Research on Application of Double Fuzzy Algorithm in Voltage Filtering of Aluminum Electrolysis Cell

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Abstract. At present, the electrolytic aluminum control system uses a first-order algorithm to filter the voltage of the electrolytic cell with serious hysteresis and weak tracking. Aiming at the above problems, this paper researches and designs an adaptive filter based on double fuzzy algorithm. The change of the electrolytic cell voltage measured, the absolute value of the difference between electrolytic cell measurement voltage and filtered electrolytic cell voltage are used as the two input variables of the fuzzy controller 1. The change of the electrolytic cell voltage measured, the absolute value of the difference between electrolytic cell measured voltage and corrected electrolytic cell voltage are used as the two input variables of the fuzzy controller 2. The two fuzzy controllers calculate the filter coefficient and the correction coefficient respectively through a fuzzy algorithm. Simulation results show that the tracking time of the double fuzzy algorithm is 78% shorter than that of the first-order algorithm, and the root mean square error is reduced by 70% compared to the first-order algorithm. It can provide a feasible and excellent filtering algorithm for the intelligent control of electrolytic aluminum.

1. Introduction

The development of the electrolytic aluminum industry has made the intelligent control and expert control systems of the aluminum electrolytic process a research hot spot. The electrolytic cell voltage is the only parameter that can be measured online in real time to reflect the state of the tank. Therefore, it is important to complete the filtering and tracking analysis of the electrolytic cell voltage as quickly as possible. After the signal analysis, it is possible to obtain as much real-time information as possible about the operation status of the electrolytic cell, which is beneficial to timely prevent and deal with abnormal working conditions of the electrolytic cell, such as the anode effect of the electrolytic cell and the change in the concentration of alumina in the electrolyte, so as to control the Al₂O₃ feed. The amount provides a reference basis to improve the efficiency of aluminum electrolysis and energy conservation. The filtering algorithm currently applied in the electrolytic aluminum industry is a first-order algorithm, and a first-order algorithm with a fixed filtering coefficient makes it difficult to take into account the algorithm's stability and sensitivity. Fuzzy algorithms[1-5] can be used to obtain filtering coefficients. These algorithms still have insufficient filtering and tracking capabilities when the electrolytic cell voltage changes a lot. This paper intends to design a double fuzzy algorithm[6-7] to obtain filter coefficients and correction coefficients. This algorithm has the advantages of strong anti-interference ability, fast response speed, etc., and has strong robustness to parameter changes.
2. Filter algorithm design

2.1 Electrolytic cell voltage filtering algorithm

At this stage, a first-order filtering algorithm with inertial filtering performance is used. The mathematical model of the filtering algorithm is:

\[ x_n = (1 - \varphi)x_{n-1} + \varphi h_n \]  
\[ x_0 = h_0 \]  

(1)

(2)

In formula (1), \( x_n \) is the filter value at time \( n \), \( h_n \) is the measurement value at time \( n \), \( x_{n-1} \) is the filter value at time \( n-1 \), \( \varphi \) is the filter coefficient. The electrolytic cell voltage sampling frequency is 1 Hz, the electrolytic cell voltage frequency range is 0.002 ~ 0.04 Hz[8], and the noise frequency is about 0.03 Hz. In order to effectively filter the noise, the filter coefficient takes a fixed value \( \varphi = 1/32 \). This algorithm has a good filtering effect when the voltage change of the electrolytic cell is small. Due to the influence of the production process (such as the lack of Al\(_2\)O\(_3\) in the electrolytic cell), the voltage signal of the electrolytic cell is biased in the 0.005HZ ~ 0.04HZ frequency band due to the large change in the electrolytic cell voltage. The filter coefficient value is small, the pass band is narrow, the voltage signal attenuation in this frequency band is up to -20dB, the algorithm has low sensitivity and serious hysteresis, and cannot meet the requirements of electrolytic cell voltage filtering.

