DESIGN OF ENERGY MANAGEMENT STRATEGY FOR DUAL-MOTOR-DRIVEN ELECTRIC TRACTORS

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双电机驱动电动拖拉机能量管理策略的研究

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ABSTRACT

At present, electric tractors experience significant battery energy loss during operation, resulting in a short continuous running time. Therefore, in order to reduce the power consumption of the tractor drive system, minimize battery energy loss, and extend the operating time under various conditions, this paper presents a method for driving an electric tractor based on dual-motor coupling. Based on the characteristics of the transmission structure, an online torque distribution strategy for dual-motor coupling-driven electric tractors using a fuzzy control approach is proposed. First, an enhanced genetic algorithm is utilized to optimize the fuzzy rule table. Simultaneously, it is compared with the offline optimization strategy of dynamic programming. Subsequently, a method that integrates test data models and theoretical models is employed to establish an efficiency model of key components of the electric tractor drive system and a longitudinal dynamics model of the entire machine. The performance of the entire vehicle was simulated and analyzed under plowing conditions. Finally, on the experimental bench, conduct steady-state load tests and dynamic performance tests on the dual-motor coupled drive system. The results show that the State of Charge (SOC) change trends of the fuzzy control strategy based on the improved genetic algorithm and the dynamic programming strategy are similar. The SOC change values are close, which enhances the adaptability of the electric tractor in various operating conditions. Compared with the fuzzy control strategy, the improved strategy reduced average power consumption by 8.8%, demonstrating that the fuzzy control energy management strategy based on the enhanced genetic algorithm is both economical and superior. The bench experiment demonstrated that the dual-motor drive system can adapt to load changes to achieve power distribution between the two motors, meeting the required workload while reducing power consumption.

摘要

目前电动拖拉机在在工作时电池能量损耗较大，持续运行时间较短，因此，本文为降低拖拉机驱动系统功率消耗，减少电池能量的损耗，延长工况运行时间，根据双电机耦合驱动电动拖拉机的传动结构特性，提出了一种基于模糊控制策略的双电机耦合驱动电动拖拉机的在线转矩分配策略，首先采用改进遗传算法对模糊规则表进行优化，同时与动态规划的离线优化策略进行对照，随后采用试验数据模型和理论模型相结合的方法，建立了电动拖拉机驱动系统关键部件效率模型和整机纵向动力学模型，在犁耕下对整车性能进行仿真分析，最后在搭建的实验台架上对双电机耦合驱动系统进行稳态负载试验和动态性能试验。结果表明：基于改进遗传算法的模糊控制策略与动态规划策略的 SOC 变化趋势相似，SOC 变化值接近，改善了电动拖拉机不同作业工况的适应性，且改进后的策略与模糊控制策略相比，平均耗电量降低了 8.8%，证明了基于改进遗传算法的模糊控制能量管理策略具有良好的经济性和优越性，台架实验表明双电机驱动系统能够跟随负载变化实现两电机的功率分配，满足作业负载的同时降低了功率损耗。

INTRODUCTION

In the midst of the current global energy crisis and the increasingly severe environmental pollution problems, the use of electric tractors in agriculture has become an unavoidable trend (*Cao, 2013*). As a novel form of agricultural machinery that emphasizes environmental protection, energy efficiency, and high performance, the electric tractor presents clear advantages.

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Traditional tractors produce a significant amount of harmful gases in the field due to the use of diesel generators. They also contribute to high noise levels and low efficiency. Pure electric tractors can effectively address these limitations. Currently, pure electric tractors are mainly powered by a single motor, which often results in insufficient power when encountering complex operating conditions in the field with high power requirements (*Volpato et al., 2016; Chen, 2018*). Therefore, to improve the efficiency and performance of pure electric tractors, the dual-motor driving system is a promising solution. In cases where low speed and power requirements are needed, small motors are used to drive tractors. However, an effective energy management strategy is crucial for the advancement of dual-motor driving electric tractors (*Wang et al., 2022*).

Currently, the majority of research on dual-motor driving systems is focused on electric vehicles, with relatively limited research conducted on dual-motor-driven pure electric tractors. *Zhang et al.* (*2015*) proposed a rule-based power distribution control strategy based on Pontryagin's Minimum Principle (PMP) control strategy through six cycle conditions to enhance the operating efficiency of dual-motor-driven electric buses. *Chen et al.* (*2023*) developed a torque allocation strategy aimed at minimizing losses in a real-time electric drive system. This strategy is based on the loss mechanism of the electric drive system and has been shown to enhance the economic performance and adaptability of the vehicle under various working conditions. *Chen* (*2021*) from Jiangsu University proposed a torque allocation system for a dual-motor coupling driving electric tractor based on the linear diminishing weights particle swarm algorithm. *Wen et al.* (*2022*) proposed a set of innovative design and verification methods for the dual-motor power coupling drive system of electric tractors. The aim was to address the issues of excessive focus on static indicators, neglect of the distribution of high-efficiency power source areas, and incomplete simulation and test verification systems in the design and parameter optimization of multi-power source tractors.

In a detailed study of the transmission system of electric tractors, *Zhang et al.* (*2023*) proposed a dynamic optimization method for the speed ratio of the transmission system based on motor coupling characteristics. This innovative method utilized a simulation environment and the advanced Deep Deterministic Policy Gradient (DDPG) algorithm of reinforcement learning for iterative solutions. It significantly improved the power performance and overall work efficiency of electric tractors. *Wang et al.* (*2023*) focused on the rotary tillage unit of extended-range electric tractors. Based on the background of dual-motor independent electric drive, they pioneered the use of dual-input variable inverse modeling technology. By combining actual measurement data and empirical formulas, they successfully established an accurate model that reflects the periodic characteristics of rotary tillage conditions. *Liu* (*2023*) designed a dual-motor power-coupled drive system for electric tractors. They conducted in-depth discussions and experimental verification on structural design and key parameter optimization using a method that combines the particle swarm optimization algorithm and dynamic programming. *Chen et al.* (*2019*) proposed a parameter matching and optimization design method for the electric tractor powertrain based on a dual-motor coupling drive approach. They utilized a particle swarm optimization algorithm incorporating a hybrid penalty function to address the optimization of the traction performance of the electric tractor.

Therefore, for the dual-motor-driven electric tractor, improving system efficiency is the top priority, making a well-planned energy management strategy essential.

This paper uses dynamic programming to globally optimize the power system. By analyzing the results of dynamic programming, a fuzzy control strategy is designed based on the characteristics of the power system. The fuzzy rule table is optimized, and finally, through simulation experiments and comparison with the dynamic programming strategy, the effectiveness of the energy management strategy is verified.

