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On-Line Adaptive Switching Control for Open-Loop Stable and Integrating Processes

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***Abstract*—The advantage of switching control is that the set-point is reached in a minimum time without excessive overshoot. But, the sensitiveness to modeling error is a common difficulty. A 2-df control scheme consists of an external close-loop model and a conventional feedback loop can solve the servo-tracking and load-rejecting problems individually and simultaneously. In the loop model, the switching-on-position control is used to drive the system to its set-point in a minimum amount of time, while the conventional loop is used to deal with modeling error and some possible unknown disturbances. The switching-on-position control is constrained by system parameters, and, a lead/lag compensator is used to relax this constraint in case it is necessary. Simulation results show that this presented method is effective for both open-loop stable and integrating processes.**

I. INTRODUCTION

During the start-up of a chemical process or during a course of a batch process to follow an optimal trajectory, it is desirably that the set-point is reached in a minimum amount of time without excessive overshoot and kept staying there when subjected to possible disturbances. The objectives mentioned are difficult to achieve with any conventional controller, but can be possible with non-linear controllers, such as the switching controllers [1] or the Time-optimal plug controller [2] being used. The key approach adopted in these reported works is to apply some maximum or minimum inputs to drive the system to its new steady-state and, then, switch the controller to the regulatory mode without producing bumping. But, these non-linear types of controllers are sensitive to modeling errors, and are constrained by its parameters. The switching time or switching position must be calculated based on precise knowledge of the process. As a result, switching-on-time (abbrv. SOT) control is sensitive not only to the modeling error, but also to the time origin assigned. Thus, for practical feedback control, it is desirable to switch the control on position in stead of on time. But, as what will be shown later, switching-on-position (abbrv. SOP) control is constrained by the parameters of the dynamic system itself, and is possible only if the parameters satisfy a given constraint. On the other hand, the performance objectives regarding set-point tracking and regarding disturbance rejecting are conflict in a conventional PID control system, especially, for integrating process. A controller good for regulatory control will cause large overshoot in response to step set-point change. Thus, many modified Smith predictors with different structure have been proposed. But, these proposed Smith predictors are complicated and sensitive to modeling errors [3], [4]. For the reason aforementioned, a two-degree-of-freedom (abbrv. 2-df) control scheme is proposed. A switching control that provides satisfactory servo-response is conducted by an external closed-loop model, while the modeling error and disturbances are regulated by a conventional loop. In order to overcome the sensitiveness of the control to modeling error, an adaptive modification to adjust the open-loop model in the external loop is presented. Meanwhile, since the SOP control is constrained by the system, A compensator with lead/lag form is used to relax the constraint if it is necessary. Furthermore, the same design approach is extended to control the integrating processes or high-order processes.

II. PROPOSED ON-LINE SWITCHING CONTROL

A. Proposed Control Strategy

A 2-df controller with external loop model for open-loop stable and integrating processes is given in Fig.1. A similar approach is also used to design Smith predictor controllers of [5], [6]. As shown in Fig. 1, $G_p(s)$ is the practical process and $G_m(s)$ denotes the process model. $G_{c1}(s)$ and $G_{c2}(s)$ are the controllers of external loop and the conventional regulatory loop, respectively. Because of the devised control scheme, the set-point tracking can be speeded up as much as we want, without concerning the stability of the real main closed-loop. Thus, the maximum input, u_{max}, is used to drive the system to its new steady-state y_s, and, then, switch the controller without bumping to its new steady-state value, u_s. We can achieve maximum servo tracking performance by this nonlinear type controller, $G_{c1}(s)$. For the regulatory problem, a conventional PID controller, $G_{c2}(s)$, is applied to reject load disturbance and to enhance the system under modeling error. The switching controller uses a maximum amount of output to drive the system as a servo-type controller, and the regulatory controller is designed for disturbance rejection. Thus, it has the potential capability of achieve both servo-tracking and disturbance rejection at the same time.

