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IAE Based Tuning of Controller Anti-windup Schemes for First Order plus Dead-time System

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***Abstract*—The paper is focused on IAE based tuning the anti-windup feedback in a controller of a first order plus dead time model. The problem is addressed to two types of controllers, finite order PI and infinite order Internal Model Controller (IMC) with the delay compensation. For the PI a classical finite order feedback known as back-calculation method is utilized, whereas for the IMC, a novel functional feedback is proposed. For both the cases, the feedback setting is optimized with respect to minimizing the IAE criterion. The analysis is performed on a dimensionless form of the model so that the results are valid to a broad class of systems. For both PI and IMC, the 'optimal' dynamics of the anti-windup loop is of first order with the time constant being close to the time constant of the plant model.**

I. Introduction

The control loop design and tuning based on linear models may exhibit a strikingly different behaviour from its implementation as soon as the always existing *actuator saturation* affects the operation. Primarily, the actuating variable of the controller implemented by digital components is to be artificially prevented from any possibility to exceed the saturation boundaries and particularly from any undue getting stuck at these boundaries. This faulty effect is referred to as *windup* and the schemes getting the controller saturation rid of this fault are considered as *anti-windup* schemes.

The windup problem results from the controversy between the inevitable actuator saturation and the generally required integrating nature of the controller action. This often leads to inconsistency between controller output and the actual input of a controlled process. As a result, behaviour of the control loop differs from the designed one and even the stability can be lost. The history of anti-windup techniques has gone through a variety of techniques and schemes of digital implementation. One of the first and fundamental methods is the *back calculation*, proposed by Fertik and Ross [1] for PID controllers. Then a *conditioning technique* was presented in [2] as an extension of back calculation scheme for a general class of controllers, see also [3] for generalization of the method. As foreseen in [4] the anti-windup conditioning schemes should be viewed not only as the actuator constraint but rather as a means of the control loop tuning to some extent. An easy to apply anti-windup design for IMC scheme optimizing performance of the entire closed loop was presented in [5], see also [2].

As a consequence of consistently increasing number of anti-windup schemes, a unified framework for investigating their performance was proposed in [6]. The conditioning schemes were further investigated and developed by Edwards and Postlethwaite [7], and Weston and Postlethwaite [8] with the extension towards the multivariable systems. A low-order observer scheme is presented in [9] and the robustness issue of the anti-windup scheme design was investigated in [10].

Considerable number of the proposed anti-windup schemes is based on an observer-like state feedback closed from the *saturation error* i.e. from the difference between the original and the saturated signal. These observer-like schemes have been investigated e.g. by Åström and Rundquist [11] and Kapoor et al. [12]. Recently, the observer-based anti-windup scheme has been presented in [13] with two-stage controller design by the loop shaping approach. Subsequently, in [14], the control action reduction caused by saturation is considered as an input/output controller disturbance. In this work, an LMI approach for finding parameters of the anti-windup scheme has also been proposed. To conclude, a recent survey on modern anti-windup techniques including open problems discussion such as the presence of time delays in a control loop has been presented in [15].

The objective of this paper is to address tuning of the anti-windup feedback for a controller designed for a system with considerable dead time, which is represented by a first order plus time delay model. The contribution lies in applying optimization based strategy in tuning the anti-windup scheme for PI and IMC controllers of this class of systems.

II. Problem formulation and Preliminaries

We consider the first order stable model with an input time delay

$$G(s)=\frac{y(s)}{u(s)}=\frac{K\mathrm{e}^{-s\tau}}{Ts+1} \tag{1}$$

where y, u denote the system input and output, respectively. The system parameters are static gain $K>0$, time constant $T>0$, and time delay $\tau>0$.

A. PI controller

Concerning the control strategy, we first consider a PI controller

$$R_{PI}(s) = \frac{u(s)}{e(s)} = \frac{r_p s + r_i}{s} \tag{2}$$

where $e = w - y$ is the control error, with w representing the set-point value. The parameters are the proportional r_p and integration $r_i = r_p/T_i$ gains (both positive), where $T_i > 0$ is an integration time constant. The state space model of the controller (2) is given by

$$\dot{x}(t) = r_i e(t) \tag{3}$$

$$u(t) = x(t) + r_p e(t) \tag{4}$$

equations. Let us note that the PI controller is preferred from the PID here due to transparency of the results when the control saturation is in action. The action of the derivative part highly depends on the selected filter which makes the problem more difficult to handle.

