Research on electrode position fuzzy control system of calcium carbide furnace based on constant power

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Abstract. The adjustment methods of calcium carbide furnace conditions include voltage regulator switches, electrode lifts, and changes in charge resistivity. For slight load changes, electrode lifts are commonly used. In order to have a positive effect on the control, furnace conditions and energy loss of the calcium carbide furnace, this paper proposes a fuzzy control method for the electrode lift of calcium carbide furnace based on constant power. By detecting the electrode current and electrode voltage, the electrode position is obtained indirectly, and then the fuzzy control idea is used to determine the control amount of the electrode lifting, and the control volume is converted into a pulse signal to act on the hydraulic solenoid valve to control the electrode lifting, so as to achieve a constant power consumption of the calcium carbide furnace the goal of. Simulation and practical applications show that this method can effectively avoid arc extinguishing and short-circuit phenomena, and has a certain positive effect on the operation of calcium carbide furnace, improvement of furnace conditions, and energy saving and consumption reduction.

1. Introduction
Calcium carbide furnace is a metallurgical equipment for smelting calcium carbide (calcium carbide, Ca2), and the smelting temperature of calcium carbide is about 2200°C [1]. It mainly relies on the electric arc generated by the discharge between the electrode and the charge to convert the electric energy into heat energy in the arc, and uses the direct action of the thermal radiation and the electric arc to heat, melt, and smelt to produce calcium carbide. The electric energy consumed by the calcium carbide furnace is introduced from the electrode buried in the charge. The current distribution in the furnace is constantly changing with the charge resistance, the electrode voltage, the electrode current, and the discharge, collapse and other factors. The above factors lead to the smelting process. It is more complex, and its notable features are multivariable, nonlinear, large lag, strong coupling, time-varying and random[2-4].

The electrode is the key equipment of the calcium carbide furnace, which is responsible for the conduction, heat transfer and adjustment of the smelting conditions. The main factor that affects the furnace temperature is the length of the arc. The position of the electrode can adjust the length of the arc, that is, the active power input to the calcium carbide furnace can be adjusted. The electrode position is higher, the arc area (melt pool radius) is smaller, the arc length becomes longer, the input power is reduced, and the melting time is prolonged; the electrode position is lower, the arc length becomes shorter, and the input power increases, causing increased heat loss and electrode The consumption of [5].
Therefore, the electrode lifting control is the key to adjusting the smelting conditions of the calcium carbide furnace.

Scholars and industry practitioners at home and abroad have conducted a lot of research on the electrode lifting control of calcium carbide furnace. In summary, there are mainly three control schemes of constant current, constant resistance and constant power [10]. This article takes the large-capacity enclosed calcium carbide furnace driven by a hydraulic device as the research object. By detecting the electrode voltage and electrode current, using the idea of constant power consumption of the calcium carbide furnace, a fuzzy controller-based calcium carbide furnace electrode lifting control system is designed to maintain the calcium carbide furnace in the best operating condition.

2. Power constant control scheme of calcium carbide furnace

During the smelting process of the calcium carbide furnace, the furnace temperature is adjusted by the electrode position, that is, the input power is changed. The electrode control requirement is that the electrode position follows the level of the molten pool liquid level, that is, before the furnace is discharged, the molten pool liquid level is high and the electrode position is also high; after the material is discharged, the molten pool liquid level drops, and the electrode position also drops; The liquid level of the pool gradually rises, and the electrode position also rises slowly. If the electrode position is not adjusted in time, it will cause arc extinguishing or short circuit, which will cause the interruption of the smelting process. The schematic diagram of the electrode position detection of calcium carbide furnace is shown in Figure 1.

