A Fast Energy Equalization Control Strategy of Flywheel Array System Based on Fuzzy Power Distribution Control

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Abstract. Flywheel array is a kind of energy storage device with good performance, but there is still no suitable power distribution strategy which hinders its development. This paper proposed a flywheel array energy distribution control strategy based on fuzzy control. This control strategy takes the balance of residual energy among the flywheel units as the target, and by establishing appropriate fuzzy control rules to allocate the power required by the array. This method solved the problem of residual energy imbalance among each unit in flywheel array and improved the reliability of the flywheel array. Simulation results based on Matlab/Simulink verify the effectiveness of the proposed strategy.

1. Introduction
Flywheel energy storage system is a new type of energy storage system, it has attracted wide attention because of its high efficiency and no pollution. Because the capacity of a single flywheel is difficult to expand, people often use multiple flywheels to form an array to increase the capacity of the system [1-2].

However, there are few researches on power distribution strategy of flywheel array. Several commonly used control strategies are equal power strategy, equal torque strategy and equal time strategy but they don't achieve the energy balance of each flywheel unit [3-4].

In flywheel array, the flywheel which stores least energy in the flywheel array will determine the maximum working time of the array, and the flywheel running in high speed long time will reduce the life of the flywheel. Therefore, controlling the energy of each unit to balance in the array can effectively improve the maximum working time and the reliability of the system.

Fuzzy control can combine human operation experience into the control process. Mamdani fuzzy controller is adopted in this paper. This control strategy can quickly balance the stored power of each unit in the flywheel array during operation, thus improving the stability of the flywheel array system and the maximum power working time.

2. Fuzzy Power Allocate Strategy
Flywheel is a device that converts electrical energy into kinetic energy and stores it. The energy stored in it can be calculated by (1):

\[ E = \frac{1}{2} J \omega^2 \]  \hspace{1cm} (1)
Where \( \omega \) indicates the current rotate speed of the flywheel rotor, \( J \) indicates the rotational inertia of the rotate, it is determined by the flywheel itself. Thus, the energy stored in the flywheel can be measured by the speed of the motor. State of charge (SOC) is usually used to represent the standard value of the residual energy of the flywheel.

The flywheel array has two working modes: charging and discharging. Taking discharge as an example, the flywheel array needs to satisfy two constraints expressed in the equation (2). Where, \( p_i \) indicates the output power of each unit in the array, and \( P_{\text{ref}} \) indicates the power reference of the whole array.

\[
\begin{align*}
\sum_{i=1}^{n} p_i &= P_{\text{ref}} \quad i = 1, 2, ..., n \\
p_i &> 0
\end{align*}
\]  

Due to the need to reduce the energy imbalance of each flywheel unit, energy deviation (\( \Delta\text{SOC}_i \)) is defined by equation (3) to represents the energy imbalance degree of each unit in the flywheel.

\[
\begin{align*}
\text{SOC} &= \frac{\sum_{i=1}^{n} \text{SOC}_i}{n} \quad i = 1, 2, ..., n \\
\Delta\text{SOC}_i &= \text{SOC}_i - \text{SOC}
\end{align*}
\]  

When the system works in the charging state, state of discharge (SOD) is used to represent the remaining capacity of the flywheel, and the control strategy is the same as the discharge state.

3. The Design of Fuzzy Controller

Take the flywheel array composed of four 400kw flywheels as an example. In the flywheel array, the output of each flywheel unit is related to both the \( P_{\text{ref}} \) of the array and the residual energy of each flywheel. The input of the fuzzy controller is the energy deviation (\( \Delta\text{SOC}_i \)) of the flywheel units and the power reference (\( P_{\text{ref}} \)) of the flywheel array. The output is the weight (\( x_i \)) of the power of this unit in all powers. The range of each quantity is: \(-1<\Delta\text{SOC}_i<1; 0<P_{\text{ref}}<1600 ; 0<x_i<1\). The structure of the fuzzy controller is illustrated as Figure 1.

![Figure 1: Structure of fuzzy power distribution controller.](image)

Then, the input and output range are divided into different fuzzy intervals and the membership functions of each fuzzy set are determined. Among them, the fuzzy set with steep membership function curve has high resolution and the controller has high sensitivity, the resolution of fuzzy sets with gentle membership function is low, but the stability of the system will be better. Therefore, relatively gentle membership function is used in the region with large energy deviation, and relatively
steep membership function is used in the region with small energy deviation. As for the \( P_{\text{ref}} \), the fuzzy set can be divided according to the rated power of each flywheel.

The membership function of each variable can be obtained and illustrated in Figure 2.

![Membership function of \( \Delta \text{SOC} \)](image1)

![Membership function of \( P_{\text{ref}} \)](image2)

![Membership function of \( x_i \)](image3)

**Figure 2.** The membership function of each variable

In the discharge process of flywheel array, when \( P_{\text{ref}} \) is small, the unit with large residual energy is controlled to share the most of the power, and the unit with small remaining energy shares the least of the power or even does not share power. With the increase of \( P_{\text{ref}} \), the unit with large residual energy cannot continue to increase its shared power due to the limitation of its rated power. At this time, the unit with small residual energy is required to share more power. According to this rule, a fuzzy control rules table of the control system can be established as shown in Table 1.

**Table 1.** Table of fuzzy control rules

| \( \Delta \text{SOC} \) | NB | NM | NS | M   | S   | M   | B   |
|---------------------|----|----|----|-----|-----|-----|-----|
| \( P_{\text{ref}} \) | VS | NB | NB | NM  | NS  | M   | PS  | PM  |
|                     | S  | NB | NM | NS  | M   | PS  | PM  | PB  |
|                     | M  | NM | NS | M   | PS  | PM  | PB  | PB  |
|                     | B  | NS | M  | PS  | PM  | PB  | PB  | PB  |
|                     | VB | M  | PS | PM  | PB  | PB  | PB  | PB  |

After \( x_i \) of each unit is obtained through the fuzzy controller, the output power of each flywheel unit can be calculated by equation (4).
4. Simulation Results and Analysis

The given power reference of the array in this experiment is 800kw. The fuzzy power distribution control is compared with the equal power distribution and equal time distribution. The residual energy and output power of each unit under different control strategies are shown as below.

\[ p_i = P_{\text{ref}} \frac{x_i}{\sum_{i=1}^{4} x_i} \quad i = 1, 2, 3, 4 \]  

(a) The residual energy of each unit  
(b) the output power of each unit

**Figure 3.** Simulation result under fuzzy power allocate control strategy

(a) The residual energy of each unit  
(b) the output power of each unit

**Figure 4.** Simulation result under equal time control strategy

(a) The residual energy of each unit  
(b) the output power of each unit

**Figure 5.** Simulation result under equal power control strategy
From the simulation results, it can be seen that among the two current common power allocation strategies, the equal power control cannot balance the remaining capacity of each cell in the array, thus leading to the reduction of the maximum power working time of the array, and the equal time control strategy cannot balance the remaining capacity of each unit quickly. Fuzzy power allocation control strategy can quickly reduce the energy imbalance of each unit in the system and effectively prolong the maximum power working time of the array.

5. Conclusion

In this paper, a power allocation method based on fuzzy control is proposed to solve the power allocation problem of flywheel array system. The residual energy of each unit and the power reference of the array are fuzzified, and the output power of each unit is obtained after a certain fuzzy control strategy. This control strategy effectively increases the effective charge and discharge time of the system, and reduces the energy imbalance among the units, thus improving the stability of the system.

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