In this paper, we focus on the closed loop responses to the set-point w change, in which the control signal saturation plays the key role. The closed loop transfer function (1)-(2) reads

$$G_{c,PI}(s) = \frac{y(s)}{w(s)} = \frac{K(r_p s + r_i)\mathrm{e}^{-s\tau}}{Ts^2 + (1 + Kr_p\mathrm{e}^{-s\tau})s + Kr_i\mathrm{e}^{-s\tau}}. \tag{5}$$

Let us remark that the spectrum of the system poles, given as the solution of the equation

$$Ts^2 + (1 + Kr_p\mathrm{e}^{-s\tau})s + Kr_i\mathrm{e}^{-s\tau} = 0, \tag{6}$$

is infinite. As the controller (2) is of finite order, the achievable closed loop performance is rather limited concerning the length of the delay τ.

For the cases when the delay τ length is substantial with respect to the time constant T, rather an infinite order controller compensating the delay should be applied. An efficient scheme for such a case is the IMC scheme, which is addressed next.

B. IMC controller

For the model (1), an Internal Model Controller (IMC) [16] is given as follows

$$R_{IMC}(s) = \frac{Ts + 1}{K(T_f s + 1 - \mathrm{e}^{-s\tau})}. \tag{7}$$

The single tuning parameter T_f determines the time constant of the closed loop

$$G_{c,IMC}(s) = \frac{y(s)}{w(s)} = \frac{\mathrm{e}^{-s\tau}}{T_f s + 1}, \tag{8}$$

which is of first order dynamics for the nominal case. Let us note that the dynamical properties still need be considered as infinite order due to always present mismatch between the design and true parameters of the system, i.e. the compensation is never entire. However, if the differences between nominal and true parameters are small, the infinite spectrum chains are located far to the left of the stability boundary and the dynamics properties are predominantly given by the rightmost pole with the nominal value $s_1 = -\frac{1}{T_f}$. Such a case will be considered further on in the paper.

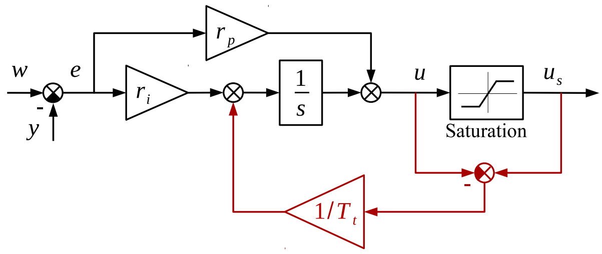

Fig. 1. PI controller with back calculation anti-windup

The state space model of the IMC controller, is given by

$$\dot{x}(t) = \frac{1}{T_f}(x(t-\tau) - x(t)) + \frac{T}{T_f}(e(t-\tau) - e(t)) + e(t) \tag{9}$$

$$u(t) = \frac{1}{KT_f}(Te(t) + x(t)). \tag{10}$$

Unlike PI controller, which has a single pole $s_1 = 0$, the number of poles of the IMC controller, given as solutions of the equation

$$T_f s + 1 - \mathrm{e}^{-s\tau} = 0, \tag{11}$$

is infinite. However, the controller is still astatic with a dominant pole $s_1 = 0$.

C. Anti-windup scheme for a PI controller

The most common solution of the anti-windup problem is based on the back calculation technique [1] (also known as *tracking anti-windup*) which is for PI controller designed as shown in Fig. 1. In order to handle the anti-windup task, the state equation of the PI controller (3) is extended by a feedback to the *observer like* form

$$\dot{x}(t) = r_i e(t) + \frac{1}{T_t}(u_s(t) - u(t)) \tag{12}$$

where T_t is a single tuning parameter commonly called *tracking time constant* and u_s denotes the saturated control action with saturation limits u_{min} and u_{max}

$$u_s(t) = \begin{cases} u_{max}, & u \geq u_{max} \\ u, & u_{min} < u < u_{max} \\ u_{min}, & u \leq u_{min} \end{cases} \tag{13}$$

which then acts as the system (1) input.