MATERIALS AND METHODS

Main Component Parameters and Power System Composition

The reason for choosing to use two low-power motors instead of a single high-power motor is that a dual-motor coupled drive is more energy-efficient than a single-motor drive. A dual-motor coupled drive can meet different requirements while still satisfying the power needs of the electric tractor. Through reasonable energy management strategies, the driving efficiency of the two motors can be improved to achieve energy-saving effects under load conditions. When the electric tractor is working with a low load, the single-motor drive mode is used. To improve the working efficiency of the motor and achieve energy saving under the same torque demand, increasing the motor load rate is the key. When the electric tractor needs to work at high speeds with loads in the field, the main motor and the auxiliary motor are coupled to drive.

The dual-motor coupled drive system has the advantage of having a high-efficiency area. Due to the increase in the high-efficiency area, the motor can run in the high-efficiency area more frequently, thereby achieving the goal of energy saving. The purpose of this research is to further optimize the energy management strategy of the dual-motor electric tractor designed by the team. Figure 1 shows the actual picture of the designed dual-drive electric tractor, and Figure 2 shows the schematic diagram of the high-efficiency range of the dual motors.

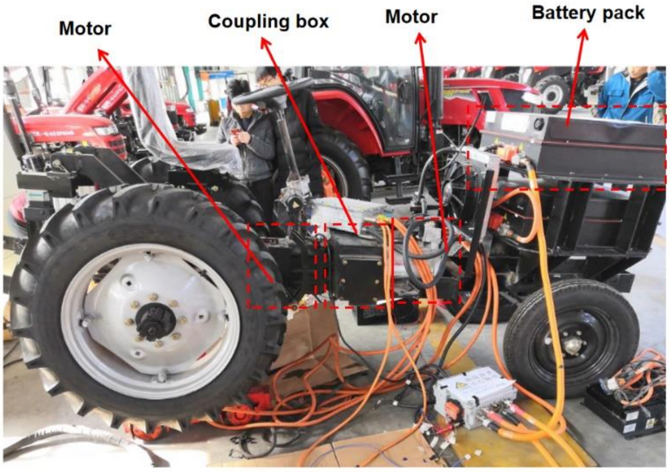


Fig. 1 - Actual picture of electric tractor

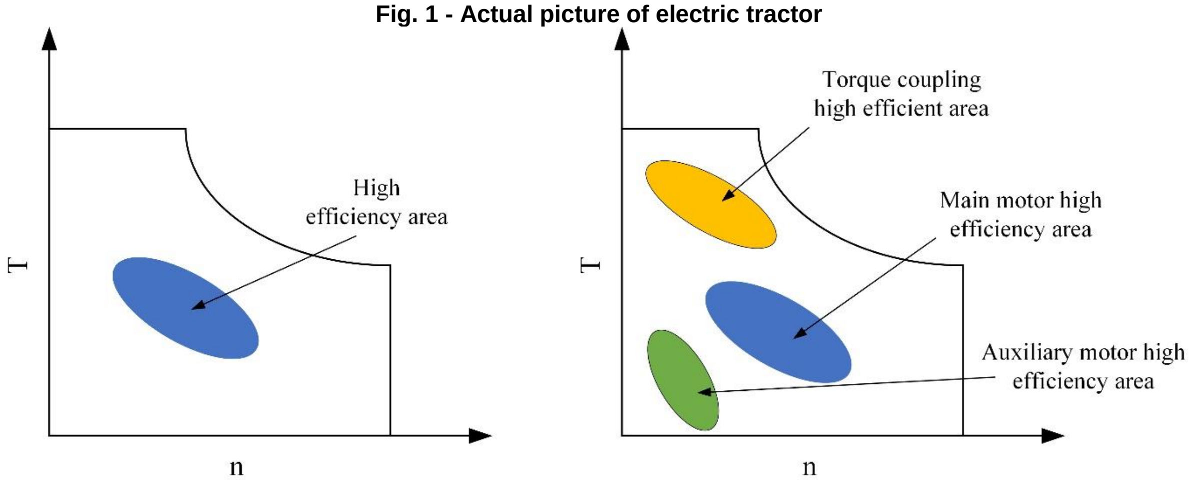


Fig. 2 - Comparison diagram of high efficiency area between single motor and dual motor

The power source of the electric tractor driven by two motors is the main motor and the auxiliary motor. The two motors are connected through the coupling device to realize the dynamic coupling of the two motors, and then the power is transmitted to the driving wheel through the components such as the gearbox and the differential (*Hu 2018; Enang and Bannister, 2017*), as shown in Fig. 3, and the main parameters are shown in Table 1.

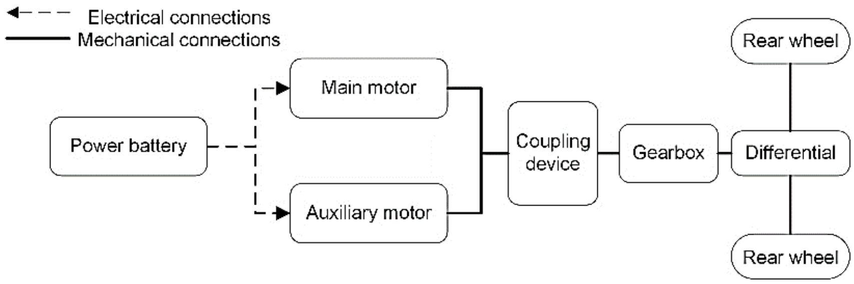


Fig. 3 - Schematic diagram of a dual-motor-driven electric tractor

Table 1

Basic parameters of tractor

Parameter	Value
Tractor mass/kg	2100
Drive wheel radius/m	0.51
Rolling resistance coefficient	0.07(Field) 0.016(Road)

Establishment of Theoretical Model

- **Vehicle Longitudinal Dynamics Model**

The wheeled electric tractor needs to overcome the resistance to carry out the working condition operation. The main resistances include rolling resistance, acceleration resistance, slope resistance, and traction resistance. The speed of the tractor is slow and the air resistance is ignored. The longitudinal dynamic model of the electric tractor is as follows.

$$T_w = (mgf\cos\theta + mg\sin\theta + \delta m\frac{dv}{dt} + F_t)\cdot r_w \tag{1}$$

where:

T_ω is the driving wheel torque, (N·m); m is the mass of the tractor, (kg); g is the acceleration of gravity, (m/s²); f is the rolling resistance coefficient; θ is the slope, (°); δ is rotation mass conversion coefficient; F_t is the hook traction force, (N); r_ω is the radius of the driving wheel, (m).

- **Battery Model**

The battery is a critical component of the electric tractor. The lithium battery undergoes a complex chemical reaction during the charging and discharging processes. It is difficult to establish a reliable working model without an accurate model. As a result, this paper does not discuss the thermal temperature effect and transient response of the battery. The influence of state of charge on electromotive force and internal resistance is the main focus, and the Rint model is selected (*Onori et al., 2016*), as shown in Fig. 4.

