Predictive functional control (PFC) and its application in chlorinated polyethylene process*

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Abstract: The main principle and the characteristic of Predictive Functional Control (PFC) strategy are presented in this paper and the corresponding control system aid design software APC-PFC is also introduced. For a chlorinated polyethylene (CPE) process, a design scheme of cascade predictive functional control system is described and the control performance is improved obviously.

Key words: Predictive control, Predictive functional control (PFC), Base functions, Chlorinated Polyethylene (CPE)

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INTRODUCTION

With the development of science and technology, requirements for the satisfactory performance of the control processes are largely enhanced. However, modern control theory based on the state-space method cannot meet the requirement of the practical control problem due to the fact that it is very difficult to obtain the precise mathematical model of processes, especially for non-linear, uncertain, time-delay and time-varying processes. Ordinary predictive control strategies can solve some of these control problems, but are usually only limited to the slow processes because of the complex on-line computation. Thus, Predictive Functional Control (PFC) is used to deal with the quick tracking control problems as a new kind of predictive control method (Su, 2000).

PFC has been regarded as an effective control method for rapid processes since it was presented at the beginning of the 1980's. Recently, PFC has successfully been used in some practiced industrial processes, such as those for nonage robot, rocket, object dogging, reactor and heater, etc.

In this paper, the PFC algorithm is described and then a PFC aid design software package is introduced. Finally, the PFC technology is applied to control a process for producing chlorinated polyethylene and the result is very nice.

THE PFC ALGORITHM

PFC is based on the same principle as that of classical predictive control strategy, i.e. use a model to predict the future output of a process, achieve optimization and feed-back correction. The main difference between general predictive control strategy and PFC is that in PFC, the structure of the control variables is considered as a linear combination of a set of base functions (Richalet, 1987). The control variables can be obtained by calculating the weight coefficients of the base functions' linear combination. The choice of base functions is related to the characteristic of the process and the desired setpoint.

The key function of PFC is the selection of base functions, predictive model, reference trajectory and coincidence points.

1. Predictive model

PFC is a model-based predictive control strategy. The predictive model is often described by the following discrete state equation

$$\begin{aligned} \boldsymbol{X}_m(k) &= \boldsymbol{A}\cdot\boldsymbol{X}_m(k-1)+\boldsymbol{B}\cdot\boldsymbol{U}(k-1) \\ \boldsymbol{Y}_m(k) &= \boldsymbol{C}\cdot\boldsymbol{X}_m(k) \end{aligned} \quad (1)$$

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Where $X_m \in R^{n \times 1}$ is the state vector of the internal model process. $Y_m \in R^{l \times 1}$ is the output vector of the internal model process. $U \in R^{l \times 1}$ is the control input vector of the system. $A \in R^{n \times n}$, $B \in R^{n \times l}$ and $C \in R^{l \times n}$ are the coefficient matrices of the discrete state space model.

The model (1) can be obtained by general identify methods because PFC is mainly used to deal with single input/single output systems and possesses strong robustness.

2. Base functions

One feature of the PFC is that the control variables are expressed as the linear combination of a set of base functions

$$u(k+i) = \sum_{j=1}^{J} \mu_j(k) f_{kj}(i) \tag{2}$$

where $f_{kj}(i)$ is base function with corresponding output when applied to a process, expressed by $g_{kj}(i)$, $\mu_j(k)$ is the weighted coefficient ($j = 1, \cdots, J$); J is the number of the base functions.

The choice of these base functions depends on the nature of the process and the setpoint. Generally step, ramp, parabola, $\cdots$ are used.

3. Reference trajectory

In PFC algorithm, in order to control the system so that its output can reach the setpoint gradually and avoid overshot or control variables changing dramatically, the following reference trajectory is commonly used:

$$y_r(k+i) = c(k+i) - \alpha^i (c(k) - y_p(k)) \tag{3}$$

where $c(k)$ is the desired setpoint, $y_r(k+i)$ is the reference trajectory, $y_p(k)$ is the system output, $\alpha = e^{-3T_s/T}$, T_s is the sample time, T is the response time of the corresponding reference trajectory. The tracking speed of the reference trajectory tending to the desired set-point value depends on the value of α.