The primary objective for introducing the feedback is to remove the controller astatism when the control signal gets to the saturation points. Once the controller output exceeds the saturation limits, a feedback signal is generated from the difference of the saturated and the unsaturated control action in order to adjust controller state value. Thus, the feedback is active if and only if $u(t) > u_{max}$ or $u(t) < u_{min}$. Otherwise, $u_s(t) = u(t)$.

Expanding (12) to the full state space form

$$\dot{x}(t) = r_i e(t) + \frac{1}{T_t}(u_s(t) - x(t) - r_p e(t)) \tag{14}$$

it can be easily seen that the parameter T_t determines the time constant of the first order dynamics, i.e. the single pole, when back calculation is employed. Thus, the stability condition reduces to the condition $T_t > 0$. It can be seen, that smaller parameter T_t resets integrator more rapidly, which may seem to be an advantage at first sight, but it brings slow response of the process [17]. On the other hand, bigger values of T_t cause overshoot in process output.

Finding a suitable value of the parameter T_t has been studied in many works since back calculation anti-windup method was developed. For example, a basic rule of thumb for the setting of the tracking time T_t for PID controller (with integral time constant T_i and derivative time constant T_d) has been recommended $T_t = T_i$ in [18] or $T_t = \sqrt{T_i T_d}$ in [19]. In [17] two stage adjustment procedure of the tracking time constant T_t was proposed. First, the parameter is chosen large ($T_t = 10T_i$), which causes long stay at saturation limit. Then, after the process output reaches to a certain percentage value of system reference, the parameter is decreased ($T_t^{new} = \alpha T_i$). This leads to a fast response time (big T_t) with a satisfactory (reduced) overshoot (small T_t).

A simple switching condition for two degrees of freedom PID has been also proposed in [20]. The method is focused on processes with different normalised dead times described by the model (1). The proposed scheme should be able to provide a good performance over a wide range of processes without the need to tune an additional parameter of the controller, i.e. tracking time constant T_t. Based on the presented experiments, the results of the method were always satisfactory despite the value of the tracking time constant T_t ($T_t = 0.03T_i$ in that case). Properties of the listed switching methods and their comparison have been presented in [21]. Other practical discussion about proper selection of T_t can be found in [22]. To conclude this short survey, let us remark that the default value of T_t in the PID saturated PID controller in Matlab is $T_t = 1$.

D. Optimization task formulation

Even though a relatively large number of references can be found to handle the task of tuning the tracking time constant T_t, a general agreement on its optimal value has not been reached. Thus, the key objective of this paper is to contribute to this tuning task by an optimization study performed for a model (1), which is widely used for approximating processes with non oscillatory dynamical properties and dead time.

In what follows, the performance of the control loop is analyzed with the objective to determine the optimum value of T_t in the sense of minimizing the IAE criterion

$$I_{IAE} = \int_0^{\infty} |e(t)| dt \qquad (15)$$

in the case when the control action induced by the set-point is saturated.

Before the analysis is performed for PI controller, the dimensionless first order plus dead time model is introduced with the objective to generalize results for a whole class of systems of given structure. Next to optimizing the anti-windup scheme of the PI controller, the same task is performed for IMC controller next.

E. Dimensionless first order plus dead time model

Following the approach proposed in [23] for the second order model, scaling the dimension of the control input with respect to K by introducing $\bar{u} = Ku$ and subsequently scaling the time with respect to time constant $\bar{t} = \frac{1}{T}t$, the first order model (1) can be considered in the universal form

$$\bar{G}(\bar{s}) = \frac{y(\bar{s})}{\bar{u}(\bar{s})} = \frac{\mathrm{e}^{-\bar{s}\bar{\tau}}}{\bar{s}+1} \qquad (16)$$

where the single parameter is the scaled time delay $\bar{\tau} = \frac{\tau}{T}$. Note also that $\bar{s} = sT$ is the dimensionless Laplace operator. Thus, the results derived for this system (16) will be valid for a whole class of systems which have the equivalent ratio $\frac{\tau}{T}$.

III. Optimizing the anti-windup feedback for PI controller

The key objective of this section is to tune the anti-windup feedback to obtain the optimal response to the step change of the set-point value in the cases when the saturation point is reached.

