Robustness of Systems with Various PI-like Fuzzy Controllers for Industrial Plants with Time Delay

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Abstract: - The robustness of the systems with fuzzy logic controllers (FLC) has lately focused the attention of researchers in relation with the expansion of their industrial application. The contemporary complex, nonlinear, time varying processes with time delay and various disturbances and the high demands for their control require to account for system stability and robustness in the FLC's design. The simplicity of the design is of great importance in connection to its easy practical application. The aim of the present investigation is to develop a generalised procedure for the design of various PI-like FLCs with regard to system performance robustness and to compare the robustness of the control systems. The approach is developed for PI incremental and position FLCs based on the single input fuzzy controller (SI FC), Popov stability and Morari robustness and considers the control of industrial plants with time delay and model uncertainty. The main contributions are: 1) a generalised design procedure for FLCs accounting for system stability and robustness; 2) FLCs' general tuning algorithm. The results are applied for the stabilisation of the air temperature in a furnace using MATLAB™. The performance of the designed FLC systems is assessed and compared to the performance of control systems with internal model controller via simulations.

Key-Words: - frequency domain PI-like process FLC design, MATLAB, robust performance, temperature control, time delay, tuning algorithm

1 Introduction and State-of-the-Art

A remarkable progress has recently been noticed in the industrial application of fuzzy logic controllers (FLCs) for controlling of complex time-variant nonlinear inertial processes without reliable plant model. The latest developments in the FLC design attempt to tackle together system stability and robustness. Stability is approached in [1-8] from the viewpoint of nonlinear system theory either in the time domain, using the bounded-input- output and the Lyapunov (or linguistic Lyapunov [5]) direct method, or employing the Popov and the describing functions frequency domain approaches. The design procedures often are very complicated, require plant model usually in state space, lead to complex FLC and are not applicable to industrial plants with time delay and uncertainty. Robustness considerations are rarely included in the design objectives [6-8]. The H_∞ and the H_2 optimisations [9] lay the mathematical framework to robustness. However, these techniques produce higher order solutions and do not consider plants with time delay.

A variety of FLCs have been suggested to simplify the FLC design, tuning and structure [10, 11]. By assuming PI-like FLC the rule base can be easily derived. Normalised universities of discourse and tuning scaling factors facilitate tuning.

The single input fuzzy controller (SI FC) [1, 12-15] reduces the redundancy of tuning parameters enabling simple FLC structure and design rules to be developed, which bind together stability and robustness requirements. Having 1-D uniquely determined rule base and a nonlinear control curve, the SI FC allows combining Popov stability with Morari [16] robustness approaches to design FLC for plants with time delay under uncertainties.

The aim of the present investigation is to develop a generalised procedure for the design of various PI-like FLCs with regard to system performance robustness and to compare the robustness of the control systems.

2 Theoretical Preliminaries

The block diagram of a system with PI-like FLC is depicted in Fig.1. It consists of a LTI plant with transfer function $P(s)$ and a PI-like FLC $C_{fPI}(s)$. The system error $e=y_r-y$ is the difference between reference y_r and measured plant output y. The FLC

