varlese et al., 2025*).

Relying on their technological advantages in small and medium-horsepower models, Japan and South Korea focus on research and development in this field, promoting the integration of electrification and intelligence to adapt to small-scale and refined farming operations. Some scholars have carried out relevant experimental verifications, laying a foundation for industrialization (*Xu, 2021*).

Research Progress in China

In recent years, the hybrid tractor industry in China has developed rapidly. A number of leading enterprises, including China YTO Group Corporation, Yuchai Group and Zoomlion Heavy Industry, have launched a variety of innovative products suitable for different scenarios, achieving breakthroughs in high-horsepower models, small and medium-sized facility horticulture models and other fields. For example, more than 20 types of power equipment were displayed at the on-site demonstration of high-end intelligent agricultural power equipment held in Yangling, Shaanxi Province in 2025, highlighting the progress of China in this field.

As a leading enterprise in China's agricultural machinery industry, China YTO Group launched the Dongfanghong HB 2204 series hybrid tractor in 2022, which is equipped with a 161.7 kW China IV diesel engine and an Electric Continuously Variable Transmission (E-CVT) system, with a localization rate of over 85%. Field tests conducted in the corn planting area of Zhoukou, Henan Province show that this model has a plowing fuel consumption of 15.2 L/h, which is 23% lower than that of traditional tractors, an operating efficiency of 6.5 hectares per hour, and a brake energy recovery efficiency of 18% (Anon., 2023). Yuchai Group boasts mature powertrain technology. As shown in Figure 3(e), the IE-POWER series hybrid powertrain released in 2021 consists of an engine, a generator, a drive motor and an electric-shift gearbox, suitable for tractors with 200–260 horsepower. Applications in the sugarcane planting areas of Guangxi show that this powertrain reduces the comprehensive fuel consumption of tractors by 10%-30%, and decreases the failure rate by 5%-30% compared with traditional transmission systems (*Anonymous, 2022*).

(a) John Deere 8R 410 Hybrid (USA) (Series-Parallel Power-Split Type, 2024)

(b) Antonio Carraro SRX Hybrid (Italy) (Parallel-Torque Coupling Type, 2018)

(c) Germany Fendt X concept series (Series Type without Energy Storage Device, 2019)

(d) STEYR Hybrid CVT Tractor (Asymmetric Power Distribution + Intelligent Coupling Control, 2023)

(e) IE-POWER Hybrid Powertrain (Centralized Electric Drive Continuously Variable Power System, 2021)

(f) "Honghu" T300 High-Power Hybrid Tractor (400 HP New Energy Intelligent Agricultural Machinery, 2022)

(g) Guangxi Liugong LT3504-CE Tractor (Conventional Series Type, 2023)

(h) SDLG T3204-7E Tractor (Series-Parallel Power-Split Type, 2024)

(i) ZOOMLION Hybrid Wheeled Tractor (Series-Parallel Hybrid Configuration, 2025)

Fig. 3 - Typical hybrid electric tractor products worldwide

SDLG Agricultural Machinery adopts the power-split technical route. Studies have shown that power-split technology transmits power through the parallel combination of hydraulic and mechanical systems, which can significantly improve transmission efficiency. Especially under medium and low-speed working conditions such as plowing, the hydraulic power split ratio can be lower than 20%, with a high proportion of mechanical transmission, and the efficiency is close to that of pure mechanical transmission (*Li et al., 2026*). In vegetable greenhouse operations in Shouguang, Shandong Province, this model features a turning radius of only 1.8 m, a gradeability of 25°, reduces comprehensive fuel consumption by 28% compared with conventional models, and is equipped with an electric output function to adapt to various agricultural implements. Zoomlion focuses on small and medium-sized hybrid tractors.

The CA504ET distributed drive model launched in 2023 has a power of 74.6 kW, adopts wheel motor differential steering with a turning radius of less than 1.5 m, and supports 1-hour fast charging. In tea planting operations in the hilly areas of Hunan Province, this model achieves a pure electric driving range of 80 km and a comprehensive energy-saving rate of 22%, making it the first facility horticulture hybrid tractor practically promoted in China (*Zhang et al., 2003*).

In addition, as shown in Figure 3(f), the 300-horsepower "Honghu" T300 pure electric intelligent tractor launched by the Chinese Academy of Sciences in 2022 is customized for black soil farmland. It adopts a pure electric drive configuration without internal combustion engine and hybrid energy storage system, achieving high efficiency and stability in power output. This design optimizes energy utilization through the hybrid power system and significantly improves continuous operation capacity, with a single operation duration of up to 10 hours and an operation efficiency of 12 hectares per hour, representing an efficiency improvement of approximately 30% compared with traditional models. This indicates that China has joined the ranks of international advanced levels in the field of high-power pure electric intelligent tractors (*Ren et al., 2022*).

Notably, although some domestic models have achieved a high localization rate, China still has weak independent research and development capabilities for high-end core components, whose performance indicators lag behind international advanced levels, leading to high import dependence. This has become the primary bottleneck restricting the development of the industry. The constraints are mainly concentrated in core modules of high-end Electric Continuously Variable Transmission (E-CVT), high-performance motor controllers, special sensors and other fields (*Mocera, 2020*). Compared with the independently developed CVT gearboxes of international brands with a transmission efficiency of over 95%, domestically produced E-CVT gearboxes in China still have gaps in transmission efficiency, load-bearing capacity and service life. Problems such as wear and shift shock are more likely to occur under long-term high-load operation. For high-horsepower models, the permanent magnet synchronous motors independently developed in China are inferior to international counterparts in terms of power density and heat dissipation performance. In addition, the insufficient precision manufacturing level of core components and the poor quality stability of basic parts such as high-end bearings and seals also contribute to the performance gaps (*Wu, 2019; Huang et al., 2025*).

On the other hand, compared with the intelligent optimization algorithms widely adopted internationally, such as Model Predictive Control (MPC) and Equivalent Consumption Minimization Strategy (ECMS), most enterprises in China still apply simple logic threshold control strategies, which can only realize basic power mode switching and fail to optimize energy flow distribution in real time according to load fluctuations and varying operating scenarios in field farming (*Qiu, 2026*). For example, although the Zoomlion CA504ET model has achieved breakthroughs in pure electric range and comprehensive energy-saving rate during tea planting operations in the hilly areas of Hunan Province, the energy switching response lags under sudden load changes, resulting in partial energy waste.

Horizontal Comparison of Technical Routes for Hybrid Tractors Worldwide

As shown in Table 2, the differences in the technological development of hybrid tractors worldwide are not prominent, and several key distinctions mainly originate from variations in technological accumulation, industrial foundations, and market demands. Foreign manufacturers focus on the optimization of power-split series-parallel hybrid technology, which is adaptable to multiple horsepower ranges and operating scenarios with mature industrialization. Series, parallel, and series-parallel configurations each have their own emphases and are suitable for regional application scenarios, among which the series-parallel configuration acts as the core technology with extensive coverage of application scenarios.

The domestic technical route emphasizes practicality and presents a diversified development trend. Series and extended-range configurations represent the mainstream, parallel configurations have achieved gradual breakthroughs, and series-parallel configurations remain in the research and development (R&D) and pilot stage. Series configurations are widely applied, parallel configurations are dedicated to refined agricultural operations, and the core technologies of series-parallel configurations rely on imports, failing to realize large-scale industrialization.

In terms of energy sources, foreign countries feature a diversified pattern, with lithium-ion batteries as the primary energy source and composite energy storage as the auxiliary; new energy sources such as hydrogen fuel have already been industrialized. In China, lithium-ion batteries are the absolute mainstream, composite energy storage is in pilot application, and hydrogen fuel is still in the R&D and demonstration stage (*Hu et al., 2025*).

In terms of intelligence, foreign countries have formed a complete intelligent operation system. Combined with technologies such as intelligent algorithms and autonomous navigation, adaptive operating conditions and full life cycle management have been realized. In contrast, China is still in the basic stage, with core focus on navigation and simple operating condition switching, poor system coordination, and lack of full life cycle management functions.

At the supply chain level, foreign countries have an extremely high localization rate of core components and a complete supply chain. In China, the localization of medium and low-end components is mature, while high-end components rely on imports, resulting in polarized cost control. Overall, foreign countries focus on high-end and diversified intelligence, while China emphasizes practicality and economy. With technological breakthroughs and the improvement of the industrial chain in the future, the gap is gradually narrowing (*Yu, 2022*).

Table 2

Horizontal Comparison of Technical Routes for Hybrid Tractors Worldwide

Comparison Dimension	Foreign Status	Domestic Status	Core Differences
Topology Configuration	Dominated by series-parallel (power-split) configuration;	Dominated by series/extended-range configuration; series-parallel configuration is in pilot stage	Foreign countries focus on high-end development; China focuses on practicality
Energy Source	Mature industrialization application of Lithium-ion battery + hybrid energy storage + hydrogen fuel	Lithium-ion battery as the main energy source, hybrid energy storage in pilot application; hydrogen fuel in R&D stage	Diversified energy sources abroad; single energy type in China
Intelligence Level	MPC/ECMS algorithms + autonomous navigation + remote diagnosis	Basic navigation + logic threshold control	Mature system collaboration abroad; domestic intelligence at basic stage
Localization Rate of Core Components	Localization rate of core components ≥ 95%	Independent production for medium and low-end components; 15%–30% of high-end components imported	Complete supply chain abroad; domestic high-end components rely on imports

Multi-Energy Coupling Mechanism

The multi-energy coupling mechanism serves as the foundation of a hybrid power system. Its core function is to coordinate, superpose, or distribute the power from different sources such as the engine and drive motor. Through three core coupling modes, it adapts to the varying load demands of tractors in different operations, ensuring smooth and efficient power output while maximizing energy utilization. The three coupling modes have clear divisions of labor and different applicable scenarios. There is no absolute superiority or inferiority among them, as all are designed to balance the overall power performance and energy efficiency of the tractor.

