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Designing of Fuzzy rule based switching mechanism for IMC controller for temperature controlling process

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Abstract

A fuzzy rule based switching mechanism for IMC controller is reported here. The switching scheme is realized through online adjustment of the controller settings between *smooth control* and *tight control* methodologies based on nine fuzzy rules. Initial settings of IMC controller is done by SIMC [5] tuning. The tuning parameters of SIMC controller i.e. closed-loop time constant (λ) and integral time (τ_I) are modified depending on the instantaneous process behaviour instead of their fixed settings as with conventional IMC tuning. Thus, due to proposed switching, closed-loop time constant (λ) and integral time (τ_I) of the IMC controller gets varied instead of their fixed tuning. Superiority of the reported scheme is verified based on practical experimentation of a closed-loop temperature control process.

Keywords: internal model control; fuzzy rule based switching; smooth control; tight control; temperature control loop

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1. Introduction

Presently a number of industrial control loops adopt internal model control (IMC) technique based proportional-integral-derivative (PID) controllers [1] due to their simple tuning guideline. Primarily, Rivera *et al.* [2] proposed

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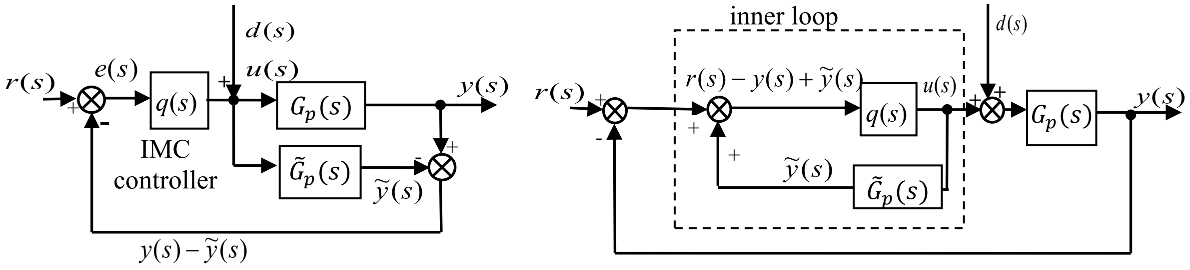
IMC controller for first-order processes, subsequently Chien [3] extended the IMC scheme for second-order processes and a vivid discussion on the development of IMC-PID controllers are reported by Morari and Zafiriou [4]. Based on the closed-loop responses obtained from IMC controllers it is found that they are reasonably capable to provide satisfactory set point response but load recovery is quite sluggish for processes with lag dominating in nature. In [5] Skogestad proposed SIMC controller where smaller integral time is opted for lag dominating processes to enhance load rejection behaviour.

To ascertain improved load recovery most of the researchers suggested tight control [5-7] mode for IMC controller. In contrast, smooth process response is relatively preferred during set point tracking [8]. Hence, to ensure improved overall performance for IMC-PID controller [9-10] during closed-loop operation; smooth set point tracking along with faster load recovery is usually preferred. For achieving such desirable dynamic behaviour in control policy, various techniques are reported in the literature such as adaptive control [11-12], conventional as well as fuzzy based auto-tuner [13-16], and condition based switching scheme [17-19] for conventional IMC-PID controller.

Here, an online switching scheme is suggested for IMC-PID controller using a set of fuzzy rules. As a result, controller setting switches between *tight control* and *smooth control* based on the instantaneous process behaviour. Initially, IMC controller is tuned by SIMC settings [5, 15].The reported switching algorithm is quite simple and straightforward in nature with minimal computation and hence suitable for real-time application. To validate the efficacy of the reported methodology, closed-loop performance evaluation is made on a real-time hot air flow temperature control process by Quanser [20]. For quantitative assessment, performance indices – IAE (integral of absolute error) and ITAE (integral time of absolute error) are calculated separately during set point response and load regulation.

2. Designing of IMC-PID controller

Fig. 1(a) shows the block diagram of an internal model control (IMC) scheme [2, 14, 19], and its corresponding feedback structure is depicted in Fig. 1(b).



(a) (b)

Fig. 1 (a) Block diagram of IMC structure, **(b)** IMC equivalent feedback structure.

