

Research on Power System Design and Energy Efficiency Improvement of New Energy Agricultural Machinery

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Abstract: Driven by the dual objectives of agricultural green transition and carbon neutrality, new energy agricultural machinery has emerged as a pivotal solution to replace traditional fuel-powered equipment while enhancing energy efficiency in farming. This study investigates powertrain systems for new energy agricultural machinery, analyzing design characteristics of mainstream technologies, including pure electric, hybrid, and clean fuel systems. Through critical design phases such as core component matching, drive configuration optimization, and energy management strategy formulation, the research proposes multidimensional energy efficiency enhancement methods tailored to operational conditions. Experimental validation confirms the feasibility and efficiency improvements of proposed designs. Results demonstrate that optimized powertrain systems with intelligent energy management can reduce energy consumption by 15–25% and increase operational efficiency by over 10% during typical tasks like plowing, rotary tilling, and transportation. Addressing existing challenges such as inadequate core technology compatibility and efficiency bottlenecks, the study offers technical breakthrough recommendations and industrial development strategies, providing theoretical references and practical pathways for advancing new energy agricultural machinery research and promotion.

Keywords: New energy agricultural machinery; Power system design; Energy efficiency improvement; Energy management; Drive configuration optimization

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1. Introduction

Traditional diesel agricultural machinery remains dominant in farming operations, yet its high fuel consumption, excessive emissions, severe noise pollution, and soil compaction issues not only increase production costs but also conflict with modern agriculture's green and low-carbon development goals. Particularly in China's hilly regions and facility agriculture scenarios, traditional heavy-duty diesel equipment, due to its bulky size and limited maneuverability, faces low operational adaptability. There is an urgent need for lightweight, low-disruption power solutions to overcome these operational constraints ^[1].

2. Operation condition characteristics and power system design indicators of new energy agricultural machinery

2.1. Typical operating conditions and load characteristics

The operation scenarios of new energy agricultural machinery include plowing, rotary tillage, paddy field operation, road transportation, etc. The load characteristics of different working conditions are significantly different, which puts forward different requirements for the torque, power and response speed of the power system.

Ploughing condition is a heavy load operation with large load fluctuation, which requires the power system to have high torque and high power output, and the motor needs to operate stably in the low speed and high torque range.

For rotary tillage condition, the load is relatively stable, but the operation time is long, so the power system should have high reliability and energy utilization efficiency to reduce energy loss. The working environment of paddy field operation is harsh, the soil is strong adhesion, the sealing performance and anti-interference ability of the power system are required, and the light-weight and power are also needed ^[2].

Road transportation condition belongs to light load high speed condition, requires the power system to have wide speed regulation range, maintain high transmission efficiency in the middle and high speed range.

The measured results of 55kW class new energy tractor under typical working conditions show that the rated torque of motor should be $\geq 200\text{N}\cdot\text{m}$ and the rated power should be $\geq 60\text{kW}$ under ploughing condition, the torque fluctuation range of motor should be $80\sim 150\text{N}\cdot\text{m}$ under rotary tillage condition, and the motor speed should reach $2000\sim 3000\text{r}/\text{min}$ under road transportation condition ^[2].

2.2. Basic principles of powertrain design

Combined with the working conditions of agricultural machinery, the design of power system of new energy agricultural machinery should follow the following basic principles:

- (1) The principle of working condition adaptability: The selection of core components and the design of drive configuration should match the operation characteristics of agricultural machinery, such as low speed, high torque and large load fluctuation, to ensure the stability of power output under different working conditions;
- (2) Energy efficiency maximization principle: Optimize the power transmission path to reduce energy loss during transmission and enhance the collaborative efficiency of the motor, battery, and transmission system;
- (3) Reliability and lightweight principle: Considering the structural strength and lightweight design of the power system, it adapts to the harsh working environment of agricultural machinery, reducing the overall weight and energy consumption of the machine;
- (4) Intelligent and cost-effective principles: By integrating smart control technologies, the system achieves adaptive regulation of operating condition recognition and power output, while controlling core component costs to enhance market promotion potential ^[3].

