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РАЗМИТ РЕГУЛАТОР НА СМИТ ЗА НЕЛИНЕЙНИ ОБЕКТИ С ЧИСТО ЗАКЪСНЕНИЕ НА ПРИНЦИПА НА ПАРАЛЕЛНО РАЗПРЕДЕЛЕНА КОМПЕНСАЦИЯ

Снежана Йорданова

Резюме: *Предложен е метод за синтез на размит Смит предиктор (РСП) за нелинеен обект със закъснение. РСП е изграден на база на Takagi-Sugeno-Kang (TSK) размит модел на обекта, съставен от локални линейни обекти със значителни чисти закъснения. Използва се принципът на Паралелно Разпределена Компенсация (ПРК) и локалните линейни регулатори се синтезират като класически Смит предиктори за съответните локални обекти за компенсиране на закъсненията им. Изведени са условия на Ляпунов за анализ на устойчивостта на глобалната размита система като линейни матрични неравенства. Синтезиран е РСП за управление на температурата в лабораторна пещ и затворената система е изследвана чрез симулация.*

Ключови думи: *закъснение, нелинеен обект, паралелно разпределена компенсация, размит Смит предиктор, симулация, устойчивост*

FUZZY SMITH PREDICTOR FOR NONLINEAR PLANTS WITH TIME DELAY BASED ON PARALLEL DISTRIBUTED COMPENSATION

Snejana Yordanova

Abstract: *A method for the design of fuzzy Smith predictor (FSP) for a nonlinear plant with time delay is developed. The FSP is based on Takagi-Sugeno-Kang (TSK) plant model, comprised of linear local plants with significant time delays. The principle of Parallel Distributed Compensation (PDC) is employed and the local linear controllers are designed as classical Smith predictors for the corresponding local linear plants aiming at compensation of their time delays. Lyapunov conditions for analysis of the global fuzzy system stability are suggested in the form of linear matrix inequalities. A FSP is designed for the control of the temperature in a laboratory furnace and the closed loop system is investigated via simulations.*

Keywords: *fuzzy Smith predictor, nonlinear plant, parallel distributed compensation, simulation, stability, time delay compensation*

1. INTRODUCTION AND PRELIMINARY INVESTIGATIONS

In the development of fuzzy control there have emerged two main approaches. The first one is the model-free expert Mamdani controller [1-4]. The recent and the more

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advanced is the model-based approach, built on dynamic fuzzy Takagi-Sugeno-Kang (TSK) plant model [5-7]. The TSK plant model allows modelling of any nonlinear plant by local linear plant models in the conclusions of the fuzzy rules and blending the qualified conclusions of the activated rules by the inference mechanism. According to the Parallel Distributed Compensation (PDC) the fuzzy logic controller (FLC) and the TSK plant model have fuzzy rules with common premises. Each conclusion is a local linear controller - usually a state feedback, designed to compensate the corresponding fuzzy rule in the plant [4-10]. Thus the PDC controllers have only a few rules – one for each plant model. The PDC-TSK approach is gaining popularity for being systematic in considering system stability, robustness and performance and also for the use of the well-developed linear control technique for the design of the local controllers.

The PDC fuzzy logic controller design is decomposed into local linear controllers design from the requirement to ensure local linear systems stability and robustness and a global fuzzy nonlinear system stability analysis, employing Lyapunov stability direct method and Linear Matrix Inequalities (LMIs) numerical technique [4-8, 10] for solving the Lyapunov stability conditions. The local controllers design and the Lyapunov global system stability problem may become computationally hard and even insolvable for plants with immeasurable state variables, time delay and model uncertainties.

Most industrial processes are inertial complex nonlinear time-varying plants with significant time delay [4, 8-12]. Fortunately the nonlinear plant in most cases can be represented by a TSK plant model of finite number of local linear models with time delay, each for a given operation sub-domain. This makes the application of the advanced and simple fuzzy PDC-TSK approach suitable for achieving of the high performance demands to the control of such plants as it accounts for the time delay, the nonlinearity, the model uncertainty and complexity [4-10]. The significant time delay and the nonlinearity of both plant and controller make system stability and robustness essential for the practical feasibility of the designed control system [4-8, 10].

