Soft-Sensing Model of Coke Oven Flue Temperature

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Abstract: Soft-sensing technology is a novel industrial technique for some key parameters not being obtained online. The paper establishes the Soft-sensing model of coke oven flue temperature, a key technical index in coke oven heating process, which is so difficult to measure directly online. A soft-sensing model of flue temperature based on case-based reasoning is consists of four modules: data collection and pretreatment model, soft-sensor model, online modification model and online estimate model. The output of prediction data is processed with the case-based reasoning algorithm and the self-adjusting algorithm to get the target value of the case solution. The industrial application results show that the soft-sensing model can reflect the actual operation condition and meet the requirement of real-time control. Its effectiveness is proved.

Keywords: Soft-sensing, Case-based reasoning, Flue temperature, Coke oven, Intelligence soft-sensor model, Self-adjusting algorithm.

1. Introduction

Soft-sensing technology is an online estimate sensing technology for some production variables (i.e. dominant variable) which cannot be measured or those are difficult to measure, which adopts the software instead of the instrument to measure and estimate based on certain criteria for the model computation with selecting the easy measured variables as the secondary variables, such as temperature, pressure, etc. The final model through selected variables not only has simple structure and less parameters, but the prediction accuracy and generalization ability is higher [11-13]. The coke oven flue temperature, as very important process parameters, refers to the measurement flue temperature average of the whole furnace chamber and can reflect the overall temperature of coke oven.

Due to the cost and process in the process of coke oven heating, it is very difficult to achieve the real-time online measurement of coke oven flue temperature so that it can only be acquired through artificial measurement. Here are some main reasons why cannot meet production need:

1) Long measurement cycle, temperature sensing once every four hours is too long time interval to detect accurately the instantaneous temperature, therefore, not conforming to the requirement of real-time control.

2) Different measurer often achieves some inaccurate sensing data once every four hours according to the different measurer experience. How to obtain the oven flue real-time temperature to meet the need of control has become the key issue for restricting coke oven temperature control. It is an important practical significance for coke oven
heating process to realize the on-line measurement of coke oven flue control by application of soft-sensing technology. At present, soft-sensing technology, as an effective method to estimate some unpredictable variables in the process of industrial, is gaining more and more application [1-3]. Soft-sensing technology research content mainly aims at the issue of a process variable to establish mathematical model, which is called the Forecasting Model based on the characteristic and function of its model.

The current domestic existing soft-sensing model is mostly the unary linear regression model [4-5] about the establishment of regenerator top temperature and coke oven flue temperature or the dual parabola model [6] between them, the model that it is as the linear relationship or dual parabola relationship between the regenerator top temperature and coke oven flue temperature has some limitations and low accuracy.

Case-based Reasoning (CBR) technology based on past experience and knowledge reasoning has been successfully applied in various fields, such as medical diagnosis, fault diagnosis, the weather forecast [7-9]. Model of CBR is easy to implement and maintain with directly using the past knowledge and experience, its training is simple and effective. To improve the ability of judgment and reasoning: Good at using empirical knowledge to learn; Adopting the incremental learning method; cultivating a strong independent learning ability.

In this paper, the intelligent forecast model of the key process parameters for the problems and needs above based on CBR technique is put forward and applied to a coke oven flue soft-sensing of certain coking plant. The practical application effect shows that the method has high estimation precision and strong versatility, owning wide application prospect.

2. Modeling Method Based on Case-based Reasoning Technology

First of all, a lot of problems and their solutions be expressed and stored in the form of case, when new problem (case) happening, the old case is match by system according to the new case description with certain similarity in the case library to retrieve the most similar case and employ or revised its solution to produce a solution about new problem. The typical case is added into the case library to implement a learning process of CBR.

The intelligent soft-sensor model [10] for the critical variables, which can predict complex industrial process, is shown in Fig. 1. The output of the reasoning forecast module is \( \vec{X} \); the output of correction is \( \bar{X} \); \( \Sigma \) is obtained from the process data set of distributed control system (DCS); artificial measurement data set \( \Theta \) is obtained through detection model; \( \epsilon \) is the online calibration parameters exported by an online calibration module; the input of the controlled object is \( u \); The output of the controlled object is \( y \).

