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RESEARCH ARTICLE

A General Design Methodology for Fractional Cascade Control Systems

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ABSTRACT In this paper we propose a design methodology for a cascade control system where the two controllers are of fractional-order-proportional-integral-derivative type. The tuning of the inner (secondary) controller aims to achieve a high performance (in terms of the integrated absolute error) in the load disturbance rejection task by exploiting the fractional-order derivative action. Then, a fractional-first-order-plus-dead-time transfer function of the inner feedback system in series with the primary process is estimated and the outer (primary) controller is tuned to maintain performance in rejecting load disturbances while achieving a satisfactory set-point response. Simulation results show the effectiveness of the methodology and the key role played by the additional flexibility in the design introduced by the fractional-order controllers.

INDEX TERMS Cascade control, FOPID controllers, tuning, disturbance rejection.

I. INTRODUCTION

Cascade control is very often used for industrial processes when the presence of an additional sensor allows the designer to achieve a significant performance improvement in rejecting disturbances. This secondary sensor splits the process dynamics into two parts. The secondary part is controlled by a (inner) feedback controller to rapidly reject load disturbances. Then, the process (primary) output is fed back to the primary controller, which is usually designed to obtain the required performance in the set-point following task [1].

The classic feedback controllers employed in this context are of Proportional-Integral-Derivative (PID) type, for which many tuning rules for single-loop structures have been devised [2]. However, the presence of two controllers makes the overall design more complex, and for this reason, many design techniques have been proposed in the literature specifically for cascade control systems. For example, the well-known relay-feedback autotuning method [3] has been extended to cascade control systems in [4]. A simultaneous tuning of the two controllers, based on the Internal Model Control concept has been proposed in [5]. The concept of simultaneous tuning has also been pursued in [6], [7], [8], and [9]. However, the typical design procedure applied in industry is to tune, as a first step, the inner loop with the outer loop disconnected. In this phase, the performance in the load disturbance rejection is of main concern, and the PID parameters are selected to obtain a large bandwidth. Then, the primary controller is connected, and it is tuned to recover the set-point following performance. This task can be challenging as the overall system seen by the controller consists of the series of the secondary closed-loop system (which can have underdamped dynamics) and the primary part of the process.

Recently, significant research effort has been devoted to fractional control [10] and, in particular, to Fractional-Order-Proportional-Integral-Derivative (FOPID) controllers, which are a generalization of PID controllers, as the integral and derivative actions are of real order [11]. This gives additional flexibility in the controller design as there are more degrees of freedom in the loop shaping approach, but this also implies an increased complexity in the design. In order to facilitate the design task, tuning rules for the five parameters of the controllers have been proposed in the literature (see, for example, [12], [13], [14], [15]).

In the same spirit, we propose exploiting the advantages of FOPID controllers in a cascade control structure, devising design methodologies that enable the user to increase the

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overall control performance without significantly increasing the design effort. The use of FOPID cascade control systems has been recently explored in the literature. In particular, such a kind of structure has been applied to power systems in [16], [17], [18], and [19]. In these cases, specific applications have been addressed, and the considered processes have no dead time. Also in the applications considered in [20] (level control) and in [21] (permanent magnet synchronous motor drives), the processes have no dead time. In [22] and [23], a parallel cascade control architecture is employed, and the regulator has a Smith predictor structure to compensate for the dead time, thus making the overall control architecture more complex than the classic one used for industrial processes.

It appears that a procedure for designing a fractional cascade control system to be applied in general is still missing. In this paper, we propose a design methodology for a classic cascade control structure with FOPID controllers. The parameters of the inner controller are determined by applying a tuning rule that minimizes the integrated absolute error (IAE) in the load disturbance step response while constraining the maximum sensitivity. Then, the dynamics of inner closed-loop system in series with the primary part of the process (that is, the process seen by the primary controller) is estimated as a fractional-first-order-plus-dead-time (FFOPDT) transfer function. This is a key step of the procedure as a FFOPDT transfer function is capable of modeling systems with both overdamped and underdamped responses, thus making the approach general. Finally, the primary controller is tuned by first selecting the fractional derivative action in order to cancel the fractional pole of the FFOPDT system and then selecting the remaining parameters to maximize the gain crossover frequency (*i.e.*, the closed-loop bandwidth) of the system subject to a constraint on the maximum sensitivity. The main contribution of this paper can be summarized as follows.