Different new developments, based on linear control analogies, have been proposed to the classical PDC-TSK approach [5-7] in case of local plants with immeasurable state space variables, time delay and model uncertainty. Dynamic PI local controllers are designed in [4, 8-9]. A fuzzy internal model controller (FIMC) is suggested in [10] to compensate plant model uncertainty.

The aim of the present investigation is to develop a method for the design of a fuzzy Smith predictor (FSP) for a nonlinear plant with local low order linear plant models with relatively significant time delays. The FSP is PDC-TSK based with dynamic local controllers, which are derived on the principle of linear Smith predictor to ensure local linear systems stability and to improve their performance by compensating the corresponding local plant time delay.

The time delay is due to modelling error, distribution in space of the parameters of the plant, high order or multi-capacitance of the plant, transport delay, inertia caused by finite rate of reactions, restricted flow velocities, time required to overcome resistance, etc. The pure time delay reflects the total effect of transient, transport and approximation delays. Plants with time delay are difficult to control since the control action is not felt right away. Stability constraints should be carefully observed as well. In case of high relative time delay $\tau/T > 0.5$ with respect to plant model time constant T, special measures for compensation of the time delay are recommended in order to improve system stability and performance [11, 12]. The Smith predictor is one of the most popular.

The block diagram of a control system with a Smith predictor is shown in Fig.1. A plant model with transfer function with time delay $P_o(s)e^{-\tau s}$ represents the plant. The Smith predictor $R(s)$ consists of a conventional controller $C(s)$, enclosed by a feedback $C_{fb}(s)$, and has the following transfer function:

$$R(s) = \frac{C(s)}{1 + C(s)C_{fb}(s)}. \quad (1)$$

The necessary feedback $C_{fb}(s)$, derived to ensure no time delay in the characteristic equation of the closed loop system, is:

$$C_{fb}(s) = P_o(s)[1 - e^{-\tau s}] \quad (2)$$

As seen from (2), $C_{fb}(s)$ depends entirely on the plant model. Substituting (2) in (1) results in:

$$R(s) = \frac{C(s)}{1 + C(s)P_o(s)[1 - e^{-\tau s}]}. \quad (3)$$

The stability of the closed loop system is not influenced by the time delay τ as it is not present in the denumerator of the transfer function of the closed loop system with the Smith predictor:

$$\Phi_{Smith}(s) = \frac{R(s)P_o(s)e^{-\tau s}}{1 + R(s)P_o(s)e^{-\tau s}} = \frac{C(s)P_o(s)e^{-\tau s}}{1 + C(s)C_{fb}(s) + C(s)P_o(s)e^{-\tau s}} = \frac{C(s)P_o(s)e^{-\tau s}}{1 + C(s)P_o(s)}$$

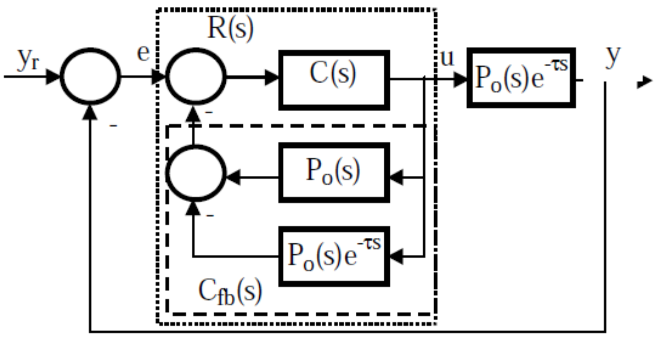

Fig.1. Block diagram of a closed loop system with Smith predictor $R(s)$

This allows for $P_o(s) = \dfrac{K}{Ts + 1}$ a PI controller $C(s)=K_p(1+1/T_i s)$ to work with a very great gain K_p without violation of system stability as the open loop system $C(s).P_o(s)$ is of second order and its Nyquist plot never crosses the negative abscise axis – the system remains stable at high controller's gain. This ensures high dynamic accuracy, insensitivity to model uncertainty and good disturbance filtration can be ensured.