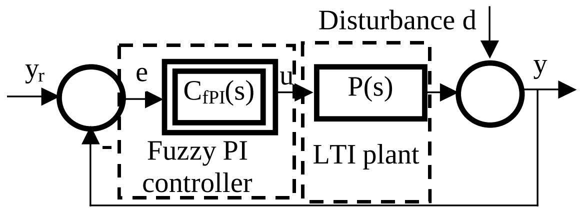

Fig.1. System with PI-like FLC

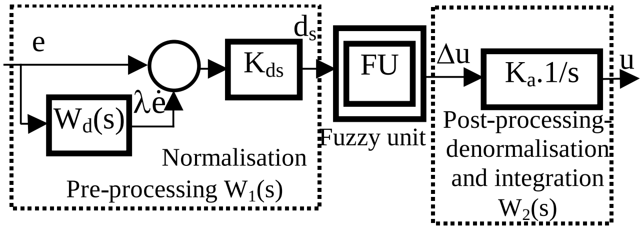

Fig.2. Incremental PI Single Input Fuzzy Controller

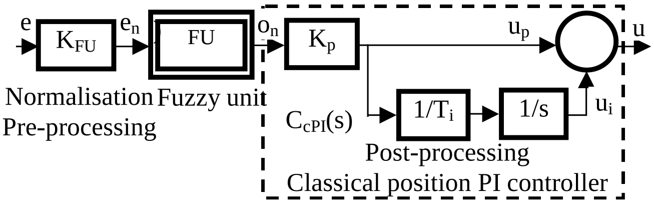

Fig.3. Position PI Single Input Fuzzy Controller

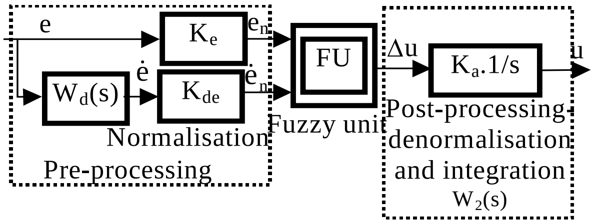

Fig.4. Incremental PI Fuzzy Logic Controller

can be an incremental PI SI FC – Fig.2, a position PISIFC – Fig.3 and an incremental PI FLC - Fig.4. They all consist of a pre-processing unit, a fuzzy unit (FU) and a post-processing unit. The SI FCs have one normalised input to the FU – the signed distance $d_s = e + \lambda\dot{e}$ for the incremental PI, and the normalised error e_n for the position PI. The corresponding scaling factors are K_{ds} and K_{FU}. The incremental PI FLC has two inputs – the normalised by the help of K_e e_n and the normalised by K_{de} $\dot{e}_n$. The pre-processing part of the incremental PI controllers contains a differentiator $W_d(s)$ to obtain the derivative of error signal $\dot{e}$ or the scaled $\lambda\dot{e}$. The post-processing unit in the position PI SI FC is a classical position PI controller and in the incremental PI SI FC and FLC - an integrator $W_2(s)=K_a/s$ with $K_a=K_{\Delta u}.K_i$ uniting the denormalisation factor $K_{\Delta u}$ and the integrator gain K_i. A one time-step memory element or an integrating actuator performs the integration.

The FU is a static element with sector bounded nonlinearity and gain $C(d_s)=\dfrac{\Psi(d_s)}{d_s}$ with normalised in the range [-1, 1] input(s) and output $\Delta u=\Psi(d_s)$ for the incremental controllers and o_n – for the position controller, uniquely determined for the SI FCs from the requirement output=-input. Thus the rule base of the SI FC is the 1-D FAM, shown in Table 1, where LDS_k is the k-th linguistic value for the input (d_s or e_n) and LDU_l is the l-th linguistic value for the output (Δu or o_n).

Table 1. 1-D FAM of SI FC

Input	LDS_{-2}	LDS_{-1}	LDS_0	LDS_1	LDS_2
Output	LDU_2	LDU_1	LDU_0	LDU_{-1}	LDU_{-2}

The pre-processing unit in the incremental PI SI FC $W_1(s)=K_{ds}[1+W_d(s)]$ computes the dynamic components of the PI-like algorithm. The product $W_1(s)W_2(s)=C_{PI}(s)=K_p[1/(T_d s+1)+1/T_i s]$ for $W_d(s)=K_d.T_d s.(T_d s+1)^{-1}$ yields a transfer function of a PI controller [12, 13] with gain $K_p=K_d.T_d.K_{ds}.K_a$ and integral action time $T_i=K_d.T_d$, which makes the two SI FCs in Fig.2 and Fig.3 equivalent to a certain extent – $C_{cPI}(s)=C_{PI}(s)$ for $T_d=0$.