$G_p(s)$ = Process
$\tilde{G}_p(s)$ = Process model
$q(s)$ = Internal model controller
$\tilde{y}(s)$ = Model output
$G_c(s)$= IMC-PID controller

$r(s)$ = Set point
$e(s)$ = Error = $r(s)-y(s)+\tilde{y}(s)$
$d(s)$ = Load disturbance
$u(s)$ = Controller output
$y(s)$ = Process output

From the inner loop of Fig. 1(b) IMC-PID expression is obtained as given by

$$G_c(s) = \frac{q(s)}{1-\widetilde{G}_p(s)q(s)} . \tag{1}$$

Now, considering a first-order plus dead time (FOPDT) process $\widetilde{G}_p(s) = \frac{k_p}{\tau_p s+1}e^{-\theta s}$ where k_p is the process gain, τ_p is the open-loop time constant, and θ is the time delay. Consequently, IMC-PID controller can be formulated for the said FOPDT model through the following steps –

Step I: The chosen FOPDT model is divided into two portions – inverting ($\widetilde{G}_{p+}(s)$) and non-inverting ($\widetilde{G}_{p-}(s)$) i.e. $\widetilde{G}_p(s) = \widetilde{G}_{p+}(s)\widetilde{G}_{p-}(s) = \left(\frac{K_p}{(\tau_p s+1)(0.5\theta s+1)}\right)(-0.5\theta s+1)$ where the dead time is approximated by first-order *Pade's approximation* $e^{-\theta s} = \frac{-0.5\theta s+1}{0.5\theta s+1}$.

Step II: IMC controller is realised by cascading a first-order filter $f(s) = \frac{1}{(\lambda s+1)}$ with invertible part ($\widetilde{G}_{p+}(s)$) i.e. $q(s) = \widetilde{q}(s)f(s) = \widetilde{G}_{p+}{}^{-1}(s)f(s) = \frac{(\tau_p s+1)(0.5\theta s+1)}{K_p}\frac{1}{(\lambda s+1)}$.

Step III: Substituting the expressions obtained from Step I and Step II in Eqn. (1) and comparing with the relation of non-interacting PID [21] controller $\left(k_c\left[\frac{\tau_I\tau_D s^2+\tau_I s+1}{\tau_I s}\right]\right)$, IMC-PID tuning parameters (k_c : proportional gain, τ_I : integral action time, and τ_D : derivative time) are obtained.

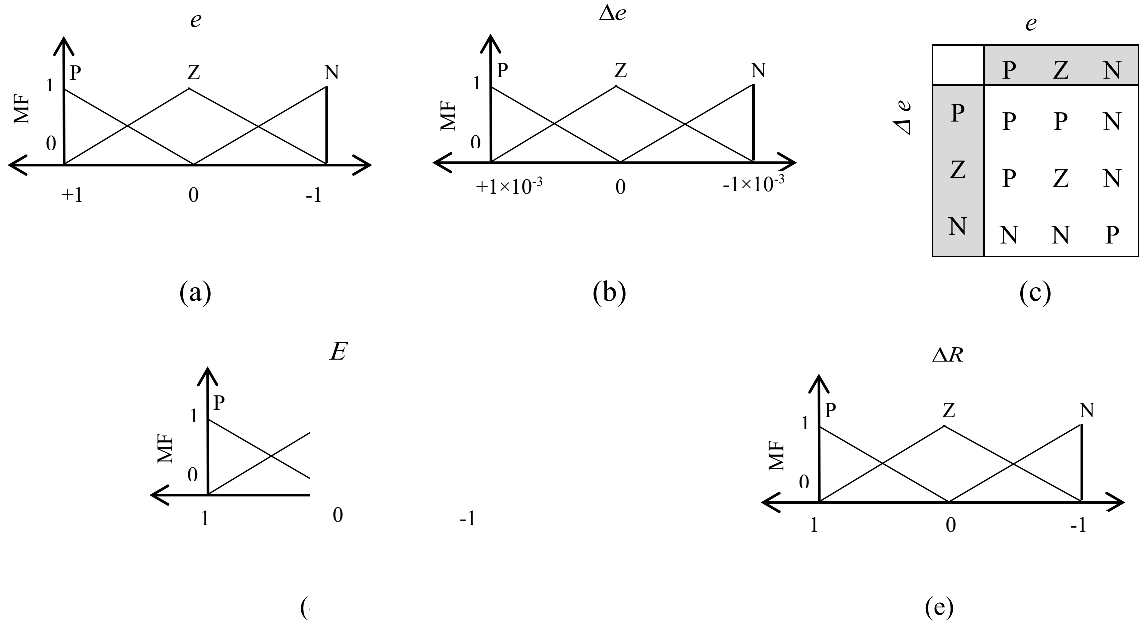
$$k_c = \frac{\tau_p+\theta/2}{k_p(\lambda+\theta/2)},\ \tau_I = \tau_p+\theta/2\ ,\ \tau_D = \frac{\tau_p\theta}{2\tau_p+\theta} . \tag{2}$$