- A unified tuning method that allows us to design a cascade control system irrespective of the dynamics of the series of the closed-loop secondary process and the primary process.
- A method that does not require a closed-form model of the process.
- A method that allows the designer to maximize the closed-loop bandwidth subject to explicit constraints on the robustness of the closed-loop system.

The paper is organized as follows. The control architecture is presented in Section II. The tuning procedure is explained in Section III. Illustrative simulation examples are given in Section IV before the conclusions in Section V.

II. CONTROL ARCHITECTURE

We consider the two-loop cascade control scheme in Figure 1, where the process $P(s) = P_2(s)P_1(s)$ is split into two parts thanks to the measurement of the secondary variable y_2. The secondary controller C_2 and the primary controller C_1 are FOPID controllers in series form; that is, their transfer functions are

$$C_2(s) = K_{p2}\frac{T_{i2}s^{\lambda_2}+1}{T_{i2}s^{\lambda_2}}\frac{T_{d2}s^{\mu_2}+1}{\frac{T_{d2}}{N_2}s+1}, \tag{1}$$

$$C_1(s) = K_{p1}\frac{T_{i1}s^{\lambda_1}+1}{T_{i1}s^{\lambda_1}}\frac{T_{d1}s^{\mu_1}+1}{\frac{1}{20\omega_{gc}}s^2+\frac{\sqrt{2}}{20\omega_{gc}}s+1}, \tag{2}$$

where K_{p1} and K_{p2} are the proportional gains, T_{i1} and T_{i2} are the integral time constants, T_{d1} and T_{d2} are the derivative time constants, λ_1 and λ_2 are the fractional orders of the integral actions, and μ_1 and μ_2 are the fractional orders of the derivative actions. The secondary controller has a first-order filter (whose time constant depends on the parameter N) while the primary controller has a second-order filter (in order to improve the system robustness) whose bandwidth depends on the parameter ω_{gc}. Note that this filter, by construction, has a damping ratio of $\frac{1}{\sqrt{2}}$, which guarantees the fastest transition at the filter cut-off frequency. Finally, in order to improve the performance of the set-point following task, a set-point weight β can be conveniently employed for the primary controller, thus exploiting a two-degree-of-freedom structure [1], [24].

Note that a FOPID controller is a generalization of a PID controller. Indeed, if the fractional orders of the integral and derivative actions are set to one, a (filtered) PID controller in series form is obtained.

The control problem consists of determining all the controller parameters in order to compensate for load disturbances d and to track changes in the set-point signal r. In particular, the transient of process output y is evaluated when either a load step disturbance or a set-point step signal occurs.

III. DESIGN METHODOLOGY

The design methodology consists of two subsequent steps. Initially, the inner FOPID controller is tuned based on the transfer function $P_2(s)$ and mainly considering the load disturbance rejection performance (whose improvement is the reason for using a cascade rather than a single-loop control scheme). Then, the primary controller parameters are determined to achieve a satisfactory set-point step response while ensuring that the load disturbance rejection performance is preserved.

