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Unified PID Tuning Approach for Stable, Integrative and Unstable Dead-Time Processes

Julio E. Normey Rico * **José Luis Guzmán** **

* *Federal University of Santa Catarina*
88040-900 Florianópolis-SC-Brazil (julio@das.ufsc.br)
** *Dep. de Lenguajes y Computación, Universidad de Almería*
04120 Almería-Spain (joguzman@ual.es)

Abstract: This paper presents a unified approach for tuning PID controllers for stable, integrative and unstable dead-time processes. The approach is based on a PID approximation of the Filtered Smith Predictor that allows to control this kind of processes looking for a trade-off between performance and robustness. The proposed control tuning method is simple to analyze and use. Cases studies are included to illustrate the advantages of the proposed tuning rules. Furthermore, comparisons with other existing methods are presented to show that the proposed unified method provides promising results.

Keywords: dead-time systems, Filtered Smith predictor, FOPDT models, IPDT models, UFOPDT models, process control, PID controller

1. INTRODUCTION

PID controllers are widely used in industry; mainly in process control applications, where more than 95% of the controllers are of PID type (Åström and Hägglund, 2005). As pointed out in (Skogestad, 2003), although PID controller has only three parameters, it is not easy, without a systematic procedure, to find adequate values (settings) for them. In industry, large number of PID controllers are poorly tuned (Åström and Hägglund, 2005). Despite the development of other more powerful control algorithms, and the fact that hundreds of tuning rules for PID controllers have been proposed since 1942, every year new works are developed aiming for the improvement of PID tuning (O'Dwyer, 2003).

It is important to note that most of proposed tuning rules are based on simple models, like stable first-order plus dead time model (FOPDT), integrator plus dead time model (IPDT) or unstable first-order plus dead time model (UFOPDT). This is motivated by the fact that these simple models are easy to obtain in industry from process data. Many of these tuning rules are derived only for FOPDT models (see for example, (Cohen and Coon, 1953; Rivera et al., 1986; Wang et al., 2001)), only for IPDT models (see for instance (Tyreus and Luyben, 1992; Luyben, 1996)), or only for UFOPDT models (see for example (Depaor and O'Malley, 1989; Venkatashankar and Chidambaram, 1994; Marchetti et al., 2001; Visioli, 2001)). In some cases, the proposed rules are valid for two cases: FOPDT-IPDT (Ziegler and Nichols, 1942; Skogestad, 2003; Åström and Hägglund, 2004), IPDT-UFOPDT (Lee et al., 1998) or FOPDT-UFOPDT (Padma et al., 2004). Moreover, different control objectives are used to obtain the PID parameters; for example in (Ziegler and Nichols, 1942) and (Cohen and Coon, 1953), settings result in a very good disturbance response for integrating processes, but give aggressive settings for set-point changes and poor performance for dominant dead-time processes. Robustness and good set-point responses are obtained with the IMC approach (Rivera et al., 1986), however with slow disturbance rejection in lag dominant plants. More recently, a simple tuning was proposed (Skogestad, 2003) which gives satisfactory set-point and disturbance responses for stable and integrative cases. On the other hand, the AMIGO method proposed by Åström and Hägglund (2004) provides simple tuning rules for stable and integrative dead-time processes looking for a compromise between robustness and performance. However, there are not too many time domain tuning rules to be applied for all cases, stable, integrative and unstable processes, using a unique design approach.

Thus, this paper presents a PID tuning procedure which can be used to control FOPDT, IPDT and UFOPDT processes. The proposed PID is based on a simple modification of the ideal dead-time compensation structure of the Filtered Smith Predictor (FSP) (Normey-Rico and Camacho, 2007, 2009), where both the design and tuning of the controller are intuitive and simple. In fact, the proposed method has been developed looking for the objectives proposed by Skogestaad in (Skogestad, 2003): (i) the tuning rules are well motivated, model-based and analytically derived; (ii) they are simple and easy to memorize (the rules are simple and easy at the current version, although perhaps not for all cases can be easy to be memorized); (iii) they work well on a wide range of processes. Further-

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more, the proposed method considers a real PID controller, which includes the filter of the derivative action in the design.

