Research on Energy Management Strategy of Pure Electric Vacuum Vehicle Based on Fuzzy Control

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The current pure electric vacuum vehicle is equipped with main and auxiliary motors, and the two motors work independently without affecting each other. The traditional auxiliary motor usually operates with constant power while the main motor is only responsible for the vehicle driving. The lack of cooperation between the two motors results in high energy consumption. Therefore, formulating a reasonable strategy for the two motors has a significant effect on the performance of the vacuum vehicle. This paper takes a pure electric vacuum vehicle as an example to propose an energy management strategy based on fuzzy control. First, for the working motor, a fuzzy controller is designed by taking the vehicle speed and acceleration as input and motor speed and torque as output. Therefore, the vacuum vehicle can automatically adjust the operating power of the cleaning system according to the real-time road conditions; the driving motor control strategy adopts a closed-loop control strategy that combines driver input and vehicle state parameter feedback based on considering the operating motor. Finally, the effectiveness of the strategy is verified by simulation. The results show that the energy-saving control strategy effectively reduces the power consumption per 100 km and increases the driving range, which is of great significance to the development and design of the vacuum vehicle.

Keywords: pure electric vacuum vehicle, energy management strategy, fuzzy control, control strategy, energy-saving

1 INTRODUCTION

As the country pays more and more attention to environmental issues, the traditional working methods of road sanitation workers can no longer meet the current needs. As a road cleaning vehicle, the vacuum cleaner effectively relieves the pressure on sanitation and plays an important role in improving the environment. However, compared to the developed countries, domestic vacuum vehicles have some disadvantages, such as noise, and have more power consumption (Zhang, 2020). Different from the pure electric vehicle driven by dual motors (Ruan and Song, 2019; Wu et al., 2019; Wu and Zhang, 2021), for the research object of this article, the main motor is equipped to drive the car, and the auxiliary motor provides power for the bodywork system (Yang, 2016), so a reasonable strategy is developed for the two motors. It has a great effect on the working performance of the vacuum vehicle.

Lee (Lee et al., 2019), Wang (Wang et al., 2021), Kant (Kant et al., 2021) et al. have optimized the structure of the motor to make its performance more prominent, and the focus of this paper is mainly on the control strategy. The drive motor in this paper is similar to the traditional car, and the research
strategies to reduce energy consumption mainly focus on the drive control strategy, the regenerative braking energy feedback strategy, and the power limiting strategy (Zhang, 2014). At the same time, different scholars have applied different control methods to achieve the ideal effect. Luo et al. select the corresponding drive mode to give appropriate torque compensation according to the driver’s operation intention and improves the power and economy of pure electric vehicles (Luo and Niu, 2020). Ye et al. use a fuzzy control method to determine the ratio of mechanical braking force and regenerative braking force according to different braking intensities to formulate energy recovery control strategies (Ye et al., 2021). Justo et al. proposed a control strategy to predict torque using the fuzzy model of the permanent magnet synchronous motor of an electric vehicle, and the control is simple (Justo et al., 2017). At the same time, the energy management strategy based on fuzzy rules can realize the power distribution of the power system by setting the logic threshold, thereby improving the economy of the vehicle (Guo et al., 2021).

The working motor is only used in some special vehicles, and scholars have not studied it much, Dong constructed a torque control model of the multi-motor power system of an electric sweeper based on a fuzzy control strategy (Dong, 2019). Wang et al. developed and validate an efficiency model for electronically commutated motor fan systems (Wang et al., 2020). Long established the mathematical model of the control relationship of the hydraulic motor tracking servo motor, and the PID parameter setting combined control algorithm is adopted (Long et al., 2018). Shao designed a digital throttle control scheme for the speed of the disc brush motor using a fuzzy control algorithm so that the speed of the disc brush can be adjusted automatically, but the power consumption is not taken into consideration (Shao, 2005).

In addition, the research on multi-motor systems mainly considers the torque distribution between motors (Zhai et al., 2016; Liu et al., 2019), which provides certain ideas for multi-motor power systems. However, in general, there are few studies on energy-saving strategies for multi-motor commercial vehicles with large energy consumption. In this paper, for a certain pure electric vacuum vehicle, comprehensively considering SOC, vehicle speed, operating conditions, etc., an energy-saving strategy for pure electric vacuum vehicle based on fuzzy control is established. The torque output of the two motors is controlled separately, and the Simulink-Cruise joint simulation model verifies the economics of the strategy.