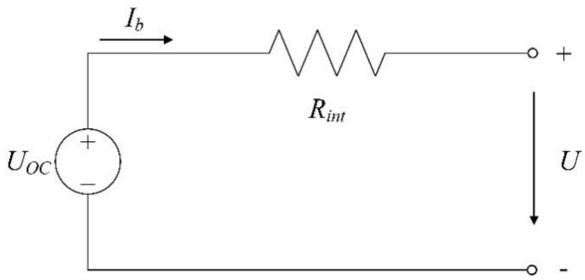


Fig. 4 - Battery Equivalent Circuit Model

For the battery internal resistance model, there are:

$$U = U_{OC} - I_b R_{\text{int}} \tag{2}$$

The calculation formula of battery power output and current module is:

$$P_m = U \cdot I_b \tag{3}$$

$$I_b = \frac{U_{OC} - \sqrt{U_{OC}{}^2 - 4P_m R_{\text{int}}}}{2R_{\text{int}}} \tag{4}$$

where:

U_{OC} is the open-circuit voltage of the battery, (V); P_m is battery output power, (W); R is the equivalent internal resistance of the battery, (Ω); I_b is battery charge and discharge current, (A).

The battery state of charge equation is:

$$SOC(t) = SOC_0 - \frac{1}{Q_b}\int_0^t \eta I_b(t)dt \tag{5}$$

where:

$SOC(t)$ is the SOC of t at that moment in time, (%); Q_b is the rated capacity of the battery, (Ah); η is the battery discharge efficiency, (%).

- **Motor Model**

This paper utilizes a brushless DC motor and employs experimental modeling to measure the motor's experimental data using a built test bench. It also utilizes the spline interpolation method to establish the motor's efficiency model (*Rizzoni et al., 1999*). The parameters of the motor are shown in Table 2.

Most of the working conditions for electric tractors involve towing agricultural tools in the field, where the vehicle typically travels at a relatively slow speed. Hence, there is no need to consider the effects of acceleration resistance and wind speed resistance. The main consideration is the effect of traction resistance on the tractor's field operations. When the main motor is working, it directs the majority of power to the output shaft to enhance the tractor's power output during rotary tillage operations. Therefore, initially calculate the power requirements of the main motor to meet the rotary tillage conditions. The average power consumed by a tractor during rotary tillage work is typically calculated using the soil-specific resistance method.

$$P_X = 0.1K_\lambda h_k vB \tag{6}$$

where:

P_X is the average power consumed by the main motor of an electric tractor during rotary tillage operations, (kW); K_λ is rotary tillage specific resistance, (N/cm²); h_k is tillage depth, (cm); v is the driving speed of electric tractor during rotary tillage, (m/s); B is the ploughing width, (m)。

While the main motor drives the power output shaft, a portion of the power is transmitted to the driving wheels and the auxiliary motor to propel the vehicle. In order to ensure that the tractor can operate stably in various working environments, the traction capacity of the main motor should be increased by 20-30%. Therefore, the formula for calculating the rated power of the main motor is:

$$P_{m1} = (1.2 \sim 1.3)P_X \tag{7}$$

The sum of the power of the main motor and the power of the auxiliary motor is equal to the traction power, so the rated power of the speed-regulating motor can be determined as:

$$P_{m2} = \frac{P_{Tn}}{\eta_T} - P_{m1} \tag{8}$$

where:

P_{Tn} is the rated driving power of tractor, (kW); η_T is the traction efficiency.

Table 2

Basic parameters of motor

Parameter	Value
The rated power of the main motor/kW	20
The rated speed of the main motor/r·min^{-1}	3000
The rated torque of the main motor/N·M	70
The rated power of the auxiliary motor/kW	10
The rated speed of the auxiliary motor/r·min^{-1}	3400
The rated torque of the auxiliary motor/N·M	28

- **Driver Model**

The driver model is an essential component of the simulation platform, used to replicate driver behavior in real driving scenarios. The input signal of the model comprises the desired vehicle speed and the actual vehicle speed of the driving cycle, while the output signal is the command for the accelerator/brake pedal. The driver model uses PID control (Proportional-Integral-Derivative Control) to provide feedback on the accelerator/brake pedal opening based on the difference (e) between the target vehicle speed and the actual vehicle speed.

$$acc = K_P e + K_I \int edt + K_D \frac{de}{dt} \tag{9}$$

where:

acc is the pedal opening degree; e is the difference between the target speed and the actual speed, (m/s); K_P is the proportional coefficient of the driver model; K_I is the integral coefficient of the driver model; K_D is the differential coefficient of the driver model.

Based on the MATLAB/Simulink environment, the vehicle longitudinal dynamics model and driver model were built, as well as the key components of the power system, the battery, and the motor, for focused modeling. The final simulation model diagram is as follows.

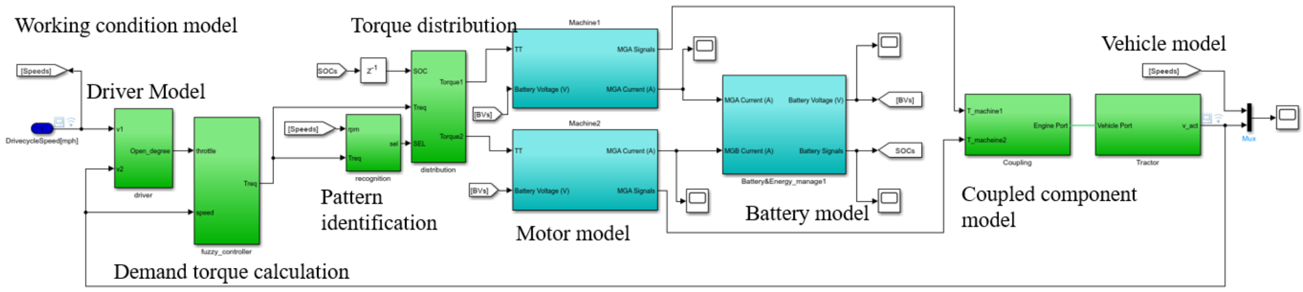


Fig. 5 - Schematic diagram of simulation model of electric tractor

Pattern Analysis

Based on the performance indicators and evaluation standards of the electric tractor, the power coupling mechanism is designed to achieve different drive modes, specifically the torque coupling drive mode and the main motor-independent drive mode.

