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Validating Continuous Tuning Rules for Event-Based PI Control of Lag-Dominant Processes

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Abstract: One of the difficulties of the tuning of event-based proportional-integral (PI) controllers using symmetric send-on-delta sampling (SSOD) is the appearance of a stable limit cycle, especially when rules designed for continuous control loops are applied. This oscillation is explained by the intersection in the Nyquist map of the system, that is, of the loop transfer function, with the negative reciprocal of the describing function (DF) of the SSOD sampler. However, as the DF theory is based on neglecting the high-order harmonics in the closed loop system, it introduces errors in the prediction of the oscillations. The paper presents an experimental study that establishes the boundaries of the PI controller parameters (proportional and integral gains) that avoid any limit cycle considering that a lag-dominant first order process model is used for the tuning. By taking into account the boundaries, a safety application in an event-based framework of any tuning rule designed for the classical time-driven case is possible.

Keywords: event-based, limit cycle, PI control, send-on-delta, tuning constraints.

1. INTRODUCTION

One of the main issues to consider when an event-based PI controller is introduced in an industrial control loop is the appearance of persistent oscillations or limit cycles if a tuning rule designed explicitly from a time-driven perspective is directly applied (Cervin and Astrom, 2007) (Vasyutynskyy *et al.*, 2008). To avoid that, there are researchers working in the development of specific tuning rules that take into account the features of the sampling strategy used to trigger the events. In most cases the sampling strategy considered is the send-on-delta (SOD) sampling (Miskowicz, 2006), that triggers an event each time a signal crosses a threshold that is a multiple of δ . The result of this sampling is that the input signal is quantized by a quantity multiple of δ . The first event-based PI controllers found in the literature were based on a SOD sampling applied to the control error signal $e(t)$ to produce a quantized output $e^*(t)$ as input to the PID algorithm (Arzen, 1999), (Vasyutynskyy and Kabitzsch, 2007), (Duran and Marchand, 2009), (Pawlowski *et al.*, 2009). In those works, the tuning is based on methods designed in the continuous-time domain.

When the relationship between the input and the output of the sampler is symmetric with respect to the origin, the variation of the SOD is known as symmetric send-on-delta (SSOD). Most of the research work on event-based PI controllers has been developed considering the SSOD sampling paradigm and, more specifically, applying the SSOD to the control error signal $e(t)$. This combination of a SSOD sampler and a continuous PI controller is known as SSOD-PI controller and it is the form considered in this paper. The initial studies about the performance of SSOD-PI controllers were performed by applying tuning rules designed again for continuous-time control loops (Beschi *et al.*, 2012a, 2015a, 2015b), (Pawlowski *et al.*, 2016).

The first works where a tuning rule is specifically designed for an SSOD-PI controller are (Beschi *et al.*, 2012b) and (Beschi *et al.*, 2014). Other three studies on a specific SSOD-PI design method are described by (Romero and Sanchis, 2016, 2018) and (Miguel *et al.*, 2019); in the first two contributions the tuning is based on maximizing the control integral gain using the phase margin as constraint to avoid the oscillations; the third one is based on tuning the controller by an optimization problem consisting in minimizing the IAE fulfilling a constraint based on a parameter derived from the Tsypkin method. A robust tuning methodology is presented in (Ruiz *et al.*, 2017) to ensure that the system reaches the steady state avoiding the limit cycles. Finally, Sanchez *et al.*, 2019 describes a non-standard tuning rule for an event-based PI controller devised to force the system to oscillate with a frequency and amplitude specified by the operator.

However, knowing that a rule designed for the continuous can be safety applied in an event-based context, avoiding persistent limit cycles, would let operators take advantage of both worlds: (1) events, that means control actions, would be just produced in presence of disturbances or set-point changes but the rest of the time the system would be stable without control actions being executed; (2) the system would be tuned according to the robustness margins and performance index fixed by the design method applied. In addition, the number of events and the error in the steady state could be reduced by playing with the threshold value of the SSOD sampler without affecting the robustness.