Despite of the advantages of the Smith predictor its industrial application is still not widely spread due to the difficulties in the completion of the necessary feedback $C_{fb}(s)$ and the high demand for precise plant model parameters. System performance may be greatly deteriorated in case of deflection between plant and model parameters caused by model uncertainties, changes of plant parameters with time or with the shift of the operation point along nonlinear characteristics, etc.
In order to make the Smith predictor more robust and to extend its application to non-linear plants a method for the design of FSP on PDC-TSK scheme is suggested in the next chapter 2. In chapter 3 a FSP for the air temperature in a laboratory furnace is developed. Simulation investigations of the system with the FSP are described in chapter 4. The final chapter 5 contains analysis of results and conclusion and outlines the future work.

2. METHOD FOR THE DESIGN OF FUZZY *Smith* PREDICTOR

The fuzzy Smith predictor is based on the PDC-TSK scheme. It requires a TSK plant model, derived from identification for industrial processes with time delay in [4, 8-10]. Experimentally recorded plant step responses in different operation points are approximated by Ziegler-Nichols models. Then sub-domains of linearisation are determined by grouping similar adjacent step responses, to which correspond models with close parameters. In each sub-domain an average Ziegler-Nichols model $P_i(s) = K_i(T_i s + 1)^{-1}.e^{-\tau_i s} = P_{io}(s).e^{-\tau_i s}$ is computed, which is accepted as the local linear plant in the corresponding fuzzy rule of the TSK plant model. The sub-domains are recognized by the plant output $y(t)$ or its reference $y_r(t)$. When under closed loop control, the plant output follows the reference y_r and smoothly passes through all sub-domains from the current to the final. This causes the model parameters K_i, T_i and τ_i to vary with the operation point or the sub-domain.
Each local linear controller is designed as a Smith predictor to compensate one local linear plant and its relatively great time delay. Thus each local closed loop system has the block diagram, depicted in Fig.1. After an equivalent transformation, shown in Fig.2, the resemblance with a system with Internal Model Controller (IMC) $Q(s)$ becomes obvious [10, 12]. The local IMCs, however, have transfer functions $Q_i(s)=[P_i(s)]^{-1}.F_i(s)$. The filter $F_i(s)$ is designed to make proper the transfer function of the ideal controller $Q_i^o(s)=[P_i(s)]^{-1}$ for precise plant model

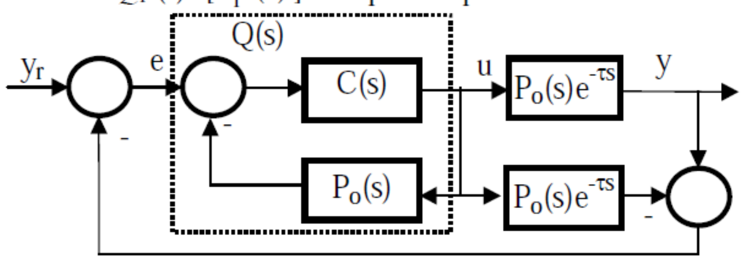

Fig.2. Equivalence of systems with Smith predictor $R(s)$ and internal model controller $Q(s)$

$P_i\ (s)$ and no noise and disturbances, and also to ensure no steady state error for step inputs. The non-minimal phase plant time delay can be omitted in obtaining the inverse plant and the result is the following:

$$Q_i(s)=[P_{io}(s)]^{-1}.F_i(s)=[(T_i\ s+1)/K_i].(\lambda s+1)^{-1}. \quad (4)$$

The time constant λ of the filter is the only tuning parameter. It is selected to be small for fast system step response but also high enough to satisfy the system robustness criterion [4, 10].