The SI FC design is based on the derived in [12, 13] robust stability and robust performance of the SI FC system for a given plant family, defined by $[P^o(s), l(s)]$, where $P^o(s)$ is the nominal plant model and $l(s)=[P(s)-P^o(s)]/P^o(s)$ is the plant model multiplicative uncertainty, both assessed by experts. All input signals are assumed absolutely vanishing functions of time.

3 Problem Formulation

The plant to be controlled is approximately described by the couple $[P^o(s), l(s)]$, where $P^o(s)=k^o\exp(-\tau^o s)(T^o s+1)^{-1}$ since robustness as a control objective saves the need for more precise and sophisticated high-order plant models. This model is comprehensible, simple, well studied, commonly used in the engineering practice to describe a wide range of industrial plants with a few generalised parameters with clear physical interpretation. The pure time delay represents the general effect of plant inertia, transport delay, high order and parameter distribution. The nominal values of the gain k^o, the time constant T^o and the time delay τ^o are easily estimated by experts for the most typical operating conditions. The multiplicative plant model uncertainty $l(s)$ describes the changes in the model as a result of set point shifting along nonlinear characteristics due to disturbances, aging of elements, changes in the operation conditions and modes, etc. It is estimated from the greatest possible increase of the plant model gain and time delay and decrease of the time constant, and the impact of the unmodelled dynamics. All these simultaneous deviations from the nominal plant model characterise the most unfavourable case of perturbations with respect to system stability and time domain specifications that can take place over the whole operating range.

The input signals to the closed loop FLC system - the reference y_r and the disturbance d, are assumed 2-norm bounded and in stability studies – absolutely vanishing functions ($y_r(t)\to 0$, $d(t)\to 0$ for $t\to\infty$).

The control objectives include:

1) High performance of the nominal and the varied FLC system, estimated in terms of static and dynamic accuracy and short settling time;

2) Robust stability and performance, i.e. preservation of system stability and enclosure of system time response when bounded within a narrow envelope around the nominal response $y^o(t)$ when signal and plant model uncertainties in known ranges take place.

So, this work addresses the following problems. Given a family of possible plants [$P^o(s)$, $l(s)$] and various PI-like FLCs with tuning parameters, related to the static nonlinearity - the FU control surface (parameters of the membership functions (MFs), inference and defuzzification methods, etc.) and the pre- and post-processing units (scaling factors, differentiator and actuator gains)

(I) Develop a generalised robust stability and robust performance design procedure for various PI-like FLCs

(II) Develop a tuning algorithm for the FLCs

(III) Apply (I-II) for the design of various FLC systems for an industrial plant and assess their performances comparing with internal model controller (IMC) system [16].

4 Robust Stability and Robust Performance Design Procedure for PI-like FLCs

The design procedure for PI incremental and position SI FCs and for PI-incremental FLCs that esures robust stability and robust performance is built following the algorithm below.

Case A: A SI FC is required

1. The plant is extended by a PI controller thus splitting the open loop system into two subsystems – a linear dynamic one $C_{(c)PI}(s).P(s)$ and a static one with sector bounded nonlinearity, consisting of the FU – Fig.5.

2. The extended plant being marginally stable is stabilised by enclosing it in a local feedback configuration with feedback gain r. The transfer function of the stabilised plant is $P_s(s)=\dfrac{C_{(c)PI}(s).P(s)}{1+r.C_{(c)PI}(s).P(s)}$.

3. The Nyquist plot of a modified plant for a nominal plant $P^o_{1m}(j\omega)$ is computed as $P_{1m}(j\omega)=\mathrm{Re}P_s(j\omega)+j\omega\mathrm{Im}P_s(j\omega)$.

4. The Popov line is defined by its cross point with the abscissa ($-1/K_1$, $j0$) and slope of $1/q$ (q can take any real value), where $K_1=K-r>0$ is determined by the angular coefficients of the sector lines l_1 and l_2, bounding the SI FC control curve as shown in Fig.5.