2 OBJECT DESCRIPTION

Pure electric vacuum vehicles use batteries as power sources to drive motors to realize the vehicle’s walking and operating functions. Therefore, they can be divided into two parts: the driving system and the working system. According to the needs of vacuum vehicles, they can be equipped with single or dual motors. The research object of this paper is a dual-motor arrangement type. The main motor (that is, the driving motor) drives the vacuum vehicle to travel, and the auxiliary motor (that is, the working motor) provides power for the working device. The block diagram is shown in Figure 1. The vehicle and motor parameters of the research vehicle are shown in Table 1.

3 MODEL ESTABLISHMENT

3.1 Driving Model

During the driving process, the vehicle is affected by driving resistance, slope resistance, air resistance, and acceleration resistance. The required torque of the driving motor can be calculated by the dynamic equation of the driving system:

\[
\frac{Ti_o \eta_i}{r} = mg f \cos \alpha + mg \sin \alpha + \frac{C_d A u^2}{21.15} + \delta m \frac{du}{dt}
\]

where, \( T \) is the required torque, \( i_o \) is the transmission ratio, \( i_0 \) is the main transmission ratio of the differential box, \( \eta_i \) is the transmission efficiency, \( r \) is the wheel rolling radius, \( m \) is the mass of the vehicle, \( g \) is the acceleration of gravity, \( f \) is the rolling resistance coefficient and \( \alpha \) is the slope angle. \( C_d \) is the coefficient of air resistance, \( A \) is the windward area, \( u \) is the vehicle speed, and \( \delta \) is the conversion coefficient of the rotating mass.

3.2 Operating Model

In the operating system, the auxiliary motor mainly provides power for the fan and hydraulic components. The fan generates negative pressure and uses the force generated by the pressure to
suck in garbage and dust. The hydraulic components are used to achieve the lifting and moving of the suction cup (Zhang, 2019). Since the power consumed by hydraulic components is much lower than the fan. It is ignored and only the power consumed by the fan is taken into consideration.

The needed torque of the working motor is:

\[ T_{fan} = \frac{9550QP \times 130\%}{\eta_f n_f \rho} \]  

(2)

Where, \( Q \) is the air volume, \( P \) is the air pressure, \( \eta_f \) is the working motor efficiency, \( n_f \) is the working motor speed, and \( \rho \) is the force rate.

### 3.3 Motor Model

The motor has complex structure and varies methods to establish its model with different complexity. In this case, the model is part of the vehicle, the performance of the components inside the motor is ignored. Thus, a simplified model with the torque and power characteristics is established (Tian et al., 2020). When the motor speed is less than the base speed, the motor works in the constant torque region, and the output power increases with the increase of the speed. When the motor speed is greater than the base speed, the motor works in the constant power area, and the output torque decreases as the speed increases. The motor's operating characteristics are shown as the following equation.

\[ P_m = \frac{T_m n}{9550 \eta_m} \]  

(3)

Where, \( P_m \) is the motor output power, \( T_m \) is the motor output torque, \( n \) is the motor speed, and \( \eta_m \) is the motor efficiency.

The operating characteristic of the electrical motor is shown in Figure 2. The motor efficiency changes with the output speed and torque. The efficiency map of the driving motor is shown in Figure 3.

### 4 ENERGY MANAGEMENT STRATEGY

#### 4.1 Working Strategy

For traditional road vacuum vehicles, when the vacuum suction system is operating, it will clean the road garbage with constant power. Since the amount of garbage on the road does not always remain in a large state, the bodywork system of the vacuum vehicle always working at the same power will inevitably cause unnecessary energy loss (Li, 2020).

At the same time, during the operation of the electric vacuum vehicle, the relationship between the rotation speed, torque, and vehicle speed of the working motor is non-linear, which makes it impossible for us to establish an accurate mathematical model of the operation system. Therefore, a fuzzy controller is designed. It allows the vacuum vehicle to automatically adjust the operating power of the auxiliary motor according to the real-time road conditions, to achieve the goal of energy-saving.

During the operation, the driver adjusts the speed of the vehicle based on the garbage and dust on the road. At the same time, the cleaning efficiency decreases with the increase of the vehicle speed (Li et al., 2019), so when the driver recognizes that there is a lot of garbage on the road, he often reduces the vehicle speed and improves the cleaning degree. With the change of the vehicle speed, the rotation speed and torque of the working
motor also varies. Therefore, this paper selects the vehicle speed $v$ and acceleration $a$ as the input, and the rotation speed of the working motor $n$, Torque $q$ is the output, and a two-dimensional fuzzy controller is designed.