A. TUNING OF THE SECONDARY CONTROLLER

The tuning of the secondary FOPID controller $C_2(s)$ is performed by identifying the (possibly unknown) dynamics of $P_2(s)$ with a FOPDT transfer function

$$P_2(s) = \frac{K_2}{T_2s+1}e^{-\theta_2 s}, \tag{3}$$

where K_2 is the gain, T_2 is the time constant and θ_2 is the dead time. It is worth stressing that the process model (3) is capable of representing effectively the dynamics of many industrial plants, and it can be determined through well-established identification methodologies, for example, based on the open-loop step response [1]. Then, we exploit the tuning rules presented in [13], which minimize the integrated absolute error, defined as

$$IAE = \int_0^\infty |e(t)|dt \tag{4}$$

for the load disturbance rejection, where $e(t)$ is the control error when a step signal is applied to the load disturbance

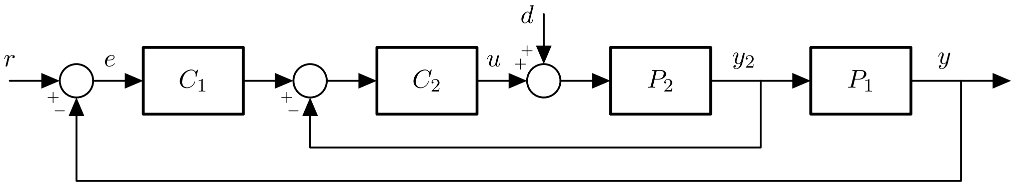

FIGURE 1. The considered cascade control scheme.

input d and the reference r is zero. The IAE is minimized by constraining the maximum sensitivity of the inner loop, defined as

$$M_{s2} = \max_{\omega\in[0,+\infty)} \left|\frac{1}{1+C_2(s)P_2(s)}\right|, \tag{5}$$

to the value $M_{s2} = 2$. Note that the maximum sensitivity is the inverse of the minimum distance between the Nyquist plot of the open-loop system and the critical point, which provides a measure of the robustness of the closed-loop system. By denoting as

$$\tau_2 = \frac{\theta_2}{T_2+\theta_2} \tag{6}$$

the normalized dead time of the secondary process. The resulting tuning rules are

$$K_{p2} = \frac{1}{K_2}\left(0.1804\tau_2^{-1.449}+0.2319\right), \tag{7}$$

$$T_{i2} = T^{\lambda_2}\left(0.6426\left(\frac{\theta_2}{T_2}\right)^{0.8069}+0.05627\right), \tag{8}$$

$$T_{d2} = T^{\mu_2}\left(0.597\left(\frac{\theta_2}{T_2}\right)^{0.5568}-0.09536\right), \tag{9}$$

$$\lambda_2 = 1, \tag{10}$$

$$\mu_2 = \begin{cases} 1.0 & \text{if } \tau_2 < 0.2 \\ 1.1 & \text{if } 0.2 \le \tau_2 < 0.6 \\ 1.2 & \text{if } 0.6 \le \tau_2. \end{cases} \tag{11}$$

B. TUNING OF THE PRIMARY CONTROLLER

The tuning of the primary controller is performed by considering the transfer function of the inner loop in series with the primary process $P_1(s)$, that is,

$$F(s) := \frac{C_2(s)P_2(s)}{1+C_2(s)P_2(s)}P_1(s). \tag{12}$$

Depending on the process parameters and the resulting FOPID parameters of the inner controller $C_2(s)$, the system $F(s)$ can exhibit either overdamped or underdamped dynamics. In addition, an analytical expression for $F(s)$ is in general unknown because we do not have a closed-form expression for $P_1(s)$. For this reason, it is convenient to estimate $F(s)$ as a FFOPDT model

$$\tilde{F}(s) = \frac{\tilde{K}}{\tilde{T}s^{\alpha}+1}e^{-\tilde{\theta}s}, \tag{13}$$

where the parameters $\tilde{K}$, $\tilde{T}$, α and $\tilde{\theta}$ can be determined via an optimization method that minimizes the difference (in terms of integrated absolute error) between the open-loop step responses of $F(s)$ and $\tilde{F}(s)$ [25].

