Optimized control design of sliding plug door for high-speed EMU

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Abstract. With the continuous improvement of people's requirements for the convenience of going out, high-speed EMUs came into being. As one of the important components of the high-speed EMU, the sliding plug door is located at the junction between the carriage and the carriage, and is one of the important passages for passengers. When the EMU is running at high speed, once the control system fails, it will cause damage to the personal safety and interests of passengers. Therefore, as the speed of the EMU increases, the stability of the electric end door control system of the EMU also needs to be enhanced. First, analyse the motor drive process of the sliding plug door control system, design the sliding plug door control system at the hardware level, and build an experimental platform for analysis and testing. Because the operating environment of high-speed EMUs is very complicated, in order to make the sliding plug door control system work stably for a long time, it is necessary to analyse the overall process of the sliding plug door opening and closing movement in stages, and adopt fuzzy-PID combined control. The algorithm further optimizes the movement process. The control method of the brushless DC motor is digital control, and the rotation speed of the motor is controlled by controlling the duty ratio applied to the motor side. Finally, through experimental testing, it is verified how the fuzzy-PID combined control algorithm can improve the stability of the door opening and closing movement.

Keyword: fuzzy-PID brushless DC motor EMU electric end door

1. Introduction
As a part of the EMU, the sliding plug door control system puts forward higher requirements for its stability. By analyzing the overall flow of the sliding plug door opening and closing, using the digital fuzzy-PID combination algorithm, it is aimed at different stages of motion. Use different control algorithms to optimize the control process of the sliding plug door to meet the technical requirements of the sliding plug door control system.

2. Motion process optimization control of sliding plug door control system for high-speed EMUs
The core of the electric end door control system of the EMU is the drive control of the brushless DC motor to ensure that the sliding plug door of the motor can smoothly realize the door opening and closing movement process according to the technical indicators. According to the overall architecture of the
sliding plug door control system and the various parts and control requirements, seek theoretical solutions and practical solutions.

2.1. **Operation platform of electric end door control system**

![Figure 1. The mechanical structure of the sliding plug door control system.](image)

The overall structure of the control system is shown in Fig 1. It is mainly composed of a brushless DC motor, a toothed belt, a controller that is easy to fix, and a double door body. When the drive motor rotates, the wheel axle will drive the toothed belt to move, which is equivalent to driving the pulley, thereby opening and closing the door. The distance between the door opening and closing position is 750 mm.

2.2. **The control requirements of the electric end door control system**

![Figure 2. Door opening and closing process.](image)

According to the control requirements of the sliding plug door control system of the high-speed EMU, the door opening and closing movement process of the double-leaf door is required to be completed as shown in Fig 2. After the brushless DC motor is started, it accelerates quickly, allowing the sliding plug door to enter high-speed and smooth operation Stage: After running smoothly for a period of time, control the motor to decelerate, the double-leaf end door enters low-speed operation, and then reach the designated position, the motor stops running. After the plug door receives the door opening command from the system, it will open the door first, then wait a few seconds, then close the door, and finally reach the designated position, continue to wait for the next command to trigger such a cyclic movement process.
2.3. Design of Digital Fuzzy PID Control Algorithm
The internal timer of the STM32F103 single-chip microcomputer has the function of specifically capturing Hall logic signals and outputting PWM pulse signals, which can adjust and process the speed and position of the sliding plug door.

2.3.1. Optimal control strategy of brushless DC motor. In order to strengthen the control of the brushless DC motor speed regulation process and realize fast and stable stepless speed regulation, this paper selects an adaptive fuzzy PID control algorithm to optimize the opening and closing process of the double sliding plug door [1, 2].

As shown in Fig 3, the design idea of the control scheme is: when the actual speed of the motor is inconsistent with the set speed, a speed deviation value ‘e’ will be generated. According to the size of the deviation value ‘e’, two different control strategies will be carried out. When ‘e’ is greater than the set boundary value ‘k’, enter the Fuzzy controller; When ‘e’ is less than the set boundary value ‘k’, the deviation value enters the PID controller for adjustment.