The paper is structured as follows. To explain the phenomena of limit cycles in a control loop with a SSOD-PI controller, the describing function (DF) of the SSOD sampler is analysed in Section 2. The proposed method to validate a tuning rule is based on defining the k-k_i region of a process where any controller parameter set located inside such region is limit cycle free and the system is not supposed to oscillate. As the DF theory is based on the fundamental harmonics in the closed-loop system, it can introduce errors in the prediction of the oscillations depending on the filtering capabilities of the open loop transfer function; so although the DF theory cannot always be used to validate any tuning rule designed for the continuous-time case, it can provide a first approach. Thus, in Section 3, a set of k-k_i regions for PI control of a category of first order plus time delay (FOPTD) processes is obtained using the theory of Section 2. This category is composed of FOPTD processes where the time constant is dominant over the dead time. Following the terminology by (Åström and Hägglund, 2006), these processes are labelled as lag-dominant. As the k-k_i regions of Section 3 contain errors, they are experimentally delimited and approximated by a polynomial function in Section 4. To finish, a validation study for a group of time-driven tuning rules and a new tuning rule derived from the safety regions are presented in Sections 5 and 6.

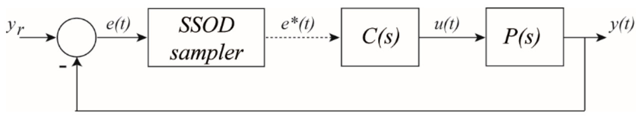


Fig. 1. Event-based architecture considered.

2. OSCILLATIONS IN SSOD-PI CONTROL LOOPS

The control scheme considered in this work (Figure 1) corresponds to the SSOD-PI control loop used in the most recent event-based PI related control literature and presented for the first time in (Beschi *et al.*, 2012a). The $C(s)$ block corresponds to a PI controller where the algorithm considered is given by

$$C(s) = k + k_i/s \tag{1}$$

where k and k_i are the proportional and the integral gains, respectively. The $P(s)$ block in Figure 1 represents the approximation of the current process by a FOPTD model

$$P(s) = \frac{K_p}{1+sT}e^{-sL} \tag{2}$$

where K_p is the static gain, T the lag or time constant, and L the time delay. So, the control scheme of Figure 1 is composed of a non-linear part represented by the SSOD block and the linear part that corresponds to the following open loop transfer function

$$G(s) = C(s)P(s) \tag{3}$$

Regarding the SSOD sampler block of Figure 1, its input-output non-linear relationship is graphically represented in Figure 2. With this sampling strategy, the SSOD block receives a continuous signal $e(t)$ as input and generates as output a quantized signal $e*(t)$. The describing function of the SSOD blocks for a sinusoidal input is (Romero and Sanchis, 2016),

$$N(A,\delta) = \frac{2\delta}{\pi A}\left[1+\sqrt{1-\left(\frac{\delta}{A}m\right)^2}+2\sum_{k=1}^{m-1}\sqrt{1-\left(\frac{\delta}{A}k\right)^2}\right] - j\frac{2\delta^2}{\pi A^2}m \tag{4}$$

where A is the amplitude of a sinusoidal input signal, and $m = \lfloor A/\delta \rfloor$. It is known from (Romero and Sanchis, 2016) than a sufficient condition for the existence of a persistent oscillation in the control loop is the satisfaction of

$$G(j\omega) = \frac{-1}{N(A,\delta)} \tag{5}$$

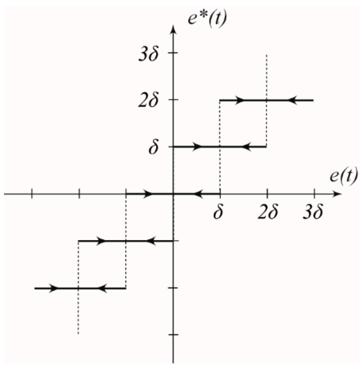


Figure 2: Input-output relationship in a SSOD block.

Thus, an oscillation can exist at the frequency and amplitude given by the intersection of the two curves $-1/N(A,\delta)$ and $G(s)$ in a Nyquist diagram. The polar plot of $-1/N(A,\delta)$ is shown in Figure 3 for $A \in [\delta, \infty)$. Each intersection of $G(s)$ with $-1/N(A,\delta)$ represents an oscillation of different amplitude and frequency (to be accurate, depending on how the intersections take place some of them could introduce unstable limit cycles (Gelb and Van der Velde, 1968)). In this example, the intersection of $G(s)$ with the point $C_1 = -\pi/4 - j\pi/4$ represents the existence of a limit cycle of amplitude $A=\delta$ and frequency ω_{osc} ; this frequency satisfies the expression $G(j\omega_{osc})=C_1$.