Power coupling is the most commonly used coupling mode. Its core logic is to superpose or distribute the output power of the engine and the drive motor, and dynamically allocate the power proportion of the two power sources according to the operating load, so as to avoid overload or inefficient operation of a single power source. The core equation is as follows:

$$P_{total} = P_{engine} \pm P_{motor} \text{ or } \tau_{output} = \tau_1 + \tau_2 \tag{1}$$

where: P_{total} is the total output power of the hybrid power system [kW];P_{engine} is the output power of the internal combustion engine [kW]; P_{motor} is the output power of the drive motor [kW]; τ_{output} is the total output torque of the hybrid power system [N·m]; τ_1 is the output torque of the internal combustion engine [N·m]; τ_2 is the output torque of the drive motor [N·m].

Its working process does not require strict synchronization of the rotational speed and torque of the power sources; power coordination is only realized through the coupling device, making it suitable for scenarios with large load fluctuations (*Wang et al., 2026*).

Speed coupling mechanisms typically employ planetary gears, differentials, or dedicated transmission devices to synthesize the speeds of the engine and motor in a fixed ratio, enabling continuously variable transmission or power splitting. In a study by Zuo Tiantian et al., Lagrange equations and dynamic models were established to analyze the differential transmission characteristics of the power coupling device for hybrid tractors, verifying the effectiveness of speed coupling mechanisms in coordinating the speeds of different power sources (*Zuo et al., 2013*). Deng Xiaoting (*Deng, 2012; Deng et al., 2026*) and his colleagues designed a test bench for parallel hybrid electric tractors. Torque and speed sensors were used to monitor the speed difference between the engine and the motor in real time, and the coupling device was adopted to realize dynamic matching, which significantly improved the transmission efficiency.

Torque coupling directly superimposes the output torque of the engine and the drive motor and transmits it to the drive wheels through a coupling device. Its core advantage is fast dynamic response, making it suitable for scenarios requiring instant high torque such as slope climbing and heavy-load starting (*Wang et al., 2026*). Its working principle is that the torques of the two power sources are directly superimposed through gear meshing, clutches and other structures, without complicated speed coordination, enabling rapid output of high torque and improving the overall power performance. Torque coupling technology resolves the contradiction between instantaneous high-torque demand and system energy efficiency through efficient coordination of multiple power sources. Future research can further explore the dynamic response optimization of electromagnetic couplers, torque distribution strategies for hybrid energy systems, and thermal management schemes for high-power-density motors (*Dong, 2026*).

Power Mode Switching Logic

Power mode switching logic serves as the control center of a hybrid power system. Its core function is to automatically or manually switch among the four primary power modes based on real-time parameters such as tractor operating conditions, load magnitude, and energy storage status, so as to realize “on-demand energy supply” and maximize energy-saving effects and operational efficiency. The switching process is smooth without power interruption, adapting to the complex operating environment in farmland. Currently, the four core power modes are: pure electric drive mode; hybrid drive mode; regenerative braking mode; and idle stop mode. The specific trigger conditions and operating states are shown in Figure 4.

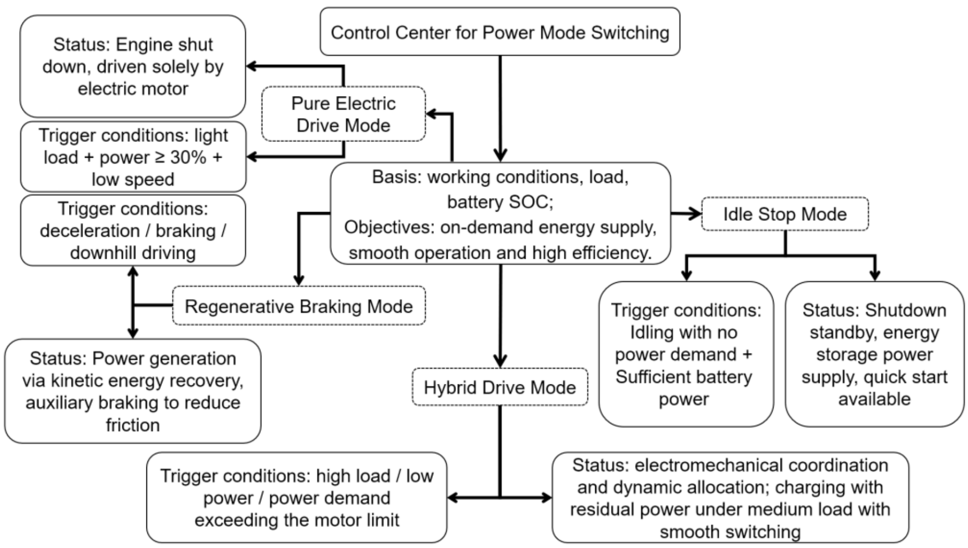


Fig. 4 - Block Diagram of Power Mode Switching Conditions and Operating States

Dynamic Regulation Principle of Energy Flow

The dynamic regulation principle of energy flow is the core of energy saving in hybrid power systems. It focuses on establishing a closed-loop mechanism of "energy recovery–storage–reuse". Through an intelligent control system, it monitors the generation, consumption and storage status of energy in real time, recovers and stores otherwise wasted energy, and redistributes it according to operational requirements, thus maximizing energy utilization efficiency.

Energy recovery marks the starting point of the closed-loop mechanism. Its core is to capture redundant energy generated during tractor operation and convert it into storable and utilizable electric energy, which mainly includes two types of recovery scenarios. The first is braking energy recovery, corresponding to the regenerative braking mode mentioned earlier. When the tractor decelerates, brakes or travels downhill, the motor operates in reverse, converting the kinetic energy of the whole machine into electric energy. The energy flow path is: Kinetic energy → Motor (generator mode) → Electric energy → Energy storage device. This is the primary scenario for energy recovery (*Wang et al., 2023*). The second is excess engine power recovery.

When the tractor operates under medium load, the engine maintains a high-efficiency speed range, and the part of output power exceeding the operational demand drives the generator to produce electricity, recovering the excess power and avoiding energy waste.

Energy storage acts as the core hub of the closed-loop mechanism. Its key lies in classified storage via different energy storage devices according to energy characteristics, balancing the requirements of "short-term rapid storage" and "long-term stable power supply". The mainstream storage scheme adopts a hybrid energy storage system of "hydraulic accumulator + power battery", and some high-end models are equipped with supercapacitors. Among them, hydraulic accumulators focus on short-term rapid energy storage and release, mainly storing the instantaneous large amount of energy generated during braking with fast response speed, which can quickly provide auxiliary power for high-load operations (*Wang et al., 2026*). Power batteries focus on long-term stable storage, storing electric energy recovered from excess engine power and braking, ensuring power supply for pure electric drive mode and auxiliary equipment. Supercapacitors are used for supplementary storage to improve the response speed of energy recovery and release, adapting to scenarios with frequent load fluctuations (*Ren et al., 2018*).

Energy reuse is the final stage of the closed-loop mechanism. Its core lies in rationally distributing the stored electric energy to various power components through an intelligent energy regulation system according to the real-time operational demands of the tractor, thereby achieving efficient energy utilization. It specifically includes three application scenarios:

First, driving energy supply. The stored electric energy is converted into power via the drive motor to assist the engine or independently provide power for the tractor's travel and operation, adapting to pure electric drive and hybrid drive modes.

Second, auxiliary energy supply. It supplies power to auxiliary components such as the whole-machine control system, hydraulic system, and navigation equipment, reducing energy loss caused by the engine driving the generator for power supply.

Third, emergency energy supply. When the engine malfunctions or the energy storage device has sufficient power, the pure electric drive mode can be used to complete emergency operations or field transfer, avoiding delays to the work progress (*Li et al., 2024*).

In summary, the core operating logic of a hybrid power system is as follows: it achieves power coordination through the multi-energy coupling mechanism, adapts to different operating scenarios relying on flexible power mode switching logic, and maximizes energy utilization efficiency via the closed-loop energy regulation of "recovery-storage-reuse". This ultimately fulfills the dual goals of energy conservation, consumption reduction and power performance enhancement, meeting the diverse and complex field operation demands of hybrid tractors.

Typical Structures and Extensions

The series hybrid topology, also known as the electrically coupled hybrid system, is characterized as shown in Figure 5.