As the first step, similarly as for the system, with the objective to generalize the achieved results, also the controller is turned to the dimensionless form

$$\bar{R}(\bar{s}) = \frac{\bar{u}(\bar{s})}{e(\bar{s})} = \frac{\bar{r}_p\bar{s} + \bar{r}_i}{\bar{s}}, \qquad (17)$$

where $\bar{r}_p = Kr_p$ and $\bar{r}_i = KTr_i$. The state equation with the anti-windup feedback then changes from (14) to

$$\dot{x}(\bar{t}) = \bar{r}_i e(\bar{t}) + \frac{1}{\bar{T}_t}(\bar{u}_s - x(\bar{t}) - \bar{r}_p e(\bar{t})). \qquad (18)$$

Before optimizing the parameter $\bar{T}_t$, the parameters of the PI controller are optimized with respect to minimizing IAE criterion (15) for the unsaturated case. As a preliminary step, we demonstrate the dependence of the closed loop responses on $\bar{T}_t$ in Fig. 2. Next to the unsaturated IAE optimal response, saturated closed loop responses with $\bar{u}_{max} = 3$ are shown for the anti-windup feedback values ranging from $\frac{1}{\bar{T}_t} = 0$ to $\frac{1}{\bar{T}_t} = 1000$. As can be seen, the response with $\frac{1}{\bar{T}_t} = 0$, i.e. without any anti-windup action, results in undesirable overshoot. On the other hand, the very large value of the gain $\frac{1}{\bar{T}_t} = 1000$ results in rather sluggish response.

In order to find an optimal value of $\bar{T}_t$ that minimizes the IAE criterion, the brute-force method has been applied based on sweeping the parameter $\frac{1}{\bar{T}_t}$ over the interval $[0, 10]$ and evaluating the criterion (15) for every grid point. This procedure has been applied for three classes of systems with $\bar{\tau}_1 = 0.1$, $\bar{\tau}_2 = 0.5$ and $\bar{\tau}_3 = 1$ and various values of the $\bar{u}_{max}$ for each of the system classes. The results of this straightforward optimization procedure are shown in Figs. 3, 4 and 5. Next to the I_{IAE} with respect to $\frac{1}{\bar{T}_t}$, the optimal responses are shown for each of the considered values of $\bar{u}_{max}$.

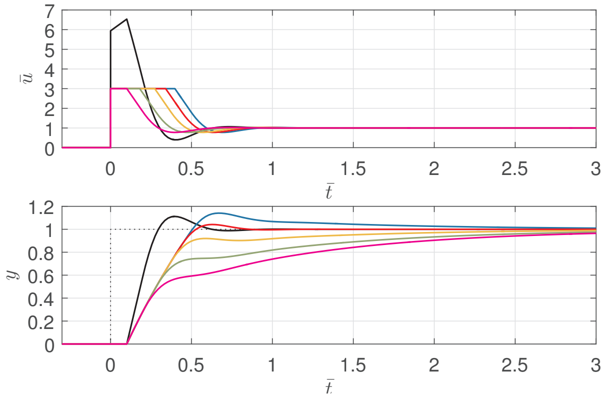

Fig. 2. Closed loop ((16) with $\bar{\tau} = 0.1$ and (17)) responses for i) IAE optimal unsaturated controller (black), and ii) saturated controller with $\bar{u}_{max} = 3$ for the anti-windup feedback gain $\frac{1}{\bar{T}_t} \in [0, 1, 3, 10, 1000]$, colored from blue (0) to purple (1000).

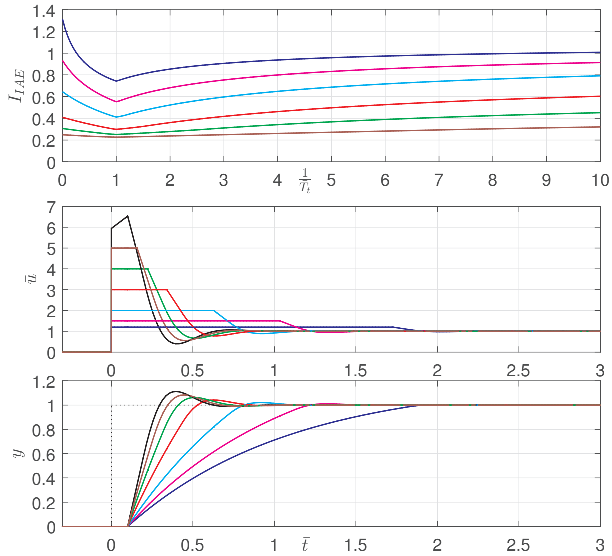

Fig. 3. Results of optimizing the IAE criterion for the system class (16) with $\bar{\tau} = 0.1$, PI controller (17) with the anti-windup feedback (18) (up-most figure), and the optimal responses for the considered values of the control signal saturation