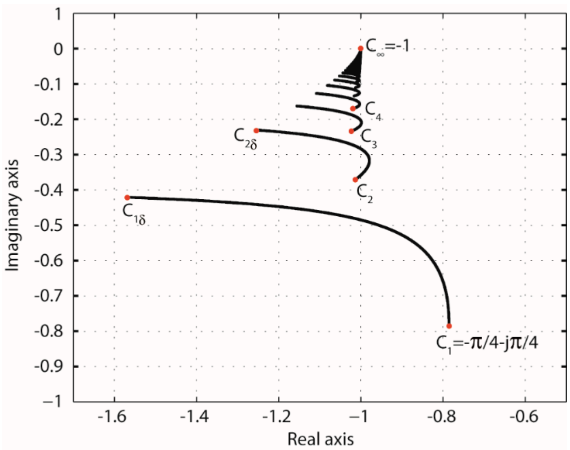


Figure 3: Polar plot of $-1/N(A,\delta)$.

From the polar plot of Figure 3, it results intuitive that, in order to avoid a persistent oscillation, the controller tuning rule applied must never generate a set of parameters that produces an intersection of $G(s)$ with the point of $-1/N(A,\delta)$ located most to the right, that is, the critical point $C_1=-\pi/4-j\pi/4$. That means that a PI tuning rule will be considered safe for its application in a SSOD-PI control loop when any set of control parameters [k, k_i] generated by the rule avoid that G encircles C_1 for any frequency. Note that

$$G(j\omega)=\left(k+\frac{ki}{j\omega}\right)P(j\omega) \tag{6}$$

However, the main assumption of the DF analysis is that G contents sufficient low-pass filtering to warrant excluding from consideration the harmonics in the output of the SSOD sampler. The consequence is that the expression (4) and the polar plot of its negative reciprocal are just approximations that depend on the low-pass filter features of G. Thus, to guarantee that the controller tuning produces a system located to the right of C_1 is not sufficient because this point is just an approximation of the real critical point where the oscillation appears.

3. THEORETICAL SAFETY REGIONS FOR LAG DOMINANT FOPTD PROCESSES

It is possible to isolate the formulas that establish the theoretical DF-based boundaries of the safety regions for k and k_i. By replacing (2) in (6) and equating the new expression to C_1, that is,

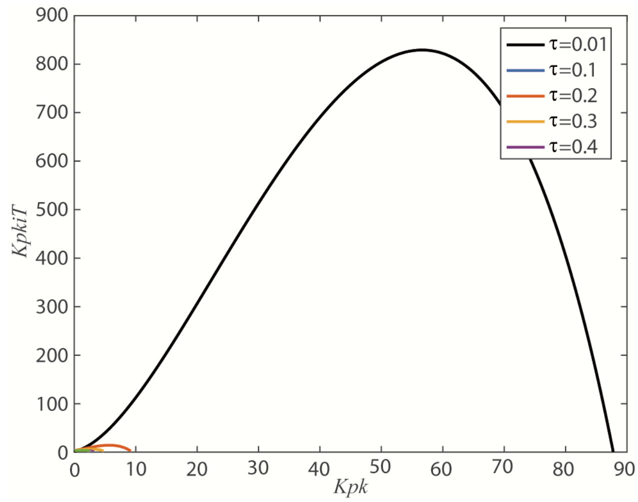
$$G_{re}(j\omega)=-\frac{\pi}{4} \quad \text{and} \quad G_{im}(j\omega)=-\frac{\pi}{4} \tag{7}$$