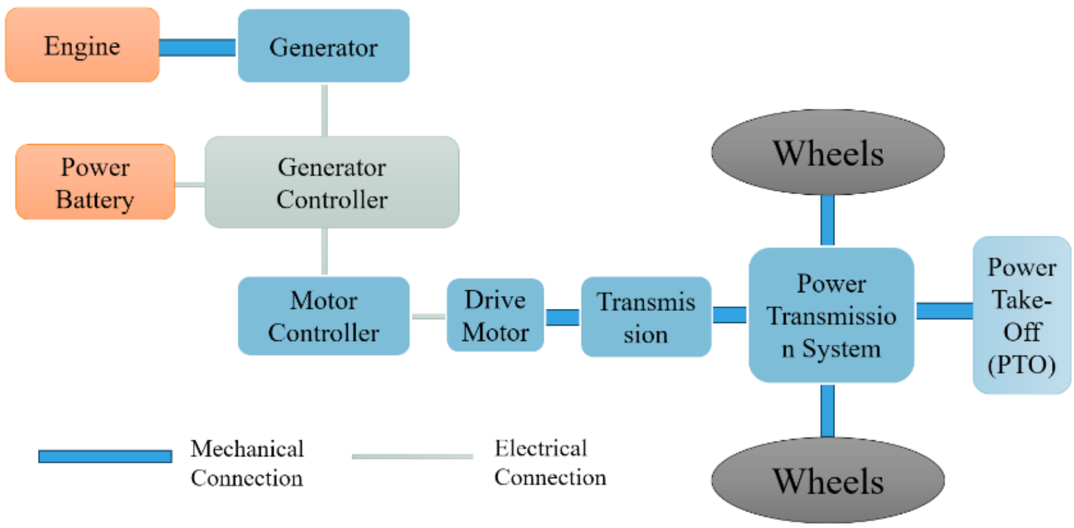


Fig. 5 - Topology Diagram of Series Hybrid Tractor Power System

There is no mechanical connection between the engine and the drive wheels; the engine directly drives the generator to produce electricity, and the electric energy is converted into mechanical energy by the motor to drive the wheels. The advantage of this structure is that the engine can always operate in its high-efficiency range regardless of actual driving conditions, thus significantly improving fuel economy. Another merit of the series configuration is the simplified transmission system. However, since energy undergoes two conversions (mechanical energy → electric energy → mechanical energy), efficiency losses may occur under certain operating conditions. Therefore, this structure is particularly suitable for working scenarios with large load fluctuations and frequent start-stop operations (*Wen et al., 2025; Luo, 2025; Lu et al., 2017*).

The parallel hybrid topology is characterized by the fact that both the engine and the motor can directly drive the wheels, with a mechanical coupling relationship between them. This structure offers the advantage of a more direct energy transfer path, avoiding losses caused by multiple conversions, resulting in higher energy efficiency especially under high-speed and steady working conditions. Parallel hybrid tractors show significant potential in energy optimal control (*Wang et al., 2020*).

Figure 6 shows a torque-coupled parallel hybrid configuration. Mechanical power from the diesel engine and power from the electric motor supplied by the power battery are combined via a torque coupler, then transmitted to the rear wheels through the transmission and final drive. Meanwhile, the transmission is also connected to the PTO, enabling independent output of working power to realize coordinated power supply for both driving and field operations.

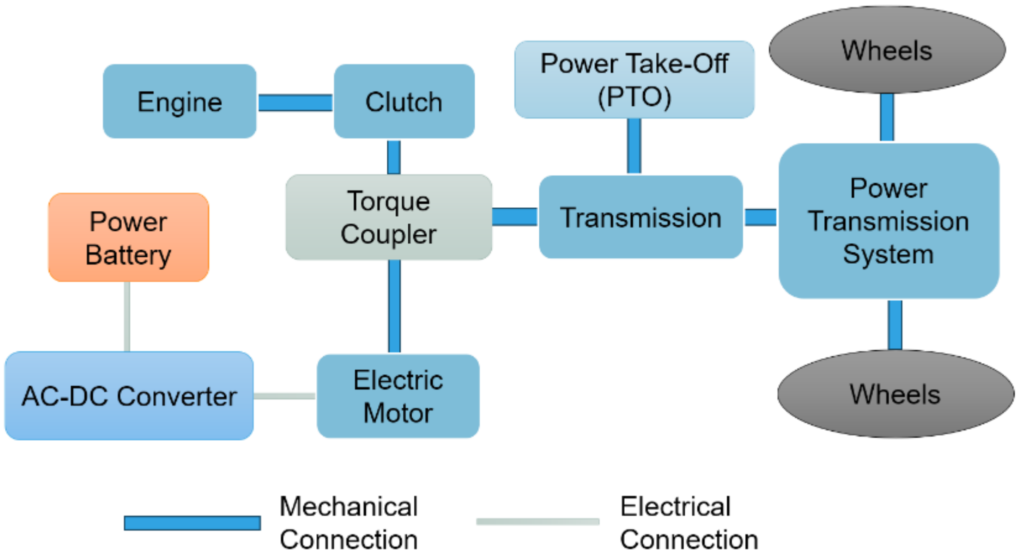


Fig. 6 - Schematic Diagram of Torque-Coupling Parallel Hybrid Powertrain Configuration

Figure 8 shows the power-split series-parallel hybrid topology, which combines the characteristics of series and parallel configurations. It can not only decouple the engine from the drive wheels, but also retain a direct mechanical drive path, enabling more flexible energy flow. This structure typically realizes power splitting via a planetary gear mechanism or complex transmission device, yet also introduces challenges of structural complexity and higher cost. Among series-parallel layouts, the planetary gear-based electric continuously variable transmission (ECVT) has become a research focus due to its multi-node and multi-power-source arrangement. ECVT often adopts a dual or triple planetary row configuration, and realizes multiple operating modes through the combination of actuators such as clutches and brakes.

For instance, in Tan Mengqi's research on the energy management strategy of a dual planetary row hybrid system, the dual planetary row hybrid powertrain was systematically designed using the equivalent tree graph method. Its tree graph representation is shown in Figure 7(a).

The configuration mainly consists of an engine (E), two motors (MG1, MG2), two planetary gear sets (S1, C1, R1) and (S2, C2, R2), two brakes (B1, B2), and three clutches (CL1, CL2, CL3), with its structural diagram shown in Figure 7(b) (*Tan, 2025*).

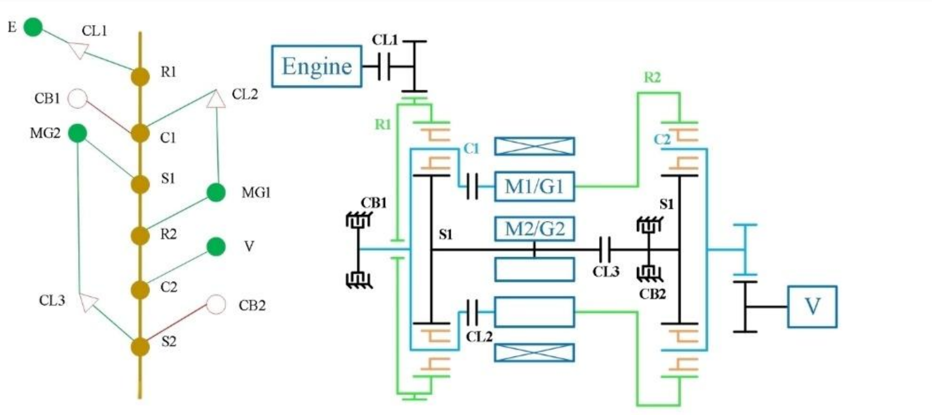


Fig. 7 - Schematic of Dual Planetary Gear Hybrid Powertrain (*Tan, 2025*)

The advantage of the series-parallel hybrid structure lies in its ability to intelligently select the optimal operating mode according to different working conditions. Under low-speed and heavy-load conditions, the system can adopt series mode to ensure the engine operates in its high-efficiency range. Under high-speed and steady working conditions, it can switch to parallel mode or direct mechanical drive mode to reduce the number of energy conversions. Under heavy-load conditions such as rapid acceleration or climbing, the engine and motor can output power simultaneously to provide maximum driving capability *(Yan, 2023)*.

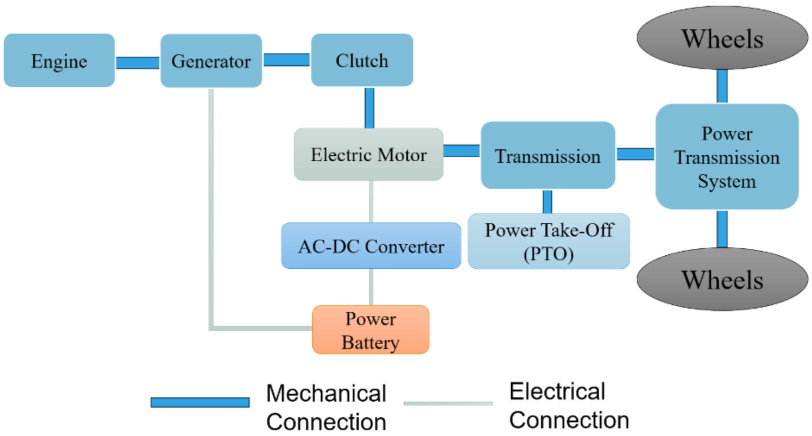


Fig. 8 - Series-Parallel Hybrid Drive Schematic

Extended topologies are optimized and extended hybrid forms based on series, parallel and series-parallel basic configurations, combined with the requirements of operating scenarios and energy-saving goals. They mainly fall into two categories: range-extended hybrid and plug-in hybrid. Both adopt the principle of "electric drive as the main, fuel as the auxiliary", but differ significantly in power transmission, energy replenishment methods and scenario adaptability. They are the mainstream extended directions for the industrial promotion of current hybrid tractors, suitable for farming conditions and infrastructure levels in different regions (*Zhao et al., 2018*).

The configuration innovation and technological extension of hybrid tractors mainly center on three core objectives, namely energy conservation and efficiency enhancement, scenario adaptability, and cost optimization. On the basis of basic topologies and extended topologies, and in combination with emerging energy storage technologies, intelligent technologies and actual field operation demands, the diversified upgrading of power configurations and cross-border extension of core technologies are realized. Meanwhile, such innovation and extension make up for the inherent shortcomings of conventional configurations, promoting the development of hybrid power systems toward high-end, diversified and adaptive trends while balancing technological advancement and engineering feasibility. Furthermore, technological extension should cover the independent localization of core components. Domestic enterprises have gradually broken through the technical bottlenecks of key components such as high-end CVT gearboxes and high-performance motor controllers, promoted the collaborative matching between core components and hybrid power configurations, and continuously reduced the dependence on imported key parts.