![Figure 1: Schematic diagram of electrode position detection of calcium carbide furnace](image)

Principle of electrode position detection of calcium carbide furnace (take electrode A as an example): In Figure 1, the PLC controller detects electrode current $I_A$ and electrode voltage $V_A$ through signal conversion, A/D conversion and other links, which can be obtained by data processing in the PLC. Corresponding to signals $U_{A1}$ and $U_{A2}$, the control value $U_K$ can be obtained as:

$$U_K = \begin{cases} 
-k*U_{A2} & U_{A1} = 0 \\
k*(U_{A1}-U_{A2}) & U_{A1} \neq 0, U_{A2} \neq 0 \\
k*U_{A1} & U_{A2} = 0 
\end{cases}$$

(1)

In formula (1), $k$ is the transform coefficient. $U_{A1} = 0$ means that the electrode current is close to zero, causing arc extinguishing phenomenon, indicating that the electrode position is too high; $U_{A2} = 0$ means that the electrode voltage is close to zero, resulting in a short circuit phenomenon, indicating that the electrode position is too low.
Based on the control idea that the power consumption of the calcium carbide furnace is constant: if the electrode is at the ideal position $h^*$, the values of voltage $U_{A1}$ and $U_{A2}$ are equal through parameter matching, then $U_K = 0$. In normal production, adjust the electrode position to $U_K = 0$; when there is an abnormal phenomenon in production, for example, the distance between the electrode and the molten pool liquid level decreases, at this time the electrode current $I_A$ increases, and the electrode voltage $V_A$ decreases, then $U_K > 0$; on the contrary, when $I_A$ decreases, $V_A$ increases, then $U_K < 0$. Therefore, the $U_K$ signal can be used as the control signal of the electrode lifting hydraulic device, and the signal is logically converted to control the rise or fall of the electrode to maintain $U_K = 0$. Maintaining $U_K = 0$ is actually to maintain the power supply of calcium carbide furnace unchanged.

3. Fuzzy Control of Electrode Position of Calcium Carbide Furnace

3.1. Language Variables of Fuzzy Controller

Take electrode $A$ as an example to discuss. The input language variable of the fuzzy controller can be selected to detect output voltages $U_{A1}$ and $U_{A2}$, and the output language variable is electrode lift control signal $u$. In this way, the electrode lifting control system is a fuzzy controller with dual input and single output. The schematic diagram of the electrode lifting control system is shown in Figure 2.

![Figure 2](image)

In Figure 2, $h^*$ is the ideal position of the electrode, and $h$ is the actual position of the electrode. The control variable $u$ (continuous value, positive value is rising signal, negative value is falling signal) obtained by the fuzzy controller, is converted into two pulse signals with adjustable pulse width through the pulse conversion link, which act on the electrodes of the large vertical cylinder respectively. The ascending solenoid valve and the descending solenoid valve are used to control the lifting of the electrode.

3.2. Membership function of linguistic variables

After normalization, the physical theory domain of input linguistic variables $U_{A1}$ and $U_{A2}$ is $[0, 10]$, and the physical theory domain of output linguistic variable $u$ is $[-10, 10]$. If the discrete domain of the input language variable $U_{A1}$ is selected $X=[-3, -2, -1, 0, +1, +2, +3]$, then the quantization factor of $U_{A1}$ is $k_1=2 \cdot 3/10=0.6$; the language value selected for $U_{A1}$ is NB (small), NM (small), NS (slightly small), Z (normal), PS (slightly large), PM (large) and PB (large). Each language value is defined by the trapezoidal membership function shown in Figure 3.
Figure 3  Trapezoidal membership function of input language variable $y_2$

Discrete domain $Y=X$ of input linguistic variable $U_{x2}$, quantization factor $k_2=k_1=0.6$; The language value and membership function of the language variable $U_{x2}$ are the same as that of $U_{x1}$.

The discrete domain of the output language variable $u$ is $Z=[-3,-2,-1,0,1,2,3]$, then the scale factor of $u$ is $k_3=20/6=3.33$. Similarly, the language values selected for language variable $u$ are NB (fast down), NM (down), NS (slow down), Z (not moving), PS (slow up), PM (up) and PB (fast up). Each language value is defined by the triangle membership function shown in Figure 4.

Figure 4  Single-valued membership function of output language variable $u$

3.3. Fuzzy control rule table
Design fuzzy rules based on the operating experience of calcium carbide smelting professionals. The standard for fuzzy rule design is:

Rule 1: The electrode is short-circuited, and the electrode rises rapidly;
Rule 2: The electrode current is large, the electrode voltage is small, and the electrode rises;
Rule 3: The electrode current is small, the electrode voltage is large, and the electrode drops;
Rule 4: The arc is extinguished and the electrode drops quickly.