Offline Optimization Strategy based on Dynamic Programming

The essence of energy management for electric tractors driven by dual-motor coupling is to optimally distribute the output power between the two motors to achieve optimal driving costs for the entire vehicle. Therefore, the process of power allocation can be regarded as a multi-stage decision-making problem with time as a step. Dynamic programming is an idea or approach to solving multi-stage decision-making optimization problems (*Wang et al., 2018*; *Bertsekas, 2012*). Its main idea is to divide the problem into multiple interconnected sub-stages. After the decision-making in one stage is determined, it often affects the next stage. Finally, the optimal solutions of the sub-stages are combined to obtain the optimal solution of the original problem.

The global optimal solution can be found using the DP algorithm. However, this method can only be utilized when the operational cycle is known, and the computational cost is exceedingly high. Therefore, the optimization results of DP can serve as a benchmark for evaluating the performance of various energy management strategies.

It can be seen from the evolution of the dual-motor coupling drive system that the power battery SOC fluctuates with the operation of the vehicle, and the SOC can reflect the status of the tractor system. Therefore, the battery SOC is defined as the state variable of the optimal control system of the electric tractor. As shown in the following equation (7):

$$x(k) = SOC(k) \tag{10}$$

During the driving process of an electric tractor driven by dual motor coupling, the output power of the tractor determines the change of the control variable, so the torques T_{m1} and T_{m2} of the two motors of the vehicle are selected as the control variables of the system. As shown in the following equation (8):

$$u(k) = [T_{m1}(k), T_{m2}(k)] \tag{11}$$

At the same time, the cyclic working conditions are discretized according to time, the discretization accuracy is selected to be 1 s, and the following model is established in the time discrete state space:

$$x(k+1) = f(x(k), u(k)) \tag{12}$$

where: $x(k)$ is the state vector of the system; $u(k)$ is the control vector; f is the state transition function.

Set the initial value of SOC to 0.9, △SOC to 0.025, and △Tm to 1 N·m. At the same time, according to the battery equivalent model established in the previous section, it is known that the state quantities of the two adjacent sub-stages satisfy the following relationship.

$$SOC(k+1) = SOC(k) - \frac{(V_{oc} - \sqrt{V_{oc}{}^{2} - 4RP})\Delta t}{2R \cdot Q} \tag{13}$$

In order to ensure normal decision-making, the actual situation of the variables related to the battery and motor needs to be reasonably constrained.

The specific constraint functions are as follows:

$$\begin{cases} SOC_{\min} \le SOC(k) \le SOC_{\max} \\ T_{\min\_m1} \le T_{m1}(k) \le T_{\max\_m1} \\ T_{\min\_m2} \le T_{m2}(k) \le T_{\max\_m2} \\ n_{\min\_m1} \le n_{m1}(k) \le n_{\max\_m1} \\ n_{\min\_m2} \le n_{m2}(k) \le n_{\max\_m2} \end{cases} \tag{14}$$

where:

SOC_{min} and SOC_{max} represent the minimum and maximum SOC of the battery, respectively, (%); T_{min_m1}, T_{max_m1}, T_{min_m2} and T_{max_m2} represent the minimum and maximum output torque of the main motor and the auxiliary motor, respectively, (N·m); n_{min_m1}, n_{max_m1}, n_{min_m2} and n_{max_m2} represent the minimum and maximum speed of the main motor, respectively, (rpm).

For a dual-motor-driven electric tractor, the focus of the strategy is mainly on the vehicle's economy. Therefore, the objective is to minimize the power consumption of the drive system of the electric tractor during working conditions. The cost function for the entire operating time from 0 to N is established as follows:

$$J = \sum_{k=0}^{N} L_k(x(k), u(k)), k = 0, 1, ..., N-1 \tag{15}$$

$$L = \frac{P_{m1}}{\eta_{m1}} + \frac{P_{m2}}{\eta_{m2}} \tag{16}$$

where: L is the instantaneous transfer cost; N is the total number of stages after the discrete driving cycle time domain; J is the cost function value accumulated during the iteration process; P_{m1} and P_{m2} represent the output power of main motor and auxiliary motor, respectively, (kW); η_{m1} and η_{m2} represent the efficiency value of main motor and auxiliary motor, respectively.

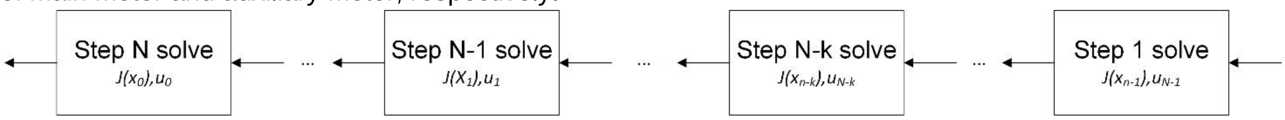


Fig. 6 - Schematic diagram of the reverse solution process

As depicted in Fig. 6, during dynamic programming, the entire operational time needs to be traversed, and the state and control quantities are calculated simultaneously. The dynamic programming reverse solution starts from the final stage N, and calculates and saves the optimal cumulative objective function and control quantity for each step. At this point, the reverse solution concludes. At this time, the initial quantity of the state is known. In the reverse solution process, the optimal control solution for each stage is used to perform the forward solution sequentially. This process yields the optimal control variables in different states, representing the optimal distribution under cycle conditions.

Energy management that relies on dynamic programming can obtain solutions. However, it heavily depends on accurate predictions of cycle conditions and has poor real-time which makes it unsuitable for direct application. Therefore, the optimal results obtained from the dynamic programming strategy serve as a benchmark for comparing the effects of the following energy management strategies and for guiding the selection of rules for energy management strategies based on fuzzy control (*Wang et al., 2022*).

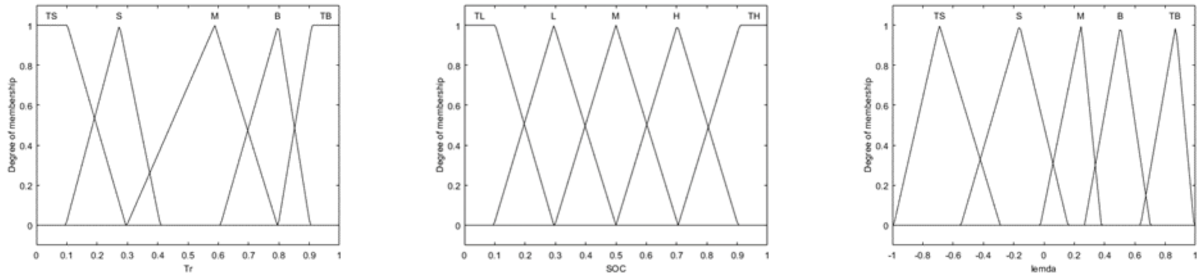
Online Energy Management Strategy based on Fuzzy Logic Control

- **Establishment of Fuzzy Logic Control Strategy**

Fuzzy control does not require an accurate mathematical model of the controlled object and offers robustness and fault tolerance. It can also address dynamic control problems in nonlinear systems and is highly suitable for the control system of electric tractors (*Zhu et al., 2022*).