Performance Comparison

Based on relevant domestic and international research data, field test results of benchmark models and simulation analysis conclusions, three typical hybrid power topologies, namely the power-split type, series type and series-parallel type, present significant differences in four core dimensions: power performance, fuel economy, emission characteristics, and reliability and maintainability, making them adaptable to different operating scenarios and application demands. The performance differences, main advantages and disadvantages of the three topologies are shown in Table 3 and Table 4. In terms of comprehensive performance comparison, different hybrid power technical routes show distinct characteristics. For fuel economy, the power-split topology achieves the optimal performance, with a fuel consumption rate as low as 10.8 L/h during tillage operations and an energy-saving rate of 32%; the series topology has prominent advantages in low-speed operations, with a fuel consumption rate of 15.2 L/h during seeding operations and an energy-saving rate of 23%; the series-parallel topology features excellent multi-condition adaptability, with a comprehensive energy-saving rate of up to 28%. In terms of power performance, the series-parallel topology holds remarkable advantages: the maximum gradeability of series-parallel models can reach 35°, and the power response time is only 0.2 s, making it particularly suitable for complex hilly terrains; the power-split topology ranks second, with a power split efficiency exceeding 90% in some models and a 15% improvement in acceleration performance; while the power output of the series topology is 10% to 15% lower than that of the series-parallel topology under high-load operations. In terms of cost and reliability, the assembly price of the series topology is about 30% lower than that of the series-parallel topology, and the failure rate is reduced by 40%; the power-split topology has a 20% lower maintenance cost than the series-parallel topology due to its moderate structural complexity; the series-parallel topology has a relatively high control system failure rate owing to multi-mode switching requirements, and the failure probability of the coupling device reaches 8% after 1000 hours of continuous operation (*Tong, 2025; Liu et al., 2018; Liu et al., 2025*). Hybrid tractor schemes rely on industry, supply chains and markets instead of mere performance. Series topology suits domestic mass production for low R&D costs. Power-split series-parallel types excel in Western high-power tractors. For hilly and greenhouse farms, simple series/parallel structures are more cost-effective.

Table 3

Comparison of Performance Indicators for Different Hybrid Powertrain Configurations

Performance Indicators	Series Type	Power-Split Type	Series-Parallel Type
Fuel consumption rate (L/h, plowing condition)	15.2~18.0	10.5~12.8	12.0~14.5
Energy-saving rate (compared with conventional models)	20%~30%	25%~35%	22%~32%
Power response time (s)	0.2~0.4	0.1~0.2	0.15~0.3
Maximum gradeability (°)	25~30	30~35	32~38
Structural complexity	Low	Medium	High
Manufacturing cost (relative value)	1.0	1.3~1.5	1.4~1.6
Battery capacity requirement (kWh)	20~40	15~25	25~50
Applicable operating conditions	Long-term operation at low speeds	Continuous operation at medium and high speeds	Operation under complex working conditions

Data source: Original Strength Document "What Are the Respective Characteristics of Series and Parallel Hybrid Electric Vehicles?"

Table 4

Comparison of Characteristics for Hybrid Tractors with Different Powertrain Configurations

Drive Configu-ration	Sub - Configu-ration	Core Characteristics	Key Advantages	Main Disadvantages
Series Type	Range-extended type / General type	Load decoupling; range-extended type is dominated by pure electric drive, while the general type mainly relies on the engine-generator set.	Continuously variable transmission; simplified transmission system.	High energy conversion loss; relatively large system weight.
Parallel Type	Torque / speed / traction coupling type	Torque/speed/traction coupling; adaptable to time-varying loads and complex terrains.	Efficient engine operation; satisfactory load response; simplified transmission system.	Dependence on large-capacity batteries; high control complexity; high development cost.

Drive Configu-ration	Sub - Configu-ration	Core Characteristics	Key Advantages	Main Disadvantages
Series-Parallel Type	Series-parallel type / Power-split type	A power generation system is added on the basis of the coupling system, supporting the switching of multiple driving modes.	Multi-mode drive; maximized energy efficiency.	Complex power system; high development cost; difficult control.

Analysis of Key Component Technologies

The performance, reliability and domestic localization level of hybrid tractors mainly depend on the technical maturity of four key components: power source, energy storage system, power coupling device and electronic control system. Combined with the current industry technology status, authoritative test data and domestic localization progress, this paper systematically analyzes the detailed technical points of each component, identifies the technical bottlenecks and development directions, and explains the root causes of the performance differences among the three topologies mentioned above.

The power source is the core driving unit of hybrid tractors, which is divided into two major categories: diesel engines and new energy motors. The cooperative operation of the two determines the power output and energy-saving effect of the topology, and its technical level directly affects the operation adaptability of tractors. At present, mainstream hybrid tractors are equipped with China IV emission diesel engines, and some high-end models have been upgraded to China V emission standards. The core of the upgrade focuses on three goals: reducing emissions, improving efficiency, and adapting to hybrid collaboration. Currently, domestic diesel engines for agricultural machinery have achieved domestic localization of China IV emission technologies, but some core aftertreatment components for China V emission standards still rely on imports (*Liu, 2023*).

New energy motors constitute the core of the electric drive for hybrid tractors. The performance differences among the three mainstream motor types determine their adaptability to different topological structures and operating scenarios, as detailed below.

(1) Permanent magnet synchronous motors feature high power density, high operating efficiency, excellent speed regulation performance, and stable low-speed torque output. They are suitable for the high-frequency mode switching requirements of series-parallel and power-split topologies, and can accurately match the load fluctuations in complex hilly terrains, making them the mainstream choice for high-end hybrid tractors at present. Their shortcomings lie in the relatively high cost and the tendency of permanent magnets to demagnetize under high temperature and vibration. Additional protective structures are required when adapting to the high-dust and high-temperature field operating environment of tractors, resulting in slightly higher maintenance costs (*Lu, 2023; Zhu, 2025; Zhao et al., 2021*).

(2) Asynchronous motors feature a simple structure, high reliability, and moderate cost, with outstanding high-temperature resistance and anti-vibration performance. They are suitable for the "engine generation + motor drive" mode of series topology and can meet the continuous power output demand of long-term low-speed operation. Their shortcomings include low power density, poor low-speed efficiency, and relatively slow dynamic response, making them unsuitable for series-parallel topologies with high-frequency load fluctuations and rapid mode switching (*Gui, 2026*).

(3) Switched reluctance motors have relatively high power density, robust structure, low cost, and large starting torque, making them suitable for high-load operating scenarios. Furthermore, they have no risk of permanent magnet demagnetization and feature low maintenance costs. However, their shortcomings include complex control logic, significant noise and vibration during operation, and poor low-speed running smoothness. At present, they are mainly applied in low-end series hybrid tractors for light and medium-load operations, and have not been widely used in high-end models (*Li, 2026*).

In conventional tractors, continuously variable transmission (CVT) refers to a technology that realizes uninterrupted speed regulation of the whole machine by continuously adjusting the transmission ratio between the input and output shafts of the transmission system without changing the engine speed. In the field of hybrid tractors, this technology has been further extended to the smooth and continuous control of the whole machine's operating speed. The current mainstream technical routes include the centralized electric-drive CVT system shown in Figure 3(c), the distributed electric-drive CVT system shown in Figure 9, and the electromechanical coupling CVT system. Their technical characteristics and typical products are presented in (*Wen et al., 2025*).

(a) *STEYR Konzept Continuously Variable Transmission Power System (Wheel-Hub Electric Drive)*

(b) *John Deere eAutoPower Continuously Variable Transmission System (Electromechanical Coupling Type)*

Fig. 9 - Main Technical Characteristics and Typical Products of CVT Power System and Engine

The energy storage system serves as the core carrier for energy recovery and power compensation of hybrid tractors. It is responsible for storing energy generated by the engine and recovered via braking, and supplementing energy to the drive system under high-load conditions. Its performance directly affects the energy-saving rate and power response speed of the topology, and is mainly divided into three categories: power batteries, supercapacitors, and fuel cells.

Power battery technology functions to store surplus engine energy and braking recovery energy, providing high-energy-density supplementary energy support for electric motors. Most hybrid tractors adopt lithium-ion batteries, which feature high energy density but relatively low power density. In the single-motor drive hybrid system proposed by Wang Zhiguo et al., efficient collaboration between the internal combustion engine and the electric motor was achieved through optimized control strategies, raising the charge-discharge efficiency of power batteries to over 90%. However, the core problems of power battery technology lie in low-temperature performance attenuation and limited cycle life *(Scolaro et al., 2021, Troncon et al., 2019)*.

Supercapacitor technology is designed to compensate for the low power density of batteries and quickly respond to instantaneous load demands (e.g., tractor startup or climbing). It has a power density of 5–10 kW/kg and a charge-discharge efficiency exceeding 95%, making it suitable for frequent start-stop operating conditions. Yue Dongpeng et al. pointed out that supercapacitors in hybrid systems can realize short-term energy buffering, reduce peak current pressure on batteries, and extend their service life (*Sunil et al., 2026*). Their limitation is low energy density, requiring combined use with batteries (*Wang et al., 2026; Wang, 2015*).

Fuel cell technology, as an auxiliary power source, provides continuous electric energy output through hydrogen energy conversion, but has not yet been promoted or piloted.