In the fuzzy control module, the fuzzy subsets, domains, and membership functions of input and output variables are defined. The explanation is as follows: The domain of the vehicle speed during the operation of the vacuum vehicle is set as $(0, 20)$ km/h, and the fuzzy subset is taken as $(S, MS, M, MB, B)$, which indicate that the vehicle speed is at low speed, low-to-medium speed, medium speed, medium-to-high-speed, and high-speed state respectively, the domain of the vacuum vehicle acceleration $a$ is determined as $(-1, 1)$ m/s$^2$, and its fuzzy subset is taken as: (NB, NS, ZO, PS, PB). It represents the acceleration is negatively large, negatively small, zero, positively small, and positively large. For output, the fuzzy domain of the operating motor speed $n$ is determined to be $(1500, 3500)$ r/min, use $(S, MS, M, MB, B)$ to correspond to low speed, medium-low speed, medium speed, medium high speed, high-speed. The fuzzy domain of torque $q$ is $(50, 100)$ Nm, $(S, MS, M, MB, B)$ indicates that the working motor is in the state of the small, medium-small, medium, medium-large, and large torque, respectively.

The membership function is often formulated based on experience. This article refers to some related literature (Cui et al., 2019; Luo et al., 2021). At the same time, according to the simulation analysis and theory, the membership function is adjusted to make it adapt to the energy control strategy. The membership degrees of input and output variables are shown in Figure 4:

The corresponding fuzzy rules follow the following principles:

1) Under the premise of ensuring the cleaning efficiency, when the vehicle speed increases and the acceleration is relatively large, cleaning the road with the same garbage level requires greater power of the working motor, and the speed and torque of the working motor should be increased;

2) When the vehicle decelerates and the acceleration is small, it is less difficult to vacuum. To reduce energy consumption, the rotation speed and torque of the working motor should be reduced accordingly.
Based on the above rules, the fuzzy logic rules expressed by if-then sentences are established, and the inference surface of fuzzy control deduced is shown in Figure 5.

4.2 Driving Strategy
The driving strategy should meet the drivers’ intention while maintaining the motor works in the relatively high efficiency region. The proper driving strategy could extend the mileage of the electric vehicle (Asher et al., 2019). The drive motor torque control strategy proposed in this paper adopts a closed-loop control strategy that combines driver input and feedback of the vehicle state parameter. It does not only reflect the driver’s actual driving intentions but also considers the current vehicle system state. Figure 6 illustrates the torque control architecture. Among them, the output torque is defined as:

\[ T = T_{eco} + T_{com} \]  

Where, \( T_{eco} \) is the economic torque, \( T_{com} \) is the compensation torque, and \( T_{act} \) is the actual torque.

4.2.1 Economic Torque MAP
During the operation of the vacuum vehicle, the driver obtains different required motor torques by controlling the position of the accelerator pedal. The operating characteristics of the motor can well meet the vehicle’s high torque at low speed and high power demand at high speed. To make the torque output corresponding to different accelerator pedal position more uniform, this paper will adopt the following interval division:

\[ T_{e} = \begin{cases} 
LT_{max}, & n \leq n_c \\
\frac{9550LT_{max}n_e}{n}, & n > n_c 
\end{cases} \]  

Where, \( T_{e} \) is the target demand torque, \( L \) is the torque load factor, \( T_{max} \) is the peak torque of the motor, \( n_c \) is the base speed, and \( n \) is the current speed of the motor.

It can be seen from Figure 3 that the working efficiency is the highest when the motor speed \( n \) is within the range of 1700–4500 rpm, and the accelerator pedal position \( S \) is set as 40–80%. The relationship between them is shown in Table 2. According to Eq. 7, the relationship between the vehicle speed and rotation speed of the motor is established.

\[ n = \frac{i_gi_0u}{0.377r} \]  

Where, \( i_g \) is the transmission ratio, \( i_0 \) is the main reducer transmission ratio, \( u \) is the vehicle speed and \( r \) is the wheel rolling radius.

In this case, the corresponding vehicle speed is around 34 km/h-91 km/h. Assuming that the vehicle is driving at a constant speed on the road without any slope, ignoring the gradient
resistance and acceleration resistance, the following formula can be obtained:

$$T_{\text{need}} = \left( mgf + \frac{C_d A u^2}{21.15} \right) \frac{u}{3600 \eta_i} \frac{9550}{n} \quad (8)$$

Where, $T_{\text{need}}$ is the demand torque.