According to this fuzzy rule design standard, a fuzzy rule table is established, as shown in Table 1.

| Electrode lift $z$ | Electrode current $x$ | NB | NM | NS | Z | PS | PM | PB |
|-------------------|----------------------|----|----|----|---|----|----|----|
| NB                |                      | NB | PB |    |    | PS | PM | PB |
| NM                |                      | PM | PM | PB |    | PS | PM | PB |
| NS                |                      | Z  | Z  | PS | PM | PB |    |    |
| Z                 |                      | NB | NS | Z  | Z  | PS | PB |    |
| PS                |                      | NB | NM | NS | Z  | Z  |    |    |
| PM                |                      | NB | NM | NM |    |    |    |    |
| PB                |                      | NB | NB |    |    |    |    |    |

3.4. Fuzzy reasoning and inverse fuzzification operations
According to the previously defined linguistic variables, domains and membership functions, as well as the formulated fuzzy control rules, the corresponding fuzzy relationship matrix $R$ can be calculated in the Matlab simulation software as:
Taking into account the control requirements and real-time performance of the electrode lifting control system, the fuzzy reasoning plans to use the CRI look-up table method, which is to calculate the output corresponding to various possible input quantities in advance, and establish the table of the corresponding relationship between the input and the output. In control, the control amount can be determined by just looking up the table. Taking into account the characteristics of calcium carbide furnace electrode lifting control is not suitable for fast and frequent operation, the inverse fuzzification calculation is to adopt the relatively simple calculation of the average maximum membership method.

4. Control system design

4.1. Electrode lifting hydraulic device model

In the current electrode control of calcium carbide furnace, the control method of lifting or lowering the electrode through the AC and DC transmission system has been eliminated, and replaced by a hydraulic lifting device powered by hydraulic pressure. The rise and fall of the electrode is controlled by controlling the on-off time of the solenoid valve. The model of the hydraulic lifting device is a typical nonlinear model, which can be identified through the output response process to the input. The transfer function of the mathematical model obtained by using this method in literature [10] is:

$$G_{\text{raise}}(s) = \frac{0.45}{(1.33s + 1)s} e^{-s}$$

$$G_{\text{low}}(s) = \frac{1.1}{(2.5s + 1)s} e^{-s}$$

In formula (2), $G_{\text{raise}}(s)$ and $G_{\text{low}}(s)$ are the transfer functions of the electrode ascending and descending process, and the difference is caused by the length of the oil pipeline, the characteristic deviation of the solenoid valve and the electrode's own weight.

4.2. Control system structure

The structure diagram of the electrode lifting control system of the calcium carbide furnace designed according to the difference of the hydraulic lifting device model is shown in Figure 5.
The hardware of the control system uses Siemens S7-1200 series PLC, and the software adopts modular programming method. The sub-program modules related to electrode lifting control and their realized functions are shown in Table 2.

| Program block | name           | Description                                      |
|---------------|----------------|--------------------------------------------------|
| OB1           | Cycle Execution| FC4 (Analog filter)                              |
|               |                | FC5 (Scale transformation)                       |
|               |                | FC6 (Inverse scaling)                            |
|               |                | FC8 (Analog processing)                          |
|               |                | FC16 (Electrode manual pressure release)          |
|               |                | FC18 (Electrode manual lifting)                   |
| OB35          | CYC_INT5       | FC17 (Electrode automatic pressure release)       |
|               |                | FC19 (Electrode A automatically rises and falls)  |
|               |                | FC20 (Electrode B automatically rises and falls)  |
|               |                | FC21 (Electrode C automatically rises and falls)  |
| OB100         | Complete Restart|                                                |
| DB1           | Operating data |                                                |
| DB2           | Digital quantity|                                                |
| DB3           | Analog         |                                                |

4.3. Control results and applications
In order to verify the control effect, this system has done simulation and field test before it is applied to calcium carbide furnace. The simulation work is carried out in Matlab. The simulation models of conventional PID controller and fuzzy controller are built respectively. The electrode reference position was selected as 0.5 m from the bottom of the furnace, and the ascending and descending displacements were selected as 0.25 m. The simulation results were shown in Figure 6.