Consider the FOPDT processes of the following:

$$G_p(s)=\frac{k_p e^{-\theta s}}{\tau s+1} \tag{1}$$

Assume we estimate the process model without modeling error, i.e. $G_m(s)=G_p(s)$. When a positive step on the set-point change is applied to the external loop, the servo-control action is generated by the external loop which control the G_m to reach the set-point in a minimum time. Initially, the controller output is set to u_{max} and is switched back to its new steady-state value (i.e. r/k_p) at one dead time before the control variable of the external loop reaches the new set-point. We can determine this switching time, t_{sw}, as:

$$t_{sw}=-\tau\ln\left(1-\frac{u_s-u_b}{u_{\max}-u_b}\right) \tag{2}$$

And the corresponding switching position is:

$$y_m(t_{sw})=y_b+K_p\left[1-\left(1-\frac{u_s-u_b}{u_{\max}-u_b}\right)e^{\frac{\theta}{\tau}}\right](u_{\max}-u_b) \tag{3}$$

Where, y_b and u_b designate the initial output and input, respectively. Without loss of generality, we assume that their initial steady-state values are zero in later discussion. The controller output of the external loop is fed forward to the main loop.

We can also apply this design method to control the integrating process. A general integrating process model can be expressed as:

$$G_p(s)=\frac{k_p e^{-\theta s}}{s} \tag{4}$$

Similarly, we set u_{max} according to required set-point tracking and determine the switching time and position in the followings:

$$t_{sw}=\frac{r}{k_p u_{\max}} \tag{5}$$

$$y_{m,sw}=r-k_p u_{\max}\theta \tag{6}$$

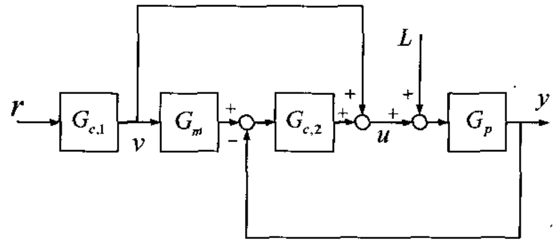

Fig. 1. The proposed control structure.

Because the steady-state value of process input is zero for integrating process, we set $u_s=0$ at the same time.

As mentioned, SOT is sensitive to the time origin assigned for starting the algorithm. Thus, a better choice is to use the SOP. As the switching position must be greater than zero, it is not feasible to all cases. It will be feasible only if the parameters of the FOPDT process satisfy the following inequality, that is:

$$1-\left(1-\frac{u_s}{u_{\max}}\right)e^{\frac{\theta}{\tau}}\geq 0 \tag{7}$$

For integrating processes, the inequality condition becomes:

$$r-k_p u_{\max}\theta\geq 0 \tag{8}$$

and

$$t_{sw}\geq\theta \tag{9}$$

When we satisfy the condition in the above mentioned, the switching control based on process output position can be practically implemented.

Until now, we have discussed a switching controller for servo problem. The optimal controller with PID form is applied to reject the load disturbance and the modeling error. A conventional PID controller can be expressed as:

$$G_{c2}(s)=k_c\left(1+\frac{1}{\tau_R s}+\frac{1+\tau_D s}{1+\tau_f s}\right) \tag{10}$$

Here, k_c, τ_R and τ_D are the proportional gain and integral and derivative times of the conventional PID, respectively. The filter time constant, τ_f, in (10) can be taken arbitrarily small (e.g. 0.05 τ_D). For the step load disturbance, we determine the controller parameters by minimizing the integral of the absolute value of the error, IAE. In order to solve this optimization problem, we define the objective function, that is:

$$J=\int_0^{\infty}|e(t)|dt \tag{11}$$

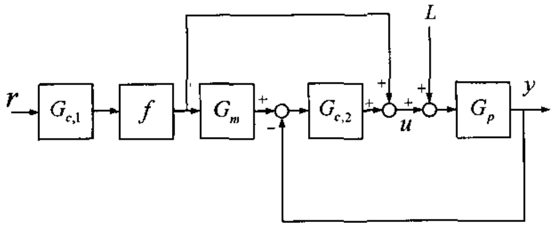

Fig. 2. The proposed control structure with a lead/lag compensator.

