Research on electrode lifting system based on recursive least square method and fuzzy PID

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Abstract. The electrode of calcium carbide furnace bears the function of conduction, heat transfer and furnace condition regulation. How to keep the furnace condition in the best condition by lifting and lowering the electrode has always been a hot and difficult point in the research. In this paper, based on the analysis of the equivalent circuit of calcium carbide furnace, the system model of electrode position-current is identified by the recursive least square method, and a fuzzy PID controller based on the constant control strategy of electrode current is designed to keep the furnace condition in the best state. The simulation and application results show that the designed system has good dynamic response, anti-disturbance ability and robustness.

1. Introduction

At present, the electrode lifting operation of calcium carbide furnace is realized through the hydraulic transmission device. The electrode lifting operation is divided into single-phase separate operation and three-phase simultaneous operation. The secondary side of the furnace transformer is usually triangular wiring mode [1-3]. When a phase electrode is operated separately, it will affect the arc current of the other two phases, which is easy to cause three-phase imbalance. The strong coupling of the calcium carbide furnace is reflected in this point. When the three-phase electrode is operated up and down at the same time, the three-phase electrical power balance can be maintained (it is assumed that the three-phase equilibrium state is maintained before the operation of the calcium carbide furnace), and the pressure of the hydraulic station (including the energy accumulator) is required to support the simultaneous action of the three-phase electrode [4-6].

Electrode lifting range is determined by the condition of calcium carbide furnace. In normal production, the electric arc current in the furnace can be adjusted through the electrode lifting operation, and the input electric power can be changed, so as to improve the direction of the furnace condition to the furnace temperature stability change; during maintenance work, the electrode end needs to be lifted to the height of the charge surface; during the operation of the oven, the electrode end needs to be pressed to a certain height from the bottom of the furnace [7-10]. Therefore, in a sense, the position of the electrode determines the condition of the calcium carbide furnace.

It is difficult to establish a definite relationship between electrode position and arc current because of the time-varying and random characteristics of calcium carbide furnace. It is found in the field operation that the closer the electrode end is to the liquid surface of the molten pool, the greater the electrode current is. Based on this, this paper intends to establish the system model of electrode position-current by using the method of system identification, and then design the model into the fuzzy PID control system. The first paragraph after a heading is not indented (Bodytext style).
2. Analysis of equivalent circuit of calcium carbide furnace

2.1. Short-net connection mode of calcium carbide furnace

Short network refers to the general term of all kinds of connected conductors from the outlet end of the secondary side of the calcium carbide furnace transformer to the electrode. The commonly used connection mode of short network is shown in Figure 1.

Fig. 1 (a) shows the connection mode between a three-phase furnace transformer and the electrode. The transformer is installed near a certain electrode, and due to the asymmetry of the physical structure of the three-phase short grid, the three-phase impedance is deviated, resulting in the unbalanced three-phase load. In addition, three-phase transformer is used for power supply. The non-linearity of transformer and the coupling between phases have a great influence, which leads to the decrease of electric heating efficiency and the increase of power loss of calcium carbide furnace.

Fig. 1 (b) shows the connection mode between three single-phase furnace transformers and electrodes. The transformer is symmetrically installed near the electrode and the short network is symmetrically arranged, which can effectively reduce the inductive reactance of the short network and thus eliminate the unbalance degree of the three-phase load. In addition, three single-phase transformers are used for power supply, which can greatly reduce the non-linearity of the transformer and the coupling influence between phases, thus improving the electric heating efficiency of the calcium carbide furnace and reducing the power loss. The disadvantage is that three single-phase transformers need to be equipped, and the cost is higher.

![Figure 1](image1.png)

Figure 1 Short-grid connection mode of calcium carbide furnace

2.2. Equivalent circuit of calcium carbide furnace

The equivalent circuit of the secondary side winding of the electric furnace transformer, the water-cooled soft cable, the water-cooled conductive cross arm, the charge between electrodes and the working conditions in the furnace are represented by the equivalent resistance, as shown in Fig. 2.
Which,  are the equivalent impedance of the secondary winding, short net and electrode of the transformer,  and  are electrode currents of electrode A, B and C, respectively;  and  are the transverse charge resistance. Form a △ connection loop:  and  is the longitudinal charge resistance, A Y connection loop is formed for the neutral point  of the molten pool:  and  are arc currents respectively.