2.3. Core design indicators

Taking 50–70kW class medium-sized new energy tractors as the research object, combining industry standards and measured data, the core design indicators of the power system are determined, as shown in **Table 1**.

Table 1. Core design indicators of power system for new energy tractors

Design index	Numerical requirements	Applicable working condition
Rated power of motor	50~70kW	Full working condition
Rated torque of motor	$\geq 200\text{N}\cdot\text{m}$	Ploughing/rotating
System transmission efficiency	$\geq 85\%$	Full working condition
Battery capacity	$\geq 50\text{kW}\cdot\text{h}$	Pure electric system
Fast charging time	≤ 1 hour (75% energy replenishment)	Pure electric/hybrid system
Endurance	≥ 6 hours (plowing condition)	Pure electric system
Comprehensive energy consumption	≤ 12 kW·h/hm ² (rotary tillage condition)	Full working condition
Torque response time	$\leq 0.5\text{s}$	Load mutation condition

3. Overall design of power system for new energy agricultural machinery

Combined with the actual demand of agricultural production, this paper focuses on the design of pure electric power system and oil-electric hybrid power system, which are respectively suitable for different operation scenes such as facility agriculture, hill and mountain, etc. The pure electric system is suitable for short-distance and fixed-area operation scenes, while the oil-electric hybrid system is suitable for long-range and large-load outdoor operation scenes.

3.1. Design of pure electric power system

3.1.1. Core component selection

The selection criteria are as follows:

- (1) Drive motor: A permanent magnet synchronous motor (PMSM) is selected for its high power density, efficiency, and high torque at low speeds, making it ideal for agricultural machinery operations. Based on design specifications, a PMSM with a rated power of 60kW, rated torque of 218N·m, and peak power of 80kW is chosen. The motor achieves a coverage rate of over 70% under operating conditions with an efficiency range of $\geq 85\%$, meeting the power requirements for heavy-load tasks such as plowing and rotary tillage;
- (2) Power battery pack: Equipped with lithium iron phosphate (LiFePO₄) batteries, this system delivers high safety, extended cycle life, and cost-effectiveness, specifically engineered for agricultural machinery in outdoor environments. The battery pack features a 52kW·h capacity and 336V rated voltage, supporting both fast and slow charging modes. A 1-hour fast charge can achieve 75% energy replenishment, ensuring continuous operation requirements;
- (3) Transmission system: Equipped with an automatic mechanical transmission (AMT) for continuous speed adjustment from 0 to 38 km/h, coupled with motor speed regulation to optimize power transmission efficiency. An independent PTO drive path is also provided to achieve separate propulsion for traction and working devices, thereby reducing energy loss ^[4].

3.1.2. Drive configuration optimization

The system employs a dual-motor coupling drive configuration with a main motor (45kW) and a secondary

motor (15kW). The main motor provides traction power, while the secondary motor supplies power to the PTO and auxiliary systems. Power distribution between the motors is achieved through a planetary gear coupling mechanism. This configuration supports three driving modes as follows:

- (1) Single-motor mode, where only the main motor operates under light loads to reduce energy consumption;
- (2) Dual-motor coupling traction mode, where both motors work together under heavy loads to enhance performance;
- (3) Dual-motor coupling PTO mode, where the motors power the PTO during high-load operations to ensure efficiency.

Intelligent mode switching ensures precise matching between power output and operational demands.

3.2. Design of oil-electric hybrid power system

The oil-electric hybrid system, with its core architecture of “internal combustion engine + battery + motor + power coupling device”, combines the long-range advantage of traditional fuel power with the high-efficiency and energy-saving benefits of electric power. The system’s overall structure consists of a small diesel internal combustion engine (range extender), power battery pack, permanent magnet synchronous motor, power coupling device, electronic control unit, and transmission system.

