Model Reference Robust Tuning of 2DoF PI Controllers for Integrating Controlled Processes

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Abstract— **The aim of this paper is to present a robust tuning method of two-degree-of-freedom (2DoF) proportional integral (PI) controllers for integrating controlled processes. This is based on the use of a model reference optimization procedure with servo and regulatory closed-loop transfer functions targets. The designer is allowed to deal with the performance/robustness *trade-off* of the closed-loop control system by specifying the desired robustness level through selecting a maximum sensitivity in the range from 1.4 to 2.0. In addition, a *smooth servo/regulatory performance combination* is obtained by forcing both closed-loop transfer functions to perform as closely as possible to non-oscillatory dynamic targets. Controller tuning equations that guarantee the design robustness level are provided for integrating second-order plus dead-time (ISOPDT) models with normalized dead-times from 0.1 to 2.0, and integrating plus dead-time (IPDT) models. The robustness of the control system is analyzed. Comparative examples show the effectiveness of the proposed tuning method.**

I. INTRODUCTION

Even though most of the controlled processes found in the process industry are self-regulating, i.e. the process output seeks a stable operating point under a constant input, there are others that under a constant input their output is unbounded, rise or decrease without limit. These non-self regulated process are named integrating or unstable if their model transfer functions have a pole at the s-plane origin or at its right-half plane, respectively. Stable processes with very long time constants may also be approximated by integrating models. Integrating and unstable processes may be operated only under closed-loop automatic control and their controller tunning needs a special treatment. Integrating characteristics may be found by example in tank level processes and communication networks [4], [8], [14].

For the integrating processes there are IMC-based tuning methods [4], [8] for one-degree-of-freedom (1DoF) proportional integral (PI) and proportional integral derivative (PID) controllers that include a design parameter, the closed-loop time constant, that can be used to deal with the control system performance/robustness trade-off. Kappa-Tau [5] and AMIGO [9], [10] methods provide tuning rules for two-degree-of-freedom (2DoF) PI and PID controllers for high robustness, $M_S = 1.4$.

Robustness was also included in the controller design for integrating processes using the gain and phase margins [16] and the maximum sensitivity [15].

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The IMC-based tuning SIMC [11] for 1DoF PI controllers is based on an integrated plus dead-time model and for 1DoF Ideal PID controllers on an integrating second-order plus dead-time model. The design parameter, the servo-control closed-loop time constant, is selected by a trade-off between fast speed of response, good disturbance rejection and robustness. With the SIMC controllers the control system has an intermediate robustness, $M_S = 1.70$.

An alternative tuning method of 2DoF proportional integral (PI_2) controllers for integrating controlled processes is presented in this communication. The proposed approach explicitly considers the *trade-off* between the performance and robustness of a control system. The distinctive feature of the resultant tuning procedure is the incorporation of the desired robustness level as measured with the maximum sensitivity, M_S, which is the explicit and only design parameter. Therefore, the designer may select the desired robustness M_S level for the control system in the range from 1.4 to 2.0.

II. PROBLEM FORMULATION

The controller design procedure described below for integrating controlled processes follows the model reference robust tuning (MoReRT) methodology proposed for over damped controlled processes [1], [2].

Consider a closed-loop control system, as shown in Fig. 1, where $P(s)$ and $C(s)$ are the controlled process model transfer function and the controller transfer function, respectively. In this system, $r(s)$ is the set-point, $u(s)$ is the controller output signal, $d(s)$ is the load-disturbance, and $y(s)$ is the process controlled variable.

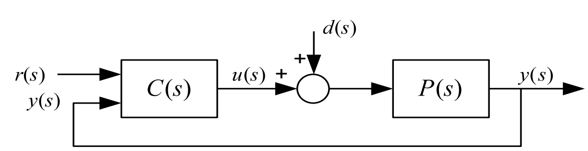

Fig. 1. Closed-Loop Control System

The closed-loop control system output, $y(s)$, in response to changes in its inputs, $r(s)$ and $d(s)$, is given by the following:

$$y(s) = M_{yr}(s)r(s) + M_{yd}(s)d(s), \tag{1}$$

where $M_{yr}(s)$ is the transfer function from the set-point to the process controlled variable, and $M_{yd}(s)$ is that from the load-disturbance to the process controlled variable. These are known as the *servo-control* closed-loop transfer function

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and the *regulatory control* closed-loop transfer function, respectively.

