Fast Energy Equalization Control Strategy for Flywheel Array System Based on the Energy Prediction

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Abstract. Flywheel energy storage array has attracted extensive attention because of its high power density, wide operating temperature and no environmental pollution. But there are few suitable power distribution strategies which hinders its development. This paper proposed an energy prediction fast equalization method (EP-FEM) to distribute the power of the array to each unit. In consideration of the current energy of flywheel and the predicted energy of next control cycle, this method can solve the problem of the unbalance of the residual energy among the units and prevent the oscillation of the output power of the unit when the control cycle is too long. A flywheel array model has been established in Matlab/Simulink and verified the effectiveness of this strategy.

1. Introduction
The configuration of large capacity energy storage system in the power grid can be of great benefit to the stable operation of the power grid. Flywheel energy storage system (FESS) has attracted extensive attention because of its many advantages like no environmental pollution, high efficiency and long service life. Due to technical limitations, the capacity of a flywheel unit is difficult to expand significantly. To solve this problem, people proposed the flywheel array energy storage system (FAESS) to increase the capacity of the system by connecting multiple flywheels in parallel. [1-3].

There are few researches on the energy distribution strategy of the array. Some commonly used control methods are equal power method, equal torque method and equal time method but they don’t take the residual energy balance into account. Maintaining the residual energy balance of each unit in the array can effectively increase the maximum power working time and improve the stability of the system. [4-6].

Based on the fast equalization method (FEM), this paper proposed an energy prediction fast equalization method (EP-FEM) to distribute the power that the system needs to provide. By predicting the energy of the flywheel in the next control cycle, the power of each unit in the flywheel array is distributed reasonably, so as to avoid the power fluctuation of the units under FEM when the system has a long control cycle. This control strategy can predict the variation of flywheel energy and make the energy of each unit in the flywheel array balance quickly.

2. Fast equalization method
Flywheel can store the mechanical energy in flywheel rotor and realize the conversion of electrical energy and mechanical energy. The residual energy of a flywheel can be obtained from (1):

\[
E(t) = \frac{1}{2}I \omega^2
\]
\[ E = \frac{1}{2} J \omega^2 \]  

Where \( \omega \) represents the rotate speed of the flywheel rotor, \( J \) represents the moment of inertia of the rotor. Thus, the energy stored in the flywheel can be measured by the rotate speed of the rotor.

The flywheel array has two working modes: charging and discharging. This paper mainly analyzes the discharging mode of the array and the control method of charging mode is similar to discharging mode. To make the flywheel array energy balance quickly, the simplest method is to let the flywheels with more energy discharge first, while those with less energy do not discharge.

In FEM, the flywheels with same state of charge (SOC) in the system first will be divided into a group \( G_k \), where \( k \) represents the number of the group and it is in the ascending order as the SOC of the flywheels decreases. Assuming that the rated power of group \( k \) is \( P_{kN} \), and the rated capacity of group \( k \) is \( C_k \). \( P_{kN} \) and \( C_k \) can be obtained from the following equation:

\[
\begin{align*}
P_{kN} &= p_{k(1)N} + p_{k(2)N} + \cdots + p_{k(s)N} \\
C_k &= c_{k(1)} + c_{k(2)} + \cdots + c_{k(s)}
\end{align*}
\]

Where \( p_{k(s)N} \) represents the rated power of \( x \)th flywheel in group \( k \), \( c_{k(s)} \) represents the rated capacity of \( x \)th flywheel in group \( k \).

Then, the power distributed to each group can be obtained from the following equation.

\[
\left[ P_1, P_2, \cdots, P_{i-1}, P_i, P_{i+1}, \cdots, P_r \right] = \left[ P_{1N}, P_{2N}, \cdots, P_{(i-1)N}, P_i, 0, \cdots, 0 \right]
\]

Where \( P_i \) represents the power distributed to group \( k \), \( P_{kN} \) represents the rated power of group \( k \). \( \sum_{j=0}^{i-1} P_{jN} \) represents the power that the \( i \)th group is required to output and it can be obtained from the following equation:

\[
\begin{align*}
P_i &= P_{\text{array}} - \sum_{j=0}^{i-1} P_{jN} \\
0 &< P_i < P_{IN}
\end{align*}
\]

Where \( P_{\text{array}} \) represents the power that the system needs to provide.

The SOC of each flywheel in the same group should change at the same speed, so the power distributed to the flywheels in group \( i \) can be obtained from (5).

\[
p_{i(s)} = P_i \frac{c_{i(s)}}{C_i}
\]

The flywheels in group 1 to \( i-1 \) work at their rated power, thus makes their residual energy change in their fastest speed.

In this method, the flywheel with less residual energy will be charged first, and the flywheel with more residual energy will be discharged first. Flywheels work at their rated power except group \( i \) or do not work. This will make their residual energy to be balance quickly.