Define the torque load factor $L$. The relationship between the speed and torque load coefficients obtained is shown in Table 3.

$$L = \frac{T_{\text{need}}}{T_{\text{pmax}}} \quad (9)$$

Where, $T_{\text{pmax}}$ is the maximum torque, which can be obtained from Figure 2.

Using the curve for fitting, the relationship between the accelerator pedal position $S$ and the torque load coefficient $L$ is shown in Figure 7.

It can be seen from Figure 7, that when the accelerator pedal opening is small, the corresponding torque load coefficient is small and at the same time torque difference is small, this makes the maneuverability of the vehicle better. It is conducive to the long-term stable driving of the pure electric vacuum vehicle. When the accelerator pedal opening is increased, the torque difference increases and the motor demand torque response is more sensitive. The final economic torque MAP is shown in Figure 8.

4.2.2 Compensation Torque

From Formula 5, when the economic torque found by the actual speed is less than the actual torque, a compensation torque is set, otherwise, the compensation torque is 0. In this paper, a compensation torque fuzzy controller is designed to obtain the value of $\Delta T$.

The acceleration pedal change rate, operating motor speed, and battery SOC were selected as input variables to calculate the compensation torque increment by fuzzy reasoning.

The fuzzy subsets of SOC are defined as: (S, M, B), representing low, medium, and high respectively; The input range of operating motor speed is defined as 1500–3500 r/min, and (S, M, B) is used to correspond to low, medium and high-speed states. The input of acceleration pedal opening change rate is defined as $-1 \sim 1$, and it is defined as (S, MS, M, MB, B) in the case of slow to urgent.

In the operation process, when the SOC is high, the operating motor speed is low, and the acceleration pedal opening change rate is large, it reflects that the driver has a high-power driving demand, and relatively high compensation torque is given. When the SOC is low, the operating motor speed is high, the acceleration pedal change rate is small, the driver’s power demand is relatively low and the compensation torque is small.

At the same time, considering that the sudden change of torque during the driving process of the vehicle will cause a greater impact, which will affect the ride comfort, it is necessary to consider the limit of the impact degree when determining the compensation torque increment (Wan, 2016), the expression of the impact degree:

| $n$ (rpm) | 1700 | 2400 | 3100 | 3800 | 4500 |
|-----------|------|------|------|------|------|
| $S$ (%)   | 40   | 50   | 60   | 70   | 80   |

| $n$   | 1700 | 2400 | 3100 | 3800 | 4500 |
|-------|------|------|------|------|------|
| $S$   | 40%  | 50%  | 60%  | 70%  | 80%  |
| $T_{\text{need}}$ | 50.4 | 57.2 | 66.2 | 77.6 | 91.2 |
| $T_{\text{pmax}}$ | 561.7 | 398 | 308 | 251.3 | 212.2 |
| $L$   | 0.09 | 0.144 | 0.216 | 0.308 | 0.4309 |

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| $L$   | 0.09 | 0.144 | 0.216 | 0.308 | 0.4309 |
Where, \( j \) is the impact received while driving, also called the rate of change in acceleration, \( \eta_t \) is the transmission efficiency.

From Formula 10, it can be obtained that the impact degree of the vehicle during driving is proportional to the rate of change of torque. The German shock degree standard stipulates \( j \leq 10 \text{ m/s}^3 \), substituting the vehicle parameters and taking a 10% margin, the maximum value of the compensation torque \( \Delta T \) is 60.1 Nm. The membership degrees of input and output variables are shown in Figure 9. The fuzzy rules of torque compensation are shown in Table 4.

### TABLE 4 | Torque compensation fuzzy rules.

| SOC | Operating motor speed | Acceleration pedal opening change rate (%) |
|-----|-----------------------|-------------------------------------------|
|     | S                     | MS                                       | M  | MB | B   |
| B   |                      | MS                                       | M  | MB | B   |
| M   |                      | MS                                       | M  | MB | B   |
| S   |                      | S                                        | MS | M  | MB  |
|     |                      | M                                        | M  | MB | B   |
| M   |                      | S                                        | MS | M  | MB  |
| B   |                      | S                                        | MS | M  | MB  |
| S   |                      | M                                        | MS | M  | MB  |
|     |                      | S                                        | MS | M  | MB  |

\[
 j = \frac{d^2 u}{dt^2} = \frac{1}{m} \left( \frac{\eta_t}{r} \frac{dT}{dt} \right)
\]  