The development of the proposed tuning method of 2DoF PI controllers for integrating controlled process will take into account not only the closed-loop control system performance, by stating target responses for step changes in the set-point and the load-disturbance, but also the control system robustness, measured in terms of the maximum sensitivity, M_S.

A. 2DoF Proportional Integral Controller (PI_2)

The process will be controlled with a two-degree-of-freedom proportional integral (PI_2) controller [5] whose output is expressed as follows:

$$u(s) = K_p \left\{ \beta r(s) - y(s) + \frac{1}{T_i s}\left[r(s) - y(s)\right] \right\}, \qquad (2)$$

where K_p is the controller *proportional gain*, T_i is the *integral time constant*, and β is the *set-point proportional weight*.

For the purposes of analysis only, not implementation, the controller output (2) will be rewritten as follows:

$$u(s) = C_r(s)r(s) - C_y(s)y(s), \qquad (3)$$

where

$$C_r(s) = K_p\left(\beta + \frac{1}{T_i s}\right), \qquad (4)$$

is the PI_2 controller aspect that operates on the set-point r, the *set-point controller* transfer function, and

$$C_y(s) = K_p\left(1 + \frac{1}{T_i s}\right), \qquad (5)$$

is the PI_2 controller aspect that operates on the feedback signal y, the *feedback controller* transfer function.

The closed-loop transfer functions of the servo control and the regulatory control in (1) are then given by

$$M_{yr}(s) = \frac{C_r(s)P(s)}{1 + C_y(s)P(s)}, \qquad (6)$$

and

$$M_{yd}(s) = \frac{P(s)}{1 + C_y(s)P(s)}, \qquad (7)$$

which are related as follows:

$$M_{yr}(s) = C_r(s)M_{yd}(s). \qquad (8)$$

III. Controller Design

Usually the design of the 2DoF PI controllers is performed in two stages [6], [9], [12]. First, as it is required to obtain the desired regulatory control performance and specific closed-loop control system robustness level, the parameters (K_p, T_i) of the feedback controller (5) are determined for a parameter set of the controlled process model $\overline{\theta}_p$. Second, the set-point controller (4) free parameter (β) is used to improve the servo-control performance.

In what follows a different approach is taken. The complete set of PI_2 controller parameters $\overline{\theta}_c = \{K_p, T_i, \beta\}$ will be obtained considering, at the same time, the regulatory control and the servo-control performance, to obtain a controller with a targeted *servo/regulatory performance combination* that will also produce a closed-loop control system with a specific robustness level.

A. Cost Functionals

For the regulatory control response, the cost functional to be minimized is defined as follows:

$$J_d \doteq \int_0^\infty \left[y_d^t(\tau_c, \overline{\theta}_c, \overline{\theta}_p, t) - y_d(\overline{\theta}_c, \overline{\theta}_p, t)\right]^2 \mathrm{d}t, \qquad (9)$$

where $y_d^t(\tau_c, \overline{\theta}_c, \overline{\theta}_p, t)$ is the step response of the regulatory control closed-loop transfer function target, that will be defined later, and $y_d(\overline{\theta}_c, \overline{\theta}_p, t)$ is that of the regulatory control system $M_{yd}(s)$ (7) with the controlled process $P(s)$ and controller $C_y(s)$ (5).

In (9) τ_c is the dimensionless design parameter, the relative closed-loop system speed. Its role will become clear after the next section when describing the target transfer functions.

In a similar way, the servo-control cost functional to be minimized is defined as follows:

$$J_r \doteq \int_0^\infty \left[y_r^t(\tau_c, \overline{\theta}_p, t) - y_r(\overline{\theta}_c, \overline{\theta}_p, t)\right]^2 \mathrm{d}t, \qquad (10)$$

where $y_r^t(\tau_c, \overline{\theta}_p, t)$ is the step response of the servo-control closed-loop transfer function target, defined later, and $y_r(\overline{\theta}_c, \overline{\theta}_p, t)$ is that of the servo-control system $M_{yr}(s)$ (6) with the controlled process $P(s)$ and controller $C_r(s)$ (4).