B. *On-line Adaptive Control*

When the modeling errors existed, the switching controller becomes sensitive due to the incorrect value of switching position. Although the regulating PID controllers can handle the error which was caused by modeling error to guarantee the robust stability, the oscillatory response may be resulted and the optimal control action for disturbance rejection becomes severe or sluggish. Base on these reasons, on-line process identification procedures are required to reset the precise switching position and process model.

An effective procedure is proposed to perform on-line updating for either the FOPDT process or integrating process. Notice that, the inequality constraints of (7) and (8) must be satisfied. The FOPDT model is updated as following:

$$y_i = \phi y_{i-1} + k_p(1-\phi)u_{i-1} \tag{12}$$

Where

$$\phi = e^{-\frac{\Delta}{\tau}} \tag{13}$$

Here, Δ is the sampling interval. The procedure of process parameters identification and update is presented as:

1) When the process output values were greater than zero, we collect continuously five data, designate as $y_1,\ldots,y_5$, of them in the equal time zone, Δ. From Eq. (12),

$$\phi_i = \frac{y_i - y_{i-1}}{y_{i-1} - y_{i-2}} \tag{14}$$

Then, ϕ can be estimated as the average value of some ϕ_i ,for example:

$$\phi = \frac{\phi_1 + \phi_2 + \phi_3}{3} \tag{15}$$

2) In the same way, another ϕ' can be estimated according to next seven data, e.g. $y_2,\ldots,y_6$.

3) If $|\phi - \phi'| < \varepsilon$, we can calculate the process time constant as following:

$$\tau = -\frac{\Delta}{\ln\phi} \tag{16}$$

Otherwise, set $\phi = \phi'$ and go to step 2. ε is the required accurate value.

4) Compute the process variable using the recursive relation:

$$y_{i+1} = y_i + \phi(y_i - y_{i-1}) \tag{17}$$

When the process variable trends to a constant value, y_∞, the process gain can be obtained as following:

$$k_p = \frac{y_\infty}{u_{\max}} \tag{18}$$

5) The process time delay is determined as:

$$\theta = \frac{A}{k_p u_{max}} - \tau \tag{19}$$

Where, A is the integral of $y_\infty - y$.

In the same way, for integrating process we obtain the process model parameters as following procedures:

1) When the process output values were greater than zero, we collect data and calculate the process gain.

$$k_p = \frac{y_i - y_{i-1}}{\Delta}\frac{1}{u_{\max}} \tag{20}$$

2) Repeat step 1, until the process gain reaches a constant.
3) Then, the process time delay is determined as following:

$$\theta = t_i - \frac{y_i}{k_p u_{\max}} \tag{21}$$

When the identification procedures are finished successfully, we adapt the process model G_m and reset the switching position by using (3) for FOPDT process or (6) for integrating process.

For the regulatory control, the loop gain, k_0, which is defined as the product of gains of controller and process becomes:

$$k_0 = k_p k_c \tag{22}$$

When the modeling error exists, the optimal control may lead to extremely results. Thus, we will continue to estimate on-line the steady-state gain of the process, k_p^*, and reset the controller gain to keep the system robustly stable. Sometime, it is convenience that the controller gain be rewritten as:

$$k_c = \frac{k_0}{k_p^*} \tag{23}$$

C. Lead/Lag Compensator

As mentioned, this type of on-line adaptive switching control has inequality constraint on the parameters of the process. Especially, if the process has longer dead time or large u_{max}, the switching position will be lower and even infeasible, and on line process identification becomes impossible. In order to release the constraints on the value of θ/τ, a lead/lag element is used to compensate on-line process dynamics to make the compensated process feasible for SOP. Thus, the process time constant is acquired for FOPDT process. As show in Fig. 2, the FOPDT process can be compensate by a lead/lag compensator, f, that is:

$$f = \frac{\tau s + 1}{\tau^* s + 1} \tag{24}$$

For integrating process, f is modified to the form as following:

$$f = \frac{s}{\tau^* s + 1} \tag{25}$$

$G_p(s)$ is reformed to become feasible for switching on position. Then, we can design controllers for the new process form according to the earlier mentions. Notice that the integrating process is reform to become FOPDT process.

