Override control

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Abstract

This paper focusses on potential issues with override control. We show that, in the presence of stochastic disturbances, the existing methods can fail due to frequent switching from one controller to the other. Based on the analysis of the cause of the problem, we propose a simple solution and demonstrate its applicability on a test setup involving a Siemens PLC and software.

Keywords: override control, PID, constrained output control, cascade control

1. Introduction

In some cases, the control must adjust a manipulated variable to control one process variable at setpoint while maintaining other process variable(s) within limits. In practice, this problem, sometimes referred to as the output constrained control problem, is often solved with the use of PID controllers. Scientific literature on this subject usually focusses on stability and performance in the presence of deterministic disturbances (Glattfelder 1988, Lopez 1996). To the knowledge of the author, the case of stochastic disturbances has not been considered so far. This paper analyses two common methods to handle output constraints and shows that they face potential problems in the presence of stochastic disturbances. Based on the analysis of the cause of the problem, we propose a simple solution and demonstrate its applicability on a test setup involving a standard Siemens PLC.

The paper is structured as follows. Section 2 defines the output constraint problem in full detail. Section 2 and 3 present two common solutions (override control and cascade control, respectively) to the output constraint problem, using PID controllers, and shows that these solutions may not work in the presence of stochastic disturbances. Section 4 analyses the problem and presents solutions. Finally, section 5 presents the conclusions.

2. Description of the output constraint problem

The main question of this paper, is: are the existing constraint handling methods (using PID controllers) capable of handling stochastic disturbances, and if not, can we fix the problem? This section describes this main question in more detail.

We assume that the process is described by the following model:

$$y_1 = G_1(s)\, m + d_1,\;\; y_2 = G_2(s)\, m + d_2 \qquad (1)$$

with m the manipulated variable, y_i (i = 1 or 2) process variable, d_i disturbance variable, $G_i(s)$ a transfer function as a function of the Laplace variable s.

This paper considers both deterministic and stochastic disturbances. The deterministic disturbances provide immediate insight in the dynamic behaviour, the stochastic disturbances are more common in practice.

The output constrained control challenge is defined in words as follows. Control y_1 as closely as possible to setpoint s_1, while the second process variable y_2 should not cross some limit (that we assume, without loss of generality, to be a high limit y_{2max}). When we are dealing with stochastic disturbances, it makes sense to try to ensure that the chance of exceeding the limit y_{2max} is less than some predefined percentage.

The controllers are assumed to be PID controllers equipped with a Tracking Mode option. Although the exact equations are usually not provided by commercial manufacturers, we shall assume, for clarity of the paper, that this means that the PID controllers can be represented by $m_i = \mathrm{C_i}(s)e_i + b_i$, with $\mathrm{C_i}(s)$ a PID controller in the Standard Form:

$$\mathrm{C_i}(s) = K_{p,i}\left(1 + \frac{1}{T_{i,i}s} + \mathrm{T_{d,i}s}\right)\mathrm{e_i} \qquad (2)$$

Furthermore, $e_i = s_i - y_i$, and b_i is a bias term, defined by $b_i = \frac{1}{T_t s}(m - m_i)$ with m the manipulated input. If the i-th PID is active, i.e. if $m = m_i$, the bias term disappears. Otherwise, in Tracking mode, the controller's output can be written as:

$$m_i = \frac{\mathrm{T_t s}}{\mathrm{T_t s} + 1}\mathrm{C_i}(s)e + \frac{1}{T_t s + 1}\mathrm{m} \qquad (3)$$

and clearly, m_i tracks m for frequencies below $\omega < 1/T_t$
Basically, the Tracking mode ensures that the output of the controller that is not active 'tracks' the output of the controller that is active, to avoid a bump when switching. The exact equations for the Tracking mode method are not essential for the results in this paper.

In the next sections, we consider different control solutions. To simulate them, we shall simulate one specific process model, according to:

$$G_1(s) = \frac{1}{3s+1}e^{-0.2s}, \qquad G_2(s) = \frac{2}{4s+1}e^{-s}$$

The disturbances vary according to:

$$d_1(s) = w_1 + d_d, \qquad d_2(s) = w_2 + d_d$$

with w_1 and w_2 independent normally randomly distributed white noise, with variance 1, and d_d a deterministic disturbance component, starting at time t = 0.4 and changing stepwise to -2 at t = 100 s.