The paper is organized as follows. Section 2 is devoted to describe the controller design and the resulting tuning rules for FOPDT, IPDT, and UFOPDT systems. First, the FSP scheme is briefly described, and afterwards the equivalent PID controller is obtained, which is then used to derive the resulting tuning rules. Three simulated case studies are presented in section 3, where the proposed tuning rule is compared with other existing methods. Finally, the paper ends with some conclusions.

2. THE PROPOSED METHOD

In a recent paper, a unified dead-time compensation structure which can be used to control stable, integrative and unstable processes with a dead-time has been proposed (Normey-Rico and Camacho, 2009). The structure is based on a simple modification of the Smith Predictor (SP) and both the design and tuning of the controller are simple and allow fast closed-loop responses than other controllers. In practice, the use of a dead-time compensator is the best solution for a dead-time process, however some times the only real-time allowable controller is a PID and a simple first-order model (FOPDT, IPDT, or UFOPDT) is used to represent the process. Therefore, the idea of this work is based on two steps, first a FSP is computed for a first-order model and then the equivalent FSP control law is approximated by a PID. Furthermore, the resulting tuning rule is derived to eliminate the slow or unstable dynamics from the disturbance rejection responses.

2.1 FSP for FOPDT, IPDT, and UFOPDT processes

This section briefly revises the FSP tuning for FOPDT, IPDT, and UFOPDT processes. The FSP controller is shown in Figure 1 (Normey-Rico and Camacho, 2009). As can be seen, the structure is the same as in the SP with two additional filters. $F(s)$ is a traditional reference filter to improve the set-point response and $F_r(s)$ is a predictor filter used to improve the predictor properties.

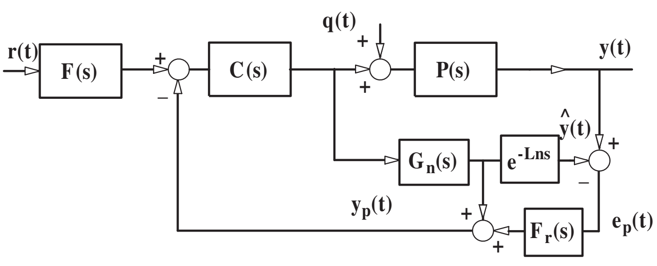

Fig. 1. FSP: structure for analysis

In the structure, used for analysis, $P_n(s) = G_n(s)e^{-L_n s}$ is a model of the process, $G_n(s)$ is the dead-time-free model, and $C(s)$ a PI primary controller, $C(s) = K\frac{1+s\tau_i}{s\tau_i}$.

For the stable case, $G_n(s) = \frac{K_p}{1+sT}$, for the integrative case, $G_n(s) = \frac{K_p}{s}$, and for the unstable case, $G_n(s) = \frac{K_p}{sT-1}$.

In the three cases the PI controller is tuned to obtain a delay free nominal closed-loop system with a pole (or double pole) in $s = -1/T_o$, giving:

- FOPDT: $\tau_i = T, K = T/(T_o K_p)$
- IPDT: $K = \frac{1}{T_o K_p}$ (P controller)
- UFOPDT: $\tau_i = T_o(2+T_o/T), K = (T_o+2T)/(T_o K_p)$

Filter $F_r(s)$ is designed to avoid the effect of the open-loop pole in the disturbance closed-loop response. This allows for a internally stable system which rejects steps in steady state with time constant T_o (Normey-Rico and Camacho, 2009). The obtained filter is

- FOPDT and IPDT: $F_r(s) = \frac{1+s\beta}{1+sT_o}$
- UFOPDT: $F_r(s) = \frac{1+s\beta}{1+sT_o(2+T_o/T)}$

where β is obtained for the specified conditions and T_o is the only one tuning parameter for a trade-off between robustness and performance. Note that increasing T_o a slower and more robust system is obtained. Finally, a reference filter $F(s) = \frac{1+sT_r}{1+s\tau_i}$ can be used, if necessary, to eliminate the effect of the controller zero. In this filter, T_r regulates the overshoot of the set-point response.