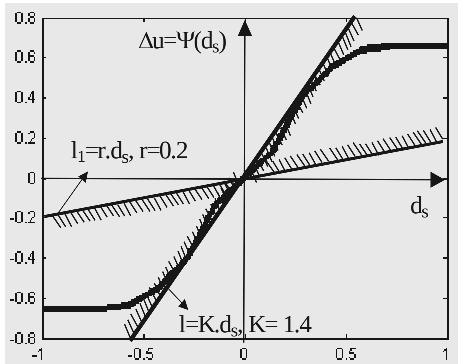

Fig.5. Sector bounded static FU nonlinearity

5. The uncertainty disks are obtained assuming that the initial plant model uncertainty $l(j\omega)$ leads to a modified plant model uncertainty $l_m(j\omega)$ in the form of disks around the modified plant nominal Nyquist plot with radiuses

$$r_i(\omega)=\left|P_{1m}(j\omega)\right|-\left|P^o_{1m}(j\omega)\right|=\left|\Delta P_{1m}(j\omega)\right|=\left|l_m(j\omega).P^o_{1m}(j\omega)\right|.$$

6. The SI FC system robustly stability is checked if for some tuning parameters $\mathbf{p}^T=[T_d\ K_d\ K_{ds}\ K_a\ \ r]$ for incremental PI and $\mathbf{p}^T=[T_i\ K_p\ K_{FU}\ \ r]$ for position PI, the system with nominal plant is stable and the Nyquist plot $P^o_{1m}(j\omega)$ in Fig.6 with all the disks on it is located below and on the right from the Popov line for all significant frequencies. This expresses the fulfillment of the robust stability criterion:

$$\frac{|P^o_{1m}(j\omega).K_1|.|l_m(j\omega)|}{|1+P^o_{1m}(j\omega)K_1|}<1, \forall\omega\geq 0 \cdot \quad (1)$$

7. The frequency response of the closed loop system $|\Phi^o_{slin}(j\omega)|=\dfrac{|P^o_s(j\omega).(K-r)|}{|1+P^o_s(j\omega).(K-r)|}$ with nominal

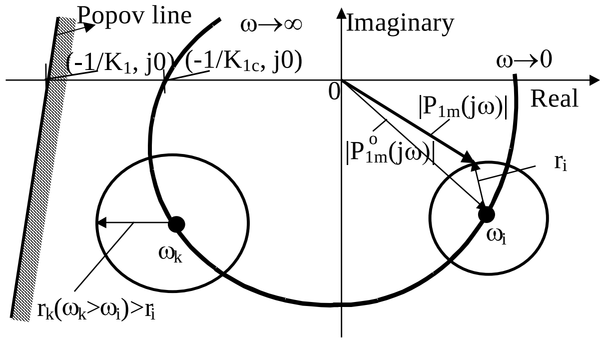

Fig.6. SI FC system robust stability

stabilised plant $P_s^o(s)$ and a linearised FU is computed.

8. The SI FC system sensitivity function $S_s^o(s)=[1+(K-r).P_s^o(s)]^{-1}$ for y_r=0, linearised FU, nominal plant and shaping filter $W_f(s)$ for the disturbance d - $d(s)=W_f(s).1$ with $|W_f(j\omega)|$=0,3 ÷ 0,9 is computed.

9. The SI FC system performance robustness is checked for all significant frequencies

(2) $$\left|S_s^o(j\omega).W_f(j\omega)\right|+\left|\Phi_{slin}^o(j\omega).l_s(j\omega)\right|<1,\quad \forall\omega\geq 0.$$

The SI FC system robust performance condition (2) includes as a second term the robust stability (1), modified for a linearised SI FC system, so it sets stronger requirements. Either of (1) and (2) can be used for tuning of the SI FC parameters K and $\mathbf{p}^T$ of the nonlinear static FU and the pre- and post-processing linear dynamic units in order to preserve system stability or moreover, system performance for given plant model uncertainties [12-15].