Fig. 1. The overall structure of intelligent soft-sensor model.

1) The module for data acquisition and processing module.

Acquiring the data from the spot which has usually all kinds of jamming noise, such as the zero drift of an instrument, should be performed the data transform and error handling in order to avoid the noise disturbance to the modeling as far as possible, namely data preprocessing. Under certain conditions, the result being output by the soft-sensor model should be properly adjusted, as the model is obtained on the premise of a series of assumptions, which cannot be in complete accord with the actual situation, existing a model error.

2) The prediction module.

First, the soft-sensor model reads the currently operating mode characteristic and retrieves a similar case in the case base according to the working condition features to match and reuse based on their similarity threshold, thereby, which described the case solution of current conditions for the soft-sensing values of the estimated dominant variable. Analysis of the error between the actual measured value of the dominant variables and the soft-sensing value and the Precision evaluation of the soft-sensing model, if it cannot reach the expected Precision, the case solution should be modified; The case solution, precision reaching the requirements, is placed into in the case base according to relevant rules.

In case-based reasoning prediction module, the function of correction and the maintenance module is: in the process of case-based reasoning prediction module in operation with the change of the object parameters such as conditions, the previously available case may become no longer apply to the object so that the case-based reasoning system should be modified and maintained to ensure that the case-based reasoning forecast module can acquire the information of object changes and the available correct results.
3) The online correction module.

The properties of object and working point will gradually change with the passage of time after using the soft-sensor model so as to make the output drift, which the corresponding corrective actions must be taken in order to guarantee the accuracy of the predicted value,

\[
e = \frac{1}{n} \sum_{i=1}^{n} \left( X_i^* - \hat{X}_i \right)
\]  

(1)

The \( e \) in type (1) is for an online calibration parameter, the output of the forecast model is \( \hat{X}_i \), the actual measured value is \( X_i^* \), the sample is \( n \), the output after correction is

\[
\bar{X} = \hat{X} + e
\]  

(2)

This calibration method is easy to implement with the type (1) and (2) correction to the output of the forecast module for compensating the drift of the output to ensure the accuracy of prediction.

4) The performance evaluation module.

This module receives the output of the case-based reasoning forecast module, compared with the artificial measurement data obtained by testing model for the evaluation of forecast accuracy.

3. Flue Temperature Intelligent Soft-sensor Model Based on Case-based Reasoning

When the soft-sensor model of the flue temperature is established, after the flue temperature of the combustion chamber analyzed considering the actual value of the detection statistics \( T^* \) of the flue temperature on a regular basis, the negative pressure \( n \) of a stove chamber, the heating gas flow \( u \), the heating gas pressure \( p \), the heating gas heat value \( h \) and the flue suction \( v \), the case-based reasoning is applied to implement the intelligent forecast of the flue temperature, the model structure is shown in Fig. 2. The intelligent soft-sensor model of the flue temperature is composed by the case-based reasoning model and the calibration model. The detection data set \( \mathcal{S} \) is obtained from in the process of coke oven heating; the output of the case-based reasoning forecast model is \( \hat{T}_i \); the actual measured value of the flue temperature is \( T^*_i \) \((i = 1, 2, \ldots, n)\) in a certain period of time; the statistics of artificial measuring values is \( T^* \); the error \( e_i \) is for the output value of case-based reasoning soft-sensor model and the artificial detection result; \( TB > 0 \) is the preset error limit; the correction output of the flue temperature is \( \bar{T} \). The detection data \( \mathcal{S} \) is acquired by model selector in the process of the coke oven heating, the forecast completed by case-based reasoning soft-sensor model to get the forecast value; then the Self-adjusting model based on the artificial measurement statistics determines to deal with the forecast results to get the final target value.

3.1. Case-based Reasoning Algorithm

The soft-sensor model of oven flue temperature completes observable and controllable analysis for all kinds of operation parameters and the correlation analysis with other variables based on case-based reasoning algorithm [14-15] and selects the following variables as auxiliary variables from the aspect of variable reduction: the heating gas flow \( u \), the flue suction \( v \), the heating gas heat value \( h \), the heating gas pressure \( p \) and the negative pressure \( n \) of a stove chamber. The flue temperature case is stored in the computer in the form of a database consists of a series of case histories as shown respectively in Table 1 and Table 2.