In the Smith predictor from Fig.2 with $C_i(s)$ a PI controller is obtained:

$$Q_i(s)=C_i(s).[1+C_i(s)P_{io}(s)]^{-1}$$

$$Q_i\ (s)=K_{pi}(1+1/T_{ii}s).[1+K_i\ .K_{pi}.(1+1/T_{ii}s).(T_i\ s+1)^{-1}]^{-1}=$$

$$=K_{pi}.(T_i\ s+1).(T_{ii}s+1).[T_{ii}s.(T_i\ s+1)+K_i\ .K_{pi}.(T_{ii}s+1)]^{-1}. \quad (5)$$

The classical controller $C_i(s)$ in the Smith predictor is tuned to have a great gain K_{pi} and employing some empirical tuning method can have $T_{ii}=T_i$ [11]. Then (5) is simplified to the following expression:

$$Q_i\ (s)=K_{pi}.(T_i\ s+1)(T_i\ s+K_i\ .K_{pi})^{-1}=[(T_i\ s+1)/K_i].\{[T_i/(K_i\ .K_{pi})]s+1\}^{-1}. \quad (6)$$

From the analogy between (4) for the IMC and (6) for the Smith predictor it can be established that:

$$\lambda=T_i\ /(K_i\ .K_{pi}), \quad (7)$$

which for the selected great gain K_{pi} can turn out to be very small and may not satisfy robustness criteria.

The transfer function (6) for $K_i\ .K_{pi}>1$ is that of a PD controller (a time lead element) $Q_i\ (s)=C_{PDi}(s)=(1//K_i).(T_i\ s+1).(\lambda s+1)^{-1}$ with a gain $K_{pdi}=1//K_i$ and a differentiating time constant $T_{di}=T_i$. The maximal value for t=0 and considering (7) is $T_i\ /(K_i\ .\lambda)=K_{pi}$ and is high.

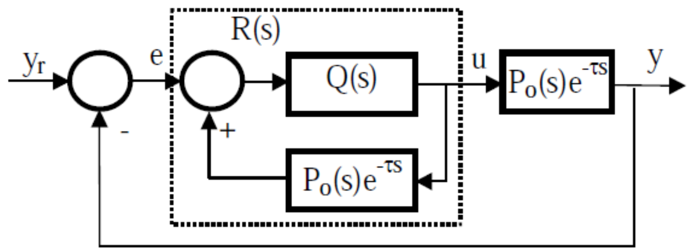

Fig.3. A system with Smith predictor $R(s)$ based on internal model controller $Q(s)$

The derivation of the conclusions in the fuzzy rules in the TSK model of the FSP requires transformation of the system in Fig.2 into the system in Fig.3. Also the following assumptions are accepted:

1) λ_i can be neglected as comparatively small with respect to τ_i - $\lambda_i << \tau_i$ since for great K_{pi} - $K_i .K_{pi} > 1$ and hence $\lambda_i < T_i$, on the other hand the Smith predictor is used when $T_i < \tau_i$, so $\lambda_i < T_i, < \tau_i$, in this case $F_i(s)=1$;

2) the time delay can be approximated by the linear term in the Taylor's series expansion - $e^{-\tau_i^o s} \approx (\tau_i^o s + 1)^{-1}$.

Under these assumptions the Smith predictor is derived as follows:

$$R_i(s) = \frac{Q_i(s)}{1 - Q_i(s) P_{io}(s) e^{-\tau_i s}} = \frac{C_{PDi}(s)}{1 - P_{io}(s)[P_{io}(s)]^{-1} F_i(s) e^{-\tau_i s}} \\ = \frac{C_{PDi}(s)}{1 - F_i(s) e^{-\tau_i s}} = C_{PDi}(s).\frac{\tau_i s + 1}{\tau_i s} = C_{PDi}(s).C_{PIi}(s) \quad , \qquad (8)$$

As seen from (8) the local Smith predictors are comprised of connected in series local linear controllers PD and PI with gain 1 and integral action time τ_i. This determines the suggested structure of the PDC FSP, shown in Fig.4. It consists of two PDC controllers in series – a PD and an incremental PI. The necessary integrator can be referred to the plant like in [4, 8-10]. The scaling factors normalise the inputs in the range [-1,1]. For a given maximal expected error magnitude $|e_{max}|$ - $K_e = K_{de} = 1/|e_{max}|$ and considering that $|u_{PDmax}| = K_{pimax}.|e_{max}|$ - $K_{uPD} = K_{duPD} = 1/(K_{pimax}.|e_{max}|)$.