10. Among the tuning parameters, which ensure stable plant $P_s(s)$ and satisfaction of (1) or (2), one optimal vector is selected that corresponds to maximal ratio K_p/T_i=max. This maximal ratio is a sign that the robust stability or the robust performance curves (the left-hand functions in (1) or (2)) remain very close to 1 and the system is both robust and has fast nominal response.

Case B: A PI incremental FLC is required

1. Design the FU of the FLC with inputs e and $\dot{e}$ and output Δu, all normalised in the ranges [-1, 1].

2. Obtain the FLC control surface – Fig.7 and its e-Δu projection – Fig.8 (the projected surface is enclosed within the sector bounding lines of the SI FC FU control curve – the projection surface can be similarly considered bounded in a sector, determined by the lines with slopes K and r respectively, with the exception of a small area – the disk with diameter δ).

3. Draw the sector lines that bound the projection surface and read K and r.

4. Use K, r, the greatest expected error $|e_{max}|$ and the data for the plant family [$P^o(s)$, $l(s)$] as input for the algorithm for tuning of the equivalent PI incremental SI FC from robust stability (1) or robust performance (2) requirement [12-14] and obtain the parameters of the SI FC $\mathbf{p}_{SIFC}^T=[T_d\ K_d\ K_{ds}\ K_a\ \ r]$, $K_{ds}=[(1+K_d)|e_{max}|]^{-1}$ is calculated to normalise d_s in the range [-1, 1].

5. Read from the projection surface the disk diameter δ and calculate the tuning parameters of the FLC $\mathbf{p}_{FLC}^T=[T_d\ K_d\ K_e\ K_{de}\ K_{a1}\ \ r]$, which differ from the SI FC parameters in the scaling factors $K_e=[|e_{max}|]^{-1}$ and $K_{de}=[K_d.|e_{max}|]^{-1}$, and in $K_{a1}=k.K_a$. The scaling gain for K_a k=0.1/δ is calculated to be in the range [0,1] for δ=0.1÷2 and to reduce the overall open loop FLC system gain inversely to the deflection of Δu from zero for error close to zero. This is to compensate the possible nonzero control action for e=0, depending on $\dot{e}$, which is equivalent to a higher gain of the FU of the FLC than K in the δ–surrounding of (e, Δu)=(0, 0).

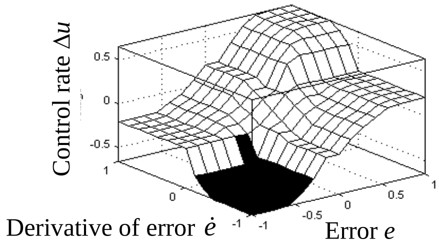

Fig.7. FU control surface of FLC

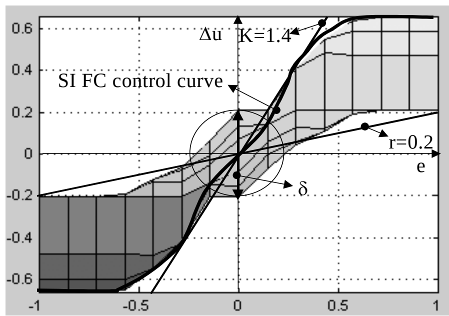

Fig.8. e-Δu projection of FU control surface of FLC

4 Performance Assessment

The developed generalised FLC design procedure is applied for the control of the temperature of the air inside a furnace [12-15]. The system error e is expressed as the difference between the measured temperature T and its reference T_r. The FLC output u controls via a pulse-width modulator a solid-state relay that connects the electric heater to the voltage supply during the pulses. The greater the signal u is the greater the duty ratio.

Experts assess the nominal plant model $P^{o}(s)=0,8.\mathbf{exp}(17s).(45s+1)^{-1}$, i.e. $k^{o}=0.8^{o}C$, $T^{o}=45min$, $\tau^{o}=17min$ and the "worst" perturbed plant model parameters are $k=2k^{o}$, $\tau=30$ min and $T=15$ min.