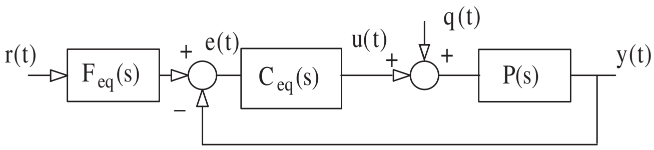

Fig. 2. 2DOF equivalent structure of the FSP

With these settings, the FSP allows to speed up the disturbance response of the SP even for the case of lag dominant processes and to control integrative and unstable processes. In practice, the FSP equivalent 2DOF controller shown in figure 2 is used for implementation purposes.

This 2DOF controller is given by:

$$C_{eq}(s) = \frac{C(s)F_r(s)}{1 + C(s)G_n(s)(1 - e^{-L_n s}F_r(s))}, F_{eq}(s) = \frac{F(s)}{F_r(s)},$$

and it is usually implemented in the discrete domain (Normey-Rico and Camacho, 2009), in such a way that $C_{eq}(s)$ does not cancel the open-loop pole of the model.

2.2 PID approximation of the FSP

As mentioned, if only a PID controller is allowable, the exact FSP solution can not be used. Thus, the idea of this paper is to approximate, at low frequencies, the FSP by a PID. To do it, first the equivalent $C_{eq}(s)$ controller of the FSP is computed for the three simple cases:

- FOPDT:

$$C_{eq}(s) = \frac{K(1+s\beta)(1+sT)}{s\tau_i(1+sT) + KK_p[1 + s\tau_i - e^{-L_n s}(1+s\beta)]}$$

- IPDT:

$$C_{eq}(s) = \frac{K(1+s\beta)s}{s(1+sT_o) + KK_p[1 + sT_o - e^{-L_n s}(1+s\beta)]}$$

- UFOPDT:

$$C_{eq}(s) = \frac{K(1+s\beta)(1-sT)}{s\tau_i(1-sT)+KK_p[1+s\tau_i-e^{-L_ns}(1+s\beta)]}$$

To obtain a PID controller $C_{pid}(s)$ that approximates $C_{eq}(s)$, a Pade approximation of the dead time is used, $e^{-L_ns} = \frac{1-0.5L_ns}{1+0.5L_ns}$. Afterwards, parameter β is calculated to eliminate the zero of $C_{eq}(s)$ at the desired value, that is, $s = -1/T$ in the stable case, $s = 0$ in the integrative case, and $s = 1/T$ in the unstable case.

The final real PID series controller (a realizable transfer function) is:

$$C_{pid}(s) = \frac{k_c(1+sT_i)(1+sT_d)}{sT_i(1+s\alpha T_d)} \qquad (1)$$

where $T_d = 0.5L_n$ and K_c, T_i, and α are given by:

- FOPDT:

$$T_i = T\Big[1 - \frac{(2T-L_n)(T-T_o)^2}{(2T+L_n)T^2}\Big] \qquad (2)$$

$$k_c = \frac{T_i}{K_p(L_n+2T_o-T_i)} \qquad (3)$$

$$\alpha = \frac{T_o}{L_n+T_o+\frac{L_nT_i}{2T_o}-\frac{T_oL_n}{2T}} \qquad (4)$$

- IPDT:

$$T_i = 2T_o+L_n, \quad k_c = \frac{2+L_n/T_o}{K_p\delta}, \quad \alpha = \frac{T_o}{\delta} \qquad (5)$$

$$\delta = T_o + 0.5L_n(4+L_n/T_o) \qquad (6)$$

- UFOPDT:

$$T_i = \frac{T_o(2T+T_o)(2+L_n/T)+2L_nT}{2T-L_n} \qquad (7)$$

$$k_c = \frac{T_iT}{K_p\delta}, \quad \alpha = \frac{T_o^2}{\delta} \qquad (8)$$

$$\delta = T_o^2 - T\big(L+T_o\big(2+T_o/T\big)-T_i\big) \qquad (9)$$

In the unstable case, the solution it is only valid for proceses with $L < 2T$. Notice that this is not a very hard constraint because it is difficult to find dominant dead-time unstable processes in practice. Moreover, as shown in (Normey-Rico and Camacho, 2007), dominant dead-time unstable processes can be unstabilized with a infinitesimal dead-time error, even using an ideal dead-time compensator structure.