Once the parameters of the process seen by the primary controller have been estimated, the fractional derivative part can be tuned by applying a fractional pole-zero cancellation method, that is, by selecting

$$T_{d1} = \tilde{T} \tag{14}$$

and

$$\mu_1 = \alpha. \tag{15}$$

Then, as it has been shown that an integer integral action provides the best performance in terms of IAE, the value $\lambda_1 = 1$ is selected, and, the values of the proportional gain K_{p1} and of the integral time constant T_{i1} are determined by maximizing the gain crossover frequency ω_{gc} of $C_1(s)\tilde{F}(s)$, which provides an accurate estimate of the gain crossover frequency of the primary loop, while limiting the maximum sensitivity of the system

$$M_s := \max_{\omega}\left|\frac{1}{1+C_1(j\omega)\frac{C_2(s)P_2(s)}{1+C_2(s)P_2(s)}P_1(s)}\right| \tag{16}$$

below a selected threshold $\bar{M}_s$. Since the cut-off frequency of the filter in the primary controller depends on the gain crossover frequency, which is unknown beforehand, in this optimization problem, we consider a simplified version $\hat{C}_1(s)$ of the primary controller $C_1(s)$ that does not have the second-order filter, thereby avoiding an implicit problem. Since the filter cut-off frequency is, by construction, $20\omega_{gc}$, we note that for the optimization problem at hand, we can safely consider $\hat{C}_1(j\omega) \approx C_1(j\omega)$. Formally, the optimization problem to be solved is defined as

$$\max_{K_{p1},T_{i1}} \omega_{gc} \tag{17}$$

subject to

$$\left|\hat{C}_1(j\omega_{gc})\tilde{F}(j\omega_{gc})\right| = 1, \tag{18}$$

$$\max_{\omega}\left|\frac{1}{1+\hat{C}_1(j\omega)\tilde{F}(s)}\right| < \bar{M}_s, \tag{19}$$

where the maximum sensitivity is computed using the FFOPDT model of the series of the inner loop and the primary process. Typically, the value of the M_s should be in the range [1.4, 2] [26], where 2 is associated with an aggressive controller that performs well in the disturbance rejection but might exhibit large overshoots and oscillations in the set point tracking. Conversely, 1.4 yields a robust controller that might lack performance thereby delivering a sluggish response. The value $\bar{M}_s$ can be therefore selected by taking into account that the main task of the primary controller is to recover the set-point following performance, as the load disturbance is primarily compensated by the secondary controller. Additionally, it is necessary to provide adequate robustness to the overall control system. For this reason, we select a default value $\bar{M}_s = 1.6$ to obtain a robust tuning. Finally, to speed up the reference tracking, a set-point weight $\beta = 2$ is employed. We refer the reader to [24] for more details on the usage of this technique with FOPID controllers.

Note that the filter parameter ω_{gc} results directly from the optimization problem (17). It is worth stressing that using a second-order filter makes the overall transfer function $C_1(s)$ strictly proper, irrespective of the value of the derivative action, which can be larger than 1. This implies that there are neither proportional nor derivative kicks in the control variable when a step signal is applied to the set-point. In other words, the control effort is limited, which is highly desirable from a practical point of view. In addition, thanks to the steeper high-frequency roll-off of the second-order filter, compared to standard first-order filters, we can push the filter cutoff frequency to $20\omega_{gc}$, thereby reducing the filter-induced phase delay around the gain crossover frequency.

IV. SIMULATION RESULTS

In order to prove the effectiveness of the proposed design methodology, we consider three different illustrative examples. In particular, the first example consists of a system where the slowest dynamics are in the primary process, the second example explores the opposite scenario, and the last example considers a high-order process comprising multiple poles. The FOPID controllers have been implemented as eight-order integer controllers by applying the well-known Oustaloup's approximation, which is based on a recursive distribution of poles and zeros [27].