the following expression are obtained

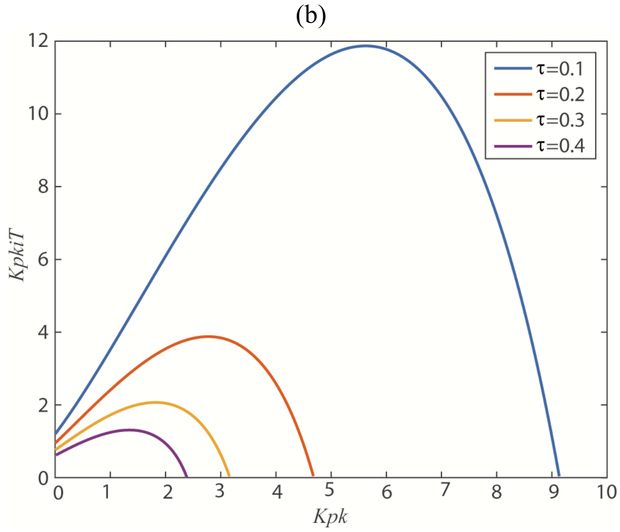
$$k=\frac{\pi}{4K_p}\left(\cos(\omega L)T\omega+T\omega\sin(\omega L)-\cos(\omega L)+\sin(\omega L)\right)$$

$$k_i=\frac{(2T^2\omega^2+2)\sin(\omega L)\cos(\omega L)+\omega^2T^2-1}{2\omega\left((T^2\omega^2+1)\cos(\omega L)^2-\frac{(\omega T-1)^2}{2}\right)} \tag{8}$$

After that, the normalized safety regions located under the boundaries were plotted by applying ω from 0 until the first frequency that produces negative values in the integral gain. Figure 4.a shows the normalized safety regions of FOPTD process with the normalized time delay $\tau=L/(L+T)$ going from 0.1 to 0.4. According to (Åström and Hägglund, 2006), this parameter is considered a good measure to characterize process dynamics and classify processes as lag dominated, balanced or delay dominated. There are no limits to categorize a process as a function of τ but the consensus is that values below 0.5 define a process as lag dominated.



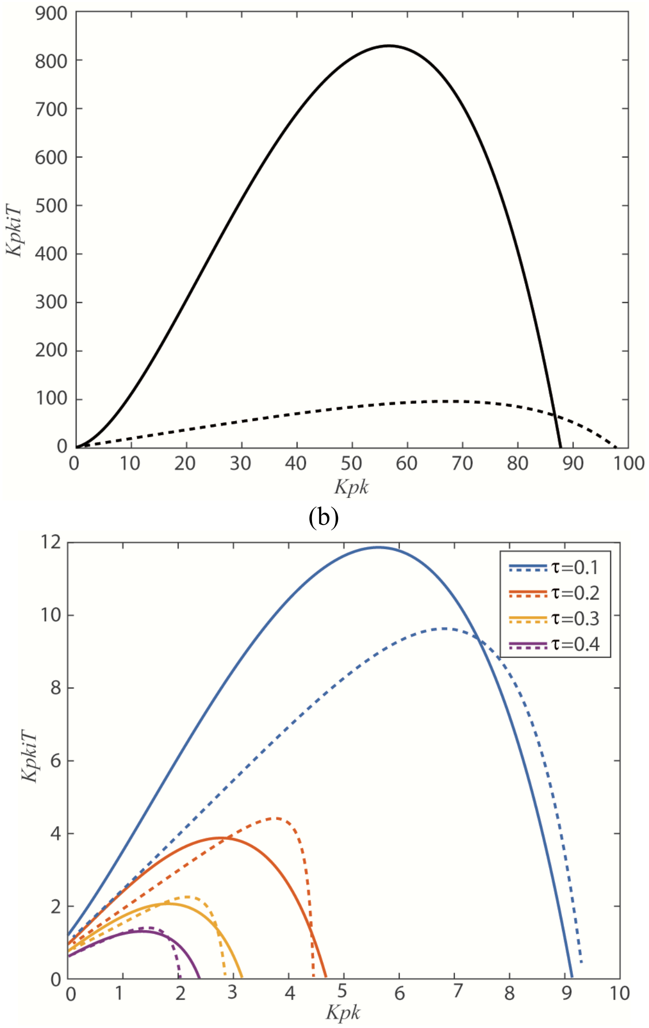
(b)



(a)

Figure 4: Normalized safety regions of FOPTD processes ranging from $\tau=0.1$ to 0.4 (a) and $\tau=0.01$ (b) located under the boundaries defined by (8).