The neutral point  of the molten pool is to facilitate the analysis of the virtual equipotential point, and the arc current flows through a circuit formed between the electrodes. Therefore, the  conversion theory is adopted, and the longitudinal charge resistance  and  are equivalent to Δ loads, and the transformation formula is:

\[
\begin{align*}
R'_{ab} &= \frac{R_aR_b + R_bR_c + R_cR_a}{R_a} \\
R'_{bc} &= \frac{R_cR_a + R_aR_b + R_bR_c}{R_b} \\
R'_{ca} &= \frac{R_bR_c + R_aR_b + R_cR_a}{R_c}
\end{align*}
\]

Thus, the total equivalent resistance between electrodes A, B and C is:

\[
\begin{align*}
R_{AB} &= R_{ab} \parallel R'_{ab} = \frac{R_{ab}R'_{ab}}{R_{ab} + R'_{ab}} \\
R_{BC} &= R_{bc} \parallel R'_{bc} = \frac{R_{bc}R'_{bc}}{R_{bc} + R'_{bc}} \\
R_{CA} &= R_{ca} \parallel R'_{ca} = \frac{R_{ca}R'_{ca}}{R_{ca} + R'_{ca}}
\end{align*}
\]

The above equivalence and conversion are carried out on the premise that the smelting condition is stable and the resistance value of each kind is equal.

2.3. Equivalent circuit of calcium carbide furnace

In the total equivalent resistance between electrodes A, B and C, the transverse charge resistance  and  change with the change of the smelting condition in the furnace, and the range of change is large, and there will be a jump when the material collapse. Longitudinal charge resistance  and  change.
show periodic changes with the process of smelting and discharging, and the resistance value is the 
minimum before discharging, and gradually increases with the decrease of molten pool liquid level in 
discharging process. In the process of electrode discharge, the transverse charge resistance and the 
longitudinal charge resistance are both greatly disturbed.

The arc current accounts for most of the electrode current, and the arc current changes with the 
change of the total equivalent resistance between the electrodes. Therefore, in the actual control, the 
amplitude of the electrode current is always used as the basis for adjusting the smelting condition of 
calcium carbide furnace.

3. Modeling of electrode position and current identification
Calcium carbide furnace condition adjustment means transformer load regulation (voltage regulator 
switch), electrode rise and fall, charge resistivity changes. A voltage regulator is usually used for a wide 
range of load adjustment; The change of the resistivity of the charge is related to the ratio of raw 
materials, which is usually not used as a method of load adjustment. For small adjustment of load, 
electrode lifting operation is generally used.

The electrode control requirements of calcium carbide furnace are that the electrode position follows 
the level of molten pool liquid, that is, before the furnace, the electrode position is also high when the 
molten pool liquid level is high. After discharging, the electrode position of the molten pool should also 
drop when the liquid level drops. With the continuous smelting of calcium carbide, the liquid level of 
the molten pool increases gradually, and the electrode position also increases slowly. The basis of the 
lifting and lowering of the electrode is to keep the electrode current basically constant. However, there 
is no definite model between the electrode position and the electrode current. In this paper, the system 
identification method is adopted to establish the relationship between the two.

3.1. Recursive least square method
Recursive least square method is a method to estimate the actual output of the system at the present 
moment based on the past operation data. The structure diagram of electrode position-current 
identification system of calcium carbide furnace is shown in Fig. 3.

![Figure 3 Structure diagram of electrode position-current identification system](image)

In Figure 3, \( u(k) \) and \( u(k) \) are the discrete input and output of system model \( G(z^{-1}) \), representing 
the K-th electrode position control quantity and electrode current respectively. Noise model \( N(z^{-1}) \) is 
mainly the interference factor \( v(k) \), representing the disturbed conditions such as carbide furnace 
collapse, discharge and electrode pressure discharge.

Recursive least square method is a method based on the ARX model, which is of the form:

\[
y(k) = -a_1 y(k-1) - a_2 y(k-2) - \cdots - a_n y(k-na) + b_1 u(k-1) + \cdots + b_n u(k-nb) + v(k)
\]  

(3)

It can also be written

\[
A(z^{-1}) y(k) = B(z^{-1}) u(k) + v(k)
\]

(4)

Which

\[
A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_n z^{-na}
\]

\[
B(z^{-1}) = b_1 z^{-1} + b_2 z^{-2} + \cdots + b_n z^{-nb}
\]

(5)
This model is to estimate the output value $y$ at time $k$ according to $u$ values and $y$ values before time $k$. Equation (4) is written in the least square format as:

$$y(k) = h^T(k)\hat{\theta} + v(k)$$ (6)

Set

$$e(k) = y(k) - \hat{y}(k) = y(k) - h^T(k)\hat{\theta}$$ (7)

The least squares estimation requires the minimum sum of squares of the deviation, that is, its objective function is:

$$J = e(k)^T e(k) = (y(k) - h^T(k)\hat{\theta})^T (y(k) - h^T(k)\hat{\theta})$$ (8)