3. CASE STUDIES

This section is devoted to analyzed the three case studies, FOPDT, IPDT, and UFOPDT, where the results obtained for the proposed tuning rule are compared with other algorithms found in literature. For all the examples, the time unit is considered in seconds.

Such as discussed at the introduction section, there exist many methods providing PID tuning rules for FOPDT, IPDT, and UFOPDT systems (although none of them give a general PID tuning for the three cases). Here, the time-domain methods proposed by (Padma et al., 2004) for FOPDT and UFOPDT, (Lee et al., 1998) for FOPDT, (Lee et al., 2000) for IPDT and UFOPDT, and (Skogestad, 2003) for FOPDT and IPDT, have been selected considering the same features of the rule proposed in this paper: simple tuning rule based on the process parameters and easy understanding design procedure. Furthermore, these four works include comparisons with other existing methods and thus they are quite valuable to be used as reference tests and to obtain adequate conclusions. The method proposed in (Padma et al., 2004) presents a tuning rule that is based on designing a standard PID controller looking for matching the numerator and denominator of the closed-loop transfer function. Simple equations (with no tuning parameter) are derived for stable and unstable processes, but the proposed rule for unstable processes is limited to $L/\tau \leq 1.2$. The IMC-PID approach presented by (Rivera et al., 1986) is generalized in (Lee et al., 1998) and to show how to obtain PID parameters for general stable process models. The standard PID controller is obtained by taking the first three terms of the Maclaurin series expansion of the single-loop form of the IMC controller. The work presented in (Lee et al., 2000) proposes a method that is an extension of the PID controller tuning presented by (Lee et al., 1998) to general unstable and integrating processes with time delay. Explicit PID controller tuning rules based on IMC are proposed for unstable and integrative processes with time delay. On the other hand, Sckogestard proposed a method based on analytic rules for series PID controller tuning that are simple and still result in good closed-loop behavior (Skogestad, 2003). They are based on the IMC-PID tuning rules, where the rule for the integral term is modified to improve disturbance rejection for integrating processes. The resulting tuning rule works well for both integrating and stable time delay processes, and for both setpoints and load disturbances.

3.1 Stable case

For the FOPDT case, an example from Padma et al. (2004) is selected where the process transfer function is given by

$$P(s) = \frac{e^{-0.5s}}{s+1} \qquad (10)$$

The methods described above for stable processes were used looking for obtaining a similar rise time (0.8 seconds) for the setpoint tracking response. This decision was made because the method proposed by (Padma et al., 2004) does not provide any tuning parameter and thus the other methods were tuned according to have similar rise time. In this way, the method proposed by (Padma et al., 2004) gives a controller with $k_c = 2.5$, $T_i = 1.25$, and $T_d = 0.217$; that proposed by (Lee et al., 1998) results in $k_c = 2.01$, $T_i = 1.21$, and $T_d = 0.18$ with $\lambda_L = 0.1$ (design parameter); the tuning rule from (Skogestad, 2003) provides $k_c = 1.96$, $T_i = 1$, and $T_d = 0$ with $\lambda_S = 0.01$ (design parameter); and the parameters for the proposed method according to (2)-(4) are $k_c = 1.94$, $T_i = 0.784$, $T_d = 0.25$, and $\alpha = 0.31$ with $T_o = 0.4$. For this comparison, a reference filter was not used.