3.2.1. Core component selection

The selection criteria are as follows:

- (1) Range extender: A small-displacement, high-fuel-efficiency diesel engine with a rated power of 30kW is selected as an auxiliary power source. It operates only when the battery is low, charging the battery to prevent the diesel engine from running in an inefficient range;
- (2) The drive motor: A permanent magnet synchronous motor with a rated power of 40kW is selected as the primary power source, capable of meeting the operational power requirements across most working conditions;
- (3) Power battery pack: Equipped with 20kW·h lithium iron phosphate batteries as energy storage units, which work in tandem with range extenders to deliver extended operational endurance;
- (4) Power coupling device: The clutch-type coupling device is selected to achieve power coupling and separation between the internal combustion engine and the motor, and to switch between three working modes (pure electric, hybrid, and range-extended) according to the working conditions.

3.2.2. Design of working mode

The design of working mode is as detailed:

- (1) Pure electric mode: When the battery level reaches $\geq 70\%$, the range extender shuts off and the motor operates independently to achieve zero-emission operation, ideal for low-emission scenarios like facility agriculture and ecological conservation zones;
- (2) Hybrid mode: When the battery level is between 30% and 70% under heavy-load conditions, the internal combustion engine and motor work in tandem to power the entire machine, boosting its power output. This mode is ideal for heavy-load tasks like plowing and paddy field operations;
- (3) Range extender mode: When the battery level drops to 30% or below, the range extender activates to recharge the battery. The motor is then powered by the battery to drive the entire machine, ensuring an

extended operational range. This mode is ideal for long-distance transportation and large-scale field operations.

3.3. Design of electronic control system

As the “brain” of the power system, the electronic control system (ECS) handles condition recognition, core component coordination, energy management, and fault diagnosis. It employs multi-sensor fusion technology, equipped with vehicle speed sensors, torque sensors, battery management system (BMS), and condition recognition modules, enabling information exchange among components via CAN bus.

Core functionalities include as follows:

- (1) Condition recognition: Sensors collect data on vehicle speed, torque, and load to identify real-time working conditions such as plowing, rotary tillage, and transportation;
- (2) Power regulation: The system adaptively adjusts motor output power and torque based on condition recognition results, switching between drive and working modes;
- (3) Energy management: Optimizes battery charging and discharging strategies to prevent overcharging and over-discharging, enhancing battery lifespan and energy efficiency;
- (4) Fault diagnosis: Real-time monitoring of core components’ operational status with timely fault alerts to improve system reliability.

4. Methods for improving energy efficiency of power systems in new energy agricultural machinery

The energy efficiency improvement of the power system of new energy agricultural machinery should be carried out from four dimensions: component collaborative optimization, energy management strategy, transmission path optimization and lightweight design. Through the integration of multiple technologies, energy loss can be reduced and the overall energy utilization efficiency can be improved.

4.1. Intelligent energy management strategy based on operating condition recognition

Energy management strategy is the core of improving the energy efficiency of power system. This paper proposes an adaptive energy management strategy based on dynamic recognition of operation condition. By establishing the operation condition recognition model and energy consumption optimization model, the precise matching of power output and operation load is realized, and the invalid energy consumption is reduced.

Based on the characteristic parameters of vehicle speed, motor torque, load fluctuation frequency and working time, the BP neural network algorithm is used to construct the condition identification model, which can classify and identify typical working conditions such as plowing, rotary tillage, transportation and idle, with the identification accuracy of 95% or more.

This model establishes an optimization framework with the objective of “minimum energy consumption” based on load characteristics under different operating conditions, employing dynamic programming algorithms to determine optimal power output solutions. For instance, dual-motor coupling drives are prioritized in plowing operations to ensure high torque output, while single-motor drives with gearbox speed regulation are used in rotary tillage operations to enhance motor efficiency. In transportation operations, the model optimizes motor speed to operate within the high-efficiency range.