2.3.2. Optimal control strategy of brushless DC motor. The internal timer of the STM32F103 single-chip microcomputer has the function of specifically capturing the Hall logic signal and outputting the PWM pulse signal, and can adjust and process the speed, position and other information of the double-leaf end door. The principle of collecting the motor speed is to find the average speed through the count difference within the sampling time, which is regarded as the instantaneous speed. In the brushless DC motor selected in this article, the rotor contains 4 pairs of poles. It can be calculated that the number of Hall signal pulses per rotation of the motor rotor is:

\[ PPR = 2 \times 3 \times 4 = 24 \] (1)

As shown in Fig 4, the motor speed sampling period.
As shown in Fig. 4, the sampling time is 20ms. Since the Hall signal will trigger a capture event every 60°, the captured value is stored in the capture register 1 (CCR1), which is the result of the two transitions of the Hall signal. The period value T between. During the sampling time, accumulate each captured value to obtain the captured cumulative value, and then use the counting frequency of the Hall sensor interface timer to obtain the average frequency of the Hall signal:

$$f_{\text{HALL}} = \frac{f_{\text{TIM}} \cdot \text{CNT}_{\text{IT}}}{\text{CCR}_{\text{sum}}}$$  \hspace{1cm} (2)

Every time the timer goes through a sampling period, a new Hall signal frequency will be generated, and then through calculation, the motor speed formula is obtained:

$$\text{Spd} = \frac{60f_{\text{HALL}}}{\text{PPR}}$$  \hspace{1cm} (3)

Every 60° electrical angle, the Hall logic signal will undergo a jump, and the signal jump will trigger the counter to reset. Before the counter is reset, a capture event will be triggered to capture the current value of the counter into the capture compare register 1 (CCR1). After reset, the counter continues to count up from 0. When the count value is equal to the comparison value of the capture compare register 2 (CCR2), the TGRO signal jumps. The transition of the TGRO signal will cause the advanced timer TIM1 to trigger a COM event, thereby enabling the commutation control.

2.3.3. Optimal control strategy of brushless DC motor. Because the control system adopts digital control mode. Therefore, the traditional analog PID control algorithm, it is no longer applicable [3, 4]. It is necessary to discretize the PID control law, and then digital PID control can be realized in the form of software programming.

The discretization process of the traditional PID control algorithm. T is the sampling period, k is the sampling number, kT is recorded as time t, the integral part in the traditional PID formula is replaced by the summation method, the differential part is replaced by the numerical difference method, and the proportional part remains unchanged:

$$t = kT$$  \hspace{1cm} (4)

$$\int_0^t e(t) \, dt = T \sum_{j=0}^k e(jT) = T \sum_{j=0}^k e_j$$  \hspace{1cm} (5)

$$\frac{de(t)}{dt} = e(kT) - e[(k-1)T] = \frac{e_k - e_{k-1}}{T}$$  \hspace{1cm} (6)

Substituting Equation 4, Equation 5 and Equation 6, the discretized PID expression can be obtained as:
If the sampling period is small enough, the results obtained by the discrete PID control algorithm are also accurate enough, and the discrete control process is basically consistent with the continuous control process [5].

For the fuzzy control algorithm, select the 7 natural languages of Positive Large (PB), Positive Medium (PM), Positive Small (PS), Zero (0), Negative Small (NS), Negative Medium (NM), and Negative Large (NB) The variable value is used as the domain of speed deviation and duty cycle change. Five of them are selected as the domain of deviation change rate, and fuzzy rules are designed based on the following control idea: when the speed deviation is positive, the deviation change rate is also a positive value indicates that the motor speed error is increasing, and the duty cycle change amount should be selected to be positive (PB) to compensate as soon as possible. when the deviation change rate becomes negative (NS), it proves that the error is gradually decreasing, and the duty cycle The amount of change should be increased appropriately, select the middle (PM) [6, 7]. The fuzzy rule table is shown in Table 1:

| E | Ec | NB | NM | NS | 0 | PS | PM | PB |
|---|----|----|----|----|---|----|----|----|
| NB | NB | NB | NB | NB | NM | 0  | 0  | 0  |
| NS | NM | NM | NM | NM | 0  | PS | PS | PB |
| 0  | NM | NM | NS | 0  | PS | PM | PM | PM |
| PS | NS | NS | 0  | PM | PM | PM | PM | PM |
| PB | 0  | 0  | PM | PB | PB | PB | PB | PB |

The control effect of fuzzy-PID combined control method:

1. The soft start control method is adopted to gradually increase the duty cycle of the armature voltage during the motor start phase to ensure a smooth start.