The power coupling device is the core of power distribution for hybrid tractors, responsible for coupling and splitting the power of diesel engines and new energy motors to realize the switching of different power modes. Its technical bottlenecks and domestic localization progress directly restrict the performance and cost control of hybrid topologies, and are mainly divided into three categories: clutches, planetary gear sets, and electronic control couplers.

The electronic control system is responsible for the overall coordinated control of the power source, energy storage system, and power coupling device. It mainly consists of an Engine Control Unit (ECU), Vehicle Control Unit (VCU), and Battery Management System (BMS). The coordinated control capability, as well as the technical level of chips and algorithms, directly determines the performance and reliability of the hybrid topology.

For the coordinated control architecture of ECU/VCU/BMS, the three units form a "hierarchical control and collaborative linkage" architecture, which is the core of power mode switching and optimal energy distribution for hybrid tractors. As the main control unit, the VCU receives real-time data from the ECU, BMS, and field operation sensors, formulates optimal control strategies according to operating conditions, sends control commands for engine speed and fuel injection volume to the ECU, charge-discharge control commands to the BMS, and power distribution and mode switching commands to the power coupling device (*Sunil et al., 2026*) ; the ECU executes VCU commands, optimizes the engine operating state to ensure the engine maintains a high-efficiency speed range, and feeds back real-time engine operating data; the BMS monitors the real-time status of power batteries and supercapacitors, controls charge-discharge speed and current to prevent overcharging and over-discharging, extends the service life of energy storage components, and feeds back the energy status of the energy storage system.

At present, the coordinated control architecture of domestic hybrid tractors has achieved initial maturity and can meet basic power distribution and mode switching requirements. However, high-end models lack sufficient coordinated control accuracy and slow response speed, and the data interaction efficiency of the three units still needs to be optimized. Chips and algorithms are the core of the electronic control system and also the main technical bottleneck of domestic hybrid tractors (*Zhang, 2024; Cheng et al., 2026*).

In terms of chips, high-computing-power Microcontroller Unit (MCU) chips and power chips required for high-end ECU/VCU/BMS mainly rely on imports. Although domestic chip enterprises have launched mid-end chips, their computing power, high-temperature resistance, and vibration resistance are insufficient to meet the high-frequency control demands of high-end hybrid tractors, and they also suffer from poor stability and high failure rates. Domestic substitution of chips is currently the core development direction (*Zhang, 2024; Jing et al., 2020*).

In terms of algorithms, the core challenge lies in adaptive control algorithms for operating conditions. The field operating conditions of tractors are complex, and traditional logic threshold control algorithms can no longer meet precise control demands. Intelligent algorithms such as Model Predictive Control (MPC) and reinforcement learning are required to realize condition-adaptive power distribution and mode switching. At present, domestic enterprises are still in the research and development and testing stage of intelligent algorithms. The adaptability and stability of the algorithms are insufficient to accurately match complex field conditions, and the compatibility between algorithms, topologies, and key components is poor, resulting in the failure to fully exert the performance of some high-end hybrid tractors *(Xie et al., 2018*).

In summary, the technical maturity and domestic localization level of the four key components directly determine the performance, cost, and reliability of hybrid tractors. At present, domestic hybrid tractors have realized the localization of mid-to-low-end components, and core shortcomings are concentrated in high-end motors, electronic control chips, high-end electronic control couplers, hydrogen fuel cells and other fields. In the future, it is necessary to carry out industry-university-research collaborative research to break through core technical bottlenecks, promote the domestic substitution of key components, and optimize the collaborative compatibility of each component to support the high-quality development of the hybrid tractor industry (*Chen, 2024*).

Energy Source Configuration and Matching Strategy

The core of energy source configuration for hybrid tractors lies in the type selection and parameter matching of diesel engines and energy storage devices. Its primary objective is to adapt to complex field operating conditions and achieve a balance between dynamic performance, energy-saving efficiency and service life. Combined with industrial research and practical applications of tractor models, three mainstream technical routes have been formed at present. The following section systematically analyzes the configuration by focusing on three core aspects: the comparison between single and composite energy source configurations, parameter matching methods, and case studies of 300-horsepower-class models, in conjunction with the technical characteristics of energy storage systems *(Paciolla et al., 2024, Sayed et al., 2024)*.

Comparative Study on Single Energy Source and Composite Energy Source Configurations

The energy source configuration of hybrid tractors can be divided into two categories: the engine plus single energy storage device configuration and the hybrid energy storage configuration. Based on different theoretical foundations, they show significant differences in performance, applicable scenarios and cost control (*Zhu et al., 2025*).

The single energy source configuration, centered on "matching a single energy storage device with the engine", features a simple structure and low development difficulty, making it the mainstream basic configuration for current hybrid tractors. Most engines adopt China IV/Euro V emission diesel engines, and lithium iron phosphate batteries are preferred as power batteries, which adapt to the high-temperature and vibratory field operating environment of agricultural machinery. With a thermal runaway temperature ≥ 600 ℃, their safety performance is superior to that of ternary lithium batteries, and the battery capacity is matched to 15–50 kWh according to the horsepower class (*Liu et al., 2025*). The IE-POWER electric continuously variable transmission powertrain released by Yuchai Group adopts a series hybrid architecture, which collaborates a single energy storage device (battery) with the engine, achieving a 10%–30% improvement in operating efficiency and a 10%–30% increase in fuel saving rate (*Huang, 2021*). This configuration simplifies the transmission system layout and reduces development complexity, and is especially suitable for 200–260 HP heavy-duty tractors (*Wang, 2024*). Its core advantages include simple structure and moderate cost, adapting to light and medium-load long-term operation scenarios. The main limitation is that battery life is significantly affected by the agricultural machinery operating environment; continuous high temperature and high-frequency vibration in the field accelerate battery degradation, resulting in a short actual service life. In addition, the peak power output is limited, making it difficult to adapt to high-load scenarios such as deep tillage and heavy-load transfer.

The composite energy source configuration is an optimized upgrade based on the single configuration, with the core logic of "integrating the high energy density of power batteries and the high power density of supercapacitors". Its theoretical foundation is "energy-power dual complementarity": power batteries undertake continuous energy supply, while supercapacitors provide instantaneous power compensation and rapid energy recovery. The two cooperate to match the engine power output and achieve optimal comprehensive performance *(Song et al., 2019*). Its core advantage is balanced comprehensive performance, which not only solves the problems of insufficient peak power and short service life of the single battery configuration, but also makes up for the shortcomings of low energy density of single supercapacitors and inability to operate in pure electric mode for a long time (*Liu et al., 2019*). The main limitation is the complex structure and high cost. A special energy cooperative control strategy needs to be designed, and the parameter matching of multiple energy storage devices is difficult. The manufacturing cost is 30%–40% higher than that of the single battery configuration. At present, it is mainly used in high-end high-horsepower hybrid tractors to adapt to complex operating conditions (*Li et al., 2026, Mocera, 2021*).

In summary, the single energy source configuration focuses on "low cost and adaptation to basic working conditions", with the core advantages of simple structure and convenient maintenance, but limited comprehensive performance. The composite energy source configuration focuses on "high performance and adaptation to complex working conditions", with the core advantages of balanced power and energy saving as well as longer component service life, but suffers from high cost and complex control. The choice between the two mainly depends on the operating scenarios, horsepower requirements and cost budget. The single energy source configuration is preferred for small and medium-horsepower tractors in basic operations, while the composite energy source configuration is prioritized for high-horsepower tractors in complex working conditions.

Energy Source Parameter Matching Method

The core of energy source parameter matching lies in optimizing the parameter combination of engine power and energy storage devices (capacity and power) according to the operating condition requirements of the typical operating cycles of hybrid tractors, so as to achieve the optimization objectives of "meeting power demand, minimizing energy consumption and maximizing service life". Its core process is "operating condition modeling - target setting - parameter optimization - verification and iteration" *(Mocera et al., 2022, Pascuzzi et al., 2024, Paciolla et al., 2024)*.

Operating condition modeling is the foundation of parameter matching, which focuses on quantifying key parameters such as load characteristics, speed variations and braking frequency of the typical operating cycles of hybrid tractors through field tests and simulation analysis, and constructing an operating condition model that conforms to actual operations. At present, the mainstream modeling method in the industry is "field tests + MATLAB/Simulink simulation". Firstly, real-time data including load power, travel speed, braking time and slope variations of tractors under typical operating conditions such as plowing, rotary tillage, sowing, transfer and braking are collected by sensors, and the proportion of different operating conditions is determined based on accumulated field operation data of more than 1000 hours. Subsequently, based on the collected data, an operating condition load spectrum model is constructed to clarify the basic power demand of the engine, as well as the peak power and energy storage requirements of the energy storage device, and a power demand time series $P_{req}(t)$ is established. Key parameters include average power P_{avg}, peak power P_{max}, load factor $\eta_L = \frac{P_{avg}}{P_{max}}$, and cycle period T, which provide data support for parameter matching. During the modeling process, the particularities of agricultural machinery operations—such as large fluctuations in field loads and complex operating environments—must be emphatically considered. Therefore, environmental impact factors should be integrated into the model to avoid the disconnection between theoretical modeling and practical applications. For example, battery capacity degradation must be considered in high-temperature environments, and power redundancy should be reserved under vibratory conditions to ensure the rationality of parameter matching. Parameter matching optimization takes "maximum energy-saving rate, satisfactory power performance, longest service life, and minimum cost" as the multi-objective optimization objective. Combined with the operating data, intelligent optimization algorithms are adopted to collaboratively optimize the engine power and parameters of the energy storage device. The details are as follows:

A multi-objective optimization framework is constructed, and the objective function is established as follows:

$$\min\left\{w_1\frac{f_1}{f_{1,ref}}+w_2\frac{f_2}{f_{2,ref}}+w_3\frac{f_3}{f_{3,ref}}\right\} \tag{2}$$

where:

f_1 is the energy consumption [kwh/m]; f_2 is the battery degradation rate [%/1000 h]; f_3 is the proportion of time with insufficient power [%]; $f_{i,ref}$ are the respective reference benchmark values of the three indicators; division is performed to normalize indicators with different dimensions and magnitudes for summation. w_i is the weight coefficient, which needs to be determined using the Analytic Hierarchy Process.

