Research on cooperative control strategy of multi-motor system based on fuzzy inference

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Abstract—General distributed multi-motor control system has a low synchronization performance and a poor coordination control accuracy. In order to improve the deficiencies, the fuzzy control method is used. Firstly, the fuzzy PID controller is designed to improve the control accuracy of a single motor in the control system; Then, aiming at the shortcomings of the traditional deviation coupling structure, an adjacent deviation coupling control strategy based on fuzzy inference and a speed compensator are designed to improve the synchronization performance of the whole control system. The simulation results show that the tracking error of single motor and the synchronization error between motors are greatly reduced.

1. Introduction

Multi-motor cooperative control system is widely used in industrial field[1], when the system executes a fixed operation mode, the parameters such as speed and angle between motors need to maintain a certain relative relationship at all times. The control mode mostly adopts the distributed control system as shown in Figure 1 to realize parallel control, each motor receives instructions from the upper computer, and there is no interaction between the controlled objects[2]. This control mode is simple in structure and easy to implement, the individual output of each motor is relatively stable. However, when one of the motors is disturbed, the other motors cannot make corresponding adjustment, which makes the motor out of synchronization with other motors, resulting in low coordination accuracy of the whole control system and easy to be affected by interference[3]. The synchronization performance of the system is very important for some occasions. There are two main indicators to judge the synchronization performance of the system, the tracking error ($e_i$) representing the difference between the actual running speed and the given speed of a single motor, and the synchronization error ($e_{ij}$) representing the synchronization degree of any two motors. The smaller the tracking error and synchronization error, the higher the synchronization control accuracy of the system[4].

For the above two indicators, the fuzzy inference method is adopted respectively. In order to reduce the tracking error of a single motor, a fuzzy PID controller is designed to improve the control accuracy and anti-interference ability; In order to reduce the synchronization error of the control system, a speed compensator based on adjacent deviation coupling control strategy is designed to improve the synchronization performance of the system. Through system simulation, it is further verified that fuzzy controller and adjacent deviation coupling strategy improve the cooperative performance of multi-motor control system.
2. Design of single motor fuzzy controller in control system

The control accuracy of a single motor is the basis of the control accuracy of the whole control system. If the anti-interference ability of a single motor is not strong and the following ability for given parameters is weak, the control accuracy and synchronization performance of the control system will be greatly reduced.

Permanent magnet synchronous motor (PMSM) is a kind of executive unit commonly used in multi-motor cooperative control system. The control method of a single permanent magnet synchronous motor is field-oriented control, and its principle is shown in Figure 2: the stator current vector of the motor is decomposed into the current component generating magnetic field (excitation current $I_d$) and the current component generating torque (torque current $I_q$) for control respectively[5].

The tracking error of the motor in speed mode is defined as the difference between actual speed ($n_i$) and given speed ($n_i^*$) of the motor. The smaller the tracking error, the higher the control accuracy of a single motor. The tracking error ($e_i$) of the i-th motor in the system can be expressed by the following formula.

$$e_i = n_i - n_i^*$$

2.1 Principle of fuzzy PID controller

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Fig.3 Principle of Fuzzy PID controller
The parameters of the fuzzy PID controller will change with the inputs error (e) and the error change rate (\( e_c \)) according to some certain fuzzy rules, so the system using fuzzy PID controller will have stronger robustness, and the influence of interference on the system will be greatly reduced[6]. The design of fuzzy PID controller mainly includes three steps: fuzzification, fuzzy inference method and rule base, defuzzification. Its principle block diagram is shown in Figure 3.

2.2 Fuzzification
Fuzzification is the process of converting the precise values of inputs and outputs into fuzzy language. First, select appropriate quantization factor \( \lambda_e, \lambda_p, \lambda_I, \lambda_D \) to quantize the inputs \( e, e_c \) and outputs \( \Delta K_p, \Delta K_I, \Delta K_D \) to their corresponding fuzzy sets \( E, EC, UP, U_L = \{-3, -2, -1, 0, 1, 2, 3\} \), then take the corresponding language to describe all fuzzy sets as \{NB, NM, NS, ZO, PS, PM, PB\}. All fuzzy sets adopt triangular membership function.