The fuzzy controller described in this paper takes the tractor's required torque (T_{req}) and the battery SOC as inputs and produces the torque distribution coefficient (λ) as the output variable. The fuzzy inference method utilizes the Mamdani direct inference method and employs triangular membership functions as the primary form, as shown in Fig. 7.

Among them, the fuzzy subsets of the input variable demand torque T_{req} are {NB, NS, M, PS, PB}, representing very small, small, medium, high, and very high, respectively. The fuzzy subsets corresponding to the battery SOC are {VL, L, M, H, VH}, representing very low, low, medium, high, and very high, respectively. The fuzzy subsets of the output variable are {VS, S, M, B, VB}, representing very small, small, medium, big, and very big (*Ji et al., 2022; Ji et al., 2022*).



(a) Demand torque membership function *(b) Battery SOC membership function* *(c) λ membership function*

Fig. 7 - Membership function

For fully electric tractors, the working conditions primarily involve field operations. Therefore, ensuring that the tractor meets the power performance requirements is essential without significantly depleting the battery energy. Based on this principle, the following fuzzy rule table is established using the output results of dynamic programming (*Zhou et al., 2023*).

Table 3

Fuzzy rule table

λ		SOC				
		VL	L	M	H	VH
T_{req}	NB	VS	S	B	VB	VB
	NS	VS	VS	M	VB	B
	M	VS	VS	S	M	M
	PS	VS	VS	VS	M	S
	PB	VS	VS	VS	S	VS

- **Genetic Algorithm Optimization Fuzzy Logic Control**

Fuzzy control is a type of intelligent control that utilizes expert knowledge to regulate the control strategy and behavior of the controlled object (*Ding et al., 2021; Lü et al., 2020*). Professional knowledge plays a crucial role in the implementation of the control strategy. Therefore, genetic algorithms need to be implemented to optimize it. The genetic algorithm is an optimization technique that simulates the process of natural evolution and is employed to solve complex optimization problems. It is based on the principles of genetics and evolution and enhances the quality of solutions from one generation to the next by simulating operations such as natural selection, crossover, and mutation to identify optimal or near-optimal solutions. Given the subjective nature of professional knowledge, this paper aims to enhance the fuzzy control table using a genetic algorithm. The flow of the optimization algorithm is depicted in the Fig. 8 below.

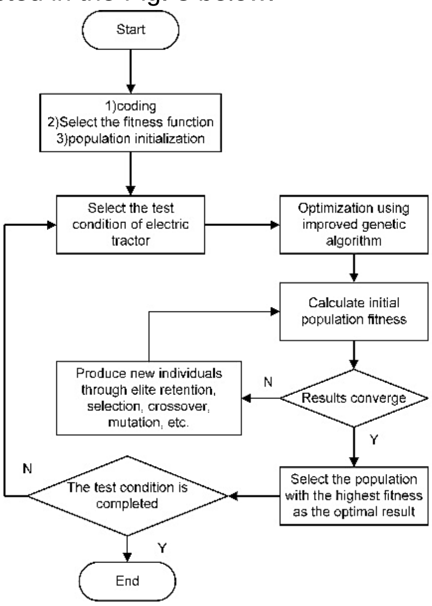


Fig. 8 - Optimized fuzzy control process

- **Genetic Algorithm Parameter Selection**

When using genetic algorithms, selecting the appropriate parameters is crucial for the performance and convergence of the algorithm.

The choice of the initial population size will impact the evolutionary efficiency and the optimization results of the algorithm. In general, the population size should be large enough to thoroughly explore the search space, but it must also take into account the limitations of computing resources. Therefore, the population size is set to 100. At the same time, the coding of the genetic algorithm selects 120 binary numbers. The crossover rate determines the probability of executing a crossover operation. A higher crossover rate can facilitate the exchange of genetic information and preserve diversity. However, an excessively high crossover rate may result in premature convergence and loss of diversity. Choose 0.6 according to the actual situation. The mutation rate determines the likelihood of a mutation operation occurring. The mutation operation helps introduce new gene combinations and explore new solutions in the search space. It is determined to occur with a probability of 0.05, based on the actual situation. The termination condition determines when the algorithm stops iterating, and 80 is chosen based on comprehensive considerations.

- **Improved Traditional Genetic Algorithm**

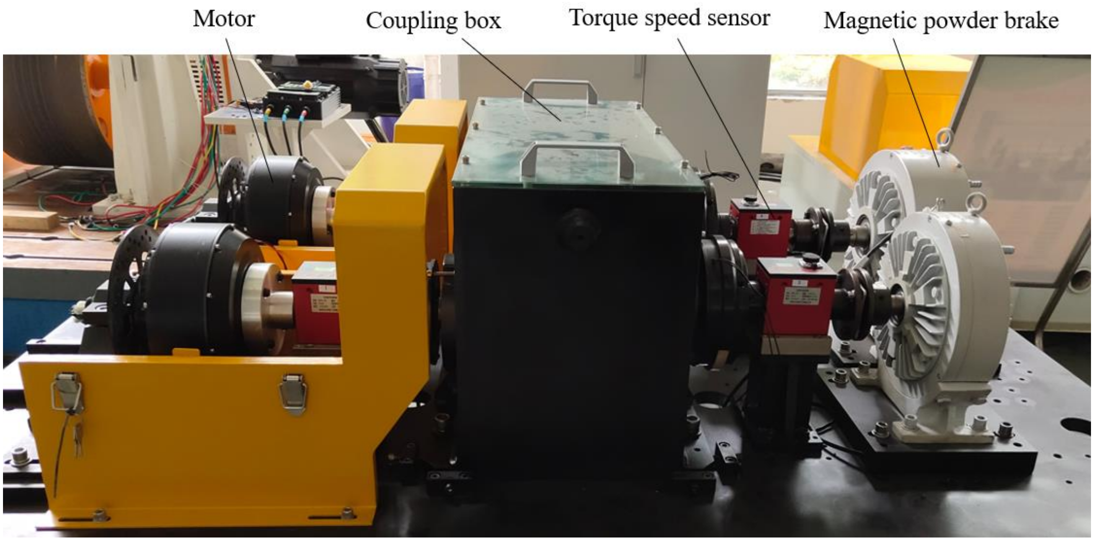
The traditional genetic algorithm is a heuristic search algorithm that relies on individuals within the population to conduct the search. In some instances, the genetic algorithm may converge to a local optimal solution and fail to identify the global optimal solution.