B. Controller Optimization

For the 2DoF PI controller design, the following overall cost functional is optimized:

$$J_T(\tau_c, \overline{\theta}_c, \overline{\theta}_p) \doteq J_r(\tau_c, \overline{\theta}_c, \overline{\theta}_p) + J_d(\tau_c, \overline{\theta}_c, \overline{\theta}_p), \qquad (11)$$

to obtain the optimum controller parameters $\overline{\theta}_c^o = \left\{K_p^o, T_i^o, \beta^o\right\}$. Note that $\overline{\theta}_c^o = \overline{\theta}_c^o(\overline{\theta}_p, \tau_c)$.

Moreover, for each $\overline{\theta}_c^o$ set obtained, the closed-loop control system robustness is measured using the maximum sensitivity M_S, which is defined as follows:

$$M_S \doteq \max_\omega |S(\mathrm{j}\omega)| = \max_\omega \frac{1}{|1 + C_y(\mathrm{j}\omega)P(\mathrm{j}\omega)|}. \qquad (12)$$

IV. Controlled Process Models and Closed-Loop Transfer Functions Targets

For the integrating processes two models are to be considered: the integrating second-order plus dead-time model, and the integrating plus dead-time model.

A. Integrating Second-Order Plus Dead-Time Models

We consider first the integrating second-order plus dead-time (ISOPDT) model given by the following:

$$P(s) = \frac{K\mathrm{e}^{-Ls}}{s(Ts + 1)}, \qquad (13)$$

were K is the gain, T the time constant and L the dead-time. The controlled process parameters are $\overline{\theta}_p = \{K, T, L\}$.

Taking into account the second-order controlled process model (13) and the feedback part of the PI controller (5), the desired regulatory control closed-loop transfer function is obtained as the following third-order transfer function target:

$$M_{yd}^t(s) = \frac{(T_i/K_p)s\mathrm{e}^{-Ls}}{(T_c s+1)^3}, \tag{14}$$

where T_c is the closed-loop time-constant.

Using (4) and (14) in (8) the servo-control closed-loop transfer function is given by

$$M_{yr}(s) = \frac{(\beta T_i s+1)\mathrm{e}^{-Ls}}{(T_c s+1)^3}. \tag{15}$$

In order to have a set-point step change response without oscillation, overshoot, or steady-state error, the servo-control closed-loop transfer function target is selected as follows:

$$M_{yr}^t(s) = \frac{\mathrm{e}^{-Ls}}{(T_c s+1)^2}. \tag{16}$$

The zero/pole cancellation required to obtain (16) ($\beta T_i = T_c$) will not be forced but taken into account by the optimization procedure to match the servo-control target close-loop target transfer function.

Then in the ISOPDT model case the global control system output target $y^t(s)$ is computed as:

$$y^t(s) = \frac{\mathrm{e}^{-Ls}}{(\tau_c T s+1)^2} r(s) + \frac{(T_i/K_p)s\mathrm{e}^{-Ls}}{(\tau_c T s+1)^3} d(s). \tag{17}$$

where $\tau_c \doteq T_c/T$ is the dimensionless design parameter, which is an indication of the closed-loop system response speed in relation to the controlled process speed.

Using the controlled process parameters $\overline{\theta}_p$ as well as the transformation $\hat{s} \doteq Ts$, the controlled process (13) and the PI controller transfer functions (4) and (5) can be expressed in a normalized form as follows:

$$\hat{P}(\hat{s}) = \frac{\mathrm{e}^{-\tau_o \hat{s}}}{\hat{s}(\hat{s}+1)}, \tag{18}$$

$$\hat{C}_r(\hat{s}) = \kappa_p \left(\beta + \frac{1}{\tau_i \hat{s}}\right),\ \hat{C}_y(\hat{s}) = \kappa_p \left(1 + \frac{1}{\tau_i \hat{s}}\right), \tag{19}$$

where $\tau_o \doteq L/T$ is the model *normalized dead-time* and

$$\kappa_p \doteq K_p\ K\ T, \quad \tau_i \doteq \frac{T_i}{T}, \tag{20}$$

are the *normalized gain* and *normalized integrating time* of the controller, respectively.

The normalized controlled process model (18) has only one dimensionless parameter, τ_o.

During the optimization procedure, the closed-loop relative speed parameter τ_c is selected in such a way that the robustness level of the resulting closed-loop system met a specific target M_S^t in the range from 1.4 to 2.0.