The quantization factors can be calculated by formulas (2) and (3). After determining the quantization factors, \( e \) and \( e_c \) can be converted into \( E \) and \( EC \) by formula (4), and subscripts H and L represent the maximum and minimum values of the corresponding inputs and outputs sets respectively.

\[
\begin{align*}
\lambda_e &= \frac{6}{e_H - e_L}, \lambda_{ec} = \frac{6}{ec_H - ec_L} \\
\lambda_p &= \frac{\Delta K_{PH} - \Delta K_{PL}}{6}, \lambda_I &= \frac{\Delta K_{IH} - \Delta K_{IL}}{6}, \lambda_D &= \frac{\Delta K_{DH} - \Delta K_{DL}}{6} \\
E &= \lambda_e \left( e - \frac{e_H + e_L}{2} \right), EC = \lambda_{ec} \left( ec - \frac{ec_H + ec_L}{2} \right)
\end{align*}
\]

2.3 Fuzzy inference method and rule base
Based on the effect, experience and research of parameters[7], the parameters adjustment rules are formulated as follows, and the rule base shown in Table 1 is established:

1. When \(|e|\) is large: in order to speed up the response speed of the system, a larger \( K_p \) should be selected; in order to reduce the overshoot of the system, a smaller \( K_I \) should be selected; in order to prevent differential saturation, a smaller \( K_D \) is selected.

2. When the values of \(|e|\) and \(|e_c|\) are medium: in order to prevent excessive overshoot, smaller \( K_p \) should be selected; the value of \( K_I \) is moderate; and select the smaller \( K_D \) to avoid prolonging the system adjustment time.

3. When \(|e|\) is small: at this time, the system basically reaches steady state, \( K_p, K_I \) should be increased appropriately to reduce the error. At the same time if \(|e_c|\) is small, increase \( K_D \) to prevent system oscillation.

| \( \Delta K_p, \Delta K_I, \Delta K_D \) | EC |
|---|---|---|---|---|---|---|---|---|---|
| NB | NM | NS | ZO | PS | PM | PB |
| E | NB | NB | NB | PM | NM | NS | PM | NM | NB | ZO | ZO | ZO |
| NM | NB | NB | NB | PM | NM | NS | PM | NM | NB | ZO | ZO | ZO |
| NS | PM | NM | NS | NM | NS | NS | PM | NM | NM | ZO | ZO | ZO |
| ZO | PM | NM | ZO | PS | NS | NS | ZO | ZO | NS | NS | NS | ZO |
| PS | PS | NS | ZO | ZO | NS | NS | NS | NS | NS | NM | PM | ZO |
| PM | PS | ZO | ZO | PS | NS | NS | PS | NM | PM | NM | PB | ZO |
| PB | ZB | ZO | ZO | PS | NM | PS | PM | PM | PM | NB | PB | ZO | ZO | ZO |

Table 1 \( \Delta K_p, \Delta K_I, \Delta K_D \) fuzzy rule base
The inference mode of inputs and outputs can be obtained from the above table: IF E and EC, THEN U. There are 49 fuzzy statements in total. The fuzzy relationship of the system can be obtained through fuzzy operation.

2.4 Defuzzification
Finally, the operation output fuzzy set $U_i$ needs to be deblurred to obtain an accurate output value, which is generally clarified by the weighted average decision method (center of gravity method):

$$u = \frac{\sum_{i=1}^{n} x_i \mu_u(x_i)}{\sum_{i=1}^{n} \mu_u(x_i)}$$

(5)

Where $x_i$ is element of fuzzy set $U_i$, $\mu_u(x_i)$ is the membership corresponding to element $x_i$.

2.5 Analysis of simulation results
Taking the PMSM as the object for modeling and simulation, using speed-current double closed-loop control. Figure 4 shows the comparison results of PID controller and fuzzy PID controller.

![Fig.4 Comparison of simulation results between PID controller and Fuzzy PID controller](image)

The given speed is 2000rpm, and apply 30N·m interference at 0.03s. It can be seen from the figure that the waveform obtained by using the fuzzy PID controller has almost no overshoot, and the time required to achieve stability is 0.005s, which is far less than the time by using the PID controller. When it is stable, the tracking error $e$ is basically 0. After being disturbed, the curve fluctuation of the fuzzy PID controller is smaller, the recovery is faster, and when it is stable, the speed is closer to the set value. Therefore, it can be concluded that the motor with fuzzy PID controller has higher precision, stronger anti-interference ability and smaller tracking error.

3. Multi-motor adjacent deviation coupling control in control system
The synchronization performance of the control system is very important for some occasions. If one motor is disturbed and the speed changes, while the other motors still move according to the predetermined speed without corresponding adjustment, it will lead to the deviation of the relative motion of the whole system and make the motion unstable and uncoordinated.