Therefore, this proposes some improvements to the traditional genetic algorithm and incorporates the adoption of an elite retention strategy (*Yu et al., 2023*). The basic idea is to directly copy the best-fit individuals in the current population into the next generation to ensure that these excellent individuals will not be eliminated due to selection, crossover, and mutation operations. It addresses the limitations of genetic algorithms, such as getting stuck in local optimal solutions, slow convergence speed, and loss of excellent solutions, by preserving excellent solutions, speeding up convergence, safeguarding genetic information of excellent solutions, and enhancing the stability of the algorithm. Finally, an improved algorithm is used to reoptimize the fuzzy control table.

Establishment of Theoretical Model

This paper presents a design for a test platform that aims to achieve precise control of the dual-motor power system of an electric tractor. The platform also aims to optimize performance, verify and improve energy management strategies, and ensure system safety under simulated conditions.

Test platforms offer several advantages, such as improved control accuracy, enhanced dynamic response, and efficient energy management. They also increase system flexibility and adaptability while reducing development risks and costs. Different power coupling and motor combination methods can be adapted to cope with various working conditions. The motor drive is controlled through the motor drive controller, and the power is output to the load through the coupling box. The platform obtains optimal key and operating parameters through testing, meeting the power requirements of different workloads while reducing energy consumption, improving the efficiency of the drive system, and extending the reliable working time. The actual picture of the bench is shown in Figure 9.



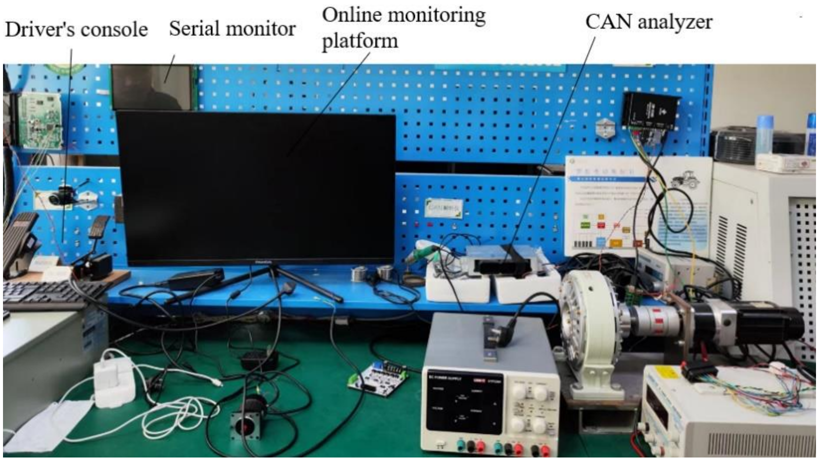


Fig. 9 - Actual picture of the bench

In order to verify the effectiveness of the electric tractor control system and the transmission performance of the dual-motor drive system, through the above experimental bench, the bench test was carried out. According to the above, the bench test is only for the dual-motor coupled-drive electric tractor under the coupling box for the torque coupling mode.

- **Steady state load experiment**

To check the functional status of the complete machine controller, first power on the complete machine test system. Then, turn the key switch and adjust it to the forward gear to start the main motor and auxiliary motor. After that, adjust the magnetic powder brake to ensure its simulated load torque stays stable at 500 N·m. During this process, the operator needs to depress the accelerator pedal. At this moment, the system will collect and calculate the signals of the pedal opening and its change rate, convert these signals into speed and torque signals, and transmit them to the motor controller. The power is then transferred to the output shaft via the coupling box. As the speed of the output shaft gradually increases from zero, the data will be collected after stable operation, and the speed curve and power curve will be obtained by fitting the data.

- **Dynamic load experiment**

In order to simulate and test large load changes in field operations, the load of an electric tractor's working environment must be limited to a range with upper and lower limits. The experiment begins with powering on and detecting the entire test system to confirm the normal operation of the entire machine controller. The main motor and auxiliary motor are then started by turning the key switch and adjusting the gear to the forward position. The magnetic powder brake is adjusted to simulate a load torque of 450 N·m and manually adjusted to achieve a load variation range of approximately 200 N·m. As the accelerator pedal is depressed, the whole machine controller begins to collect and calculate signals of the pedal opening and its rate of change. These signals are then converted into speed and torque signals and sent to the motor controller through the coupling box. The power is transmitted to the output shaft and the rotation speed of the output shaft gradually increases from zero, while data collection begins. Finally, the rotation speed and power curves are obtained.

RESULTS AND DISCUSSION

Model Validation

There are two primary transportation conditions for tractors: field transfer and suburban road transportation. Therefore, the suburban low-speed working condition EUDC (Extra Urban Driving Cycle) is referred to as the test condition for tractor transportation, as shown below:

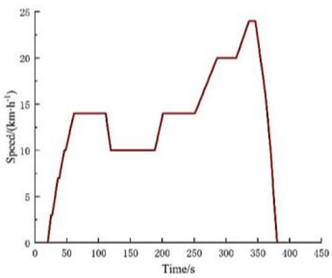


Fig. 10 - Tractor speed under road transport condition

The simulation time for the working condition is set to 400 seconds, with a maximum vehicle speed of 24 km/h during operation and an average vehicle speed of 12.49 km/h.

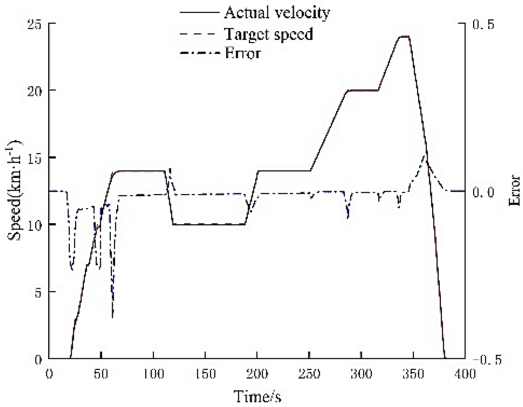


Fig. 11 - Speed tracking under road transport condition

Fig. 11 illustrates that the simulated vehicle speed of the tractor has a high degree of followability with the set target operating speed. The absolute maximum deviation between the simulated vehicle speed and the target operating speed is 0.391, while the absolute mean deviation is 0.021. The error is minor and does not affect the actual transportation situation, so it can be ignored. Therefore, it can be demonstrated that the construction of the entire vehicle model is highly accurate and can genuinely and effectively reflect the actual working conditions of the tractor.

Analysis of Simulation Results of Ploughing Test Conditions

The theoretical value can be obtained from the tractor's traction resistance calculation formula. However, in real-world conditions, ploughing is influenced by various factors, including soil conditions, ploughing depth and width, and driver's operation. As a result, the traction resistance experienced by the tractor is not constant. Therefore, the ploughing test condition depicted in the figure is established. In this scenario, the average traction resistance is 3657.64 N, the average vehicle speed is 6.11 km/h, and the simulation time is 1200 s. The specific working conditions are shown in the Fig. 12.