![Fig. 2. The composite intelligent soft-sensor model of the flue temperature.](image)

**Table 1.** The machine side flue temperature case.

<table>
<thead>
<tr>
<th>Time</th>
<th>The working conditions</th>
<th>The Case solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine side gas flow</td>
<td>Machine side flue suction</td>
<td>Gas heat value</td>
</tr>
<tr>
<td>Machine side gas pressure</td>
<td>Stove chamber negative pressure</td>
<td>Machine side flue prediction value</td>
</tr>
</tbody>
</table>
2) The calculation for case similarity.

The current operation condition is set $C_r$, described for $F = (f_1, f_2, \cdots, f_n)$; the existing cases are defined for $C_k = \{T_k, F_k, J_k\}$, $F_k = (f_{i,k}, f_{2,k}, \cdots, f_{n,k})$, $k = 1, \cdots, m$. $m$ is for the case number, the similarity between the description $f_i$ ($1 \leq i \leq n$) of the $C_r$ features and the description $f_{i,k}$ of the old case is for

$$Sim(f_i, f_{i,k}) = 1 - \left| f_i - f_{i,k} \right| / \text{Max}(f_i, f_{i,k}) \quad (3)$$

The similarity $Sim(f_i, f_{i,k})$ defined clearly in real number interval [0, 1] satisfies the symmetry and reflexivity, that is the similarity relation. In the current condition $C_r$ and the case $C_k$, the similarity function is defined for

$$Sim(C_r, C_k) = \sum_{i=1}^{n} w_i Sim(f_i, f_{i,k}) \quad (4)$$

3) The determination of the similarity threshold.

After the similarity calculation, the result is assigned to the "similarity" attribute of the corresponding cases to determine the similarity threshold before the case matched. Sim is the similarity threshold, marked as

$$Sim_{\text{max}} = \max_{k=1,2,\cdots,m} \left( Sim(C_r, C_k) \right)$$

$$Sim_i = \begin{cases} \infty, & Sim_{\text{max}} \geq X_i \\ Sim_{\text{max}}, & Sim_{\text{max}} < X_i \end{cases} \quad (5)$$

The threshold $X_i$ in type (5) is decided by the specific process or experience according to the situation object, the general value is 0.9.

4) The case retrieval and matching

Case retrieval and matching is the key to the realization of case-based reasoning, which the main purpose is to retrieve case bank according to the description of the new problems from the best case as the basis of solving the new problems. Putting forward all with the current condition in the description of similarity to the threshold of case matching is retrieved as a case. And it is arranged according to the similarity and the descending order of time attribute value.

5) Case reuse

A general rule, perfectly matched with the current condition of the description of a case, does not exist in the case repository, the matching conditions of the retrieved case cannot be directly as the current condition of the solution, thus the similar case which is retrieved should be reused.

Assuming that matching case set is: $C_k = \{T_k, F_k, J_k, Sim_k\}$, $k = 1, \cdots, h$, $h < m$, $Sim_k$ is the attribute values $C_k$ of corresponding similarity. Assuming that $C$ is the case which has the largest similarity $Sim_{\text{max}}$, the solution is $J, J_u$ as the case reused answer.

$$J_u = \begin{cases} J, & (Sim_{\text{max}} = 1 \lor Sim_{\text{max}} = Sim_{\text{max}}) \\ \sum_{k=1}^{h} \left( Sim_k \times J_k \right) / \sum_{k=1}^{h} Sim_k\text{, others} \end{cases} \quad (6)$$

In the equation (6), $\lor$ is the operator of “or”, showing that the relation is “or” between before and after.

The result after the case reuse is output, depositing the time of working condition and its solution in the real-time database.

6) Case evaluation and correction.