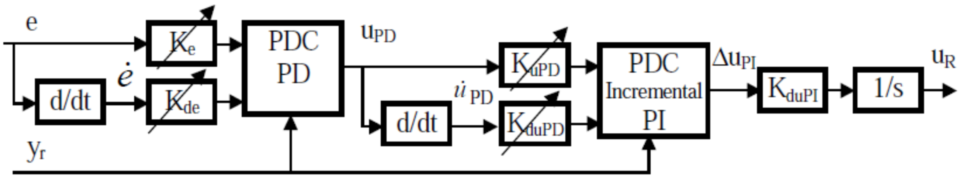

Fig.4. PDC Smith predictor $R(s)$

The fuzzy rules of the plant and the PDC Smith controller are respectively:

R$_i$: IF $y(t)$ is M_{i1} **AND** $e(t)$ is M_{i2} **AND** $\dot{e}(t)$ is M_{i3}

$$\textbf{THEN.} \left| \begin{array}{l} \dot{x}_i(t) = A_{io} x_i(t) + B_{id} \dot{u}_i(t - \tau_i) \\ y_i(t) = C_i x_i(t) \end{array} \right. \qquad (9)$$

R$_{i1}$: IF $y(t)$ is M_{i1} **AND** $e(t)$ is M_{i2} **AND** $\dot{e}(t)$ is M_{i3}

$$\textbf{THEN } u_{PDi}(t) = -F_{PDi} x_i(t) + G_{PDi} x_r \qquad (10a)$$

$$\text{or } u_{PDi}(t) = K_{pdi} e(t) + K_{pdi}.T_{di}.\dot{e}(t),$$

R$_{i2}$: IF $y(t)$ is M_{i1} **AND** $u_{PD}(t)$ is M_{i4} **AND** $\dot{u}_{PD}(t)$ is M_{i5}

$$\textbf{THEN } \dot{u}_{PIi}(t) = F_{PIi} x_{PDi}(t) \qquad (10b)$$

$$\text{or } \dot{u}_{PIi}(t) = (1/\tau_i) u_{PD}(t) + \dot{u}_{PD}(t),$$

where: M_{ij} are linguistic values, defined as membership function (MF) of fuzzy sets; $x(t) \in \mathbf{R}^n$ is the state vector; $u(t) \in \mathbf{R}^m$ is the input control vector; $y(t) \in \mathbf{R}^q$ is the output vector; $e(t) = y_r - y(t)$ is the error in the closed loop system for constant reference y_r $(\dot{e}(t) = -\dot{y}(t))$; $x_i(t) = \begin{bmatrix} x_{i1}(t) = y(t) \\ x_{i2}(t) = \dot{x}_{i1}(t) \end{bmatrix}$; $x_r = \begin{bmatrix} x_{r1} = y_r \\ x_{r2} = 0 \end{bmatrix}$; $A_{io} = \begin{bmatrix} 0 & 1 \\ 0 & -1/T_i \end{bmatrix}$; $B_{id} = \begin{bmatrix} 0 \\ K_i / T_i \end{bmatrix}$; $C_i = [1 \quad 0]$; $F_{PDi} = [K_{pdi} \quad K_{pdi}.T_{di}]$; $G_{PDi} = [K_{pdi} \quad 0]$; $x_{PDi}(t) = \begin{bmatrix} x_{PDi1}(t) = u_{PDi}(t) \\ x_{PDi2}(t) = \dot{x}_{PDi1}(t) \end{bmatrix}$; $F_{PIi} = [1/\tau_i \quad 1]$.