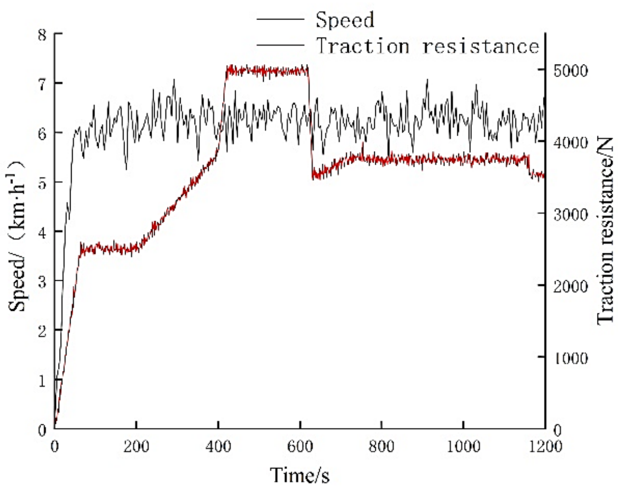
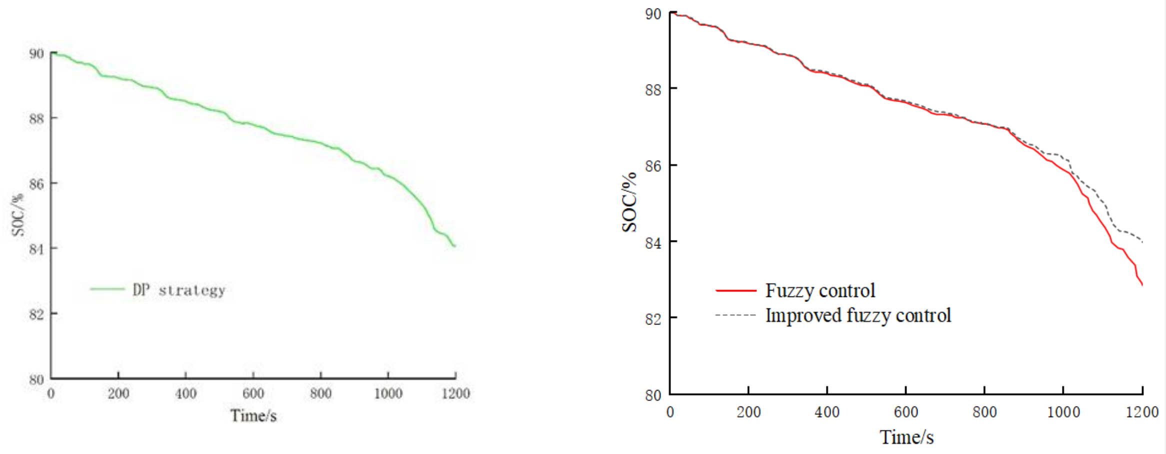


Fig. 12 - Tractor speed and traction in ploughing test conditions

- **Results of Dynamic Programming**

The SOC of the battery indicates the remaining capacity of the battery, while its magnitude indicates the amount of energy stored in the battery. The Fig. 13(a) illustrates the battery SOC change curve for the energy management strategy under ploughing cycle conditions. It is evident from the figure that the SOC change curve of the dynamic programming algorithm changes relatively smoothly. At the conclusion of the final operating cycle, the battery SOC termination value, determined using the dynamic programming algorithm, is 84.06%.



(a) Soc change curve 1 *(b) Soc change curve 2*

Fig. 13 - Soc change curve

- **Results of Fuzzy Logic Control**

The fuzzy control strategy was simulated under test conditions. The battery SOC change curve is shown in Fig. 13(b) above and compared with the improved fuzzy control strategy.

It is evident from the figure that in the early 400 s of the working condition, the variance in battery power consumption between the two energy management strategies is relatively small. However, as the operating time of the working condition increases, the disparity between the two gradually becomes larger. After the final operating cycle, the battery SOC termination value using the fuzzy control algorithm was 83.31%, whereas the SOC termination value based on the control strategy optimized by the improved genetic algorithm was 83.73%. The improved control strategy was compared with the SOC of the fuzzy control strategy. It has been improved, and the fluctuation of SOC is also smaller. Therefore, it distributes the output of the two motors more reasonably, also better improves the economic performance of the tractor, and is more adaptable to the tractor's working conditions.

Compared with the fuzzy control strategy, the average power consumption based on the improved fuzzy control strategy is reduced by 8.8%, and the average power consumption based on the dynamic programming strategy is reduced by 10.5%. The entire test condition is based on the improved fuzzy control strategy and shows a SOC change trend similar to the dynamic programming strategy, and the change range is less than 2%. Therefore, compared with the fuzzy control strategy, the other two distribute the output of the two motors more reasonably and better improve the economic performance of the tractor. This further demonstrates that the fuzzy control strategy based on improved genetic algorithm optimization has a better economy and working condition adaptability.

Table 4

Comparison of the simulation results

	Fuzzy Control	Improved Fuzzy Control	DP
SOC termination value/%	83.31	83.98	84.06
SOC change value/%	6.69	6.02	5.94
Power consumption per kilometer	1.60	1.46	1.43
Energy consumption reduction ratio/%	—	8.8	10.5

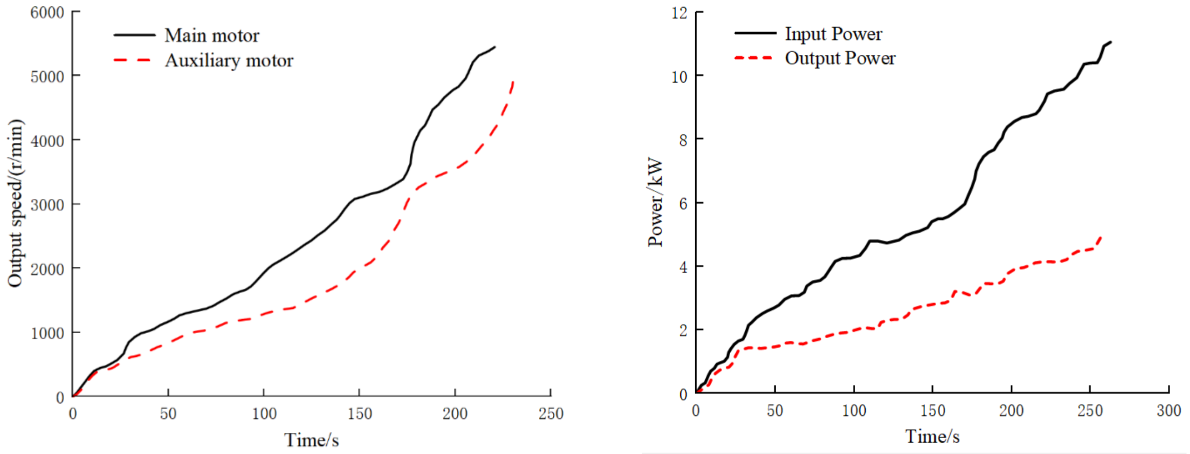
After analyzing the simulation results of three different working conditions, it was found that the energy management strategy based on improved fuzzy control is as effective as the strategy based on dynamic programming, while also making up for the flaw of poor real-time performance that the latter has. Moreover, compared to the fuzzy control strategy, the improved fuzzy control-based strategy is more efficient in reducing the energy consumption of the vehicle and is better suited to adapt to various working conditions.