For all the control systems, both a unit step load disturbance and a unit step set-point signal are applied. The control performance is evaluated by calculating the integrated absolute error. A comparison with the use of PID controllers is also provided. In this case, the transfer functions of the controllers are

$$C_2(s) = K_{p2}\frac{T_{i2}s+1}{T_{i2}s}\frac{T_{d2}s+1}{T_{f2}s+1}, \tag{20}$$

$$C_1(s) = K_{p1}\frac{T_{i1}s+1}{T_{i1}s}\frac{T_{d1}s+1}{T_{f1}s+1}. \tag{21}$$

A. EXAMPLE 1

As a first illustrative example, we consider the following process:

$$P_2(s) = \frac{1}{0.1s+1}e^{-0.05s}, \tag{22}$$

$$P_1(s) = \frac{1}{2.71s+1}e^{-1.2s}. \tag{23}$$

By applying the tuning rules (7)-(11) we obtain $K_{p2} = 1.118$, $T_{i2} = 0.0424$, $T_{d2} = 0.0247$, $\lambda_2 = 1$, $\mu_2 = 1.1$. The parameters of the transfer function $\tilde{F}(s)$ are then estimated as $\tilde{K} = 1$, $\tilde{T} = 2.718$, $\alpha = 1$, $\tilde{\theta} = 1.232$. The step responses of $F(s)$ and $\tilde{F}(s)$ are shown in Figure 2, where it appears that the two transients are virtually overlapped, and the inner closed-loop system is actually of integer order. The primary controller is then tuned by first setting $T_{d1} = \tilde{T} = 2.718$, $\mu_1 = \alpha = 1$, $\lambda_1 = 1$ and then by solving the optimization problem (17)-(19) (with $\bar{M}_s = 1.6$) that yields $K_{p1} = 0.30$ and $T_{i1} = 0.70$ (the resulting gain crossover frequency is $\omega_{gc} = 0.45$). The set-point weight is set as $\beta = 2$. The load disturbance and set-point step responses are shown in Figures 3 and 4, respectively. They are compared with those achieved by using two PID controllers tuned with an IMC-based method [8], obtaining $K_{p2} = 0.357$, $T_{i2} = 0.025$, $T_{d2} = 0.1$, $T_{f2} = 0.0071$, $K_{p1} = 1.0840$, $T_{i1} = 2.71$, $T_{d1} = 0.02$, $T_{f1} = 0.002$, from which the resulting value of the maximum sensitivity is also $M_s = 1.6$. Note that the control variable is plotted with a different time scale with respect to the process variable in order to highlight the initial part of the transient, which is the most interesting. The performance improvement obtained with the FOPID controllers in the load disturbance rejection task is clearly observable in Figure 3, and it is confirmed by the values of the integrated absolute errors, which are $IAE = 0.033$ for the FOPID scheme and $IAE = 0.070$ for the PID scheme. Regarding the set-point step response, we have $IAE = 2.12$ for the FOPID scheme and $IAE = 2.72$ for the PID scheme. It appears that the performance in the rejection of the load disturbance in the fractional-order system is significantly better than that of the integer-order one. Additionally, the set-point response obtained with the FOPID controllers is also improved with a shorter rise time and less overshoot, despite the maximum amplitude of the control variable being much smaller compared to the PID one, thanks to the second-order filter that removes proportional and derivative kicks.

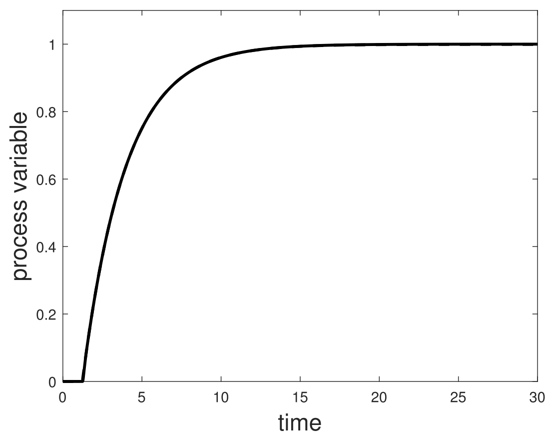

FIGURE 2. Step responses of $F(s)$ (solid line) and $\tilde{F}(s)$ (dashed line) for Example 1. Note that the two responses are overlapped.