2.2 Improved filtering algorithm

Aiming at the problem of fixed filter coefficient first-order filtering algorithm when the electrolytic cell voltage changes a lot, the filter has a narrow pass band, serious hysteresis, and low sensitivity. This paper designs a first-order low-pass filter with variable filter coefficient \( \gamma_n \). The formula is shown in (3). In order to filter the noise more effectively and improve the filtering performance of the filtering algorithm, a correction equation with a variable correction coefficient \( \lambda_n \) is designed. The expression is shown in equation (4). The system model of the improved filtering algorithm based on equations (1) and (2) is equations (3)-(5):

\[ V'_n = (1 - \gamma_n)V_{n-1} + \gamma_n V_n \]  
\[ V_n = V'_n + \lambda_n (V_n - V'_n) \]  
\[ V_0 = V'_0 = V_0 \]  
\[ e_n = |V_n - V_{n-1}| \]  
\[ \partial e_n = |V_n - V_{n-1}| \]  
\[ \nabla e_n = |V_n - V_{n-1}| \]  

(3)

(4)

(5)

(6)

(7)

(8)

In equations (3)-(8), \( V_n \) is the electrolytic cell voltage at the \( n \) moment, \( V_{n-1} \) is the electrolytic cell voltage at the \( n-1 \) moment, \( V'_n \) is the electrolytic cell voltage at the \( n \) moment after correction, \( V_{n-1} \) is the electrolytic cell voltage at the \( n-1 \) moment after correction, \( V'_n \) is the electrolytic cell voltage at the \( n \) moment after filtering, \( V_{n-1} \) is the electrolytic cell voltage at the \( n-1 \) moment after filtering, \( e_n \) is the absolute value of the difference between the electrolytic cell voltage at the \( n \) time and the
electrolytic cell voltage at the $n-1$ time, $\Delta e_n$ is the absolute value of the difference between the electrolytic cell voltage at the $n$ time and the electrolytic cell voltage at the $n-1$ time after the correction, $\nabla e_n$ is the absolute value of the difference between the electrolytic cell voltage at the $n$ time and the electrolytic cell voltage at the $n-1$ time after filtering, $\gamma_n \in [0,1]$ is the variable filter coefficient calculated by the fuzzy controller, $\lambda_n \in [0,1]$ is the variable correction coefficient calculated by the fuzzy controller.

3. Design of Double Fuzzy Control Algorithm

The working principle of the double fuzzy algorithm is shown in Figure 1. The double fuzzy algorithm has two fuzzy controllers. The inputs of fuzzy controller 1 are $e_n$ and $\nabla e_n$, the output is the filter coefficient $\gamma_n$ at the $n$ time. The inputs of fuzzy controller 2 are $e_n$ and $\Delta e_n$, and the output is the correction coefficient $\lambda_n$ at the $n$ time.

Under normal working conditions, the voltage of the electrolytic cell is about 4V. When the electrolytic cell voltage is greater than 8V, the anode effect occurs in the electrolytic cell, so the electrolytic cell voltage higher than 8V is not analyzed. Therefore, the initial argument of the input variable in this article is $[0,E], E = 4$. The initial universe of $e_n, \Delta e_n$ and $\nabla e_n$ is $[0,4]$, and the membership function of the input variable $e_n, \Delta e_n$ and $\nabla e_n$ are shown in Figure 2 (a). The universe of output variable $\gamma_n$ and $\lambda_n$ is $[0,1]$, and the membership function of output variable $\gamma_n$ and $\lambda_n$ are shown in Figure 2 (b).
In Figure 2, the input variable and output variable both use a triangular membership function with an amplitude of 1. The fuzzy subset of the input and output variables is \{S(Small), SM(Small Medium), M(Medium), MB(Medium Big), B(Big)\}, \(e_n, \bar{e}_n, \nabla e_n, \gamma_n, \lambda_n = \{S, SM, M, MB, B\}\), the fuzzy controller determines the output of the fuzzy controller according to the size of the input. If \(e_n\) is small and \(\nabla e_n\) is small, the output \(\gamma_n\) of the fuzzy controller 1 is small; if \(e_n\) is big and \(\nabla e_n\) is big, the output \(\gamma_n\) of the fuzzy controller 1 is big. If \(e_n\) is small and \(\bar{e}_n\) is small, the output \(\lambda_n\) of the fuzzy controller 2 is small; if \(e_n\) is big and \(\bar{e}_n\) is big, the output \(\lambda_n\) of the fuzzy controller 2 is big. Based on this, a total of 25 fuzzy control rules can be derived:

Fuzzy controller 1:
- If \(e_n = S\) AND \(\nabla e_n = S\), THEN \(\gamma_n = S\);
- If \(e_n = B\) AND \(\nabla e_n = B\), THEN \(\gamma_n = B\);
- ....