The biggest safety region corresponds to the process with lowest τ . For a better detail, Figure 4.b shows the region for $\tau = 0.01$ compared to the regions for higher τ . As processes with higher τ are more difficult to control, the safety regions consequently reduces its size because the controller parameters space is more reduced. In Figure 4 it can be observed that an increase of ω in (8) is always associated to an increase in the proportional gain but not in the integral gain. The integral gain reaches its maximum and starts decrease until zero; from the value of ω associated to $k_i = 0$, any higher frequency will produce negative integral gains.



(b)

(a)

Figure 5: Experimental (dashed) and theoretical (continuous) safety regions of FOPTD processes ranging from τ = 0.1 to 0.4 (a) and $\tau = 0.01$ (b).

4. EXPERIMENTAL CONSTRUCTION OF THE SAFETY REGIONS

As already mentioned, theoretically, each set of PI parameters located inside the safety region corresponding to a lag dominant process should avoid limit cycles. However, this is not true as the DF-based analysis is an approximation based on the fundamental harmonics and the areas of the true safety regions are reduced.

To fix experimentally the true limits of these areas, simulations in Matlab/Simulink were run by choosing sets of controller parameters distributed along the boundaries of the theoretical safety areas generated by (8) and presented previously in Figure 4.

Five processes were simulated with $\tau = 0.01$, 0.1, 0.2, 0.3, and 0.4; the static gain and the time constant were fixed to 1 for all of them. The grid of control parameters [k, k_i] to test for each process was derived from their theoretical boundaries obtained by (8). So, the set of k gains to check for each process was initially composed of eleven values equally distributed going from the minimum (that is, 0) until its corresponding maximum. It was necessary to increase the upper limit of k to check with $\tau = 0.01$ and 0.1 because it was detected that oscillations disappear even reaching the theoretical maximum (see Figure 5.b, for instance). Once a k was chosen, the k_i associated to k in the curves depicted in Figures 4 was selected. The simulation was then started with this set [k, k_i].

All the simulations were made with an integration step of h=0.001s and δ =1. To detect when an oscillation was stable, first, it was observed if the difference between two consecutive time periods was below a certain threshold (in our case $\varepsilon = 0.002$); if this condition was fulfilled for five consecutive time periods, the oscillation was considered as a stable limit cycle. Thus, when a limit cycle appeared during an experiment for a set [k, k_i], a new simulation was run but reducing the integral gain, repeating these steps until the oscillation disappeared, establishing a new safety point (another option would have been to reduce k until eliminating the limit cycle).

Once the points corresponding to the new boundaries were known, each new safety region was approximated by the following rational model using the Matlab Curve Fitting Toolbox

$$k_i = \frac{p_1 x^2 + p_2 x + p_3}{K_p T(x^2 + q_1 x + q_2)} \tag{9}$$

where $x = K_p K$. Expression (9) was chosen after several fittings with rational models with polynomials of higher degree in both numerator and denominator and checking that the accuracy did not improve considerably. However, a degree lower than 2 in the polynomials of (9) did not produce a pattern of residuals randomly scattered about zero, indicating that a better fit was possible. The coefficients for (9) are presented in Table 1 and Figure 5 shows of the new experimental safety regions using the coefficients of Table 1 plotted versus the theoretical regions. It can be appreciated in Figure 5 that the higher τ , the lower discrepancies between the experimental and theoretical regions, being very relevant the differences between the theoretical and the experimental regions corresponding to $\tau = 0.01$. Also, the differences between the DF based and the experimental areas are reduced for the lowest controller gains because they are associated to the lowest frequencies, that is, where the DF analysis is most accurate.

Table 1. Coefficients of polynomial (9) for different τ.