From the optimization results, it is possible to obtain the normalized controller parameters and the resulting control system robustness as functions of the model parameters, $\overline{\theta}_p$, and the performance specification, τ_c. However, to simplify the design procedure, the controller parameters are obtained directly as functions only of the closed-loop control system robustness parameter, which is the maximum sensitivity, M_S.

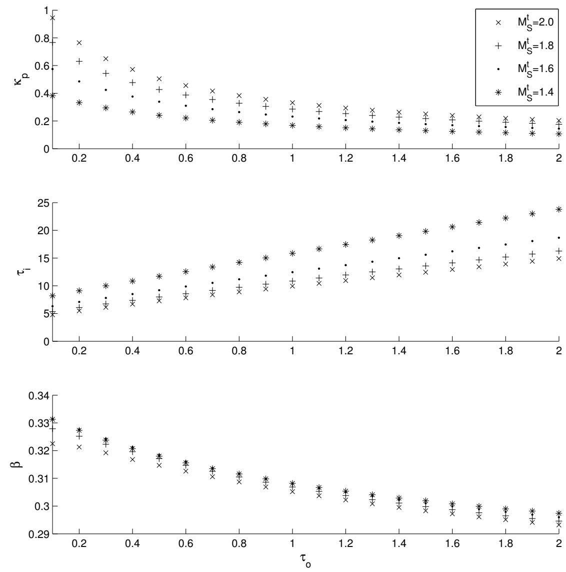

Fig. 2. PI Controller Parameters, ISOPDT Models

The controller optimum normalized parameters (κ_p, τ_i, β) obtained are shown in Fig. 2 along the entire dead-time range evaluated and the four robustness levels, $M_s^t = \{2.0, 1.8, 1.6, 1.4\}$.

This shows the influence of the controlled process dynamics (τ_o) and the desired robustness (M_S^t) over the controller parameters required to meet the target step responses.

The controller parameters obtained from the optimization procedure are used to fit the controller parameter equations of the proposed *Mo*del *Re*ference *R*obust *T*uning (*MoReRT*).

The normalized controller parameters can be obtained with the following equations:

$$\kappa_p = \frac{a_0 + a_1\tau_o}{a_2 + a_3\tau_o + {\tau_o}^2}, \tag{21}$$

$$\tau_i = b_0\mathrm{e}^{b_1\tau_o} + b_2\mathrm{e}^{b_3\tau_o}, \tag{22}$$

$$\beta = c_0 + c_1\tau_o + c_2{\tau_o}^2. \tag{23}$$

Table I lists the a_i, b_i and c_i constants for (21) to (23) for each of the four robustness levels.

B. Integrating Plus Dead-Time Models

Integrating and over damped processes with very large time constants can also be approximated by an integrating plus dead-time (IPDT) model given by the following:

$$P(s) = \frac{K\mathrm{e}^{-Ls}}{s}, \tag{24}$$

were K is the gain and L the dead-time. The controlled process parameters are $\overline{\theta}_p = \{K, L\}$.

Using the same procedure described above the desired regulatory control closed-loop transfer function is obtained

TABLE I
MORERT CONSTANTS, ISOPDT MODELS

	Target robustness M_S^t			
	1.4	1.6	1.8	2.0
a_0	0.4141	0.3781	0.3335	0.4156
a_1	0.3126	0.4085	0.4826	0.5484
a_2	0.9140	0.5324	0.3363	0.3317
a_3	2.402	1.864	1.519	1.567
b_0	18.38	12.77	10.27	9.123
b_1	0.2110	0.2408	0.2637	0.2735
b_2	-11.08	-7.192	-5.589	-4.978
b_3	-0.4811	-0.6446	-0.8042	-0.8900
c_0	0.3331	0.3336	0.3305	0.3257
c_1	-0.03254	-0.03273	-0.02941	-0.002441
c_2	0.007548	0.00713	0.005826	0.004094

as the following second-order target transfer function target:

$$y^t(s) = \frac{\mathrm{e}^{-Ls}}{\tau_c Ls + 1} r(s) + \frac{(T_i/K_p)s\mathrm{e}^{-Ls}}{(\tau_c Ls+1)^2} d(s), \qquad (25)$$

where τ_c is the design parameter.