The control objectives are minimum possible settling time t_s and overshoot σ of the nominal step response and robust performance.

The required input data for the design of the FLC is: 1) nominal and perturbed plant model parameters; 2) $|W_f(j\omega)|=0.5$ and 3) $|e_{max}|=5^{o}C$. The two SI FCs and the FLC design and tuning follows the steps of the algorithm below.

1. The FU of the FLC has been designed employing Mamdani model with five MFs for both e and Δu and three for $\dot{e}$, as shown in Fig.9, Mamdani inference and centroid defuzzification. The SI FCs use the MFs for $e_n(d_s)$ and for $u(\Delta u)$.
2. The e-Δu projection of the resulting control surface (Fig.7) is obtained and depicted in Fig.8.
3. The angular coefficients of the sector lines that bound the projection surface are K=1.4 and r=0.2.
4. The corresponding SI FC is designed and tuned from robust performance requirement (2) using MATLAB [17]. The computed SI FC parameters are T_d=5 min, K_d=4, K_a=0.15, K_{ds}=0.04.
5. From the projection surface in Fig.8 is read disk diameter δ =0.4 and the FLC parameters obtained are T_d=5 min, K_d=4, K_e=0.2, K_{de}=0.05, K_{a1}=0.04.

The procedure ends with designed and tuned PI incremental SI FC and FLC.

This procedure is repeated for the same FU for PI position SI FC, which differs in the pre- and post-processing units, leading to different stabilising plant (T_d=0) and number of tuning parameters. The computed parameters for r=0.2, K=1.4 are K_p=0.6, T_i=31.5 min, K_{FU}=0.2.

The step responses of the designed FLC and the two corresponding SI FCs systems with nominal and perturbed plant are simulated in Simulink and are depicted in Fig.10. The responses of the systems with nominal plant are in solid lines. For more realistic simulation investigations the nominal and perturbed plant in Simulink are modelled by a higher order time lag. The assessed performance indices of the designed systems - settling time t_s and maximal deviation between nominal and varied response $|\Delta y|_{max}$, are presented in Table 2.

To highlight better the achieved robustness, an internal model controller (IMC) is designed [16]. The IMC block diagram is shown in Fig. 11. Robustness is achieved for

$$Q(s)=Q^{o}(s).F(s), Q^{o}(s)=[P^{o}(s)]^{-1*}, F(s)=[\lambda s+1]^{-n},$$

where $[P^{o}(s)]^{-1*}$ is the inverse minimal phase plant model and $F(s)$ is the required filter to ensure zero