(10)
This paper uses a pure electric vacuum vehicle as the research object to verify the effectiveness and superiority of the strategy. AVL Cruise software is used to build a vehicle model, and the energy-saving control model analyzed is built in MATLAB/Simulink software. In the simulation process, the performance of the original strategy, design strategy, and CRUISE strategy are compared. The original strategy refers to the strategy that the bodywork system works with the same power and there is no vehicle state feedback during driving. The CRUISE strategy refers to the strategy that comes with the CRUISE software and uses a linear method to adjust the power of the bodywork. The results were analyzed by co-simulation.

### 5.1 Establishment of Operating Conditions

Setting the condition is an important step in AVL CRUISE software simulation. The operating conditions of pure electric vacuum vehicles include working conditions and transition conditions, in which the working conditions account for more than 75% (Ma et al., 2018). Referring to the establishment process of NEDC, Tang et al. constructed a typical working condition of a sweeping vehicle (Tang, 2020). In this paper, part of the working conditions spectrum of CHTC is selected as the reference for transition conditions. Where, CHTC condition is the driving condition for Chinese automobiles used by the commercial vehicles with a total mass greater than 5500 kg. It includes the urban cycle (342 s), suburban cycle (988 s), and high-speed cycle (470 s). And the working conditions of vacuum vehicles in a
certain area are combined to build the spectrum of the operating condition as shown in Figure 10.

5.2 Simulation Analysis

In the case of a vacuum vehicle running in AVL CRUISE software, Figure 11 shows the comparison of SOC change trends under three strategies. The SOC decreases at a lower rate when energy-saving strategies are initiated. The original strategy has the minimum SOC at the end of the simulation.

Figure 12 shows the distribution of the working efficiency points of the driving motor. According to the simulation results, although the control strategy requires the motor to work in the optimal region, the driving motor must meet the requirements of high-speed transition, while the vacuum vehicle has been operating in the low-speed zone for a long time, most of the working points are in the range of 78–88%. The proportion of efficiency points in the high-efficiency area of motors with energy management strategies has increased compared with the original strategies.

Figure 13 is a comparison diagram of the power consumption of the working motor. It can be seen that the energy-saving strategy based on fuzzy control can automatically adjust the working power of the bodywork system. Compared with the other two strategies, the power consumption is smaller to achieve the effect of energy-saving. At the same time, it can be seen from the figure that the working motor of the vacuum vehicle is turned on under the working condition, and after the 750s, it is the transition condition, and the working motor does not work.

The energy consumption per 100 km and the driving range obtained in the AVL CRUISE with the three strategies are compared in Table 5.

According to the simulation results under the constructed vacuum vehicle operating conditions, the energy consumption per 100 km of the vehicle is reduced from 88.35 kWh/100 km in the original strategy and 75.65 kWh/100 km in the Cruise strategy to 70.09 kWh/100 km in the design strategy. With a lower energy consumption, the charging and discharging time of the battery can be decreased, which means its life cycle can be extended.

Overall, the energy management strategy of the vacuum vehicle established in this paper reduces the power consumption per 100 km by 20.66%, and the driving range increases by 20.62%. In summary, the energy-saving strategy of electric vacuum vehicles based on fuzzy control proposed in this paper can effectively benefit the battery life cycle, reduce battery energy consumption and increase driving range.

6 CONCLUSION

To reduce the energy consumption of pure electric vacuum vehicles during operation, an energy management strategy based on fuzzy control is proposed. To verify the feasibility and superiority of the proposed control strategy, a vehicle dynamics model was established by AVL CRUISE and evaluated on the Simulink/CRUISE co-simulation platform. The conclusions of the study are as follows:

1) Based on the current road condition and vehicle status, the proposed fuzzy controller succeeds in managing the rotation speed and torque of the operating motor in a relatively high-efficiency region.

2) According to the simulation, compared with the original strategic control, the energy-saving strategy proposed in this paper reduces the economic performance index (power consumption per 100 km) by 20.66% and extends the driving range by 20.62%.

Since the energy consumption of the hydraulic system and mechanical lifting system is much lower than the motors, they are ignored. Therefore, the accuracy of the established model can be further improved by considering these factors in the next stage. Hence, the superiority of the proposed control strategy can be enhanced.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

YW contributes to the writing of the manuscript, SZ provides the idea of this paper. YL and LZ help YW to finish this work.

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