Assuming that there are $m$ motors in the cooperative control system, the given speed of each motor has the following relationship:

$$n_i^* = k_i n_0$$

(6)

In the formula: $n_i^*$ and $k_i$ are the given speed and the synchronous proportional parameter of the $i$-th motor, $n_0$ is called system synchronous speed. Let $n_i$ be the actual speed of the $i$-th motor, then the synchronization error between the $i$-th motor and the $j$-th motor can be expressed as:

$$e_{ij} = n_i/k_i - n_j/k_j$$

(7)

It can be seen from the above formula that the smaller the synchronization error $e_{ij}$, the better the synchronization performance between the two motors.
3.1 Adjacent deviation coupling control
There are many methods to improve the synchronization performance of the control system, such as the master-slave control structure in series. Its disadvantage is that when the slave motor is disturbed, the master motor cannot make corresponding adjustment. The cross coupling control structure can also improve the synchronization performance between motors, but it is only suitable for two motors[8]. In the deviation coupling, the compensation signal of each motor is composed of the synchronization error and moment of inertia ratio between the motor and all other motors, which greatly increases the system complexity and calculation while improving the synchronization performance. Therefore, the adjacent deviation coupling is proposed. Coupling each of the three adjacent motors not only improves the synchronization performance, but also avoids the disadvantages caused by deviation coupling[9]. For the convenience of discussion, three motors coupled with each other are selected for research, each motor uses the same field-oriented control (FOC) mode, and the structure is shown in Figure 5.

![Fig. 5 Adjacent deviation coupling control structure](image)

3.2 Design of adjacent deviation coupling velocity compensator based on fuzzy inference
The inputs of the traditional deviation coupling speed compensator are the output speeds of three motors. After calculation, the synchronization errors $e_{i(i-1)}$ and $e_{i(i+1)}$ between the $i$-th motor and two adjacent motors are obtained. Finally, the output $\beta_i$ is obtained through a fixed gain $K_{ij}$ which is the ratio of the moment of inertia of the $i$-th motor ($J_i$) to the moment of inertia of the $j$-th motor ($J_j$) [10]. The formulas can be expressed as:

$$K_{ij} = \frac{J_i}{J_j} \quad (8)$$

$$\beta_i = K_{i(i-1)}e_{i(i-1)} + K_{i(i+1)}e_{i(i+1)} \quad (9)$$

When the fixed gain speed compensator encounters complex disturbance or load, the robustness of the system is not enough. Therefore, a speed compensator structure based on fuzzy inference is proposed, and its structure is shown in Figure 6.
The design process of fuzzy controller in the improved speed compensator is consistent with that before. All motors select the same PMSM, so $K_{ij} = 1$.

### 3.3 Analysis of simulation results

Taking three motors as an example, set the given speeds as $n_1^* = 1000\text{rpm}$, $n_2^* = 1500\text{rpm}$, $n_3^* = 2000\text{rpm}$ respectively. System synchronization speed $n_0$ takes the minimum common divisor of 500rpm, so the corresponding synchronization coefficient $k_1 = 2$, $k_2 = 3$, $k_3 = 4$. Based on the single motor fuzzy PID control model, the three motors are coupled with each other by using the designed speed compensator. Add 30N·m load to motor 3 to simulate external interference at 0.03s. The speed simulation curve is shown in Figure 7.

![Fig.7 Velocity curve of uncoupled system (left)、Velocity curve of adjacent deviation coupled system based on fuzzy controller (right)](image)
Fig. 8 Synchronization error between motor 1 and motor 3 (upper left), synchronization error between motor 2 and motor 3 (upper right), synchronization error between motor 1 and motor 2 (lower) (blue: uncoupled system; black: adjacent deviation coupling system; red: adjacent deviation coupling system using fuzzy controller)

Figure 8 is the synchronization error curve between each two motors in different systems. It can be seen from the figure that in the case of interference on motor 3 in the uncoupled system, there will be a large synchronization error between motor 3 and other motors, and the synchronization error accounts for about 8% of the system synchronization speed. The adjacent deviation coupling system effectively reduces the synchronization error between motor 3 and others at the moment of interference, the synchronization error is about 5% of the synchronization speed, but there will be a very small synchronization error between motors 1 and 2, about 0.4% of the synchronization speed. It can be seen that the adjacent deviation coupling structure has greatly improved the synchronization performance of the system. In addition, the synchronous error of the adjacent deviation coupling system with fuzzy controller is significantly reduced both at the start of the motor, at the moment of disturbance, and at the stage of restoring stability. It shows that the speed compensator based on fuzzy controller can obviously reduce the system synchronization error and enhance the robustness of the system compared with the speed compensator with fixed gain.

4. Conclusion
In this paper, the fuzzy PID controller is designed based on the method of fuzzy inference, which improves the control accuracy and anti-interference ability of a single motor in the multi-motor control system. For the coordinated control of the multi-motor system, a control mode of adjacent deviation coupling is proposed, and a speed compensator is designed based on fuzzy inference, which greatly reduces the synchronization error of the system and makes the motors in the system have better synchronous following performance.
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