The state vector $x_i(t)$ can be extended with $x_{PDi}(t)$ to yield:

$$x_i^e(t) = \begin{bmatrix} x_{i1}(t) = y(t) \\ x_{i2}(t) = \dot{x}_{i1}(t) \\ x_{i3}(t) = u_{PD}(t) \\ x_{i4}(t) = \dot{x}_{i3}(t) \end{bmatrix}.$$

As a result the defined vectors and matrices will be converted into blocks from the new block vectors or matrices – for instance $A_{io}^e = \begin{bmatrix} A_{io_{2x2}} & 0_{2x2} \\ 0_{2x2} & 0_{2x2} \end{bmatrix}$, $B_{id}^e = \begin{bmatrix} B_{id2x1} \\ 0_{2x1} \end{bmatrix}$, $C_i^e = [C_{i1x2} \quad 0_{1x2}]$, $x_r^e = \begin{bmatrix} x_{r2x1} \\ 0_{2x1} \end{bmatrix}$, $F_i = [F_{PDi} \quad F_{PIi}]$, $G_i = [G_{PDi} \quad 0]$.

Then the global system stability can be proved by applying the derived in [4, 8] Lyapunov sufficient conditions. The system (9), (10a), (10b) is quadratically stable if there exist matrices $\boldsymbol{P}$>0, and $\boldsymbol{Q}$>0 such that the following matrix inequalities are satisfied for i, j=1…r, j>i:

$$\begin{vmatrix} PA_{io}^e + A_{io}^{e\,T}P + PB_{id}^e F_i Q^{-1} F_i^T B_{id}^{e\,T} P + Q < 0 \\ P.0.5(A_{io}^e + A_{jo}^e) + [0.5(A_{io}^e + A_{jo}^e)]^T P + +0.5(B_{id}^e F_j Q^{-1} F_j^T B_{id}^{e\,T} + B_{jd}^e F_i Q^{-1} F_i^T B_{jd}^{e\,T}) + Q \le 0 \end{vmatrix} \quad (11)$$

3. DESIGN OF FUZZY *Smith* PREDICTOR FOR AIR TEMPERATURE CONTROL

The developed method for the design of FSP is applied for the control of the air temperature in a laboratory furnace [10]. The experimental study showed three linearisation sub-domains, represented by Ziegler-Nichols plant models with average for the sub-domain parameters, given in Table 1.

The FSP is designed using MATLAB™ [13]. Each of the two PDC has three fuzzy rules according to (10a) and (10b) respectively – one for each linear sub-domain. The two PDC rule bases are identical. The conclusion is a different deterministic function of the inputs in each rule and different for the PD and the PI PDCs and depends only on the local plant parameters. The inputs are $[y_r \; e \; \dot{e}]$ for the PD controller and $[y_r \; u_{PD} \; \dot{u}_{PD}]$ – for the PI controller. The temperature range is [0÷80] °C and the maximal expected error $|e_{max}|$=10°C. The control action is bounded in the range [0÷2] V. The fuzzy units inputs are normalized – e, $\dot{e}$, u_{PD} and $\dot{u}_{PD}$ in the range [-1÷1] °C, and y_r -

in the range [0÷1] °C. The denormalisation factor at the output of the fuzzy unit, which serves also as an integrator gain, is fine tuned by simulation experimentations to K_{duPI} =1.2. The derivatives $\dot{e}$ and $\dot{u}_{PD}$ are obtained at the output of a noise resistive first order differentiators $s/(s+1)$. The MFs for y_r shown in Fig.5 with "H" - high, "N_{ref}" - normal and "L" – low, are designed to map the relative location of the sub-domains. Only they matter in distinguishing the linearisation sub-domains.