Through this strategy, the power consumption of the pure electric power system in ploughing, rotary tillage

and transportation can be reduced by about 20%, 10% and 15% respectively.

4.2. Power transmission path and transmission system optimization

Energy loss in power transmission systems predominantly occurs within the transmission subsystem. By optimizing the transmission path and overall system architecture, transmission efficiency can be significantly enhanced.

One effective approach involves simplifying the transmission path through the adoption of wheel-side drive or direct-drive configurations, thereby reducing the number of gear stages and minimizing mechanical friction losses. In dual-motor drive systems, the establishment of independent traction and power take-off (PTO) transmission branches can further prevent power crossover losses.

In addition, optimization of transmission components plays a crucial role in improving efficiency. The use of high-precision gears and low-friction bearings reduces mechanical losses, while surface treatment technologies enhance wear resistance and lubrication performance. Furthermore, optimizing the gearbox speed ratio ensures that the motor operates within its high-efficiency range under most working conditions.

The implementation of stepless speed control technologies, such as automated manual transmission (AMT) or continuously variable transmission (CVT), enables smooth gear shifting, thereby avoiding power interruptions and reducing energy loss during gear changes. This also improves the adaptability of the transmission system under varying operating conditions.

Through these combined strategies, the overall transmission efficiency of the power system can be increased from approximately 70% in conventional systems to over 85%.

4.3. Optimization of core components' collaborative efficiency

The energy efficiency of a power system depends not only on the performance of individual components but also on the coordinated operation of key subsystems, including the battery, motor, and electronic control system. This system-level synergy can be enhanced through several optimization strategies.

Battery-motor collaborative optimization plays a critical role. The battery management system (BMS) continuously monitors key parameters such as state of charge (SOC), voltage, and temperature. Based on these real-time measurements, the electronic control unit (ECU) dynamically regulates the motor's power and torque output. This coordination prevents the battery from operating under extreme conditions, such as overcharging, deep discharge, or low-temperature environments, thereby improving both battery discharge efficiency and motor performance.

Furthermore, motor-transmission coordinated speed control further enhances system efficiency. By dynamically adjusting motor speed and gearbox ratios according to operating conditions, the system ensures that the motor consistently operates within its optimal efficiency range. For example, within the sixth gear operating range, the coordinated control strategy achieves a coverage rate exceeding 70.6% for conditions where the overall system efficiency remains above 50%.

Overall, these coordinated control strategies significantly improve the integrated performance and energy efficiency of the power system.

4.4. Lightweight and low resistance design

Vehicle mass and rolling resistance are critical factors influencing the energy consumption of the powertrain. The

adoption of lightweight and low-resistance design strategies can effectively reduce the operational load on the powertrain, thereby improving overall energy efficiency.

Lightweight design is achieved by employing advanced materials such as high-strength aluminum alloys and carbon fiber composites in the fabrication of the powertrain housing and gearbox structure. These materials ensure sufficient structural strength while significantly reducing system weight. In addition, optimization of the structural layout minimizes redundant components, further contributing to overall weight reduction [5].

Low-resistance design focuses on reducing both rolling and aerodynamic losses. The tread pattern and structural configuration of the driving system are optimized to decrease contact resistance between the tires and the ground. At the same time, streamlined designs of exposed power system components help to reduce aerodynamic drag. For applications such as paddy field operations, anti-adhesion structural designs are implemented to mitigate additional resistance caused by soil accumulation.

Practical implementation further demonstrates the effectiveness of these strategies. For example, the Yinan County New Energy Agricultural Machinery Upgrade Project reported that lightweight design reduced the weight of a solar-powered harvester by approximately 10%, resulting in a 40% reduction in overall energy consumption [6].

5. Simulation and experimental verification

5.1. Simulation model establishment

The 60kW class dual-motor coupling drive power system of the pure electric tractor is taken as the research object. Based on MATLAB/Simulink software, the simulation model is established, which includes battery module, motor module, power coupling module, transmission system module, working condition load module, etc. The simulation time is 3600s, and the simulation step is 0.01s.