For $\bar{\tau}_1 = 0.1$ system (16) class with results shown in Fig. 3, the optimal IAE setting is close to $\frac{1}{\bar{T}_t} = 1$, which is almost independent of the value of considered $\bar{u}_{max}$. Note that for the dimensional anti-windup feedback in (14) this would correspond to the equality $T_t = T$. For the system classes with larger values of $\bar{\tau}$, the optimum is reached for $\frac{1}{\bar{T}_t} < 1$, i.e. for $T_t > T$. More specifically, for $\bar{\tau}_2 = 0.5$ the optimum is still fairly close to $T_t = T$, but is not the case for $\bar{\tau}_3 = 1$ where T_t should be considerably larger. Note however that for this last considered system class, the control saturation effect on the response is relatively small. In order to achieve 'faster' responses for the systems with $\bar{\tau} > 0.5$, an infinite order controller compensating the delay needs to be used, e.g. the IMC controller (7) which will be addressed in the next section.

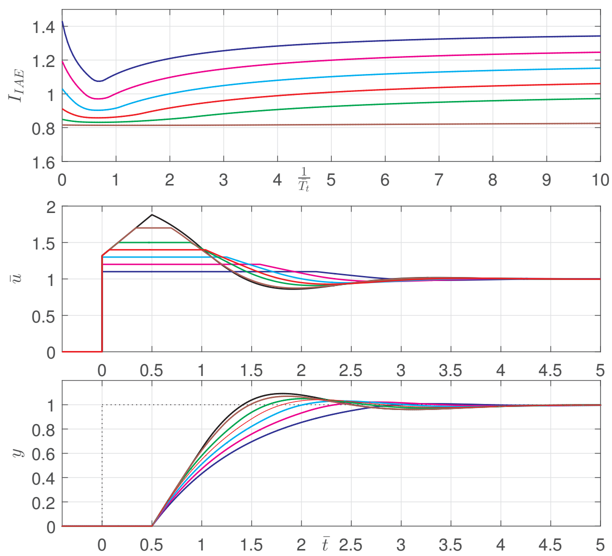

Fig. 4. Results of optimizing the IAE criterion for the system class (16) with $\bar{\tau} = 0.5$, PI controller (17) with the anti-windup feedback (18) (up-most figure), and the optimal responses for the considered values of the control signal saturation

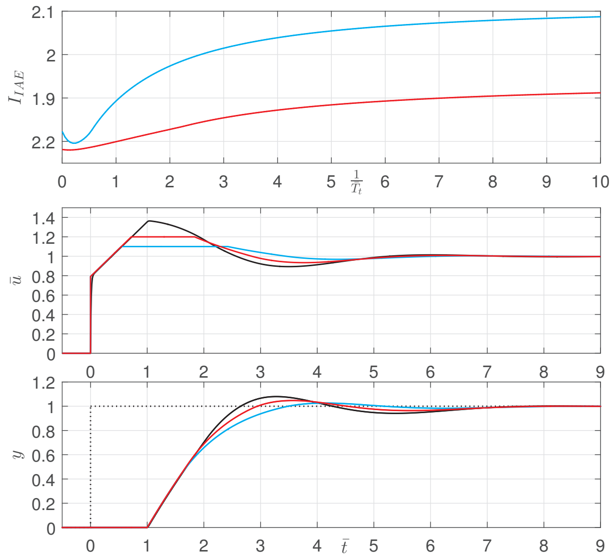

Fig. 5. Results of optimizing the IAE criterion for the system class (16) with $\bar{\tau} = 1$, PI controller (17) with the anti-windup feedback (18) (up-most figure), and the optimal responses for the considered values of the control signal saturation