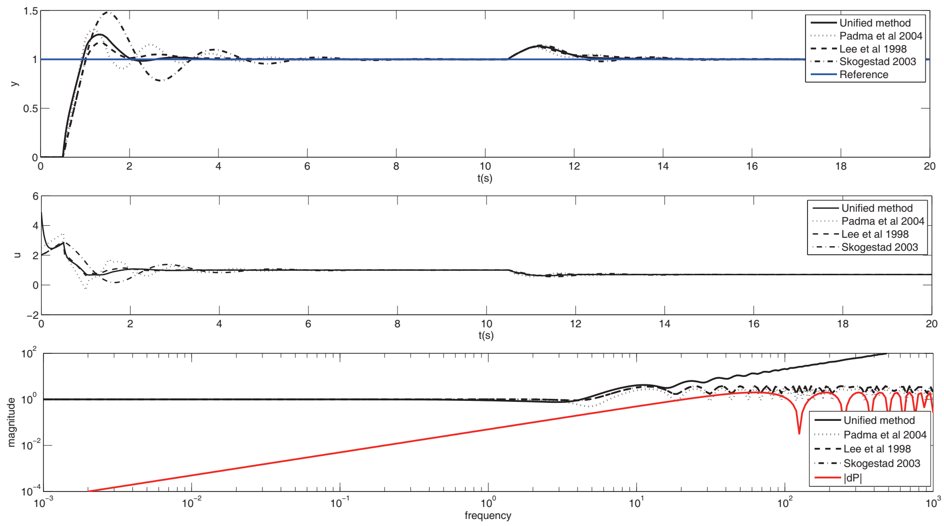

Fig. 3. Stable case. Example for transfer function $P(s) = e^{-0.5s}/(s+1)$ for a reference value of $r(t) = 1\ \forall t \geq 0$ and a load disturbance value of $q(t) = 0.3\ \forall t \geq 12.5$. Dead-time modelling error of 10% was used for robustness analysis.

Structure	OS	IAE_r	$ITAE_r$	t_r	IAE_d	$ITAE_d$
Proposed	25.32	3.93	7.68	0.80	0.52	0.87
Padma et. al.	16.98	3.97	7.87	0.81	0.60	1.20
Lee et. al. 98	30.20	4.08	8.58	0.80	0.52	1.10
Skogestad	48.02	4.46	10.64	0.81	0.63	1.31

Table 1. Numerical results for stable case

Figure 3 and Table 1 shows the graphical and numerical results for the different tuning rules, where in the table OS is the overshoot, IAE_r is the Integrated Absolute Error for the reference tracking, $ITAE_r$ is the Integrated Time weighted Absolute Error for the reference tracking, t_r is the rise time for the reference tracking, and IAE_d and $ITAE_d$ are equivalent measurements to IAE_r and $ITAE_r$ for the load disturbance response. Notice how all the methods practically reach the same rise time. Similar load disturbance responses are obtaining for the three methods. The main differences are observed at the setpoint tracking response, where an oscillatory behaviour is obtained for all the methods, as expected. The minimum and maximum overshoots are reached for the (Lee et al., 1998) and (Skogestad, 2003) methods, respectively. On the other hand, the method proposed in this paper is that obtaining better responses for setpoint tracking and load disturbance rejection based on the IAE and $ITAE$ values presented in Table 1. Finally, notice that from the robustness analysis shown in Figure 3, where a dead-time error of 10% was considered, the unified proposed method is that with better robustness properties.

3.2 Integrative case

The following transfer function has been used for the IPDT case (Skogestad, 2003)

$$P(s) = \frac{e^{-s}}{s} \tag{11}$$

In this case, the resulting PID parameters are $k_c = 0.502$, $T_i = 6.87$, and $T_d = 0.219$ with $\lambda_L = 2.75$ for the (Lee et al., 2000) method; $k_c = 0.526$, $T_i = 7.6$, and $T_d = 0$ with $\lambda_S = 0.9$ for the (Skogestad, 2003) method; and $k_c = 0.48$, $T_i = 6.4$, $T_d = 0.5$, and $\alpha = 0.56$ with $T_o = 2.75$, for the proposed tuning rule following (5)-(6). The different free tuning parameters were modified in order to obtain similar responses for setpoint tracking and load disturbance responses. In this example, a fist-order reference filter has been used for the three methods in order to obtain a underdamped response with $F(s) = (3.84s+1)/(6.4s+1)$.

The graphical responses and numerical results are presented in Figure 4 and Table 2, respectively. Notice how practically the same response is obtained for the three methods. Slight differences can be observed from Table 2, where it can be seen that the (Skogestad, 2003) method is the slowest one for the load disturbance response, although is also the method with less overshoot for the setpoint tracking response. On the other hand, the proposed method gives again the best results according to the IAE and $ITAE$ measurements, although such as pointed out before, there are only some minor differences among the three methods. Regarding the robustness analysis presented in Figure 4, the three methods showed also similar robustness properties, having both the proposed method and the Skogestad approach practically the same results.