4. Predictive output and auto-compensation

From system model (1), the predictive output of the model at the moment $k+i$ is

$$Y_m(k+i) = CA^i \cdot X_m(k) + \begin{bmatrix} \sum_{j=1}^{J} \mu_{1j}(k) \cdot g_{1j}(i) \\ \vdots \\ \sum_{j=1}^{J} \mu_{lj}(k) \cdot g_{lj}(i) \end{bmatrix} \tag{4}$$

Then the predictive output of the process is

$$\hat{Y}_p(k+i) = Y_m(k+i) + \hat{e}(k+i) \tag{5}$$

where $\hat{e}(k+i)$ is the predicted difference between the process output and the sum of internal model output and disturbance model outputs, obtained through filtered observations on a past horizon, by a polynomial extrapolation

$$\hat{e}(k+i) = Y_p(k) - Y_m(k) + \sum_{j=1}^{N_e} e_j(k) \cdot i^j$$

where N_e is the order of the predicted difference polynomial extrapolation. The coefficient of the polynomial extrapolation is $e_j(k)$, $j = 1, \cdots, N_e$. $Y_p(k)$ is the process output at time k.

5. Object function, coincidence points and control law

The goal of the optimization is to find a set of coefficients $\mu_1, \mu_2, \cdots, \mu_N$ such that the sum of the squares of the difference between process predictive output and tracking trajectory at each coincidence point is minimized, during the whole optimizing period, so that

$$\min \sum_{i=1}^{n_s} (\hat{Y}_p(k+h_i) - Y_r(k+h_i))^2 \tag{6}$$

where: $\hat{Y}_p(k+h_i)$ is the predicted future process output, $\hat{Y}_r(k+h_i)$ is the value of the reference trajectory, $i = 1, \cdots, n_s$ and n_s is the number of the coincidence points.

If the calculation equation of the setpoint is in polynomial form

$$C(k+h_i) = \sum_{j=0}^{N_c} c_j(k) \cdot h_i^j,$$

where N_c is the order of the polynomial, $c_j(k)$ is the coefficient of the polynomial.

From the above equations, we can get the control law

$$U(k) = k_0 \cdot (C(k) - Y_p(k)) + \sum_{l=1}^{\max(N_r, N_e)} k_1 \cdot (c_l(k) - e_l(k)) + k_m \cdot X_m(k) \tag{7}$$

where

$$k_0 = v \cdot \begin{bmatrix} 1 - \alpha^{h_1} \\ \vdots \\ 1 - \alpha_{h_s} \end{bmatrix}; \quad k_m = -v \cdot \begin{bmatrix} C^m \begin{bmatrix} A_m^{h_1} - I \\ \vdots \end{bmatrix} \\ \vdots \\ C^m \begin{bmatrix} A_m^{h_s} - I \\ \vdots \end{bmatrix} \end{bmatrix};$$

$$k_1 = v \cdot \begin{bmatrix} h_1^j \\ \vdots \\ h_s^j \end{bmatrix};$$

$\boldsymbol{v} = [f_1(0) \quad \cdots \quad f_N(0)] \cdot \boldsymbol{M}$;

$\boldsymbol{M} = (\boldsymbol{G} \cdot \boldsymbol{G}^{\mathrm{T}})^{-1} \cdot \boldsymbol{G}$;

$$\boldsymbol{G} = \begin{bmatrix} g_{k1}(h_1) & \cdots & g_{g1}(h_s) \\ \vdots & \cdots & \vdots \\ g_{kN}(h_1) & \cdots & g_{kN}(h_s) \end{bmatrix};$$

$g_{kj(h_i)} = C_m A_m^{h_i - 1} B_m f_j(0) + \cdots + C_m B_m f_j(i-1)$;

N_e is the order of the predicted difference polynomial extrapolation, N_r is the order of the reference trajectory.