Eqn. (2) represents the IMC-PID settings for conventional FOPDT process. It is capable to provide good set point response but load rejection response is not satisfactory owing to larger value of τ_I for processes with lag dominating in nature. To improve load recovery, literature survey [5-7, 9] reveals that there are two alternatives, either the controller is to be tuned with smaller value of integral time or it should have larger value of proportional gain. Skogestad proposed SIMC [5] controller with $k_c = \frac{\tau_p}{k_c(\lambda+\theta)}$ and $\tau_I = \min\{\tau_p,\ 8\theta\}$, but it results undesired oscillation during set point tracking.

Therefore, based on the previous discussions and recommendation made in [19] it is quite apparent that larger value for λ and τ_I is desirable for smooth set point tracking with lesser oscillation. On the contrary, during load change, smaller value for λ and τ_I is preferred for faster load recovery. Hence, to ensure enhanced closed-loop performance throughout set point response and load regulation, switching (*SW*) between *smooth control* and *tight control* will be advantageous based on the instantaneous process operating condition for providing appropriate values of λ and τ_I.

3. Proposed fuzzy rule based auto-tuning mechanism

Flow chart of the reported online fuzzy rule based switching for IMC control technique with Mamdani type inferencing [14] is shown in Fig. 3. In the following section, we will discuss in detail about the operating principle of the proposed online switching mechanism.



Δe \ e	P	Z	N
P	P	P	N
Z	P	Z	N
N	N	N	P

(a) (b) (c)

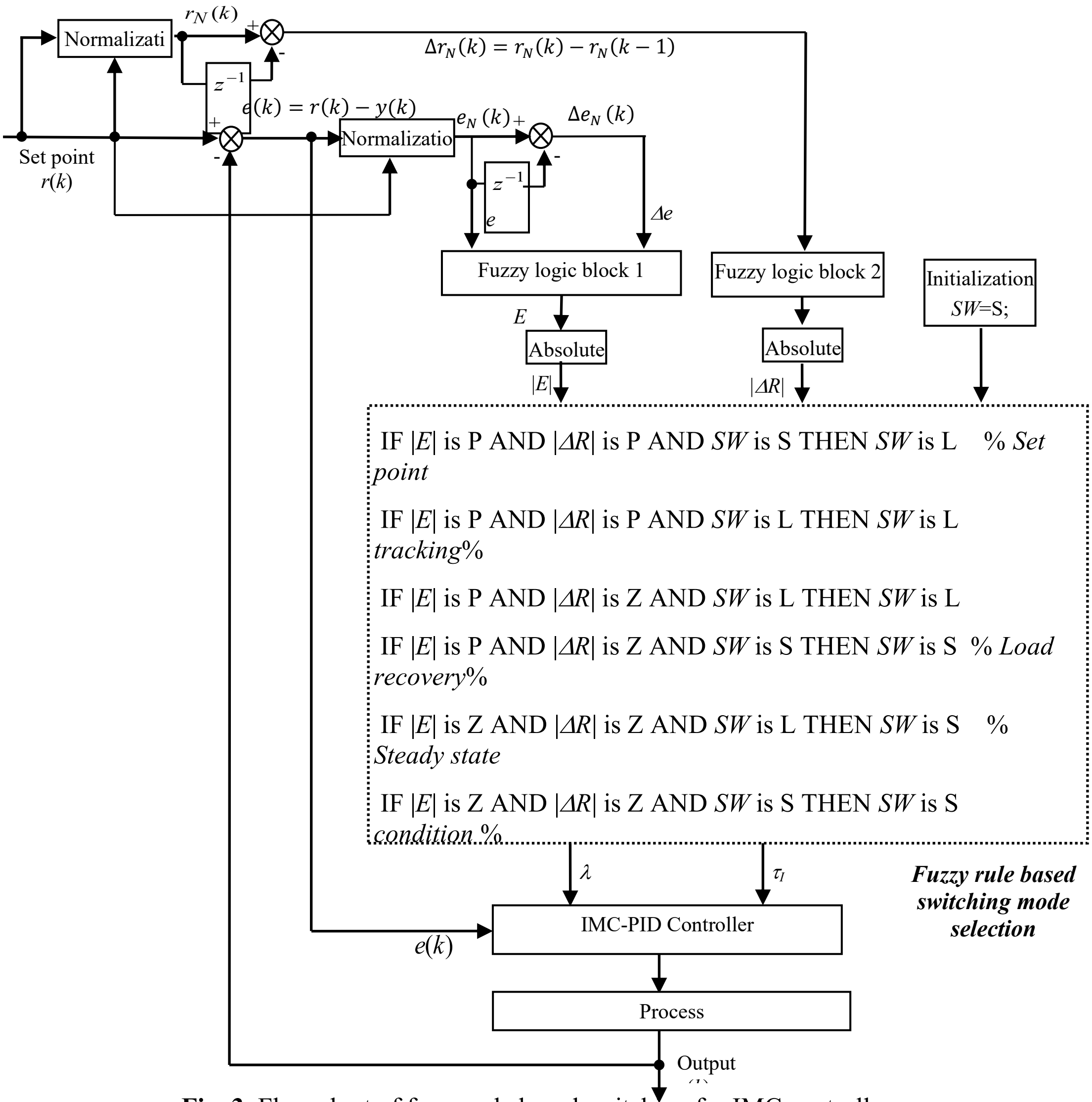
((e)