τ	0.01	0.1	0.2	0.3	0.4
p_1	-697	-253	-48.5	-7.2	-20.5
p_2	67000	2225	174.4	12.7	24.4
p_3	69700	1312	184.7	22.5	35.7
q_1	-407	-148	-50.5	-12.6	-28
q_2	38000	1463	210.8	29.8	58.4

5. VALIDATIONS OF SOME PI TUNING RULES

Knowing the true safety regions is relevant for two purposes: (a) validation of already defined time-based PI tuning rules, and (b) further design of new event-based PI tuning rules with different performance criteria. As an example of the first one, the new safety regions plotted in Figure 5 are used for the validation of four relevant PI tuning rules. This group of rules is composed of AMIGO (Åström and Hägglund, 2006), the Lambda (Dahli, 1968), the SIMC (Skogestad, 2003), and the recently published One-Third rule (Hägglund, 2019). The expressions of these four tuning rules used in the paper are:

AMIGO rule:
$$k = \frac{1}{K_p}\left(0.15 + 0.35\frac{T}{L} - \frac{T^2}{(L+T)^2}\right) \qquad T_i = 0.35L + \frac{13LT^2}{T^2 + 12LT + 7L^2} \tag{10}$$

SIMC rule:
$$k = \frac{1}{K_p}\frac{T}{2L} \qquad T_i = \min(T, 8L) \tag{11}$$

Lambda rule:
$$k = \frac{1}{K_p}\frac{T}{T+L} \qquad T_i = T \tag{12}$$

One-Third rule:
$$k = \frac{1}{3K_p} \qquad T_i = \frac{L}{3} + T \tag{13}$$

As said before, the validation of a PI rule for its safety use in an event-based context for lag-dominant FOPTD processes consists in generating the set of controller parameters for all these processes and check whether each set is located inside the corresponding normalized safety region associated to each process. Figures 6 and 7 show the graphical results of the checking.

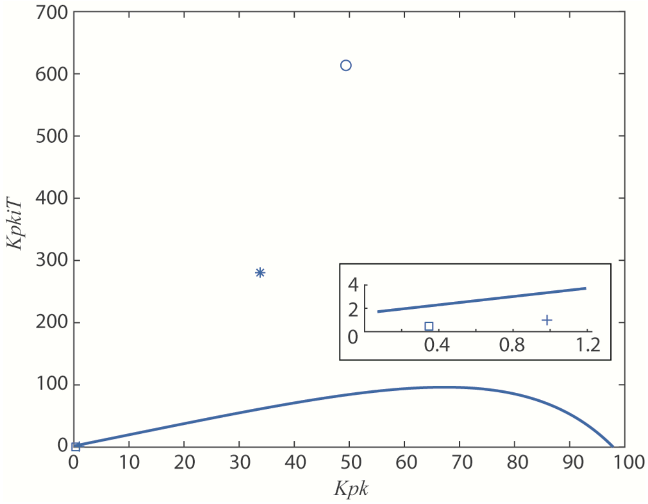


Figure 6: Position of the controller parameters in the experimental safety region of a process with $\tau = 0.01$. Controller sets: AMIGO (asterisk), SIMC (circle), Lambda (plus), One-third (square).

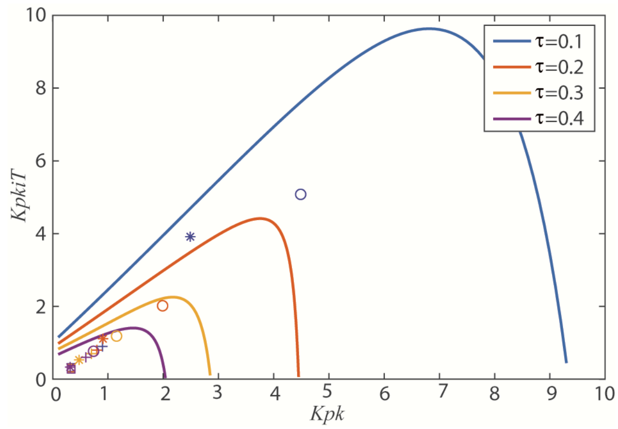


Figure 7: Position of the controller parameters in the experimental safety regions of processes ranging from $\tau = 0.1$ to 0.4. Controller sets: AMIGO (asterisk), SIMC (circle), Lambda (plus), One-third (square).