The setpoint for controller C_1 is s_1 = -0.1 and we assume that at t = 0, the system is in steady state. The maximum on output y_2 is $y_{2max} = 2$, and we wish to reduce the chance of y_2 exceeding y_{2max} to less than 2.5%. In order to allow comparison between different control options, we adopt the following control parameters for the controllers C_1 and C_2:

$K_{p1} = 5.25, \quad T_{i1} = 1.6, \qquad T_{d1} = T_{d2} = 0, \qquad K_{p2} = 0.7, \; T_{i2} = 4$

These settings were chosen based on the tuning rules as presented in (Skogestad 2001) and results in well damped and fast response under normal conditions (i.e. no switching between controllers). We have chosen not to use D-action for reasons of simplicity.

Given these control parameter settings, and the stochastic disturbance w_2 as defined above, the standard deviation (σ_2) of y_2 will be close to $\sigma_2 = 1$, if C_2 is either active or not during the entire simulation period. This implies that if we choose the setpoint s_2 as 0 or slightly lower, we can expect that the output constraint on y_2 can be met in 'steady state conditions', i.e. at all times outside the transients caused by the deterministic variations in d_d. Therefore, we select setpoint $s_2 = y_{2max} - 2\sigma_2 = 2 - 2 = 0$, since the chance of exceeding $2\sigma_2$ is less than 2.5% for a normal distribution.

The override control solutions, as described in this paper, were tested on a hardware in the loop setup, as shown in Figure 1. In this setup, the process model was simulated using the PID Tuner software described in its manual (Schuurmans 2018). The control output (m) was calculated by the Siemens S7 1200 PLC, programmed with an override control solutions as described in the manual of the PLC (Simatic 2018). The controllers C_1 and C_2 were realised with the PID Compact blocks.

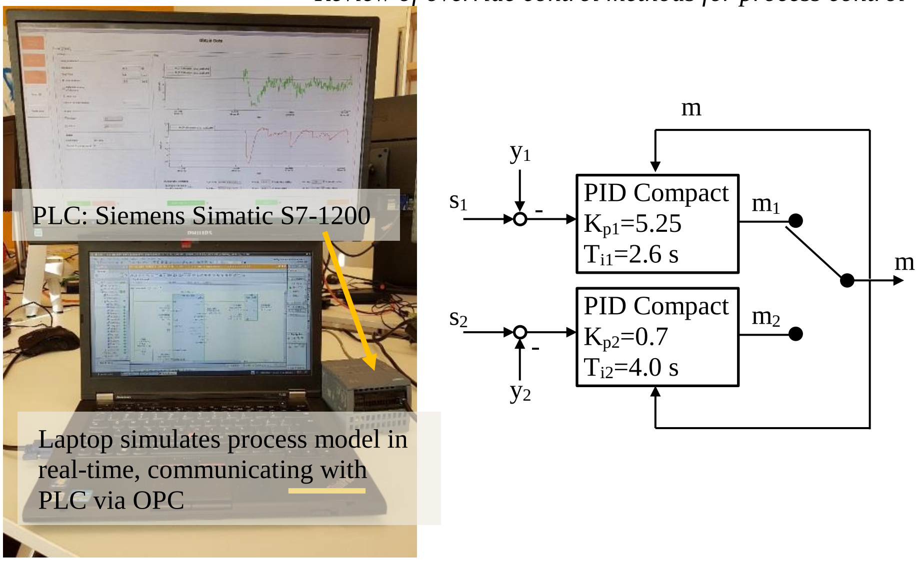

Figure 1 Photo of the Hardware in the Loop setup (left) and diagram of the control setup (right).

3. Override control

One method to handle the output constraint is Override control (Shinskey 2005) . In override control, the controller with minimal (or maximal) manipulated variable is selected, i.e. $m = \min(m_1, m_2)$. In other words, control switches to C_2 if (and only if) $m_2 < m_1$. For this method, it is clear how to set the control parameters. Indeed, the PID settings as presented in section 1 work well in the absence of stochastic disturbances, see Figure 2. This figure shows both the simulated response according to our assumed PID formulas (solid lines) and the actual PID Compact (dashed lines); the responses differ slightly, but in essence the behaviour agrees. Control switches correctly from C_1 to C_2 at t=100s.