Using the controlled process parameters $\overline{\theta}_p$ as well as the transformation $\tilde{s} \doteq Ls$, the controlled process (24) and the PI controller transfer functions (4) and (5) can be expressed in a normalized form as follows:

$$\tilde{P}(\tilde{s}) = \frac{\mathrm{e}^{-\tilde{s}}}{\tilde{s}}, \qquad (26)$$

$$\tilde{C}_r(\tilde{s}) = \kappa_p \left(\beta + \frac{1}{\tau_i \tilde{s}}\right), \; \tilde{C}_y(\tilde{s}) = \kappa_p \left(1 + \frac{1}{\tau_i \tilde{s}}\right), \qquad (27)$$

where

$$\kappa_p \doteq K_p \; K \; L, \quad \tau_i \doteq \frac{T_i}{L}, \qquad (28)$$

are the *normalized gain* and *normalized integrating time* of the controller, respectively.

As the normalized controlled process model (26) does not have any variable parameter just one optimization run is required for each robustness level.

In the same way as with the ISOPDT model during the optimization processes, the closed-loop relative speed parameter τ_c is selected in such a way that the robustness level of the resulting closed-loop system met a specific target (M_S^t) in the range from 1.4 to 2.0 and the controller parameters are obtained directly as functions only of the closed-loop control system robustness.

The MoReRT tuning equations for the IPDT models are as follows:

$$\kappa_p = a, \qquad (29)$$
$$\tau_i = b, \qquad (30)$$
$$\beta = c. \qquad (31)$$

Table II lists the a, b and c constants for (29) to (31) for each one of the four robustness levels.

TABLE II
MORERT CONSTANTS, IPDT MODELS

	Target robustness M_S^t			
	1.4	1.6	1.8	2.0
a	0.332	0.442	0.528	0.599
b	10.636	7.885	6.579	5.823
c	0.452	0.434	0.419	0.406

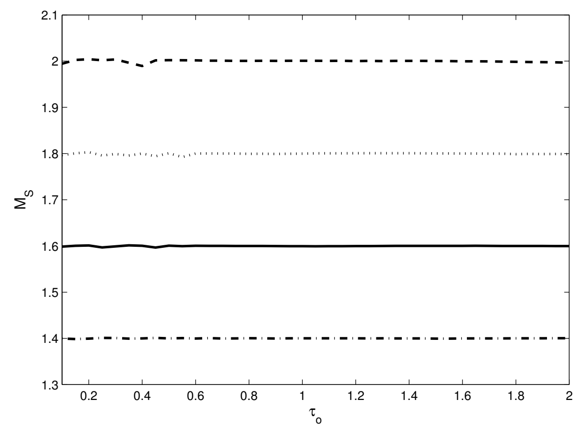

Fig. 3. MoReRT Robustness for ISOPDT Models

C. MoReRT Control System Robustness

The robustness obtained with (21) to (23) for each ISOPDT normalized dead-time in the range analyzed is shown in Fig. 3. As can be seen all the robustness profiles are nearly flat. This means that for an ISOPDT model of a controlled process the MoReRT tuning guarantees that the robustness target is attained for all normalized dead-times in the range considered.

It was also verified that the robustness obtained with (29) to (31) for any IPDT model dead-time L matches the target robustness as shown in Fig. 4.