Table 1. Local plants parameters

Plant model parameters	K_i °C/V	T_i min	τ_I min
Sub-domain 1	66	8	14
Sub-domain 2	10	6	10
Sub-domain 3	50	9	8

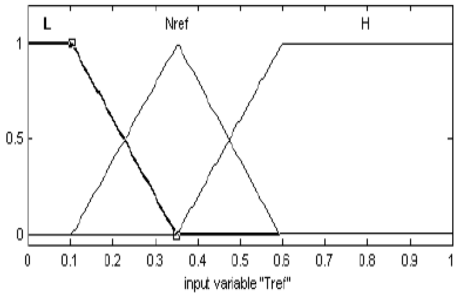

Fig.5. Membership functions for $y_r(t)$

4. SIMULATION INVESTIGATIONS OF THE FUZZY SMITH PREDICTOR CLOSED LOOP SYSTEM

The closed loop system with the designed PDC-Smith controller is studied by simulation in Simulink of MATLAB™ [13]. Its performance is assessed in comparison to several control systems with:

- PDC-PI controller, designed according to [8];
- PDC-FIMC designed in [10] with denormalisation factor of 1.2.

The simulation is carried out with nominal and perturbed plant in order to assess robustness. The used Simulink TSK nominal and perturbed plant models are developed in [10] to reproduce the experimental step responses in the different operation points. The step responses are shown in Fig. 6. The main performance indices – settling time t_s, min, overshoot σ, % and maximal deviation between

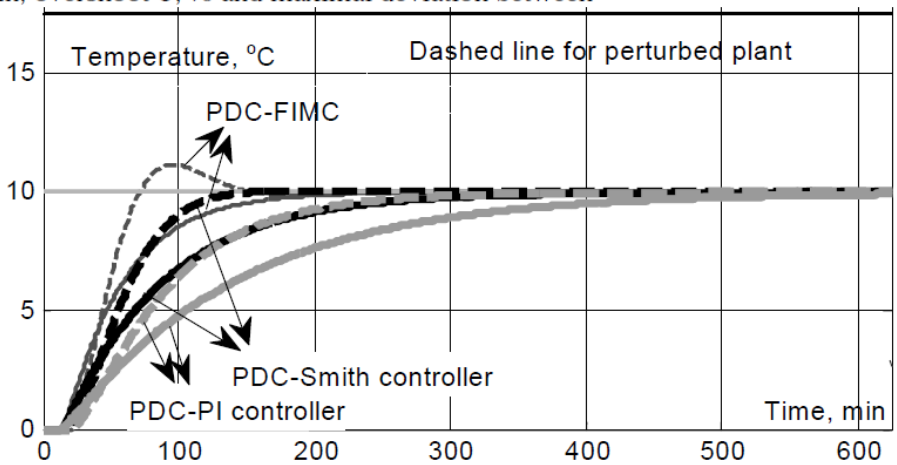

Fig.6. Step responses of systems with PDC controllers - FSP, PI and FIMC

Table 2. Systems performance for nominal/perturbed plant

System	FSP	PI	FIMC
t_s, min	300/150	500/300	150/170
σ, %	0/0	0/0	0/10
$\|\Delta y_{max}\|$, °C	2.5	2	3.5

outputs of systems with nominal and perturbed plants $|\Delta y_{max}|$, °C, as a measure for robustness, are given in Table 2.

5. ANALYSIS OF RESULTS AND CONCLUSION

The main contributions of the present investigation conclude in the following.

A method for the design of Smith predictor for nonlinear plants with significant time delays is suggested on the basis of the fuzzy PDC-TSK approach.

Lyapunov stability conditions in the form of Linear Matrix Inequalities are proposed to prove global fuzzy system stability.

The method is applied in the design of a FSP for the air temperature in a laboratory furnace.

The Simulink-based simulation investigations show that the system with the designed fuzzy PDC Smith predictor has fast step response, no overshoot and good robustness. It outperforms the system with PDC-FIMC, designed from robustness requirements, and demonstrates good compensation of the time delay when compared to the system with PDC-PI controller.

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