![Figure 6 Control effect simulation comparison](image)

As shown in Figure 6, the control effect of the fuzzy controller is obviously better than that of the conventional PID controller from the perspective of control indicators such as overshoot and follow-through. The reason for the large overshoot of the PID controller in the figure may be related to the selection of control parameters. Before the calcium carbide furnace was put into operation, the fuzzy control system of electrode lifting was tested on site. From the perspective of electrode lifting action, it could better follow the change of instructions. The specific test results are shown in Table 3.
Table 3  Field test results

| Expected itinerary | Actual itinerary | deviation |
|--------------------|------------------|-----------|
| rise 0.25 m        | rise 0.247 m     | -0.03 m   |
| interval 25s       | Action time 3.6 s|           |
| decline 0.5m       | decline 0.502 m  | 0.02 m    |
| interval 25s       | Action time 7.8 s|           |
| rise 0.5m          | rise 0.496 m     | -0.04 m   |
| interval 25s       | Action time 8.5 s|           |
| decline 0.5m       | decline 0.498 m  | -0.02 m   |
| Action time 7.9 s  |                   |           |

As can be seen from the data in Table 3, the field test results are basically consistent with the simulation results.

In a closed calcium carbide furnace with a capacity of 21000kVA, the high voltage side is supplied by 110kV power, and the electrode lifting is driven by a hydraulic device. After applying the control system designed in this paper, it is found that the electrode lifting action can be better "automatically" controlled when the smelting condition is relatively stable. However, under the conditions of opening furnace, collapsing material, discharging material and electrode pressure release, the effect of "automatic" control becomes worse and manual intervention is needed.

5. Conclusions

At present, there are three control strategies for the electrode lifting of calcium carbide furnace: constant current, constant resistance and constant power. Based on the idea of constant power control, this paper designs a fuzzy control system for the electrode lift of calcium carbide furnace. According to the control effect of the control system, the following conclusions are drawn:

(1) From the point of view of field application, this system can effectively avoid the occurrence of arc extinguishing and short circuit.

(2) Calcium carbide furnace control, furnace condition improvement, energy saving and consumption reduction have a certain positive effect.

However, due to the complex conditions of the calcium carbide furnace and too many uncertain factors in the furnace, this system is only suitable when the smelting conditions are relatively stable, and its universality is limited.

References

[1] Xiong, M.Y., Yue, H.l. (2005) Calcium carbide production and processing, product development and utilization, and pollution prevention and rectification new technology and new process practical manual. Chemical Industry Press, Beijing.

[2] Sun, H.X., Li, Y. (2019) Modeling and control of stone furnace. Chemical Industry Automation and Instrumentation, 46(06): 436-441.

[3] Chen, L. (2015) Application of PLC control in the electrode lifting control of calcium carbide furnace. Chemical Industry Automation and Instrumentation, 42(12): 1378-1380+1390.

[4] Jia, H., Guo, X.C., Liu, H.B. (2015) The realization of fuzzy PID control in the electrode control system of calcium carbide furnace. Computer Simulation, 32(02): 441-445.

[5] Gu, F., Wei, Y., Sun, H., Zhang, J.L., Xiao, Q.A. (2013) Electrode control principle and energy saving analysis of submerged arc furnace for calcium carbide production. Ferroalloy, 44(04): 24-29.

[6] Qi, Z.D., Huang, N.J., Huang, J. (2009) Design and Application of Fuzzy Control System for Calcium Carbide Furnace Electrode Lifting. Industrial Control Computer, 22(07): 43-45.

[7] Li, J.X., Jiang, X.H. (2007) Research and Application of Fuzzy Control System for Calcium Carbide Furnace Based on PLC. Journal of Fujian University of Technology, (06): 565-567+585.
[8] Chen, L., Ma, B.Y., Zhang, X.F. (2007) The application of intelligent PID control in the electrode adjustment system of calcium carbide furnace. Journal of System Simulation, (07): 1544-1547.

[9] Liu, Z.F., Ren, Q.C., Zhang, W. (2006) Control system design of calcium carbide furnace based on fuzzy decoupling algorithm. Industrial Heating, (06): 32-33 +46.

[10] Hu, H.B. (2010) Research on self-tuning PID control of calcium carbide production process. Nanjing University of Science and Technology.