The least squares estimate of $\theta$ is obtained by taking the partial derivative of $J$ with respect to $\hat{\theta}$, and setting $\hat{\theta}$ equal to 0. At time $k-1$ and time $k$, the parameter estimation result of the system is:

$$\begin{align*}
\hat{\theta}(k-1) &= (h^T(k-1)h(k-1))^{-1}h^T(k-1)y(k-1) \\
\hat{\theta}(k) &= (h^T(k)h(k))^{-1}h^T(k)y(k)
\end{align*}$$ (9)

Which, $\hat{\theta}(k)$ and $\hat{\theta}(k-1)$ are estimated values of least squares parameters that can be calculated and obtained according to the first $k$ and the first $k-1$ observation/sampling data respectively. The key to the calculation is the recursive calculation of matrix inverse. The calculation derivation process can be seen in Literature [10], and the final calculation formula is:

$$\begin{align*}
\hat{\theta}(k) &= \hat{\theta}(k-1) + P(k)\phi(k-1)[y(k) - \phi^T(k-1)\hat{\theta}(k-1)] \\
P(k) &= [I - \frac{P(k-1)\phi(k-1)\phi^T(k-1)}{1 + \phi^T(k-1)P(k-1)\phi(k-1)}]P(k-1)
\end{align*}$$ (10)

The order of calculation is $P(k)$ first, then $\hat{\theta}(k)$.

### 3.2. System parameter estimation

The operation data of a calcium carbide furnace collected on site are shown in Table 1.

| Electrode position (mm) | Electrode current (kA) |
|-------------------------|------------------------|
| A  | B  | C  | A  | B  | C  |
| 167 | 161 | 170 | 74.0 | 74.1 | 73.8 |
| 189 | 184 | 186 | 73.2 | 74.6 | 73.4 |
| 215 | 195 | 184 | 72.5 | 72.8 | 72.7 |
| 235 | 228 | 230 | 70.9 | 71.4 | 69.7 |
| 244 | 247 | 239 | 68.0 | 67.1 | 66.6 |
| 257 | 260 | 255 | 65.7 | 64.3 | 63.8 |
| 268 | 271 | 270 | 62.2 | 61.6 | 63.3 |
| 281 | 280 | 284 | 57.5 | 58.6 | 58.9 |
| 294 | 294 | 297 | 52.6 | 53.2 | 54.3 |
| 301 | 305 | 308 | 48.6 | 48.2 | 49.3 |

The data shown in Table 1 are all recorded when the smelting condition of calcium carbide furnace is relatively stable, which is characterized by basic balance of three phases.

System parameter estimation steps :(1) Collection/pretreatment of sample data; (2) Determine the model structure and order; (3) Recursive least square method was used to estimate model parameters;
(4) Carry out reliability test on the identification model and compare the corresponding data of the test method; (5) The electrode position-current model parameters of three-phase electrodes A, B and C were identified by this method.

3.3. Electrode position-current model
According to the above model identification method, the relationship model between three-phase electrode position and electrode current of calcium carbide furnace can be written as follows:

\[
\begin{bmatrix}
I_A(t) \\
I_B(t) \\
I_C(t)
\end{bmatrix} = A(z^{-1})B(z^{-1})
\begin{bmatrix}
h_A(t-nk) \\
h_B(t-nk) \\
h_C(t-nk)
\end{bmatrix}
\]

(11)

Which, \( z^{-1} \) is the delay operator, \( nk \) is the delay of the model, \( I_A(t) \), \( I_B(t) \) and \( I_C(t) \) are the current of three-phase electrode at time, \( h_A(t-nk) \), \( h_B(t-nk) \), \( h_C(t-nk) \) denotes the position of three-phase electrode at time \( t \), \( A(z^{-1}) \), \( B(z^{-1}) \) are the model parameter matrices.

\[
A(z^{-1}) = \begin{bmatrix}
A_1(z^{-1}) \\
A_2(z^{-1}) \\
A_3(z^{-1})
\end{bmatrix}
\]

\[
B(z^{-1}) = \begin{bmatrix}
B_{11}(z^{-1}) & B_{12}(z^{-1}) & B_{13}(z^{-1}) \\
B_{21}(z^{-1}) & B_{22}(z^{-1}) & B_{23}(z^{-1}) \\
B_{31}(z^{-1}) & B_{32}(z^{-1}) & B_{33}(z^{-1})
\end{bmatrix}
\]