Analysis of Bench Test

- **Results of Steady State Load Experiment**

In Figure 14(a), the output speeds of the two motors under steady load are displayed. As the main motor's output speed increases, the output torque of the auxiliary motor also increases steadily. The maximum speeds for the main motor and the auxiliary motor are 5432.6 r/min and 4667.7 r/min, respectively.

Figure 14(b) shows the power variation curve, and by analyzing this data the system efficiency can be derived by calculating the ratio of input power to output power. Upon observing this curve, it can be seen that at around 200 seconds, the ratio of output power to input power reaches its peak value. At this time, the efficiency of the entire system is at its maximum, which is about 70%.



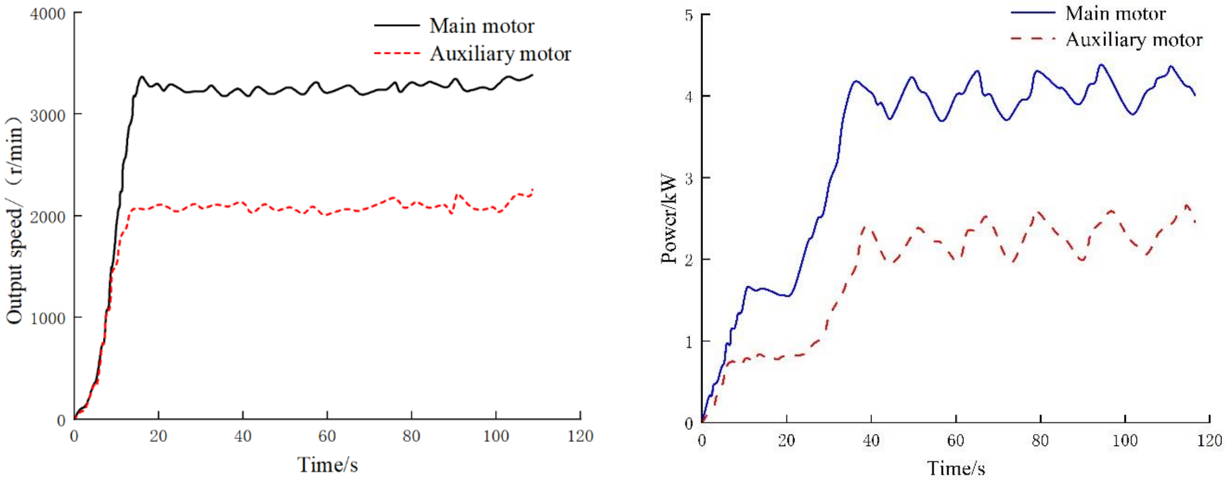
(a) Speed curve under constant load *(b) Power curve under constant load*

Fig. 14 - Results of steady state load experiment

- **Results of Dynamic Load Experiment**

Figure 15(a) shows that the output speeds of the main motor and auxiliary motor fluctuate within a range of 120 r/min due to load changes. The two motors' rotational speeds increase from 0 to 16 seconds and then stabilize, maintaining a relatively fixed range. After 16 seconds, the output speed of the entire drive system remains stable.

Figure 15(b) shows that load changes significantly impact the input and output power of the complete machine drive system, resulting in obvious fluctuations. By calculating the ratio of input power to output power, the overall system efficiency changes can be observed. When the load of the whole machine increases, the power of the main motor and the auxiliary motor increases simultaneously, improving the efficiency of the entire machine. Conversely, when the load of the whole machine decreases, the power of the main motor and the auxiliary motor decreases, reducing the overall machine efficiency.



(a) Output torque curve under dynamic load *(b) Input power curve under dynamic load*

Fig. 15 - Results of dynamic load experiment

The fluctuation range of the two motors is around 1 kW, and the power ratio of the two motors fluctuates between 1.11 and 2.79. The input power of the two motors can be distributed according to the control strategy following the load fluctuation. The highest efficiency is 79%, with a load torque of 405 N·m, main motor power of 3.5 kW, and auxiliary motor power of 1.91 kW.

CONCLUSIONS

This paper aims at the issue of inadequate power in single-motor-driven electric tractors when faced with complex working conditions and high power demands. Based on the dual-motor coupling drive system scheme, a simulation model is constructed, and detailed simulation verification of road transportation cycle conditions is carried out. The results indicate that the established vehicle, battery, and motor models demonstrate good accuracy and rationality. They can effectively simulate energy flow and power transmission under actual working conditions.

The dynamic programming strategy is capable of achieving globally optimal energy management effects in theory. However, it relies on preset settings and offline calculations, which limit its application in real-time changing working environments and its ability to adapt to real-time adjustments to working conditions. On the other hand, the fuzzy control strategy, based on an improved genetic algorithm optimization proposed in this article, has demonstrated significant practical value in simulation experiments. Simulation data shows that this strategy exhibits similar SOC curve trends and a smaller gap compared to the dynamic programming method. In comparison to the original fuzzy control strategy, this strategy reduces the average energy consumption by 5.6%, significantly enhancing the efficiency of the drive system. The enhanced endurance of the electric tractor directly reflects the effectiveness of the fuzzy control energy management strategy optimized by the improved genetic algorithm. This optimization demonstrates clear advantages in economic performance and superior real-time adaptation to changes in working conditions. It is feasible and superior. In future research, the potential loss mechanisms in dual-motor coupled-drive electric tractor systems will be further explored and efforts will be made to develop a comprehensive and accurate loss model to quantitatively analyze the interaction between mechanical coupling devices, transmission components, and motors. The focus will not only be on the direct physical losses during the power transmission process, such as friction losses, energy dissipation caused by torque fluctuations, and the efficiency of the coupling equipment itself but also the energy interactions that may occur when motors work together under different working conditions, leading to low conversion efficiency, will be considered.

Simulation and bench test results show that the power coupling gearbox designed in this paper can meet the functional requirements of the electric tractor dual-motor drive system; the designed drive control strategy can achieve power distribution and control effects of the two motors under different working conditions. The response speed is good and can meet the power needs of the real drive system.

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