Constraint conditions are set as follows:

Power constraint:

$$P_{eng}+P_{bat}\geq P_{req}(t)+\Delta P_{margin} \tag{3}$$

where:

P_{eng} is the engine output power [W], P_{bat} is the battery output/input power [W]; P_{req} is the vehicle total required power at time t (varies in real time with driving conditions) [W], ΔP_{margin} is the reserved power margin [W].

SOC boundary:

$$SOC_{min}\leq SOC(t)\leq SOC_{max} \tag{4}$$

where:

SOC is the State of Charge [%].

Engine operating range:

$$\omega_{eng}\in[\omega_{idle},\omega_{rated}] \tag{5}$$

where:

ω_{eng} is the engine rotational speed [r/min]; ω_{idle} is the minimum idle rotational speed [r/min]; ω_{rated} is the rated maximum operating rotational speed [r/min].

In terms of optimization algorithm applications, the industry currently mainly adopts intelligent optimization algorithms such as genetic algorithm and particle swarm optimization. Combined with Simulink simulation models, multi-objective optimization is performed on the parameters of engines and energy storage devices, and parameter combinations are iteratively optimized to finally determine the optimal matching scheme (*Liu et al., 2017; Li et al., 2025; Zhang et al., 2025*).

In summary, the core of energy source configuration for hybrid tractors lies in "operating condition adaptation, parameter optimization, and type matching". The single energy source configuration is suitable for basic operations and cost control, while the composite energy source configuration adapts to complex working conditions and improves comprehensive performance. The parameter matching method based on operating condition modeling and intelligent optimization algorithms can achieve the optimal balance of energy source configuration. Case studies of 300-horsepower-class models show that the hybrid energy storage configuration represents the development trend of high-end models, but the bottlenecks of cost and control complexity need to be broken through. Meanwhile, the technical characteristics of the energy storage system directly affect the selection and performance of energy source configuration. In the future, it is necessary to further optimize the performance of energy storage devices, promote the collaborative upgrading of energy source configuration with topological structures and electronic control systems, and support the high-end development of the hybrid tractor industry.

Research Progress of Typical Energy Management Strategies

For hybrid electric vehicles, there are generally two or more power sources. Therefore, it is necessary to design reasonable energy management strategies according to the power demand under different road conditions and rationally distribute the output power of each power source to achieve the optimal control objectives. At present, domestic and foreign research on energy management strategies for hybrid power systems mainly focuses on the fields of automobiles and buses. Existing multi-energy energy management strategies can be mainly divided into three categories (*Gao, 2024*), as shown in Figure 10.

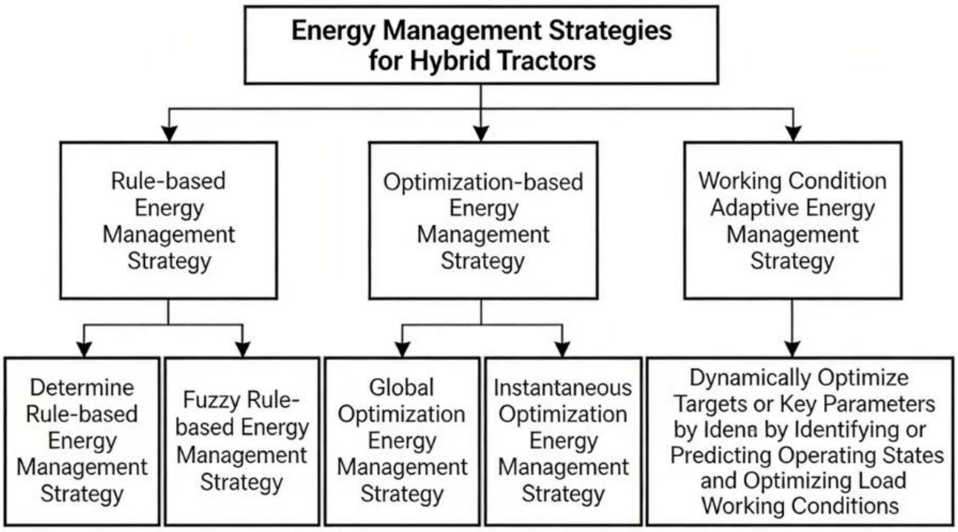


Fig. 10 - Classification of EMS for Hybrid Tractors

Rule-based energy management strategies can be divided into deterministic rule-based strategies and fuzzy rule-based strategies. Deterministic rule-based strategies predefine control rules based on engineering experience or expert knowledge to realize power distribution among multiple power sources. They are simple, practical and highly implementable, with representative ones including state machine strategy, power-following control rules and thermostat control rules. Unlike the simple switching thresholds of deterministic rule-based strategies, fuzzy rule-based strategies are a nonlinear control technology formed by combining fuzzy mathematics and mathematical logic. They can predict future driving states through fuzzy logic inference based on known driving states, exhibiting strong robustness (*Yao et al., 2023;*).

Ding Axin et al. (*2021*) used dynamic programming energy management strategy to obtain the optimal energy distribution results for a fuel cell/battery hybrid power system, and on this basis, designed an improved state machine energy management strategy. Simulation results showed that the strategy can realize real-time control and effectively reduce the system hydrogen consumption.

Chen X.R. et al. (2022) proposed an external energy efficiency maximization strategy based on power decoupling for the fuel cell + battery architecture, and compared it with traditional control strategies. The results showed that the proposed strategy can meet the power demand of ships under typical working conditions, effectively reduce hydrogen fuel consumption, improve battery utilization, and enable efficient operation of the entire system.

Fei Peng et al. (2017) further proposed a processing compensation strategy based on fuzzy logic hysteresis state machine and differential power strategy, which improved the dynamic coordination efficiency of the hybrid system and increased fuel efficiency by 7%.

Optimization-based management strategies achieve optimal system control under preset constraints, and can be mainly divided into global optimization control and instantaneous optimization control. The former takes a given driving cycle as the premise and conducts global search optimization analysis combined with modern optimization algorithms and control theory, mainly including dynamic programming control, stochastic dynamic programming, etc. The latter takes a certain working condition and driving state as the optimization interval, establishes an objective function to minimize fuel consumption in this interval, and optimizes the system energy distribution in real time online. Compared with the former, it can realize real-time dynamic optimization, mainly including Pontryagin's Minimum Principle, Equivalent Consumption Minimization Strategy, etc. (*Wang et al., 2022*).

Dima Fares et al. (2015) proposed an offline optimization algorithm based on weighted improved dynamic programming, combined with online optimization using a PID controller. The results showed that the algorithm converges faster than the ordinary dynamic programming algorithm and achieves higher fuel economy compared with rule-based algorithms. *Peng et al. (2021)* proposed an offline optimal energy management strategy combining Pontryagin's Minimum Principle and dynamic programming, and introduced a damping coefficient into the cost function, which effectively reduced the dynamic fluctuation of fuel cell output power. The feasibility of the strategy was verified through experiments.

Ding Chenguang et al. (2026) innovatively proposed an energy management strategy based on frequency division decoupling. The strategy aims to design a low-pass filtering algorithm, enabling the fuel cell to provide the main power output and low-frequency fluctuating power, while the lithium battery recovers braking energy and provides high-frequency fluctuating power. The effectiveness of the strategy was verified under Chinese urban bus driving cycles and actual bus operating conditions. In addition, with the rapid development of the automotive manufacturing industry, some control strategies based on intelligent algorithms have been applied to the energy management of hybrid power systems, typically including machine learning, artificial neural networks and model predictive control. Such strategies are relatively complex and difficult to implement, but are of far-reaching significance for in-depth research and innovation in the automotive field. *Chen Zeyu et al.* (*2022*) proposed an energy management strategy based on deep reinforcement learning, which determines the optimal variable power through the deep deterministic policy gradient algorithm. The effectiveness of the strategy was verified by real-vehicle tests and comparison with the particle swarm optimization strategy (*Kebriaei et al., 2015*).

Huang Zhenzhen et al. (*2021*) designed an online multi-objective energy management strategy for fuel cell vehicles based on BP neural network. The strategy trained simulation datasets obtained based on Pontryagin's Minimum Principle to establish neural network sub-models, and combined the obtained sub-models into a multi-neural network model. Finally, the feasibility of the strategy was verified through online software simulation and hardware-in-the-loop simulation tests respectively.

Li X. et al. (2019) proposed an energy management strategy based on explicit model predictive control, formulated the optimal control problem as a multi-parameter quadratic programming optimization problem, and realized real-time control by solving the multi-parameter quadratic programming problem offline, which effectively improved fuel economy and reduced online computation time.