2. Fuzzy algorithm is used to ensure that the motor speed change process is stable without overshooting, oscillation, etc.

3. The improved incremental PID algorithm with limit function is adopted to ensure the stable operation of the motor.

The realization process of this method:

1. Set as the switching threshold of the two algorithms, and continuously adjust according to the experimental results.

2. If the deviation value is, use an improved incremental PID control algorithm.

3. If the deviation value is, use the fuzzy control algorithm.

A new parameter needs to be introduced, the purpose of which is to improve the stability of system control. If the deviation is very small, the parameter can be introduced to avoid frequent speed adjustments by the control system; at the same time, the duty cycle incremental constant and the soft start period of the brushless DC motor can be introduced to ensure the motor The smoothness of the start-up process [8].

Combining the above, the optimization algorithm of fuzzy-PID combination can be written as:
\[
\Delta u_k = \begin{cases} 
A & (k < N) \\
\text{Fuzzy control rules} & (k \geq N, |e_k| > \epsilon) \\
K_p e_k + K_i \sum_{j=0}^{k} e_j + K_d (e_k - e_{k-1}) & (k \geq N, |e_k| \leq \epsilon)
\end{cases}
\]  

(8)

\[
e_k = \begin{cases} 
0 & (|e_k| \leq \delta) \\
e_k & (|e_k| > \delta)
\end{cases}
\]  

(9)

Through the input of the speed deviation value ‘e’ and the fuzzy-PID combined algorithm, the pulse width modulation signal’s duty cycle change ‘\(\Delta u\)’ is output [9, 10]. The output duty cycle change ‘\(\Delta u\)’ is superimposed with the original duty cycle, and the new duty cycle value is output through the single-chip microcomputer, which is applied to the three-phase bridge drive circuit to adjust the speed of the brushless DC motor.

3. Optimized control test for the movement process

Through the communication connection established between the computer and the experimental platform, collect and sort out the motor operating process data without adding the optimized control algorithm and the optimized control algorithm, and draw the sampled data through the Matlab programming software to obtain the comparison of the operating status of the door happening:

![Comparison of motor start and acceleration process.](image)

Figure 6. Comparison of motor start and acceleration process.

As shown in Fig. 6, it can be found that no matter it is the motor’s starting effect, acceleration and uniform motion effect, compared to before the optimization control algorithm is added, its running stability has been significantly improved.

Take the door opening process as an example, through the fuzzy-PID combined algorithm, the final motion state is shown in Fig. 7:
Figure 7. Optimized complete door opening process.

Record and summarize the opening and closing time of the optimized end door control system as shown in Table 2. It can be found that although the power supply voltage is higher, the door opening and closing movement process will be slightly shorter, and when the voltage is low, the movement process will be slightly longer. But the overall door opening movement time is maintained at about 3.2 seconds, and the door closing time is maintained at about 4.6 seconds. The deviation will not affect the stability of the end door control system, and its control accuracy meets the requirements.

Table 2. Plug door opening and closing schedule.

| Movement process | Voltage | Number of experiments | Maximum time | Minimum time | Average time |
|------------------|---------|-----------------------|--------------|--------------|-------------|
| Open the door    | DC24V   | 25                    | 3.12s        | 2.91s        | 3.04s       |
| Close the door   | DC24V   | 25                    | 4.57s        | 4.43s        | 4.51s       |

4. Conclusion
Through experimental comparison, it can be seen that the fuzzy-PID combined control algorithm can effectively solve the problems such as oscillation and overshoot during the operation of the sliding plug door of high-speed EMUs, and the operation of opening and closing doors. The total time can also be kept stable, ensuring the long-term stable operation of the sliding plug door control system. Through experimental comparison, it can be seen that the fuzzy-PID combined control algorithm can effectively solve the problems such as oscillation and overshoot during the operation of the sliding plug door of high-speed EMUs, and the operation of opening and closing doors. The total time can also be kept stable, ensuring the long-term stable operation of the sliding plug door control system.

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