IV. Anti-windup strategy for IMC controller

Analogously to the PI, the IMC controller (9)-(10) can be extended by the anti-windup back calculation feedback

$$\dot{x}(t) = \frac{1}{T_f}(x(t-\tau) - x(t)) + \frac{T}{T_f}(e(t-\tau) - e(t)) + e(t) + h\left(u_s(t) - \frac{1}{KT_f}(Te(t) + x(t))\right) \quad (19)$$

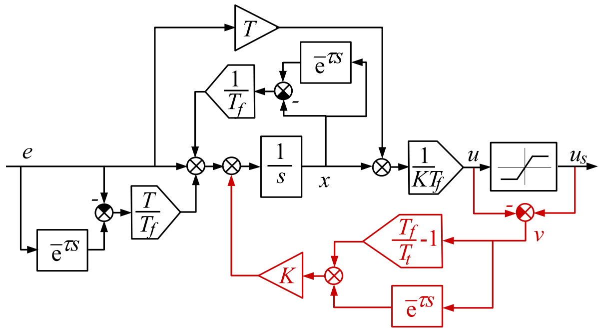

Fig. 6. IMC controller scheme with functional anti-windup feedback given by term $h(s)$ in (24)

where h is the tuning parameter. The characteristic equation of (19) then reads

$$T_f s + 1 + \frac{h}{K} - \mathrm{e}^{-s\tau} = 0. \tag{20}$$

Due to its quasi-polynomial nature, the anti-windup feedback system has infinitely many roots. This fact makes the tuning of the parameter h considerably more difficult compared to the tuning of T_t in the PI case. Even though design and spectral analysis tools are available to handle such a design task, the fact that only one of the infinitely many poles can be assigned by a single parameter is likely to bring considerable constraints concerning the stability perspective. In order to avoid this issue, we introduce a functional anti-windup feedback which will simplify noticeably the design task.

The newly designed IMC state space equation with the functional anti-windup feedback is given by

$$\dot{x}(t) = \frac{1}{T_f}(x(t-\tau) - x(t)) + \frac{T}{T_f}(e(t-\tau) - e(t)) + e(t) + \int_0^\tau \left(u_s(t-\vartheta) - \frac{1}{KT_f}(Te(t-\vartheta) + x(t-\vartheta)) \right) dh(\vartheta). \tag{21}$$

where the functional feedback is considered in the form of a Stieltjes integral where $h(\vartheta)$ is the delay term distribution. The characteristic function of (21) is then given by

$$T_f s + 1 + \frac{h(s)}{K} - \mathrm{e}^{-s\tau} = 0. \tag{22}$$

Analogously to the scheme of the PI controller (14), the objective is to design such a feedback term $h(s)$ to obtain dynamics determined by a single pole $s_1 = -\frac{1}{T_t}$, i.e. with the characteristic equation

$$T_t s + 1 = 0. \tag{23}$$

Dividing (22) by T_f and (23) by T_t, and comparing the terms corresponding to the zeroth power of s, the functional feedback term is determined as

$$h(s) = K\left(\frac{T_f}{T_t} - 1 + \mathrm{e}^{-s\tau} \right). \tag{24}$$

To simplify the time domain expression of (21) with (24), let

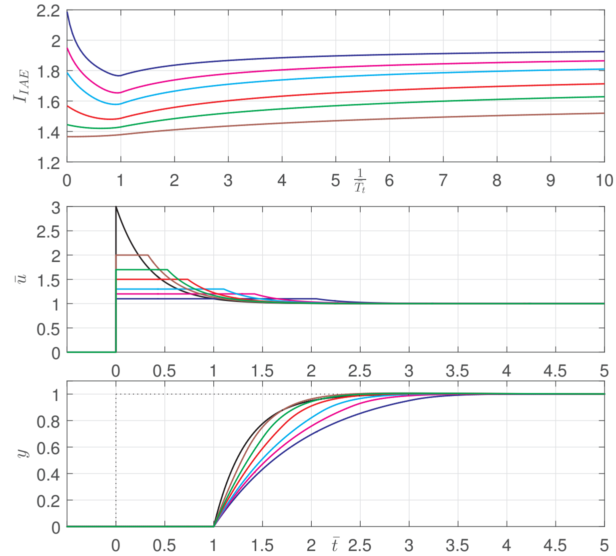

Fig. 7. Results of optimizing the IAE criterion for the system class (16) with $\bar{\tau} = 1$, IMC controller with $T_f = 13$ and the anti-windup functional feedback (25)-(26)-(27) (up-most figure), and the optimal responses for the considered values of the control signal saturation