Where $\boldsymbol{U}(k)$ is the control input signal, coefficients k_0, k_1, k_m, can be computed off-line, and $\boldsymbol{C}(k)$, $\boldsymbol{Y}_p(k)$, $\boldsymbol{c}_l(k)$, $\boldsymbol{e}_l(k)$ are known. Here, state variable $\boldsymbol{X}_m(k)$, control variable $\boldsymbol{U}(k)$ and predictive error between the process and the model are needed to compute on-line. Obviously, compared with the other predictive control strategies, PFC has simpler algorithm and less computation. (Richalet, 1987; Didier, 1991; Ata-Doss *et al*., 1991; Xi, 1993; Chu, 1995).

The structure of the predictive functional control is same as the structure of the model algorithmic control, and is shown in Fig.1.

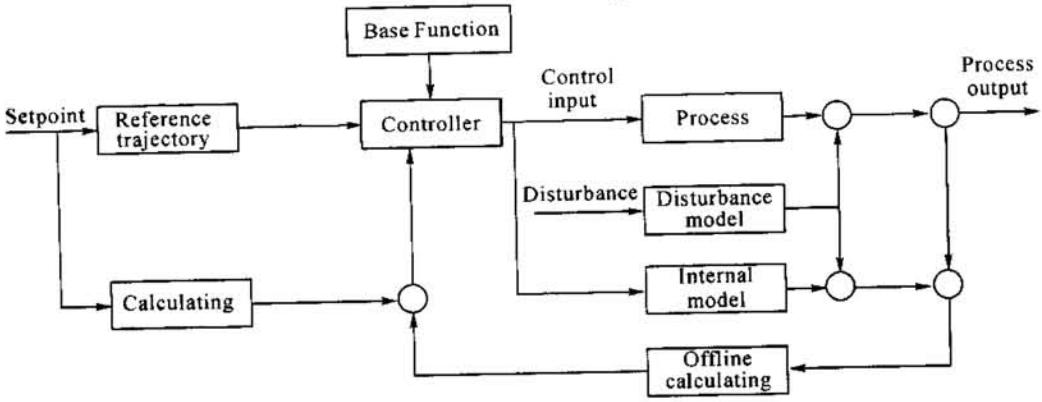

Fig.1 Block diagram of the structure of the Predictive Functional Control method

THE SOFTWARE PACKAGE OF APC-PFC

In order to use the PFC algorithm to deal with industrial control problems conveniently, a PFC aid design software package was developed and a man-machine interface of the APC-PFC is shown in Fig.2.