Figure 6 presents the result for processes with $\tau = 0.01$. As the AMIGO rule and the SIMC rule give high proportional and integral gains, they produce sets of parameters out of the safety region for this type of processes. The Lambda rule and the One-Third rule produce controllers with reduced gains doing safe its application in an event-based context.

Figure 7 shows the graphical validations for processes ranging from $\tau = 0.1$ to 0.4. The four tuning rules position their sets inside its corresponding safety regions, indicating that the rules are safe for tuning in an event-based context. As happens in Figure 6, the AMIGO and the SIMC rule produce controllers with higher gains but this time their sets are located inside the safety regions, making them safe rules for tuning of SSOD-PI controllers.

6. EXAMPLE OF APPLICATION OF THE SAFETY REGIONS FOR DESIGNING NEW TUNING RULES

An example of design of a SSOD-PI tuning rule for control of lag-dominant processes is shown in this section. As the integral gain k_i is a simple measure of control performance (Åström and Hägglund, 2006) because it is associated to the integrated control error $IE = 1/k_i$, it is easy to design a simple rule that maximizes this gain by observing the maxima of the safety regions. The proposed tuning formula is

$$k = 0.6\frac{(L+T)}{K_p L}$$

$$k_i = \frac{0.9T - 0.1L}{LK_p T} \quad \text{or} \quad T_i = -\frac{6T(L+T)}{L-9T}.$$

The positions of the controller parameters generated but this simple tuning rule are presented in Figure 8. Obviously, this is just a simple design example because the IE is a good measure of control performance only for systems without oscillatory responses that are commonly obtained under good robustness conditions, which are not addressed nor taken into account in the proposed tuning rule.

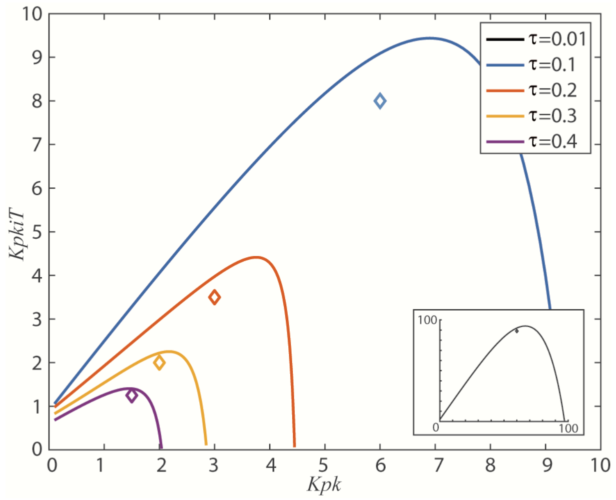


Figure 8: Position of the controller parameters.

7. CONCLUSION

The problem considered in this paper is to answer the following question: could a tuning rule designed for a continuous PI controller be used for a SSOD-PI controller with safety, which means, without introducing the system into a limit cycle, for lag dominant processes? The rationale of the method to answer the question is based on defining experimentally safety k-k_i regions for lag dominant processes. Thus if the k-k_i set generated by a PI tuning rule is located inside its corresponding safety region, then its application in a SSOD-PI controller does not produce limit cycles in normal operating conditions. The method has been applied to check the validity of four known tuning rules (AMIGO, Lambda, SIMC, One-Third) demonstrating that all of them can be applied in an event-based SSOD-PI control loop without introducing limit cycles, excepting the AMIGO rule and the SIMC rule for processes with $\tau = 0.01$.

It is important to note the validation of a tuning rule just implies that the couple of parameters does not compromise the performance criteria it was designed for. Validation just means the couple of parameters generated for a specific process can be applied without producing limit cycles. Obviously, the features of the event-based PI controller will continue existing: possible steady state error as a consequence of the dead zone of the SSOD sampler, and generation of control actions only in presence of set point changes or disturbances. The main conclusion of the paper is that it is perfectly possible to apply the knowledge developed for time-based PI controller design to the event-based paradigm with safety.

Regarding further lines of work, the validation method of tuning rules has been restricted to the most common type of process in the industry, that is, the lag-dominant. However, that can be extended to processes where transport delays are dominant ($0.4 < \tau < 1$). In this case, the safety k-k_i regions will be smaller in consonance with the known difficulties for controlling delay-dominant processes.

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