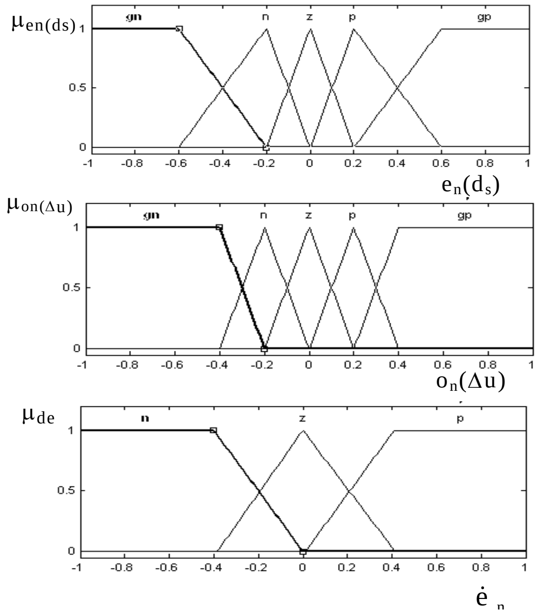

Fig.9. Basic FU membership functions

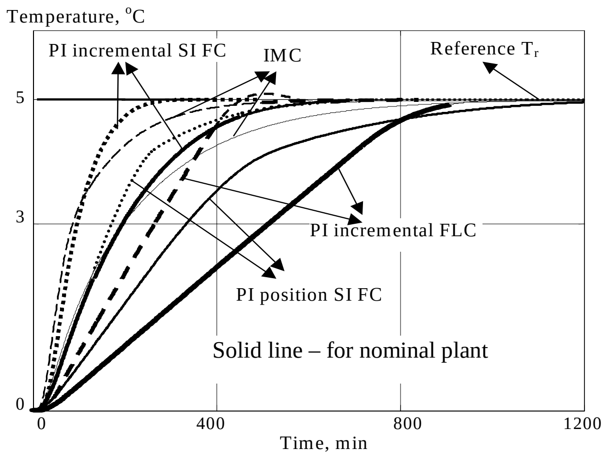

Fig.10. Step responses of PI incremental FLC, PI incremental SI FC, PI position SI FC and IMC systems

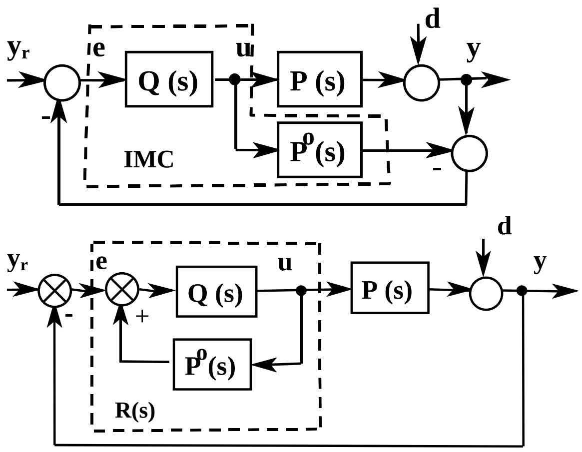

Fig.11. Block diagram of system with IMC – original and after equivalent transformation

steady state error for step inputs and to turn the ideal IMC Q^o to a proper rational function. For the plant considered $F(s)=(\lambda s+1)^{-1}$. The only tuning parameter λ is selected as the smallest possible that satisfies the robust performance criterion [16] in order to ensure fast transient response - λ=200. The step responses of the system with IMC nominal and perturbed plant are shown in Fig.10 and the performance estimates are given in Table 2.

The robust performance curves of the SI FCs and the IMC can be seen in Fig.12. The PI incremental SI FC has a curve very close to the IMC curve, which confirms the good system robustness achieved.

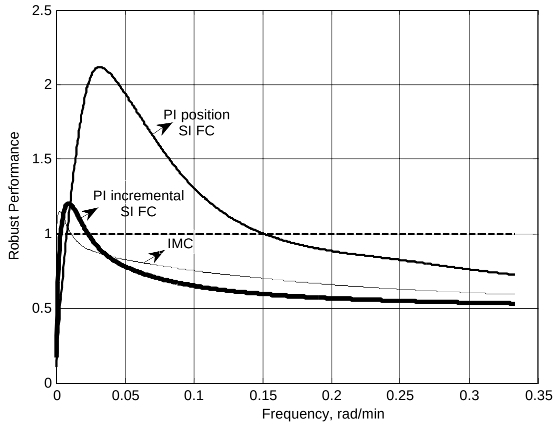

Fig.12. Robust performance curves of PI incremental SI FC, PI position SI FC and IMC systems

After transformations and Pade approximation $\exp(-\tau^o s)\approx(\tau^o s+1)^{-1}$ the IMC can be equivalently represented by PID controller

$$R(s)=(T_f s+1)^{-1}K_p\left(1+\frac{1}{T_i s}+T_d s\right),$$
$$T_f=\lambda\tau^o(\lambda+\tau^o)^{-1}, K_p=(T^o+\tau^o)[k^o(\lambda+\tau^o)]^{-1}.$$
$$T_i=T^o+\tau^o, T_d=T^o\tau^o(T^o+\tau^o)$$

This can be used to tune ordinary PID controllers out of system robustness requirements. Thus the equivalent PID controller is both standard and ensures system robustness like the IMC. The developed generalised procedure for the design of FLCs can also be used to tune ordinary PI position controllers. If the PI position SI FC once tuned is used without its FU as ordinary PI controller, the system response slightly differs from the response of the system with the SI FC. This is observed in Fig.13, where the step responses of systems with ordinary PI, PI SI FC and PID substitute of IMC are compared.