3. Energy prediction fast equalization method

The FEM has a good control effect when the system has a short control cycle. But in the actual operation of the system, the system may have a long control cycle. At this time, in FEM, after a long control cycle, the flywheels that had more residual energy might have a lower residual energy than those that had less residual energy. Thus, the power of each flywheel unit in the system will fluctuate continuously, and the flywheels in the system cannot reach the energy balance.

The energy prediction fast equalization method (EP-FEM) can consider the residual energy of the system after a control cycle, and the system can reach the energy balance after a control cycle, and avoid the fluctuation of the output power of the flywheel unit caused by a long control cycle.
First, according to FEM, the power \( p_{k,x} \) of each unit in the array can be obtained. According to their power and their current \( SOC_{i(x)} \), the predicted residual energy \( SOC'_{i(x)} \) of each unit after the control cycle under the current power can be obtained by (6).

\[
SOC'_{i(x)} = SOC_{i(x)} - \frac{p_{i(x)} \times T}{c_{i(x)}}
\] (6)

Where \( T \) indicates the control cycle time of the system.

When sorting the units by the previous method, if there are \( SOC'_{i(x)} < SOC'_{j(y)}, i < j \), it indicates that the power of the units in the array will fluctuate, and the power of these units need to be reallocated.

Assuming that after a control cycle, the residual energy of group 1 will be lower than group \( s \), and the power needs to be reallocated is:

\[
P'_{array} = \sum_{i=1}^{s} P'_{i}
\] (7)

Considering that the SOC needs of these groups of flywheels tend to be the same after one cycle, the output power of these flywheels should meet the following constraints:

\[
SOC_{i(1)} \times \frac{T \times p'_{i(1)}}{c_{i(1)}} = SOC_{i(s)} \times \frac{T \times p'_{i(s)}}{c_{i(s)}} \quad i = 1, 2, \ldots, s - 1
\] (8)

\[
\frac{p'_{i(1)}}{c_{i(1)}} = \frac{p'_{i(2)}}{c_{i(2)}} = \ldots = \frac{p'_{i(x)}}{c_{i(x)}} \quad i = 1, 2, \ldots, s
\] (9)

\[
\sum_{i=1}^{s} P'_i = P'_{array}
\] (10)

In these formulas, (8) can ensure that the energy of each unit in these groups tends to be the same after a control cycle, (9) can make the SOC of flywheels in group \( i \) change at the same speed, (10) makes the output power of the system to be the same as the reference.

The output power of each unit after reallocated can be obtained by solving the above equations:

\[
p'_{i(1)} = \left( \frac{P'_{array} + SOC_{i(1)} \times \frac{\sum_{j=1}^{s} (C_j \times SOC_{j(1)})}{T \times \sum_{j=1}^{s} C_j}}{\sum_{j=1}^{s} C_j} \right) \times c_{i(1)} \quad i = 1, 2, \ldots, s
\] (11)

\[
p'_{i(x)} = \frac{c_{i(x)}}{c_{i(1)}} \times p_{i(1)} \quad i = 1, 2, \ldots, s
\] (12)

4. Simulation results and analysis

A \( 4 \times 400kW \) flywheel array system has been built in Simulink to analyze the result under EP-FEM and FEM. In the experiment, the control system with control cycle time \( T \) of 0.1s, 0.5s and 1s have been simulated respectively and the required output power of the system is \( 600kW \). The residual energy of flywheels under different cycle time and control strategies are shown as following figures.
According to the simulation results, FEM can realize energy equalization when the system has a short cycle time, and EP-FEM had similar results to FEM. When the control cycle becomes longer, the flywheel energy in FEM will fluctuate, while EP-FEM can still maintain the flywheel unit energy to be consistent. Due to the delay of the power response and the loss of the flywheel unit, the residual energy after one cycle may not be exactly the same, but this part of unbalanced energy can be eliminated gradually by the algorithm.
5. Conclusion
In this paper, a power distribution strategy of flywheel array based on residual power prediction is proposed to solve the problem that the power of flywheel may fluctuate in the fast equalization method and realize the fast residual energy balance.

Overdischarge and energy fluctuation of flywheels may happen because the simple fast equalization method (FEM) for the system cannot monitor the energy of the flywheel timely while having a long control cycle. Energy prediction fast equalization method (EP-FEM) takes the predicted energy of the array in the next cycle into account, then redistributes the output power of the system and ensures that the SOC of each flywheel in the flywheel array tends to be the same.

A simulation model based on a $4 \times 400kW$ flywheel array has been built up to verify the effectiveness of EP-FEM. According to the results, the control effect of the flywheel array system on EP-FEM is better than the simple FEM.

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