Gao Zhi et al. (2024) conducted research on the energy management strategy of a fuel cell tractor hybrid power system. Taking a hydrogen fuel cell hybrid tractor as the research object, they determined the fuel cell/lithium battery/supercapacitor three-power-source topology, completed component selection and matching, and built a simulation model. The EEMS strategy was designed and compared with SMC and ECMS. Hardware-in-the-loop test verification showed that EEMS can ensure stable system operation, significantly reduce hydrogen consumption, and alleviate power impact on the fuel cell.

Through the analysis of existing literature, it can be found that although rule-based energy management strategies are simple, effective and easy to implement, they rely on given expert experience or rules, are difficult to adapt to real-time dynamic working conditions, and cannot guarantee optimal control of the hybrid system. Although optimization-based control strategies have outstanding theoretical performance, can maximize the optimization of hybrid systems and improve system performance and fuel economy, they have high requirements for hardware and control accuracy, and require long computation time, resulting in high production costs and difficulty in practical application. Some literatures also fail to consider field interference factors, leading to limitations in test results. Future development directions need to expand multi-field working conditions, optimize the real-time performance of EEMS to promote engineering application, improve system reliability with intelligent algorithms, and perfect the test system to adapt to actual field scenarios. Hybrid tractor energy management strategies mostly adopt road vehicle frameworks, poorly adapting to violent, irregular field operation loads. Dynamic programming is hard to engineer; MPC faces high hardware cost barriers; widely used rule-based strategies have limited energy-saving potential. Balancing accuracy, cost and adaptability is the core challenge (*Brudeli G et al.,2026*).

Research Review on Strategy Optimization Directions

The core of the energy management strategy for hybrid tractors is to dynamically allocate the power output of the engine and motor, and maintain the stability of the battery State of Charge (SOC) to achieve optimal fuel economy (*Wang et al., 2015*).

Strategies that allocate power based on preset logical rules mainly include the thermostat strategy and the power-following strategy. Among them, the thermostat strategy sets an SOC threshold range of 30%-70%: the engine starts to generate electricity when the SOC is below the threshold, and the system switches to pure electric drive when the SOC exceeds the threshold. The power-following strategy dynamically adjusts the engine output according to the real-time power demand of the tractor, enabling the engine to match real-time load fluctuations (*Dobretsov et al., 2024*).

Optimization strategies with minimum fuel consumption as the objective function optimize power distribution through algorithms, including dynamic programming (which solves the optimal solution based on global operating condition information and serves as an offline optimization benchmark), model predictive control (which realizes real-time control relying on receding horizon optimization), and nonlinear programming genetic algorithm (which optimizes key parameters via genetic algorithm to improve control accuracy) (*Wang et al., 2015*).

Intelligent algorithm strategies integrating machine learning, reinforcement learning and other technologies include fuzzy PID control, which combines fuzzy logic and PID algorithm to optimize the response characteristics of the power generation system, and deep reinforcement learning, which learns the optimal strategy through the interaction between agents and the operating environment to adapt to complex and variable field working conditions.

The selection of technical routes for hybrid tractors is restricted by three core factors: operating scenarios, power level and cost budget.

(1) Operating scenarios: Large-area plain field operations are suitable for series configuration and engine-battery energy source layout and rule-based strategy, highlighting the advantages of endurance and cost control; complex hilly field operations are suitable for series-parallel configuration and engine-battery-supercapacitor energy source layout and model predictive control strategy, emphasizing dynamic performance and environmental adaptability; facility horticulture operations are suitable for power-split configuration and engine-supercapacitor energy source layout and fuzzy PID strategy, focusing on operational flexibility and low noise.

(2) Power level: Small-horsepower tractors with a power rating lower than 50kW mainly adopt series configuration and engine-battery energy source layout; high-horsepower tractors with a power rating higher than 150kW tend to use series-parallel configuration and engine-battery-supercapacitor energy source layout.

(3) Cost budget: Economical users such as individual farmers choose series configuration and engine-battery energy source layout and rule-based strategy, with the complete machine price 10%~15% higher than that of conventional tractors; large-scale farms prefer series-parallel configuration and engine-battery-supercapacitor energy source layout and optimization-based strategy. Although the initial investment is 30%~40% higher, the annual operating cost is reduced by 24%~30%, with an investment payback period of about 3~4 years (*Zhou, 2026*).

Review on Verification Methods of Energy Management Strategies

Verification of energy management strategies for hybrid tractors is the key to their transformation from theoretical models to engineering applications. Combined with the characteristics of field operating conditions, there are four core verification methods:

(1) As a low-cost and efficient preliminary method, simulation verification builds powertrain system and strategy models relying on platforms such as MATLAB/Simulink, and completes preliminary iterations combined with field operating condition load spectra. It has the advantages of low cost, short cycle and the ability to simulate extreme working conditions, but is limited by dependence on model accuracy and detachment from the actual environment, which is suitable for the initial stage of strategy research and development (*Wang et al., 2021*);

(2) As a bridge between simulation and real-vehicle tests, bench test verification simulates field operating conditions in a controllable environment through powertrain system or complete vehicle benches to realize semi-physical verification. It features accurate data and high safety, but is difficult to simulate the complex interaction among soil, farm implements and tractors, which is suitable for the strategy optimization stage (*Li et al., 2026*);

(3) Field real-vehicle test verification is the final standard for engineering implementation, which verifie s the adaptability, reliability and economy of strategies in real field scenarios. It has high result credibility, but is restricted by long cycle, high cost and great interference from natural factors, which is suitable for the strat egy application stage (*Wu et al., 2014*);

(4) As a high-end intelligent development trend, Hardware-in-the-loop (HIL) test verification integrates virtual models and physical hardware with strong real-time performance, making it suitable for the verification of intelligent strategies. However, it has high equipment cost and technical threshold, which is applicable to t he research and development of high-end intelligent strategies (*Qiao et al., 2022*).

In practical applications, a full-process integrated system of "simulation verification→HIL test verification→bench test verification→field real-vehicle test verification" is generally adopted. In the future, it will develop towards the standardization of operating condition load spectra, the integration of digital twin and HIL, and the improvement of multi-objective verification systems.

Technical R&D Bottlenecks

In terms of power coupling and transmission efficiency, the series configuration suffers from large energy conversion losses, and the conversion efficiency of the "engine-generator-motor" chain needs to be improved; its energy consumption under high-speed operating conditions is higher than that of the series-parallel configuration. The power-split configuration has high requirements for the machining accuracy of planetary gear mechanisms, and the gear meshing efficiency of domestic enterprises is 5%~8% lower than the international advanced level. The mode switching shock problem of the series-parallel configuration has not been completely solved, and the switching shock of some models reaches 0.3g, which affects operation comfort and component service life.

In terms of energy storage system performance, batteries account for 20%~30% of the complete machine cost, and the service life of batteries in agricultural machinery operating environments is only 1/2~2/3 of that in electric vehicles. Supercapacitors have low energy density and must be matched with large-capacity batteries to meet long-time operation requirements, which increases system complexity and cost. The energy distribution strategy of hybrid energy storage systems is not yet mature, and the cooperative control accuracy between batteries and supercapacitors needs to be enhanced.

In terms of control strategies, optimization-based and intelligent algorithm strategies rely on accurate operating condition prediction models. However, agricultural operating conditions are greatly affected by soil, climate and crops with strong uncertainty, leading to reduced control accuracy. The weight distribution of multi-objective optimization strategies lacks a unified standard and requires recalibration in different operating scenarios, increasing R&D difficulty. The synergy between the control system and the operation system is insufficient, failing to achieve integrated power-operation optimization. The above shortcomings in technical R&D have led to divergences in the technical route selection of hybrid tractors.

Research Focuses and Controversies

Research and development of hybrid tractor technologies center on three core links: power coupling, energy storage system, and control strategy. Clear research focuses have been formed for key technological breakthroughs, while significant academic and industrial controversies exist due to differences in technical route selection and performance priority setting. Such controversies mainly involve three aspects: research focuses and divergences of power coupling and transmission efficiency, energy storage system performance, and control strategy.

The research focus of power coupling and transmission efficiency lies in breaking through the performance shortcomings of three topological structures:

- Firstly, optimizing the energy conversion loss of the series topology, reducing the multi-stage conversion loss of the "engine-generator-motor" chain by improving the matching parameters of generators and motors and enhancing the energy distribution accuracy of the electronic control system;
- Secondly, upgrading the processing technology of core components for the power-split topology, conquering the high-precision processing technology of planetary gear mechanisms, and narrowing the meshing efficiency gap with the international advanced level;
- Thirdly, suppressing the mode switching shock of the series-parallel topology, developing adaptive buffer control algorithms to reduce the impact load in the process of multi-mode switching. The divergences are reflected in the priority of technical routes. Some studies argue that priority should be given to the low-cost optimization of the series topology to meet the demand for large-scale promotion; other studies advocate tackling the mode switching technology of the series-parallel topology to seize the high-end market with its comprehensive performance advantages. The two sides hold different views on the route selection between "cost priority" and "performance priority".

In terms of research focuses and divergences of energy storage system performance, they mainly focus on three core issues:

- Firstly, cost control and service life extension of power batteries, improving battery reliability in agricultural machinery operating environments by developing special battery PACK technologies with vibration resistance and high temperature resistance, and exploring battery recycling and echelon utilization paths to reduce costs;
- Secondly, optimizing the collaborative mechanism of hybrid energy storage composed of supercapacitors and batteries, breaking through the precise control technology of energy distribution strategies, and balancing the advantages of high power density of supercapacitors and high energy density of batteries.

Thirdly, simplifying the structure of the hybrid energy storage system, reducing system complexity and complete machine layout difficulty through integrated design.