However, in case of stochastic disturbances, frequent switching between controllers take place, and this results in a problematic performance (solid lines in Figure 3). The Mean Squared Error (MSE) of y_1, defined as $MSE_1 = \frac{1}{n}\sum_{i=0}^{n} e_1(t)^2$ increases to 9 (with n = number of samples), whereas MSE equals just 1.2 if C_1 is active all the time.

4. Cascade control

In case of cascade control, the PID controller C_1 adjusts the setpoint of the second PID controller (s_2). By constraining the setpoint of s_2, according to $s_2 \leq y_{2\max}$, the output y_2 can be expected to satisfy the output constraint.

A disadvantage of this method is that the controller C_1 cannot be tuned optimally on the basis of the process model given by Eq. 1, but, instead, it must be tuned on the basis of the closed-loop dynamics given by $y_2 = \frac{G_2}{1+C_2G_2} s_2$. In many cases, these closed-loop dynamics are slower than the open-loop dynamics. This problem can be overcome using cleverly chosen filters, as was shown in (Lestage 1999). Nevertheless, this solution copes with the same issues as Override control, in the presence of stochastic noise, and similar results as shown in Figure 3 apply to this control solution.

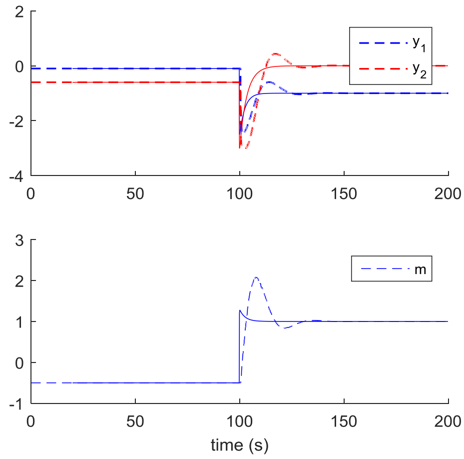

Figure 2 Simulated (solid) and measured response of the PID Compact (dashed).

5. Analysis of the problem and solutions

Override control and (cleverly chosen) cascade control boil down to the same solution, where control switches from C_1 to C_2 or vice versa. In case of stochastic disturbances, the switching may occur too frequently, resulting in lousy performance. We can analyse the switching conditions more closely. The controller that is not active, is in tracking mode. Let us, for example, assume that C_1 is active and C_2 is in tracking mode. In that case, the switching condition can be written as $C_1 e_1 > C_2 e_2$. The same condition applies when the second controller is active. Hence, the condition for switching from one controller to the other can be expressed in terms of a condition on controller deviations (e_i), weighed by the controller transfer function. Similar switching conditions, but with different 'weighting transfer functions' can be derived for cascade control, and in case of different PID implementations (such as the PID in velocity form). In the presence of noisy control deviation signals (e_i) with mean values that differ less than the variations, frequent switching will take place.

To resolve this issue, we can change the switching conditions such that switching takes only takes place when meaningful. Changing the switching conditions does not alter the stability (proofs) of the control systems, see for instance the stability proofs as presented in Glattfelder (1988, 2004) and Lopez (1996). We therefore defined a continuous 'switching' parameter α, according to

$$\frac{d\alpha}{dt} = K_{\alpha 1}(e_1 - e_2) - K_{\alpha 2}(\alpha - \alpha_c) \tag{4}$$

with $\alpha_c = \text{sat}(\alpha)$, i.e. $\alpha_c = \alpha$ if $\alpha_{min} < \alpha < \alpha_{max}$, $\alpha_c = \alpha_{min}$ if $\alpha \leq \alpha_{min}$ and $\alpha_c = \alpha_{max}$ if $\alpha \geq \alpha_{max}$.