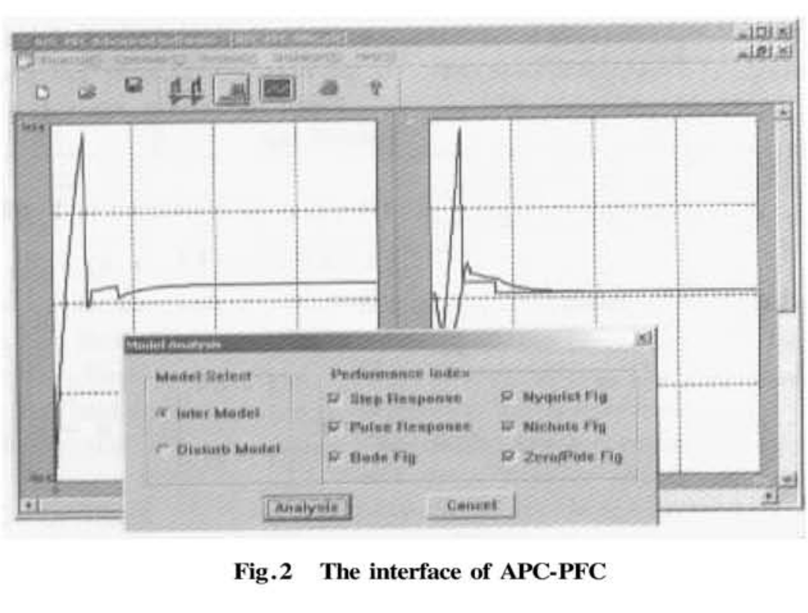

Fig.2 The interface of APC-PFC

This software has been applied in many practical industrial processes. It can be realized in DCS, PLC or industrial control computer based on the fact that this software can form C++, C and EXE files, etc.

CHLORINATED POLYETHYLENE (CPE) PROCESS

Chlorinated polyethylene (CPE) is an important chemical engineering production. The chlorinating procedure is a fitful and discontinuous process, and must react according to the given relationship among the temperature, time and total amount of chlorine. The property of the process varies greatly during reaction, so it is hard to control by using traditional control strategies such as PID control strategy. In the past, manual operation control was very difficult and troublesome, while PID control was troubled by overshot, vibration and low control precision.

The flow sheet of the CPE process is shown in Fig.3.

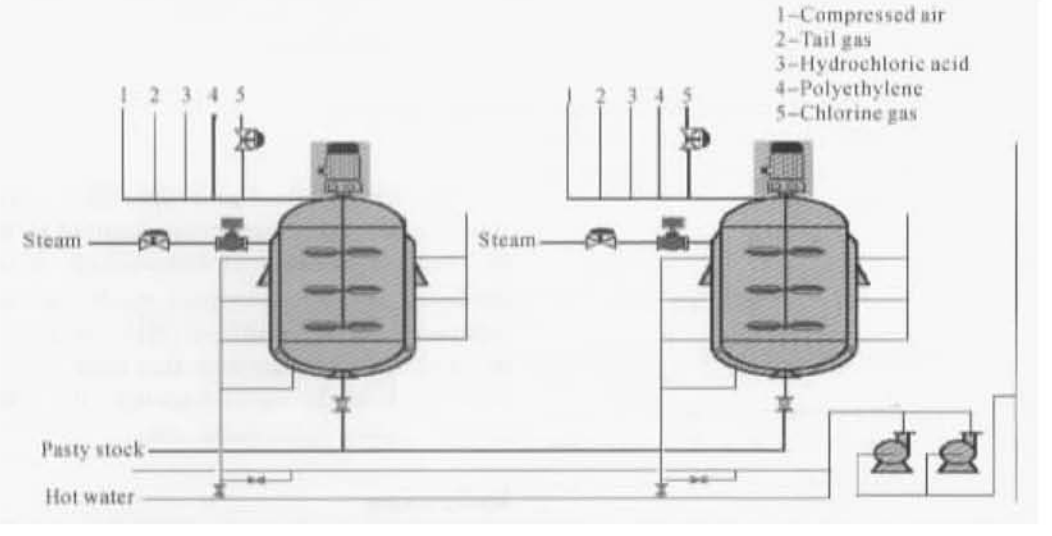

Fig.3 The flow sheet of CPE

From the raw material to the chlorinating production, the process has four stages: adding material, exhaust, heating, heat preservation. Each stage has different task and control feature.

Adding material: Adding the raw materials (polyethylene mainly), churning fully, increasing the kettle temperature by steam.

Exhaust: When the kettle temperature reaches T_1, add chlorine F to remove airs.

Heating: When the kettle temperature is T_2, close the steam valve and add chlorine gas normally. This period may be divided into some stages, with each stage having different desired temperature-time-total value that will affect the quality of production. In this period, the traditional PID control may have large overshot and abrupt transition due to the fact that the heating stage is a heat absorbing process and that the kettle temperature is adjusted only by changing chlorine gas quantity. Moreover, vibration and low precision are also the control problems of temperature tracking.