Fuzzy controller 2:
- If \(e_n = S\) AND \(\bar{e}_n = S\), THEN \(\lambda_n = S\);
- If \(e_n = B\) AND \(\bar{e}_n = B\), THEN \(\lambda_n = B\);
- ....

From Table 1, both fuzzy controller 1 and fuzzy controller 2 can obtain 25 controller fuzzy rules. After the fuzzy controller 1 completes fuzzy reasoning, it uses gravity center\[9\] to defuzzification to obtain precise control amount \(\gamma_n\), after the fuzzy controller 2 completes the fuzzy reasoning, the center of gravity is used to defuzzification to obtain the precise control amount \(\lambda_n\).

**Table 1. Fuzzy Rules Table.**

| \(e_n\) | S | SM | M | MB | B |
| --- | --- | --- | --- | --- | --- |
| \(\bar{e}_n/\nabla e_n\) |
| S | S | S | SM | M | MB |
| SM | S | SM | M | MB | MB |
| M | SM | M | MB | MB | B |
| MB | SM | M | MB | MB | B |
| B | SM | MB | MB | B | B |

4. Simulation and results analysis

4.1 Comparison of electrolytic cell voltage jump filtering

The electrolytic cell voltage data is calculated by AD conversion of the voltage acquisition circuit, and 150 voltage data are taken with a sampling frequency of 1 Hz. At the 10s, the regulation voltage amplitude increases by 1V. Using MATLAB software, the first order filtering, fuzzy algorithm filtering (without correction system module), and double fuzzy algorithm filtering were used to analyze and compare 150 experimental data.
From the analysis in Figure 3, it can be seen that the voltage change of the electrolytic cell in the interval of 1s to 10s is small, the first-order filtering algorithm, fuzzy algorithm, and double fuzzy algorithm, the three filtering algorithms have satisfactory results. In Figure 3, the voltage amplitude increases by 1V at the time 10s, the voltage data changes a lot, the filter coefficient of the first-order filtering algorithm is small, so the hysteresis is serious and the tracking ability is poor. The fuzzy algorithm uses a fuzzy controller to obtain the filtering coefficient. From Table 2, it can be seen that the filtering tracking time is 70% shorter than the first-order filtering. The double fuzzy algorithm uses two fuzzy controllers to obtain filtering coefficients and correction coefficients. From Table 2, it can be seen that the filtering tracking time is 78% shorter than the first-order filtering. The smaller the root mean square error in the filtering process, the better the performance of the filtering algorithm. According to the statistics in Table 2, it can be known that the root mean square error of the double fuzzy algorithm is the smallest, indicating that the double fuzzy algorithm has better filtering effect than the other three methods.

| Algorithm     | RMSE (mv) | Tracking Time (s) |
|---------------|-----------|-------------------|
| First-order   | 318       | 100               |
| Fuzzy         | 113       | 30                |
| Double fuzzy  | 96        | 22                |

4.2 Filter comparison when the cell voltage fluctuates

The filtering algorithm with strong tracking can improve the accuracy of effect prediction. Intelligent prediction of anode effect is one of the most effective methods to prevent electrolytic cell effect in modern aluminum electrolytic control[10]. The electrolytic cell voltage slope is calculated by filtering the electrolytic cell voltage, intelligent prediction of anode effects in electrolytic cells. Three different filtering methods are used to filter the voltage of one electrolytic cell in a 400KA series electrolytic cell of an aluminum plant. The filtering simulation is shown in Figure 4.
Figure 4. electrolytic cell voltage filtering waveform.