The achievement of the robustness target for all the

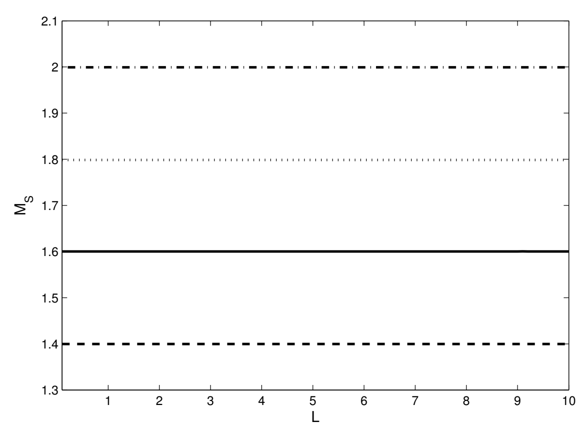

Fig. 4. MoReRT Robustness for IPDT Models

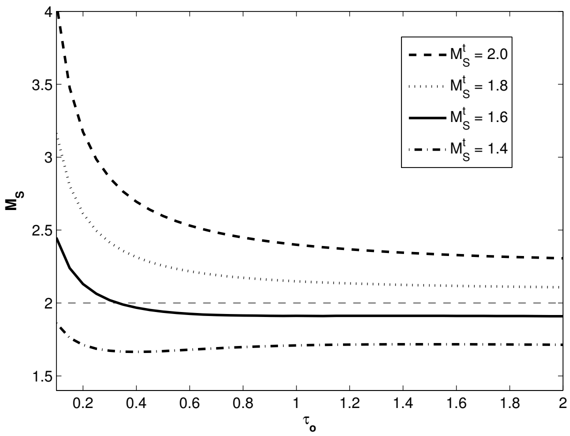

Fig. 5. ISOPDT Models - Wang & Cai Tuning Robustness

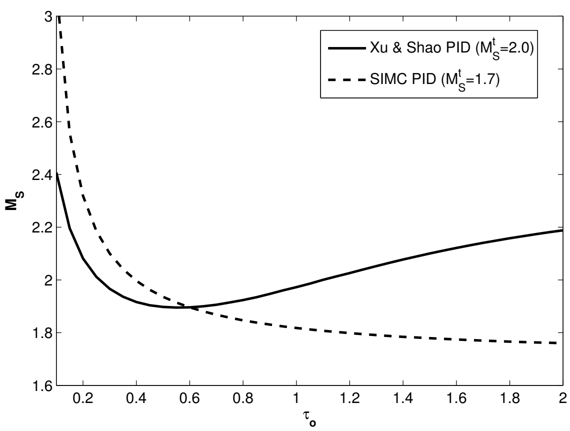

Fig. 6. ISOPDT Models - Xu & Shao and SIMC Tuning Robustness

integrating controlled process models considered (IPDT and ISOPDT) is one of the distinctive characteristics of the proposed tuning method.

V. Comparison with other Tuning Methods

For comparison purposes the target robustness accomplishment of several tuning rules for integrating process will be evaluated.

A. ISOPDT Models

For integrating second-order plus dead-time models available robust tuning rules [11], [15], [17] do not produce control systems with a constant robustness level across their applicability range as noted in Fig. 5 and Fig. 6.

B. IPDT Models

For integrating plus dead time models there are tuning rules that produce control systems with a constant M_S level along their entire applicability range but that are not robust like the PID performance optimized rules [13] that give $M_S = 16.24$ (ISE), $M_S = 8.55$ (ITSE), and $M_S = 6.42$

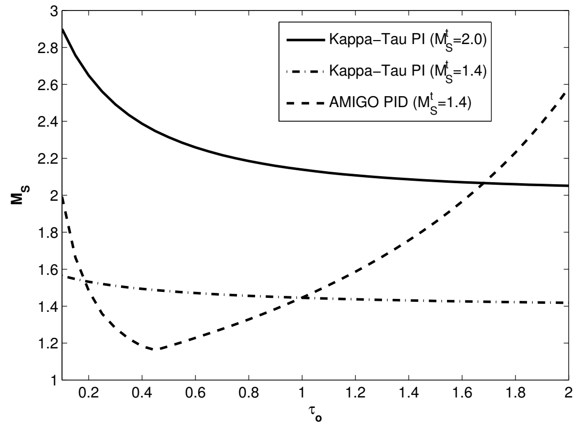

Fig. 7. IPDT Models - Kappa-Tau and AMIGO Robustness

TABLE III
Example - IPDT PI Control

Tuning Method	K_p	T_i	β	M_S	J_{eT}	TV_{uT}
MoReRT $M_S^t = 1.4$	0.66	5.32	0.45	1.40	0.69	0.14
AMIGO ($M_S = 1.41$)	0.70	6.70	1.0	1.41	0.72	0.22
MoReRT $M_S^t = 1.6$	0.88	3.94	0.47	1.60	0.46	0.17
SIMC ($M_S = 1.7$)	1.0	4.0	1.0	1.70	0.40	0.32

(ISTE), and the closed-loop transfer function polynomials matching method [7] that gives $M_S = 6.11$ (PI) and $M_S = 4.65$ (PID). The SIMC [11] PI tuning rule provides a constant intermediate robustness ($M_S = 1.7$) and the AMIGO [9] PI a constant high robustness ($M_S = 1.41$).

Other methods like Kappa-Tau [5] PI and AMIGO [10] PID do not provide a constant robustness level as shown in Fig. 7.

In contrast with the above methods the proposed robust tuning rule provides a perfect achievement of four robustness level targets for IPDT and ISOPDT models.