Heat preservation: The main goal of this period is to keep the temperature at a given area. This stage is the key for ensuring production quality, and the controller should guarantee the kettle temperature inside the given area.

The production output after the above four stages should be de-acidified, neutralized and dried to finally, yields the chlorinated polyethylene product.

PFC APPLICATION IN THE CHLORINATED POLYETHYLENE PROCESS

PFC strategy was applied to deal with the practical control problem of a chlorinated polyethylene process in Hangzhou Electrochemical Group Co., Ltd. The distributed control system was Supcon JX-300 DCS, model identification and PFC controller were designed by APC-PFC software. The control framework is shown in

Fig.4.

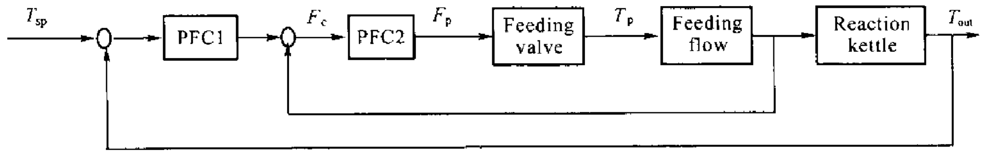

Fig.4 The control framework of cascade PFC

The inner loop of the control system was comprised of PFC 1 controller and the feed flow valve. The outer loop was comprised of PFC 2 controller, the inner loop output and the reactor kettle, which was used to regulate the set point of the feed flow so that the kettle temperature tracked the desired reaction temperature.

The PFC algorithm was programmed by system controlling language (SCL) of the JX-300 DCS application module and was downloaded to the control station of DCS.

The transfer function of the inner loop process can be obtained as $G(s)=\frac{1.72}{17.635s+1}e^{-1.02s}$, and outer loop as $G(s)=\frac{1.66}{35.33s+1}e^{-2.7s}$. The kettle temperature under PFC and PID control law is compared in Fig.5, where the x-axis is the time (minutes).

The curve above is the input of the PID control

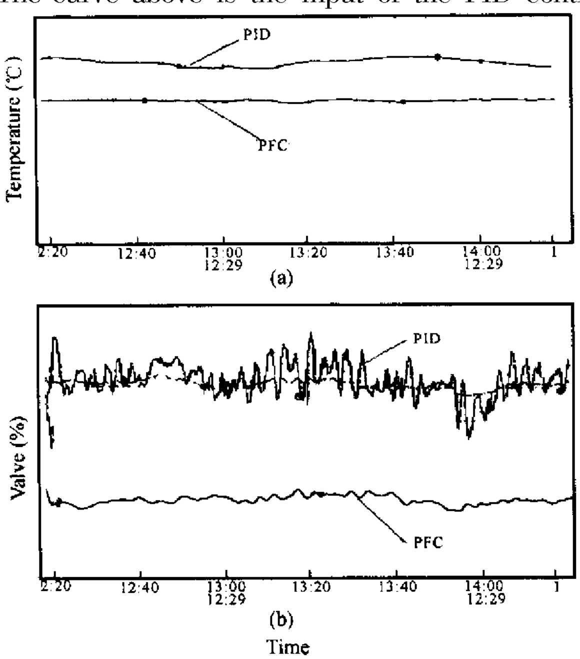

Fig.5 Comparison of two control methods
(a) Output of two control methods; (b) Input of two control methods

system, and the curve below is that of PFC. The ripples in the upper curve shows that the system has a lot of disturbances. The PFC strategy leads to a more precision, strong robustness and good tracking performance.

CONCLUSIONS

The PFC method and APC-PFC software are introduced in this paper and applied to deal with the control problem of chlorinated polyethylene process. The actual control results indicated that compared to the tradition PID control strategy, the PFC control algorithm has many more advantages such as the rapid tracking, the higher precision, strong robustness, etc.

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