B. EXAMPLE 2

As a second illustrative example, we consider the following process:

$$P_2(s) = \frac{1}{10s+1}e^{-8s}, \tag{24}$$

$$P_1(s) = \frac{1}{5s+1}e^{-2s}, \tag{25}$$

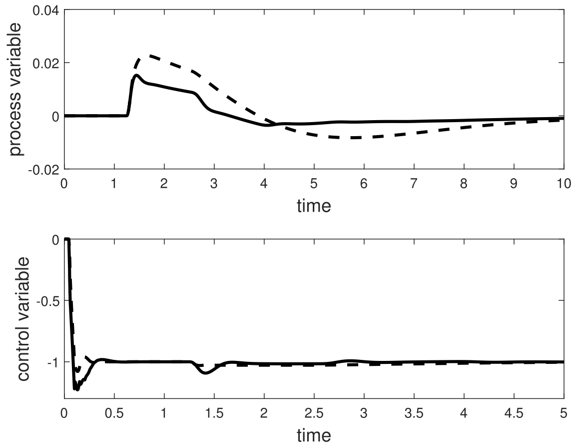

FIGURE 3. **Load disturbance step responses for the FOPID (solid line) and PID (dashed line) cascade control schemes for Example 1.**

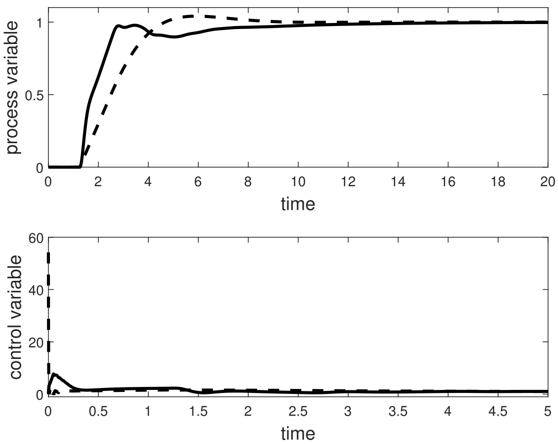

FIGURE 4. **Set-point step responses for the FOPID (solid line) and PID (dashed line) cascade control schemes for Example 1.**

where the slowest dynamics are in the secondary process (i.e., before the inner-loop feedback sensor). The tuning rules for the secondary controller yield $K_{p2} = 0.816$, $T_{i2} = 5.93$, $T_{d2} = 5.44$, $\lambda_2 = 1$, $\mu_2 = 1.1$. This results in underdamped dynamics of the closed-loop system F, which yields an estimated FFOPDT transfer function equal to

$$\tilde{F}(s) = \frac{1}{8.31s^{1.247} + 1} e^{-11.61s}. \quad (26)$$

Note that the fractional order α is greater than 1, as expected because of the overshoot in the step response. The step responses of $F(s)$ and $\tilde{F}(s)$ are shown in Figure 5, where the ability of FFOPDT systems to model underdamped systems effectively appears. Based on these values, the parameters of the derivative part of the primary FOPID controller are determined as $T_{d1} = 8.31$, $\mu_1 = 1.247$. After setting $\lambda_1 = 1$, the optimization problem (17)-(19) (with $\bar{M}_s = 1.6$) results in $K_{p1} = 0.245$ and $T_{i1} = 5.50$ (with $\omega_{gc} = 0.047$). Also in this case, the performance achieved by using the FOPID controllers is compared with that obtained by using PID controllers (tuned again as in [8]) with $K_{p2} = 0.4$, $T_{i2} = 4$, $T_{d2} = 10$, $T_{f2} = 0.8$, $K_{p1} = 0.25$, $T_{i1} = 5$, $T_{d1} = 2$, $T_{f1} = 0.2$ (the resulting value of M_s is 1.64).