The comparison among the different FLC systems shows little difference with respect to system robust properties. The best is the IMC system, followed by PI incremental SI FC with small difference, which is the fastest, then the PI position SI FC and finally the PI incremental FLC, which is also the slowest.

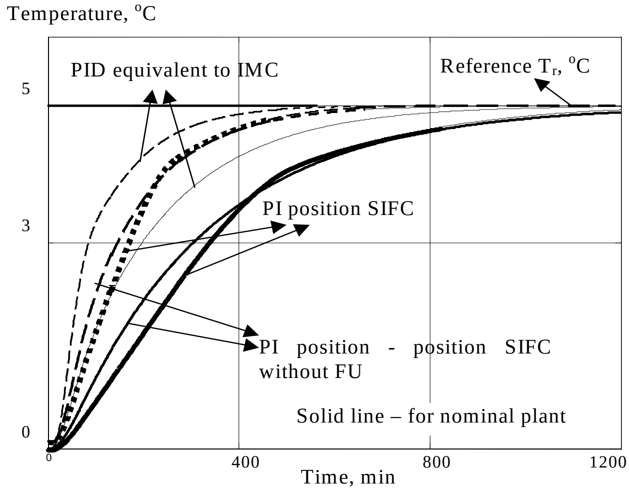

Fig.13. Step responses of systems with PI position SI FC, PI position – position SIFC without FU and PID equivalent to IMC

5 Conclusions and Future Work

The main contributions of the present paper confine to the following.

1. A general design approach for three types of FLCs - PI-like incremental FLC, PI-like incremental SI FC and PI-like position SIFC, ensuring closed loop system robust stability and robust performance, is developed for plants with time delay and model uncertainty. It is based on a modification of the Popov stability approach combined with Morari robustness and requires only basic approximate expert information about the plant.

Table 2.Comparison between FLC, SI FC and IMC systems

Performance indices	PI incremental SI FC	PI position SI FC	PI incremental FLC	IMC
t_s^o, min	600	1000	900	900
σ^o, %	0	0	0	0
t_s, min	250	700	900	550
σ, %	0	0	2	
$\lvert\Delta y\rvert_{max}$, °C	1.7	1.9	2.2	1.5

The approach steps on the similarity between position and incremental SIFCs and between the SI FC control curve and the e-Δu projection of the FLC control surface – both assumed sector bounded.

2. The FLC or the SI FC design is brought to a simple controllers' parameters tuning algorithm.

3. The tuning algorithm is applied to design three types of FLCs for the stabilisation of the air temperature in an electrical furnace. The step responses of the closed loop FLC and the corresponding SI FC systems with nominal and perturbed plant are simulated in Simulink and the performances compared.

4. The FLC and the SI FC systems performances are compared to IMC system.

5. Algorithm for tuning of ordinary PI controllers out of robustness requirements on the base of the FLC is suggested.

The FLC systems preserves stability and performance for high range of plant model uncertainties, retaining at the same time good nominal behaviour, which can hardly be ensured by other design techniques. Their performance is compatible with IMC system, which uses nonstandard and difficult to practically implement controller unless its PID equivalent is used. The tuning procedure can easily be embedded in industrial programmable FLCs. The developed general PI-like FLC design approach can be used to tune classical PI controllers to ensure system robustness.

Future work is foreseen in experimentation of the developed method for the design of various FLCs for laboratory pilot plants using MATLAB Real Time facilities.

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