5.2. Analysis of simulation results

The simulation results showed that the designed pure electric power system can meet the power output requirements in three typical working conditions, and the transmission efficiency and energy consumption of the system meet the design requirements (Table 2).

Table 2. Simulation results of typical operating conditions of powertrain

Working condition	Average efficiency of motor	System transmission efficiency	Comprehensive energy consumption	Torque response time
Ploughing	88.5%	86.2%	14.2kW·h/hm ²	0.3s
Rotary tillage	90.2%	87.5%	11.8kW·h/hm ²	0.2s
Road transport	89.8%	88.0%	8.5kW·h/100km	0.2s

The simulation results showed that the comprehensive energy consumption of the power system is the lowest under rotary tillage condition, which is 11.8kW·h/hm², meeting the design index of $\leq 12\text{kW}\cdot\text{h}/\text{hm}^2$. The transmission efficiency of the system is $\geq 85\%$ under the three working conditions, and the torque response time is $\leq 0.5\text{s}$, reflecting the good power performance and energy efficiency characteristics.

5.3. Verification by real vehicle test

Three 60kW pure electric tractors equipped with the power system designed in this paper were selected to carry out field experiments in Yinan County Modern Agricultural Demonstration Park, Shandong Province. The traditional fuel tractors were set as the control group. The comparative experiments of plowing and rotary tillage were conducted on a plot area of 2hm² with soil moisture content ranging from 20% to 25%.

The experimental results showed that the new energy tractor demonstrates a comprehensive energy consumption of 14.5kW·h/hm² in plowing mode and 12.0kW·h/hm² in rotary tillage mode. Compared to conventional fuel-powered tractors, this achieves a 40% reduction in energy costs and a 30% decrease in carbon emissions. In addition, the new energy tractor achieves plowing efficiency of 0.3 hm²/h and rotary tillage efficiency of 0.5 hm²/h, comparable to traditional fuel-powered tractors. Under certain operating conditions, the rapid torque response of the motor enhances operational efficiency by 10%. During a 6-hour continuous operation, the power system's core components function stably without failures, with the battery SOC maintained above 20% to meet continuous operation requirements.

The simulation and the test results showed that the power system of the new energy agricultural machinery has good power performance and energy efficiency, and the method of energy efficiency improvement is feasible.

6. Conclusion

This study focuses on the design and energy efficiency enhancement of power systems for new energy agricultural machinery. By analyzing typical operational characteristics of farm equipment, it establishes design parameters for power systems, completing comprehensive design of pure electric and hybrid power systems, core component selection, and drive configuration optimization. The research proposes multi-dimensional energy efficiency improvement methods including intelligent energy management based on operational condition recognition, transmission path optimization, core component coordination optimization, and lightweight design. The feasibility and effectiveness of these solutions were validated through simulations and field tests. Key findings include that the dual-motor coupled drive configuration enables intelligent switching of driving modes for different operational conditions, adapting to low-speed high-torque and variable load requirements, making it the preferred configuration for medium-sized new energy tractors. Moreover, adaptive energy management strategies based on dynamic operational condition recognition achieve precise matching between power output and working loads, reducing energy consumption by approximately 20% and 10% for pure electric power systems during plowing and rotary tillage operations, respectively. On top of that, energy efficiency improvements through transmission path optimization, core component coordination, and lightweight design can elevate transmission efficiency to over 85%, reduce comprehensive energy consumption by 15–25%, lower operational costs by 40%, and decrease carbon emissions by 30%. The development of new energy agricultural machinery power systems requires breakthroughs in specialized core technologies, infrastructure enhancement, industrial chain collaboration, and integrated application of multiple energy sources (e.g., hydrogen and solar power) to further improve energy efficiency and reliability, thereby promoting large-scale adoption of new energy agricultural machinery.

Disclosure statement

The author declares no conflict of interest.

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