3.3 Unstable case

Finally, a third example for UFOPDT system is presented where the process transfer function is described by (Lee et al., 2000)

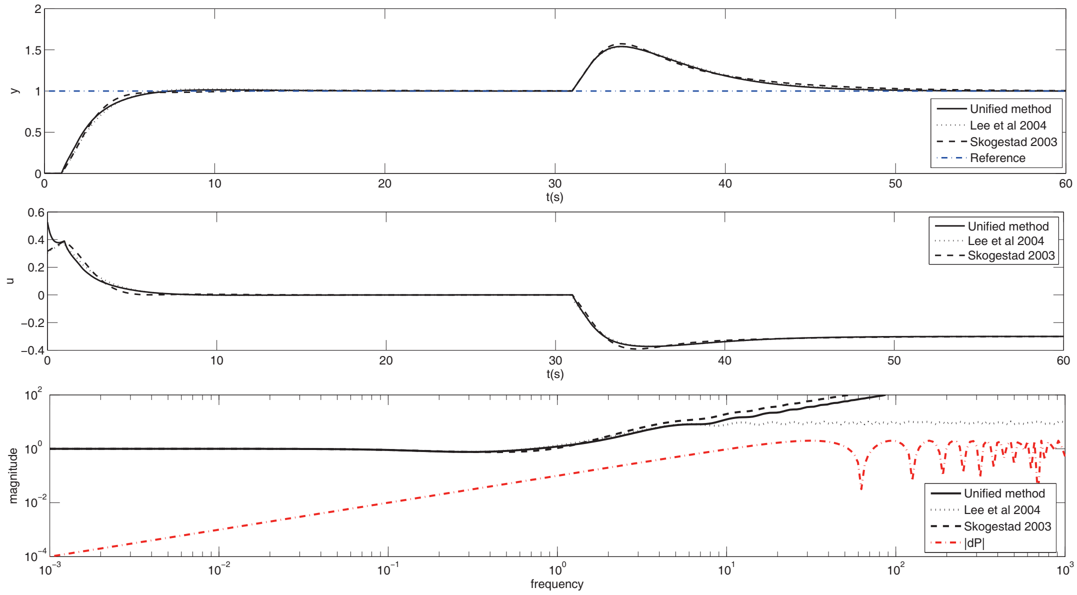

Fig. 4. Integrative case. Example for transfer function $P(s) = e^{-s}/s$ for a reference value of $r(t) = 1\ \forall t \geq 0$ and a load disturbance value of $q(t) = 0.3\ \forall t \geq 30$. Dead-time modelling error of 10% was used for robustness analysis.

Structure	OS	IAE_r	$ITAE_r$	t_r	IAE_d	$ITAE_d$
Proposed	1.04	5.81	18.60	7.80	13.2	89.90
Lee et. al. 00	2.10	6.00	20.40	7.90	13.67	96.35
Skogestad	0.59	5.81	18.90	12.7	14.46	110.42

Table 2. Numerical results for integrative case

$$P(s) = \frac{e^{-0.4s}}{s-1} \tag{12}$$

The method proposed by (Padma et al., 2004) consists in a direct design tuning rule without using any design parameter. Thus, and for comparative reasons, the other methods have been tuned trying to obtain similar load disturbance responses in order to perform an adequate conclusion. The resulting controller parameters are $k_c = 2.75$, $T_i = 2.22$, and $T_d = 0.21$ for the (Padma et al., 2004) method; $k_c = 2.90$, $T_i = 2.10$, and $T_d = 0.16$ for the (Lee et al., 2000) method with $\lambda_L = 0.4$; and $k_c = 1.07$, $T_i = 1.86$, $T_d = 0.2$, and $\alpha = 0.21$ with $T_o = 0.4$, for the proposed tuning rule by using (7)-(9). Again, a first-order reference filter was used for the three methods in order to reduce the overshoot in the setpoint tracking response with $F(s) = (0.46s + 1)(1.86s + 1)$.

Figure 5 and Table 3 present the results for this case. It can be observed how the responses for the (Lee et al., 2000) method and the proposed tuning rule are giving quite similar results. This fact can be better seen from the measurements in Table 3, where the values for both methods are practical identical. Furthermore, these two methods not only improve the results with respect to (Padma et al., 2004) method, but also both of them are providing a design tuning parameter that allows to define the desired closed-loop response. This fact is not available at the (Padma et al., 2004) tuning rule such as mentioned above. On the other hand, the three methods have similar robustness capabilities such as shown in Figure 5, being the proposed unified method slightly more robust.