Fig. 2 Membership function ig rule base of *e* and Δ*e* (d) resultant membership functions of *E* and (d) Δ*R*.

Initially, unit step input (i.e. set point change $r(k)$) is applied to the process and corresponding normalized value of set point $r_N(k)$ is calculated. Subsequently, the normalized change in set value ($\Delta r_N(k) = r_N(k) - r_N(k-1)$) is computed. For a given set point change, error signal ($e(k)=r(k) - y(k)$) is obtained and the corresponding normalized error ($e_N(k)$) and normalized change of error ($\Delta e_N(k)$) are evaluated. Both the $e_N(k)$ and $\Delta e_N(k)$ are fed to the *fuzzy logic block 1* and $\Delta r_N(k)$ is fed to *fuzzy logic block 2* as shown in Fig. 3. Membership function (MF) of $e_N(k)$, $\Delta e_N(k)$ and $\Delta r_N(k)$ are chosen as symmetrical triangles having 50% overlap with neighbouring MFs as depicted in Fig. 2(a), Fig. 2(b), and Fig. 2(e) respectively. Output of the *fuzzy logic block 1* is denoted by E whose membership function is shown in Fig. 2(c) and Fig 2(d) respectively. The output of the *fuzzy logic block 1* and *fuzzy logic block 2* are passed through an absolute block and enters into the *fuzzy rule based switching mode selection* block. Output of the *fuzzy rule based control mode selection block* is based on current process operating condition which results suitable values for λ and τ_I. Here, due to the proposed fuzzy rule based online switching, IMC-PID controller gets tuned either with *smooth tuning* (*SW* position is L) or *tight tuning* (*SW* position is H) parameters (λ and τ_I) during closed-loop operation.

4. Real-time experimentation

Real-time closed-loop experiment is performed on a temperature process manufactured by Quanser [20]. In this set-up three thermocouples are there as shown in Fig. 4. Furthest from the heater i.e. the third thermocouple (T3 in the Fig. 4) is chosen for our experimental evaluation. Quanser DAQ module is utilized to interface between the temperature process and PC. Our reported controller is designed in PC employing MATLAB-SIMULINK. To keep the temperature at the desired value axial fan speed is controlled (0-5 V) to regulate the air flow rate through the duct. In the beginning of our experimentation room temperature (i.e. ambient temperature) was measured. Subsequently, mathematical model of the experimental set up is identified using process reaction curve (PRC) method. Here, 4 V step change is applied in axial fan supply voltage and corresponding temperature change is observed. Mathematic model of the experimental set up is obtained from PRC plot (as shown in Fig. 5(a)) and it is given by $G_p = \dfrac{10.75}{50.2s+1}e^{-2s}$.