C. Control System Response Examples

Consider the IPDT model ($K = 1$, $L = 0.4$). The PI controller parameters with the proposed tuning method for $M_S^t \in \{1.4, 1.6\}$ and AMIGO and SIMC methods are listed in Table III. The Table also lists the obtained robustness and overall performance, the integrated absolute error (J_e) and the control effort total variation (TV_u). The control system response to a 10% set-point step change followed by a 5% disturbance step change is shown in Fig. 8.

For a high robustness level ($M_S \approx 1.4$) the MoReRT controller has better performance and smother control effort while at the medium robustness level ($M_S \approx 1.6$) the SIMC has better performance but with a big control output change to a set-point step.

As a second example consider the ISOPDT ($K = 1$, $T = 1$, $L = 1.2$). The PI controller is tuned with the Ali & Majhi (A&M) [3] method and with the proposed robust tuning. The control system response to set-point and disturbance unit step

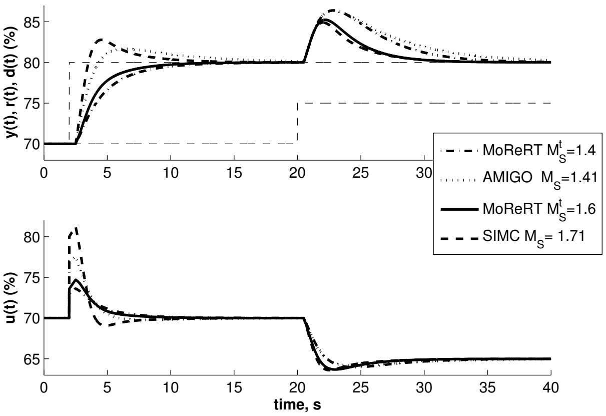

Fig. 8. Example - IPDT PI Control Responses

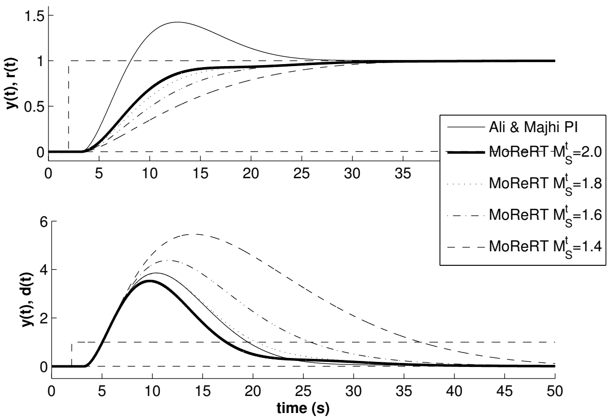

Fig. 9. Example - ISOPDT PI Control Responses

changes are shown in Fig. 9. The robustness and performance are listed in Table IV .

From this information is evident the robustness/performance trade-off and the flexibility of the proposed tuning that allows the designer to select the required robustness level while the A&M tuning produces a system with a robustness level that is model dependent.

VI. Conclusions

The proposed *MoReRT* tuning method for 2DoF proportional integral (PI_2) controllers guarantees the design robustness level for integrated second-order plus dead-time (ISOPDT) and integrated plus dead-time (IPDT) models using only one design parameter, which is the required closed-loop control system robustness as measured with the maximum sensitivity M_S.

Tuning equations were obtained for four robustness, $M_S \in \{1.4, 1.6, 1.8, 2.0\}$, allowing the designer to select the required robustness level by taking into account the expected variations in the process parameters. The integrating second-order plus dead-time models considered include normalized dead-times in the range from 0.1 to 2.0.

TABLE IV
Example - ISPDT PI Control

Tuning Method	M_S	J_{ed}	J_{er}	TV_{ud}	TV_{ur}
Ali & Mahji	1.83	43.34	7.93	1.85	0.67
MoReRT $M_S^t = 2.0$	2.00	37.27	7.65	1.95	0.29
MoReRT $M_S^t = 1.8$	1.80	47.18	8.33	1.79	0.23
MoReRT $M_S^t = 1.6$	1.60	66.55	9.55	1.65	0.19
MoReRT $M_S^t = 1.4$	1.40	116.76	12.41	1.54	0.13

Acknowledgments

This work has received financial support from the Spanish CICYT program under grant DPI2010-15230. Also, the financial support from the University of Costa Rica is greatly appreciated.

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