In order to verify the validity of the case reuse results, the case evaluation and correction must be carried out. The first step of correction is to evaluate the result of the reuse, if it is successful, the solution will not be revised, otherwise correcting the cases in order to improve the estimation precision of the model. Case evaluation is based on its running effect in the practical environment of feedback and the case revision is executed in the new process on the basis of the problems.

First the measured values of the dominant variable $J_r$ and sampling time $T_s$ is read, then in the real-time database "time" attribute value and the data record which is most close to $T_s$ is retrieved, remarking the retrieved data record as

$$\hat{C}_r = \{\hat{T}, \hat{F}, \hat{J}_r\} \ , \ \text{ solving } \Delta J = \left| \hat{J} - J \right|. \quad (7)$$

Assumption that $J_r$ is the eligibility criteria of soft-sensing precision, generally setting $J_r = 7.5$, if $\Delta J \leq J_r$, the soft-sensing precision is qualified, the case need not be corrected, storing the cases as case storage strategy; otherwise the correct result is as the following cases. $\hat{F}$ is taken to conduct case retrieval

<table>
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<tr>
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<td>Coke side flue suction</td>
<td>Gas heat value</td>
</tr>
</tbody>
</table>

Table 2. Coke side flue temperature case.
3.2. Self-adjusting Algorithm

In order to ensure the precision of prediction, the initial prediction results need to be corrected online, generally by measuring temperature of the combustion chamber flue with the handheld infrared thermometer, the artificial measurement data set is \( \{ r_i, i = 1, 2, \ldots, k \} \), using statistical process control (SPC) to process these data.

\[
T^* = \frac{\sum_{i=1}^{k} r_i}{k} \tag{7}
\]

Initial prediction value of the flue temperature obtained from case-based reasoning soft-sensor model is \( \hat{T}_f \), prediction effect of flue temperature is evaluated by the formula.

\[
e_j = \hat{T}_f - T^* \tag{8}
\]

\( e_j \) is the error between the initial prediction value and artificial test data of the output of case-based reasoning soft-sensor model. If the absolute value of \( e_j \) is greater than the preset limit \( TB \), that is \( |e_j| > TB \), it means the output of soft-sensor model needs correct, the correction parameter is \( e_j \); otherwise, the output does not need to correct, at this time \( e_j \) can be set to 0. The output \( \hat{T} \) after correction is:

\[
\hat{T} = \hat{T}_f - e_j \tag{9}
\]

4. Industrial Application

Applying the coke oven flue temperature composite intelligent soft-sensor model to coke oven heating intelligent control system of a steel joint enterprise, forecast effects of the machine side and coke side of coke oven coke side are shown in Fig. 3 and Fig. 4. According to statistics, the forecast error of coke side model and machine side model in \( \pm 5 \) \(^\circ\) respectively reach 91.8 \%, 90.1 \%, meet the requirements of industrial production.

5. Conclusions

In process of the industrial control, some vital but not directly measured variables can be monitored with the soft-sensing technology, which needs a large number of instrumental variables related to the main variables, the key of soft-sensing technology is to establish an appropriate mathematical model. Aiming at the fact that the coke oven flue temperature is difficult to measure in heating process, the intelligent forecast model is put forward based on case-based reasoning, which is consist of data collection and pretreatment model, soft-sensor model, online modification model and online estimate model. The soft-sensor model of oven flue temperature completes observable and controllable analysis for all kinds of operation parameters and the correlation analysis with other variables based on case-based reasoning prediction algorithm. The industrial application results show that the soft-sensing model can reflect the actual operation condition and meet the requirement of real-time control. Its effectiveness is proved evidently.
Fig. 3. The prediction effect of machine side soft-sensor model.

Fig. 4. The prediction effect of coke side soft-sensor model.

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References


[8]. Niloofar Arshadi, Igor Jurisica, Data mining for case-based reasoning in high-dimensional biological domains, IEEE Transactions on Knowledge and Data Engineering, 17, 8, 2005, pp. 1127-1137.

[9]. Yan Ai-Jun, Yue Heng, Zhao Da-You, etc., Intelligent soft-sensor model for a Class of Complex Industrial Process and Its Application, Control and Decision, 20, 7, 2005, pp. 794-797.