Figure 4 shows the simulation results of the first-order filtering, fuzzy algorithm, and double-fuzzy algorithm for electrolytic cell voltage filtering. In Figure 4, the electrolytic cell voltage fluctuation is small in the 1s to 10s interval. Table 3 shows that the root mean square error of the first-order filtering algorithm in this interval is 15.9mv, the root mean square error of the fuzzy algorithm in this interval is 14.0mv, and the root mean square error of the double fuzzy algorithm in this interval is 13.8mv. In Figure 4, the electrolytic cell voltage fluctuates greatly in the 75s to 85s interval. From Table 3, we can see that the root mean square error of the first-order filtering algorithm in this interval is 249.9mv, and the root mean square error of the fuzzy algorithm in this interval is 213.0mv, the root mean square error of the double fuzzy algorithm in this interval is 201.1mv.

In Table 3, $\eta_1$ is the root mean square error of the cell voltage in the 1s to 10s interval after filtering In Figure 4, $\eta_2$ is the root mean square error of the cell voltage in the 75s to 85s interval after filtering In Figure 4.

| Algorithm     | $\eta_1$ (mv) | $\eta_2$ (mv) |
|---------------|---------------|---------------|
| First-order   | 15.9          | 249.9         |
| Fuzzy         | 14.0          | 213.0         |
| Double fuzzy  | 13.8          | 201.1         |
Figure 5. Filter coefficient and correction coefficient graph.

(a) Filter coefficient. (b) Correction coefficient

Figure 5 (a) is a diagram of the filter coefficient change of the double fuzzy algorithm, the fuzzy algorithm, and the first-order algorithm in the electrolytic cell voltage filtering process in Figure 4. Figure 5 (b) is a diagram of the correction coefficient change of the double fuzzy algorithm in the electrolytic cell voltage filtering process in Figure 4. In Figure 4, the voltage data range fluctuates greatly in the 75s to 85s interval, and the electrolytic cell voltage change amount is 436mv from 77s to 78s. It can be known from Figure 5 (a) that the filter coefficient of the fuzzy algorithm becomes larger in the interval of 75s to 85s and the filter coefficient is 0.151 at the time 78s. From Figure 5 (b), it can be seen that the correction coefficient of the double fuzzy algorithm becomes larger in the 75s to 85s interval and the correction coefficient is 0.197 at the time 78s.

Combining Figure 5 and Figure 4 and the above data analysis, it is found that the filter coefficient of the fuzzy controller output becomes smaller when the absolute value of amplitude of the electrolytic cell voltage is smaller, and the smoothness of the double fuzzy algorithm is better. When the absolute value of amplitude of the electrolytic cell voltage is larger, the filter coefficient of the fuzzy controller is larger, and the tracking performance of the double fuzzy algorithm is the strongest and high sensitivity. In the electrolytic cell voltage filtering process, the correction coefficient of the double
fuzzy algorithm changes with the changes of the electrolytic cell voltage, which effectively enhances the filtering effect.

5. Conclusion
We analyze the change of the electrolytic cell voltage measured, the absolute value of the difference between electrolytic cell measurement voltage and filtered electrolytic cell voltage, the absolute value of the difference between electrolytic cell measured voltage and corrected electrolytic cell voltage. The fuzzy control system with double fuzzy algorithm is researched and designed. The double fuzzy controller controls the change of filter coefficient and correction coefficient respectively. The optimal value of filter coefficient and correction coefficient is adaptive obtained in the filtering process. Simulation results show that the tracking time of the filter algorithm optimized by the double fuzzy method is 27% shorter than that of the filter algorithm optimized by the fuzzy method, the tracking time of the filter algorithm optimized by the double fuzzy method is 78% shorter than that of the First-order filtering algorithm. The RMSE of the filtering algorithm optimized by the double fuzzy method is reduced by 16% compared with the filtering algorithm optimized by the fuzzy method, the RMSE of the filtering algorithm optimized by the double fuzzy method is reduced by 70% compared with the First-order filtering algorithm.

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