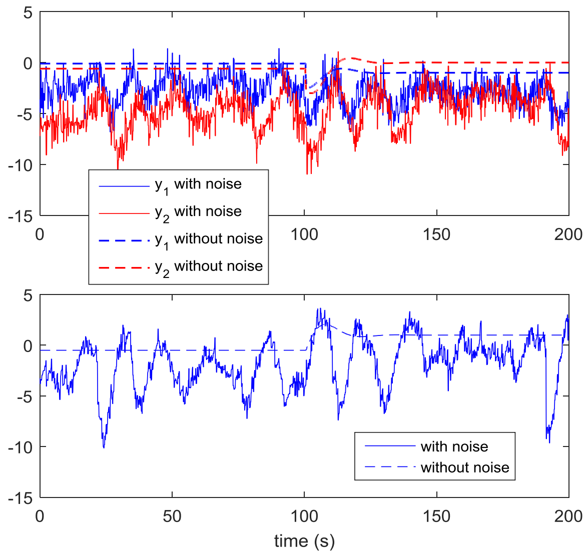

Figure 3 Measured response with stochastic disturbances (solid lines) and without (dashed) when using the Siemens PID Compact. In the case of stochastic disturbances, control switches frequently.

The parameter α is driven to 'one side' as long as there is a difference between e_1 and e_2. Control switches to C_1 if $\alpha_c > 0.45$. Control switches to C_2 if $\alpha_c < -0.45$.
For sufficiently small gain $K_{\alpha 1}$, it will not switch too frequently. The gain $K_{\alpha 2}$ feeds back on saturations of α, and basically provides anti-windup. The parameters were chosen as $\alpha_{min} = -0.5, \alpha_{max} = 0.5$, $K_{\alpha 1} = 3, K_{\alpha 2} = -3$.

Figure 4 shows the results when we changed the switching conditions in the PLC to the conditions depending on α_c described here. Clearly, control switches only when it makes sense, from controller C_1 to C_2 at t =100 seconds in the simulation. As a result, the MSE of the deviations of y_1 from setpoint have reduced from 9 to 1.76 (compared to the results shown in Figure 3), while the percentage of y_2 samples crossing the limit y_{2max} is within specifications at 1.9% (outside the transients due to the deterministic disturbance change at t = 100, so outside the time span t = 100 to 130 s).

6. Conclusions

Returning to the main question posed in this paper, if the existing constraint handling methods (using PID controllers) are capable of handling stochastic disturbances, and if not, if we can fix the problem, the answer to the first question is 'no'. This answer was based on an analysis of the existing methods, both on paper and in experiments. Analysis showed that the problem was due to too frequent switching from one controller to the other. By changing the switching conditions this problem can be overcome though.

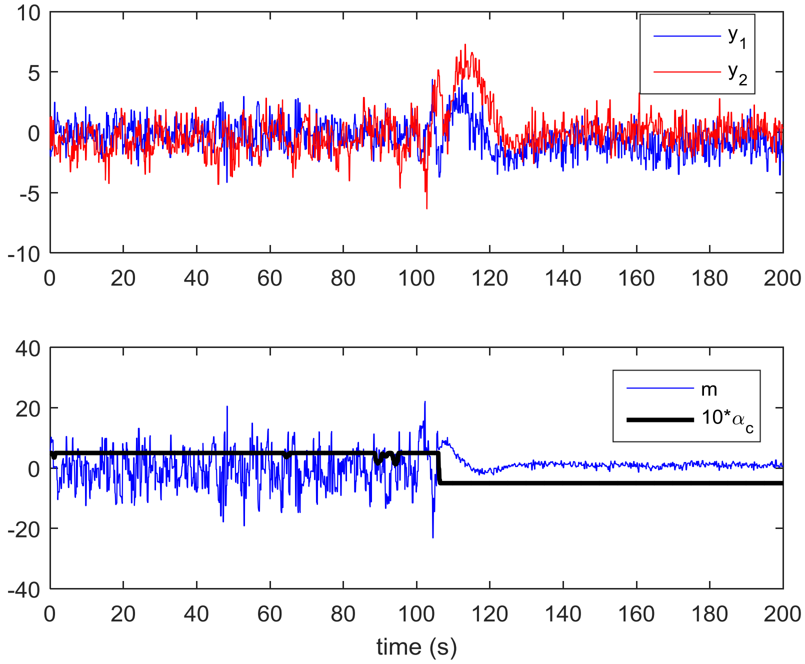

Figure 4 Results with override control with adjusted switching conditions applied to the Siemens PID Compact. Now, control switches from C_1 to C_2 at t=100s only.

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