IF $|E|$ is P AND $|\Delta R|$ is P AND SW is S THEN SW is L % *Set point*

IF $|E|$ is P AND $|\Delta R|$ is P AND SW is L THEN SW is L *tracking*%

IF $|E|$ is P AND $|\Delta R|$ is Z AND SW is L THEN SW is L

IF $|E|$ is P AND $|\Delta R|$ is Z AND SW is S THEN SW is S % *Load recovery*%

IF $|E|$ is Z AND $|\Delta R|$ is Z AND SW is L THEN SW is S % *Steady state*

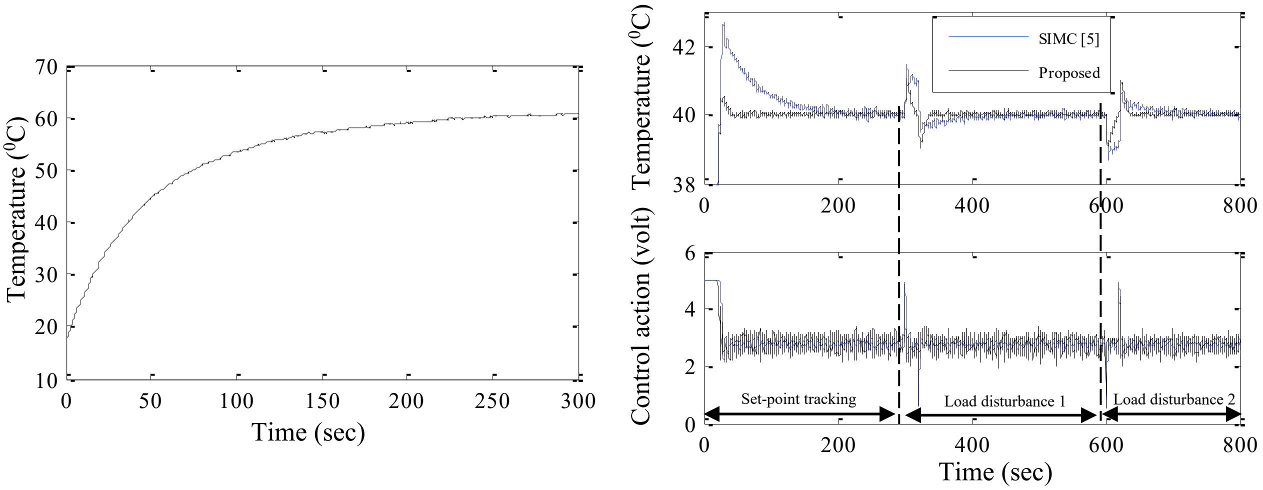
IF $|E|$ is Z AND $|\Delta R|$ is Z AND SW is S THEN SW is S *condition* %

Fig. 3 Flow chart of fuzzy rule based switching for IMC controller.

PC PC interface Temperature set-up

Fig. 4 Temperature control loop

Based on the obtained model, PID controller is tuned with SIMC [5] relation. When the temperature reaches the desired value, two separate load varying signals are incorporated separately at 250 sec (+2 V step change) and 600 sec (-2 V step change) as depicted in Fig. 5(b). Closed-loop performance indices IAE and ITAE are listed in Table I. From the Fig. 5(b) and Table I it is found that the proposed *fuzzy rule based switching* scheme is competent to provide improved performance in comparison to conventional SIMC-PI [5] settings during both set point response and two separate load recovery phases.



(a) (b)

Fig. 5 (a) PRC response of temperature loop (b) close-loop process response with control action.

Table I. Performance indices of SIMC and proposed switching IMC controller

Operating condition	**IAE**		**ITAE**	
	SIMC [5]	Proposed	SIMC [5]	Proposed
Set-point tracking	334.55	243.68	1.11×10^4	3.09×10^3
Load disturbance 1	48.90	26.76	1.75×10^4	9.78×10^3
Load disturbance 2	44.55	25.46	2.95×10^4	1.70×10^4

5. Conclusion

Here, an online fuzzy rule based switching scheme for IMC-PID controller is proposed and its performance is tested on a practical temperature control process. Initial setting of the IMC controller is chosen from SIMC-PI settings. Motivation of the reported work can be described as smooth control (larger values for λ and τ_I) is preferred during set point tracking and in contrast to ensure faster load rejection tight control (smaller values of λ and τ_I) is opted. Instead of fixed values of tuning parameters for IMC controllers as with conventional setting, i.e. static closed-loop time constant (λ) and integral time (τ_I), dynamic nature is incorporated by selecting suitable values for λ and τ_I based on the current process operating status. Real-time performance of the proposed scheme is tested on a temperature control set-up i.e. a single input single output process. In future, performance of the reported scheme may be tested on multi-variable systems having more than one process variables. Here, only nine fuzzy rules are being utilized to realize the switching mechanism, so there is a scope for employing more number of fuzzy rules to improve the closed-loop performance of the reported switching mechanism based IMC controller.

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