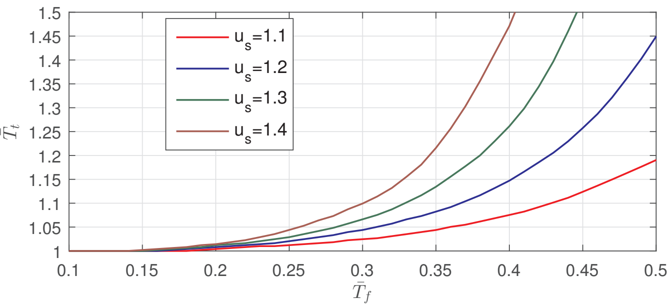

Fig. 8. IAE optimal value of T_t with respect to the single tuning parameter of the IMC controller T_f designed for the system (16) for several values of saturation value considered with respect to the unit step of the set-point.

the saturation error be introduced as

$$v(t) = u_s(t) - u(t) = u_s(t) - \frac{1}{KT_f}(Te(t) + x(t)). \tag{25}$$

Then, the final form of the IMC controller with functional anti-windup feedback is given by

$$\dot{x}(t) = \frac{1}{T_f}(x(t-\tau) - x(t)) + \frac{T}{T_f}(e(t-\tau) - e(t)) + e(t) + K\left(\left(\frac{T_f}{T_t} - 1 \right) v(t) + v(t-\tau) \right) \tag{26}$$

$$u(t) = \frac{1}{KT_f}(Te(t) + x(t)). \tag{27}$$

The full IMC controller scheme is also given in Fig. 6.

Analogously to the PI controller, the parameter T_t was optimized with respect to the IAE criterion applied to the dimensionless model (16). As the time delay $\bar{\tau}$ is compensated by the controller, the control action is independent of the delay length. Therefore, the optimization task and saturated responses have been simulated only for a single value of $\bar{\tau} = 1$, see Fig. 7 where the results are shown for $\bar{T}_f = \frac{1}{3}$. It can be seen that similarly to the PI controller case, the optimal value of T_t is close to the time constant of the system for this particular setting of the IMC.

Results of more comprehensive simulation based analysis to obtain the optimal value of T_t are given in Fig. 8 where IAE optimal value of this feedback parameter is given with respect to the IMC controller parameter T_f. The analysis has been performed for four saturation values u_s given as multiples of the set-point unit step. In fact, this figure covers a whole reasonable values of T_f (considering T being the time unit of the dimensionless model). For $T_f < \frac{T}{10}$ we obtain very aggressive control actions whereas for $T_f > \frac{T}{2}$ it is vice-versa. Note that for $T_f = T$ a step-wise control action is achieved as the response to the step change of the control action. This figure also demonstrates that the choice $T_t = T$ is a reasonable choice as it guarantees close to optimum responses when the saturation limit cuts considerably the non-saturated control action peak value. As demonstrated in Fig. 7, if the cut part of the ideal control action response is not substantial, the dependence of the objective function I_{IAE} on the parameter T_t is relatively low.

V. Conclusions

The key contribution of the paper is in a simulation based tuning of the anti-windup feedback with respect to the IAE criterion. First, the task has been solved for a conventional PI controller for which various rules exist in literature. As a rule, the anti-windup feedback time constant is related to the integration time constant of the PI(D) controller. The analysis performed in this paper for a first order plus dead time model and PI controller also tuned with respect to IAE criterion shows however that the optimal value of the parameter should rather be related to the time constant of the system.

Secondly, a novel structural solution of the anti-windup feedback scheme has been proposed for an IMC controller, also considered and tuned for the first order plus dead time model. Due to the time delay that is projected to the structure of the IMC controller, the anti-windup feedback system is of infinite order. This problem is handled by a functional feedback that turns the dynamics to the equivalent finite order form of the PI case. Consequently, similarly as for the PI controller, a simulation based optimization task has been performed for tuning the anti-windup feedback time constant. Its optimal value is also close to the time constant of the system. An important aspect of the analysis is that it has been performed on the dimensionless nominal system with both scaled gain and time constant. Thus the results derived on a relatively low set of simulations can be generalized to a broad class of systems.

Acknowledgment

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