The divergences mainly concentrate on the selection of energy storage technical routes. For the research focuses and divergences of control strategies, they mainly focus on the precision and integration of strategies:

- Firstly, constructing a high-precision prediction model suitable for agricultural operating conditions, integrating multi-source data such as soil, climate and crops to improve the adaptability of intelligent algorithms to complex operating conditions;
- Secondly, establishing a dynamic weight adjustment mechanism for multi-objective optimization strategies to achieve balanced optimization of fuel economy, power performance and component service life;
- Thirdly, promoting the collaborative integration of control system and operation system, developing an integrated algorithm of "power control-farm implement control-navigation control" to realize optimal energy distribution in the whole operation process.

The divergences are mainly reflected in the technical implementation path, with differences in the route selection between "adaptive algorithm optimization" and "systematic standardized research and development".

Industrialization Application Bottlenecks

Hybrid tractors face multiple challenges in popularization and application, especially in terms of cost and cost performance. Their selling price is 30%~60% higher than that of traditional tractor models. For instance, the Dongfanghong HB2204 is 250,000 yuan more expensive than traditional models with the same horsepower, and the price of imported hybrid tractors is even higher. Although their operating cost can be reduced by 24%~30%, the investment payback period is relatively long. In terms of infrastructure and after-sales service, there are also prominent problems including a rural charging pile coverage rate of less than 5%, which restricts the application of pure electric mode, as well as a high technical threshold and high cost for hybrid system maintenance.

Core Technology Development Trends

(1) Develop integrated power coupling devices to reduce structural complexity and improve transmission efficiency; explore novel transmission technologies such as electromagnetic coupling transmission and the integration of Hydro-mechanical Continuously Variable Transmission (HMCVT) with electric drive, breaking through the limitations of traditional mechanical transmission. For high-horsepower models, focus on the optimization of series-parallel topology, and develop lightweight and highly reliable multi-mode coupling devices to reduce manufacturing costs by 15~20%.

(2) Develop special high-power-density batteries for agricultural machinery, such as solid-state batteries, to extend endurance and reduce costs; optimize hybrid energy storage systems and dynamically adjust the energy distribution ratio between batteries and supercapacitors based on operating conditions; develop battery thermal management and vibration protection technologies to extend battery life to 5–6 years, close to the level of electric vehicle batteries.

(3) Integrate multi-source sensor technology to construct adaptive operating condition prediction models and improve the real-time performance and accuracy of optimization strategies; develop intelligent algorithms combining deep learning and reinforcement learning to realize self-learning and self-optimization of control strategies, adapting to complex and variable agricultural operating environments; develop an integrated "power-operation" control platform to collaboratively optimize energy management with implement control and path planning, improving overall operating efficiency.

Innovation of Research Methods and Verification Systems

(1) Reduce costs through large-scale production to approach the level of traditional high-end tractor models; adopt modular design to realize the standardization and generalization of powertrain, energy storage system and control system, so as to lower research and development and manufacturing costs.

(2) Build an "agricultural machinery cooperatives and charging piles" model, and deploy fast charging piles in major agricultural production areas to solve the charging difficulty; establish a professional after-sales service network, carry out technical training for maintenance personnel to shorten the fault maintenance cycle; build a remote diagnosis and operation and maintenance platform, and realize predictive maintenance via big data analysis to reduce the failure rate.

(3) Improve the technical standard system, and formulate national standards for hybrid tractors covering energy saving rate test methods, safety requirements and electromagnetic compatibility; strengthen policy support, increase the proportion of purchase subsidies, set up special research and development funds, and encourage collaborative innovation between enterprises and universities; promote the "combination of lease and purchase" and "trade-in for new" models to reduce users' initial investment proportion and accelerate the popularization and application.

CONCLUSIONS

(1) Hybrid tractors have become the core development direction under the background of global agricultural mechanization and green low-carbon transformation, forming a diversified technological pattern and industrialization promotion trend. Driven by policy support, market demand and technological innovation, this field has achieved leapfrog development from conceptual prototype to commercial explosion, and distinctive technical routes adapted to local farming scenarios have been formed both domestically and internationally. Foreign countries are represented by high-horsepower power-split hybrid tractors in North America, plug-in multi-energy coupling hybrid tractors in Europe, and small and medium-horsepower refined hybrid tractors in Japan and South Korea, with high industrialization maturity and complete core technology and supply chain systems. China has made remarkable breakthroughs in the period of independent innovation, with leading enterprises such as YTO Group Corporation, Yuchai Group and Zoomlion emerging, forming a gradient product layout covering 200~320 horsepower heavy-duty models and light and small facility agricultural models. Core indicators such as fuel saving rate and operation efficiency have reached the international advanced level. For example, the plowing fuel consumption of Dongfanghong HB2204 is 23% lower than that of traditional models with the same horsepower, and the operation efficiency of the "Honghu" T300 developed by the Chinese Academy of Sciences is increased by 30%. However, the whole industry is still in the transition stage from "domestic independent substitution" to "high-end breakthrough".

(2) The topological structure and technical level of key components determine the upper limit of the complete machine performance, and different technical routes present distinct differentiated adaptation characteristics. The three core topological structures of series, parallel and series-parallel have their own advantages and disadvantages. The series structure has become the mainstream choice for light and medium load and long-time operation scenarios due to its simple structure and moderate cost, but its energy conversion loss and energy consumption under high-speed working conditions are relatively high. The power-split structure, with a plowing fuel consumption rate of 10.5~12.8L/h and a fuel saving rate of 25%~35%, is the technical route with optimal fuel economy, suitable for medium and high-speed continuous operation. The series-parallel structure realizes adaptive operation under complex working conditions through multi-mode switching, with a maximum climbing gradient of 32~38° and a power response time of only 0.15~0.3s, making it suitable for complex terrains such as hills and mountains, but it has the shortcomings of complex structure and high manufacturing cost. In terms of key components, China has achieved domestic production of National Stage IV diesel engines and medium and low-end power batteries, but core components such as high-end E-CVT gearboxes, high-performance permanent magnet synchronous motors and high-computing power electronic control chips still rely on imports. There is a 5~8% gap in transmission efficiency, power density and other indicators compared with the international advanced level, and the lack of precision manufacturing and collaborative adaptation capabilities of core components has become the primary technical bottleneck restricting the improvement of complete machine performance.

(3) The optimization of energy management strategies and energy source configuration is the core to improve system energy efficiency, and currently faces dual challenges of working condition adaptability and real-time performance. Two routes have been formed for energy source configuration: single energy storage and hybrid energy storage. The single energy storage configuration, centered on lithium iron phosphate

batteries, is suitable for small and medium-horsepower basic operations with significant cost advantages. The hybrid energy storage configuration integrates the "energy-power dual complementarity" advantages of power batteries and supercapacitors, becoming the first choice for 300-horsepower high-end models, but its control complexity and manufacturing cost are 30~40% higher than those of the single configuration. Energy management strategies have evolved from traditional rule-based strategies to optimization algorithms and intelligent algorithms. However, most domestic enterprises still rely on logic threshold control, which is difficult to adapt to field load fluctuations and scenario changes. Although intelligent algorithms such as MPC and ECMS, which are mainstream applications abroad, can maximize energy efficiency, they have high requirements for hardware computing power and the accuracy of working condition prediction models, making large-scale engineering application difficult. In terms of verification system, the full-process integrated verification of "simulation-bench-field-hardware-in-the-loop" has become a trend, but problems such as insufficient standardization of working condition load spectra and shallow application of digital twin technology lead to deviations between strategy verification and actual operation scenarios.

(4) Multiple bottlenecks still exist in technological research and development and industrialization promotion, and core controversies focus on the priority of technical routes and performance balance. At the technological R&D level, three prominent problems are insufficient power coupling efficiency (energy conversion loss of series structure and mode switching shock of series-parallel structure up to 0.3g), limited performance of energy storage system (batteries account for 20~30% of the complete machine cost, and the service life is only 1/2~2/3 of that of electric vehicle batteries), and poor coordination of control strategies (lack of integrated "power-operation" optimization). Academic and industrial controversies are reflected in the choice between "cost priority" and "performance priority" routes, the adaptation of energy storage technical routes, and the trade-off between algorithm optimization and system standardization. At the industrialization level, the selling price of complete machines is 30~60% higher than that of traditional models, with a long investment payback period; the coverage rate of rural charging piles is less than 5%, restricting the application of pure electric mode; the high technical threshold for hybrid system maintenance and imperfect after-sales service network jointly restrict large-scale promotion.

(5) Future development needs to focus on core technological breakthroughs, improvement of industrialization ecology and innovation of policy mechanisms to promote the transformation of hybrid tractors towards high-end, intelligent and low-cost development. At the technical level, focus should be placed on developing integrated power coupling devices, special high-power-density solid-state batteries for agricultural machinery, thermal management and vibration protection technologies to extend battery life to 5~6 years; integrate multi-source sensors and deep learning algorithms to build a working condition adaptive prediction model, and develop an integrated "power-operation-navigation" control platform. At the industrialization level, realize the standardization and generalization of core components through modular design, and reduce manufacturing costs through large-scale production; build an infrastructure network of "agricultural machinery cooperatives and charging piles" and establish a professional after-sales service and remote diagnosis system; improve technical standards such as energy saving rate testing and safety requirements, increase support for purchase subsidies and special R&D funds, and promote the "combination of lease and purchase" and "trade-in for new" models to reduce users' initial investment. With the breakthrough of core technical bottlenecks and the maturity of the industrial ecology, hybrid tractors will gradually transform from "transitional technology" to "mainstream equipment", providing core power support for the sustainable development of global agriculture.

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