4. CONCLUSIONS

This paper presents a unified PID design for FOPDT, IPDT, and UFOPDT processes. The proposed controller is simple to analyze and tune and it is based on a low frequency approximation of the ideal dead-time compensation structure of the FSP. Giving the process model, only one parameter is used obtain a compromise between performance and robustness. Three case studies were presented to illustrate the tuning procedure and to show that the proposed controller allows for a closed-loop system with similar or better performance and robustness than other algorithms presented in literature. However, the main contribution with respect to other existing methods is that the proposed approach deals with stable, integrative, and unstable processes using the same unified procedure.

Furthermore, the presented method fulfills most of the recommendations proposed by Skogestad in (Skogestad, 2003), mainly those dealing with well motivated rules, model-based and analytically derived; and those others saying that the rules work well on a wide range of processes. However, Skogestad also suggests that rules must be simple and easy to memorize. As discussed through the paper, the rules presented here are easy and simple, but in some cases they are not too easy to be memorized.

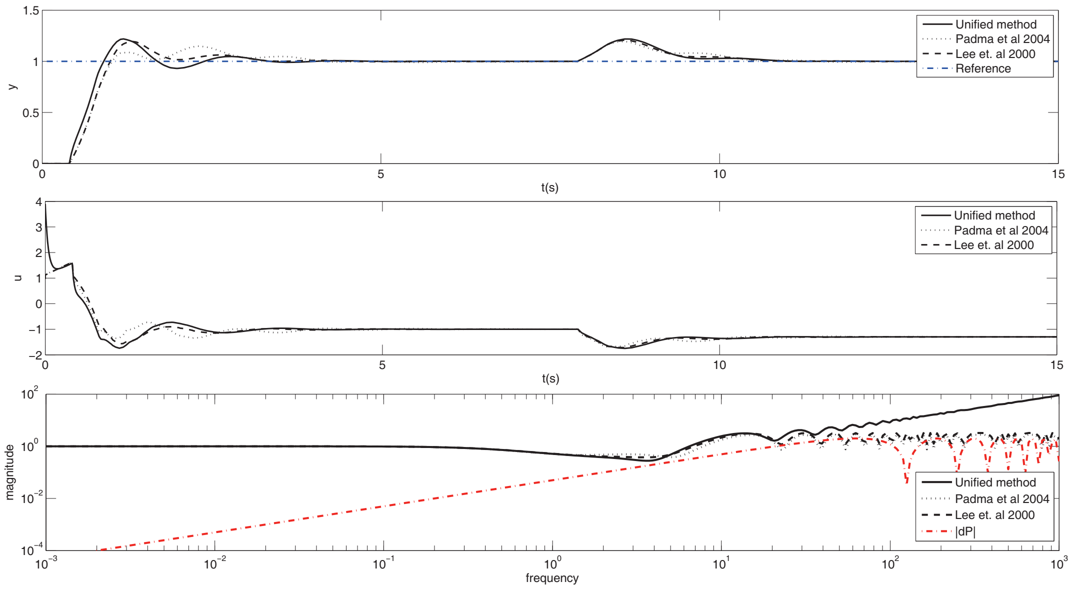

Fig. 5. Unstable case. Example for transfer function $P(s) = e^{-0.4s}/(s-1)$ for a reference value of $r(t) = 1\ \forall t \geq 0$ and a load disturbance value of $q(t) = 0.3\ \forall t \geq 12.5$. Dead-time modelling error of 10% was used for robustness analysis.

Structure	OS	IAE_r	$ITAE_r$	t_r	IAE_d	$ITAE_d$
Proposed	9.90	3.88	7.53	1.4	0.71	1.14
Padma et. al.	13.00	4.02	8.34	2.10	0.86	1.58
Lee et. al. 00	9.07	3.91	7.63	1.5	0.75	1.26

Table 3. Numerical results for unstable case

Thus, future works will be focused on simplifications of the proposed tuning rules such that they are easy to memorize.

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