III. SIMULATION RESULTS

A. FOPDT Processes

The following process has been considered:

$$G_p(s) = \frac{e^{-1.2s}}{4s+1} \tag{26}$$

Let $u_{max} = 2$, and the maximum output value of control valve is set 3 to avoid being saturated, when modeling error exists. For the unit step set-point, the inequality constraint in (7) is satisfied since switching position is greater than zero. By Using (3) the switching position y_{sw} is 0.65. When y_{sw} reaches 0.65, the control output switches to u_s whose value is one. As earlier mentioned, the optimal PID parameters are determined, they are: $k_c = 4.3467$, $\tau_R = 1.8393$ and $\tau_D = 0.5708$ and the filter time constant τ_f is $0.05\tau_D$. The set-point changes with an unit step at $t = 0$ and the load disturbance L changes its value to -1 at $t = 10$. The simulation results are shown in Fig. 3, where satisfactory performance can be achieved in both cases. We decrease ten percent of k_p, τ or θ of $G_p(s)$, respectively. By the on-line identification procedure, we will reset the switching position and adapt $G_m(s)$ to the updated model. For the process gain error, k_c is reset to 4.8300. The control results are given in Fig. 4. We can find that the effect due to modeling error will be eliminated effectively especially for dead time error.

We consider another process with larger θ/τ, that is:

$$G_p(s) = \frac{e^{-1.2s}}{s+1} \tag{27}$$

Let $u_{max} = 2$, and the maximum output value of control valve is also set to be 3. Using (7), we find that the inequality constraint is not satisfied, so, the switching control stands on the switching position is impractical. The lead/lag compensator which insert to the control structure in order to make the switching control become possible is chosen as:

$$f = \frac{s+1}{4s+1} \tag{28}$$

Then, the process is compensated to become:

$$G_p^f(s) = \frac{e^{-1.2s}}{4s+1} \tag{29}$$

Design the switching controller for this compensated model has the same results to the previous demonstration. It is notice that the process used to design optimal controller is the original process $G_p(s)$ but not the compensated model.

B. Integrating Processes

The integrating process as follows is considered.

$$G_p(s) = \frac{0.5e^{-0.3s}}{s} \tag{30}$$

First, let $u_{max} = 2$, $r = 1$ and the maximum output value of control valve is 3. Using (8), the inequality constraint is confirmed in this case. Using (6), switching position y_{sw} is 0.7. Secondly, the tuning parameters of optimal IAE PID are $k_c = 8.6929$, $\tau_R = 0.5685$, $\tau_D = 0.1482$ and $\tau_f = 0.05\tau_D$. A unit step is introduced at time $t=0$, and a load disturbance $L=-1$ is introduced at time $t=5$. The control results are shown in Fig. 5, where the control performances for either set-point tracking or load disturbance rejecting are satisfactory. In the same way, we decrease ten percent of k_p, or θ of $G_p(s)$, individually. The modeling error affects our process slightly as shown in Fig. 6.

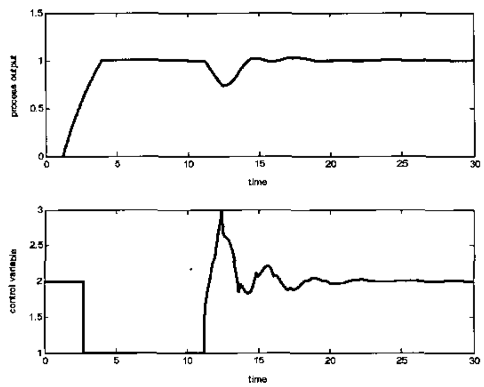

Fig. 3. Process output and control variable for the example of FOPDT process.