The identification model was selected as ARX model with order 2, that is, \( na = nb = 2 \). In Matlab, parameters for off-line identification based on measured data are as follows:

\[
A(z^{-1}) = \begin{bmatrix}
1.02 & -0.12 & 1.01(t-1) & 1.01(t-2) \\
0.98 & -0.09 & 1.01(t-1) & 1.01(t-2) \\
0.99 & -0.11 & 1.01(t-1) & 1.01(t-2)
\end{bmatrix}
\]

\[
B(z^{-1}) = \begin{bmatrix}
-1.18 & 1.57 & -0.42 & h_A(t) \\
-0.88 & 1.12 & -0.26 & h_A(t-1) \\
0.26 & -0.25 & 0 & h_A(t-2)
\end{bmatrix}
\]

\[
\begin{bmatrix}
0.22 & -0.21 & 0 & h_B(t) \\
-1.11 & 1.53 & -0.42 & h_B(t-1) \\
-0.93 & 1.30 & -0.39 & h_B(t-2)
\end{bmatrix}
\]

\[
\begin{bmatrix}
-0.84 & 1.17 & -0.33 & h_C(t) \\
0.19 & -0.20 & 0 & h_C(t-1) \\
-1.10 & 1.47 & -0.41 & h_C(t-2)
\end{bmatrix}
\]

4. Control system design
In this paper, the idea of constant electrode current is used to control the rise and fall of the electrode. The fuzzy PID control system is shown in Fig. 4.
4.1. Recursive least square method

The input variables are electrode current error $e$ and error change rate $ec$. Fuzzy rules, fuzzy reasoning and defuzzification are formulated. PID parameters $k_p$, $k_i$, $k_d$ are adjusted in real time to meet the control requirements of time-varying and randomness of the furnace condition of carbide furnace.

The fuzzy set of input variables $e$ and $ec$ is $e, NM, NS, Z, PS, PM, PB$, and the corresponding domain is $e, ec = [-3, -2, -1.0, 1.2, 3]$. The fuzzy set of output variable $k_p$, $k_i$, and $k_d$ is $k_p, k_i, k_d = \{NB, NM, NS, Z, PS, PM, PB\}$, and the corresponding domain scope is $k_p = [-0.3, 0.3], k_i = [-0.06, 0.06], k_d = [-3, 3]$.

The fuzzy rules formulated are shown in Table 2.

| $kp$ | $ki$ | $kd$ | $ec$   |
|------|------|------|--------|
| NB   | PB   | PS   | NB     |
| NB   | PB   | NS   | NM     |
| NB   | PM   | NM   | NB     |
| PM   | NM   | NB   | PS     |
| PS   | NM   | NS   | Z      |
| NS   | PM   | Z    | NB     |
| Z    | PM   | NS   | PS     |
| PS   | NS   | Z    | PS     |
| PM   | Z    | NS   | NS     |
| PB   | Z    | PS   | PS     |

Fuzzy Reasoning Zadeh approximate reasoning method is used to derive fuzzy system. To defuzzify, select Centroid, the center of gravity method, and obtain the output control quantity, so as to obtain the parameter adjustment quantity of $k_p$, $k_i$ and $k_d$ of the fuzzy PID control system.
4.2. Recursive least square method

The application object is a closed calcium carbide furnace, the capacity of which is 21000kVA, the high voltage side is powered by 110kV, the electrode lifting operation is driven by hydraulic device. The control system is composed of upper industrial computer and PLC (S7-1200 series). The two are connected by Profeibus-DP field bus. The fuzzy PID controller designed according to the control idea in this paper runs in the way of timing interrupt in PLC. The system operation data is recorded every 30s and stored in the WinCC database installed by the upper IPC.

After the control system was put into operation for about 40min, the furnace condition was relatively stable. The recorded three-phase electrode position and electrode current data were drawn into a curve, as shown in Fig. 5.

\[
\begin{align*}
    k_p &= k_p' + \{e_i, ec_i\}_p \\
    k_i &= k_i' + \{e_i, ec_i\}_i \\
    k_d &= k_d' + \{e_i, ec_i\}_d
\end{align*}
\]

(12)

In Fig.5, the positions of electrode A, B and C are 212mm, 218mm and 205mm respectively, and the corresponding electrode currents are 74kA, 72.3kA and 69.7kA respectively. When the operating time is about 50min, the operating electrode C rises 5mm, resulting in a slight increase in the current of electrode A and B, and a slight decrease in the current of electrode C. When the operating time is about
60min, the operating electrode C drops 5mm, and the current of electrode A, B and C basically returns to the original value.

5. conclusion
(1) The fuzzy PID control system based on the constant control strategy of electrode current designed in this paper, through simulation and application, shows that the system has good dynamic response, anti-disturbance ability and robustness.

(2) Starting from the equivalent circuit of calcium carbide furnace, the electrode position-current system model identified by the recursive least square method is suitable for the relationship between electrode position and electrode current of calcium carbide furnace. By adjusting the electrode position, the electrode current can be changed, and then the furnace temperature can be controlled, so that the furnace condition can be maintained in a better state.

(3) Calcium-carbide furnace condition is very complex, time-varying and random characteristics are obvious, in the occurrence of such as collapse, discharge or electrode pressure release and other large disturbance, the performance of the control system becomes worse, the need for manual intervention. However, the furnace condition is relatively stable during most period of smelting process, so the control system is applicable.

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