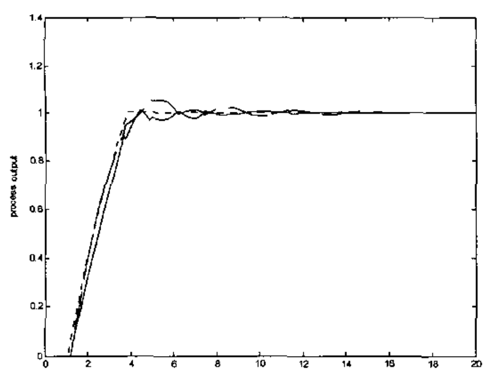

Fig. 4. Process output and control variable for the example with modeling error of FOPDT process. Solid line:-10% process gain error. Dashed line: -10% time constant error. Dotted line: -10% dead time error.

C. High-Order Process

The control structure can be also applied to high-order process. Consider a SOPDT process:

$$G_p(s)=\frac{e^{-2s}}{(20s+1)(s+1)} \tag{31}$$

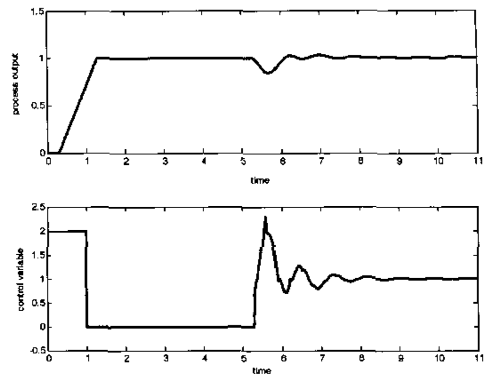

Fig. 5. Process output and control variable for the example of integrating process.

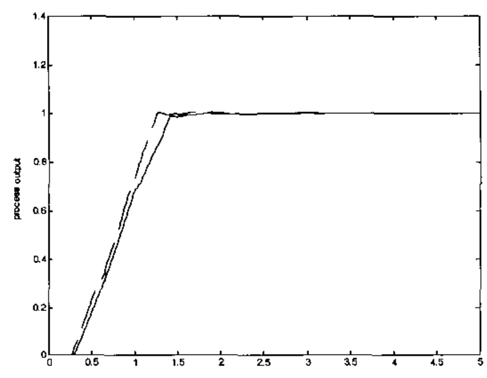

Fig. 6. Process output and control variable for the example with modeling error of integrating process. Solid line:-10% process gain error. Dashed line: -10% dead time error.

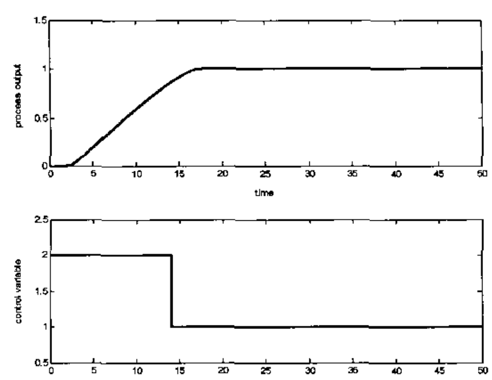

Fig. 7. Process output and control variable for the example of SOPDT process.

First, the optimal controller parameters are $k_c = 11.354$, $\tau_R = 4.508$, $\tau_D = 1.6406$ and $\tau_f = 0.05\tau_D$. Then, let $u_{max} = 2$, $G_m(s) = G_p(s)$,and the maximum value of control valve output is 3. From the bode plot of $G_p(s)$, we approximate it to a FOPDT model whose gain is 1, time constant is 20.27 and dead time is 2.03. By this approximate model, the switching position is estimated to be 0.895 and it will be updated according the on-line adaptive procedure. It shows acceptable performance as in Fig. 7.

IV. CONCLUSIONS

An external control structure which includes a switching controller and a optimal controller is proposed in this paper. The switching control which uses the maximum input to drive the system to another new steady-state without bumping can accelerate the system to achieve faster set-point tracking without excessive overshoot. The optimal controller can reject load disturbance and modeling error effectively. Furthermore, the on-line identification method has also presented to update the switching position, process model and optimal controller gain. Because the switching position has an inequality constraint, especially for longer dead time process or larger u_{max}, the lead/lag compensator is applied to make the process feasible for switching on position. The simulation results show that it has superior performance in set-point tracking and load disturbance rejecting. Moreover, the modeling is eliminated effectively.

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