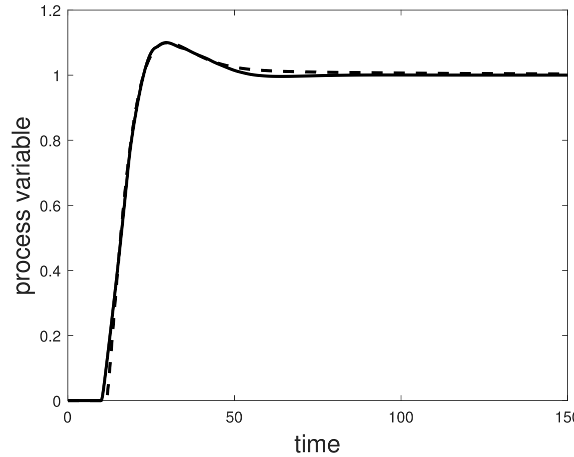

FIGURE 5. **Step responses of $F(s)$ (solid line) and $\tilde{F}(s)$ (dashed line) for Example 2.**

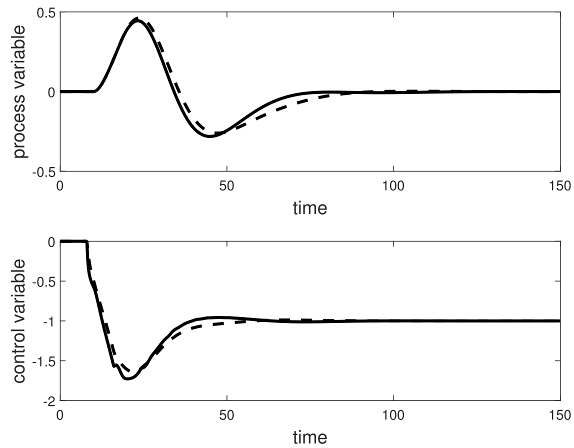

FIGURE 6. **Load disturbance step responses for the FOPID (solid line) and PID (dashed line) cascade control schemes for Example 2.**

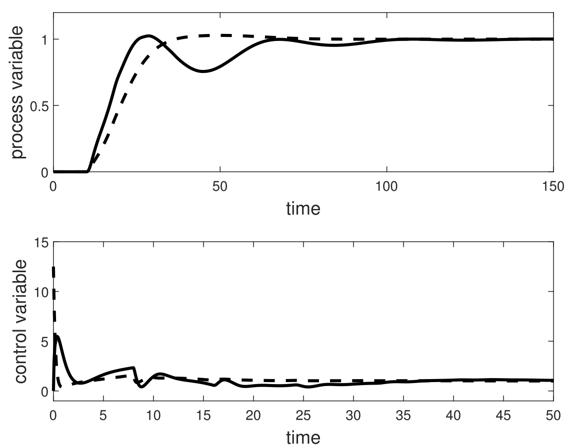

FIGURE 7. **Set-point step responses for the FOPID (solid line) and PID (dashed line) cascade control schemes for Example 2.**

The load disturbance step responses are shown in Figure 6, while the set-point step responses are plotted in Figure 7 (in this latter case, the time scale for the control variable has been again reduced to highlight the transient part). The resulting values of the integrated absolute errors for the load disturbance rejection task are $IAE = 12.0$ for the FOPID scheme and $IAE = 13.4$ for the PID scheme. Regarding the set-point step response, we have $IAE = 18.4$ for the FOPID scheme (with $\beta = 2$) and $IAE = 21.5$ for the PID scheme. The performance is improved for both the load disturbance and set-point step responses.

This example shows that the devised design method is general as it can be used disregarding the dynamics of the primary and secondary process (that is, where the secondary sensor is placed) and that the use of FOPID controllers provides an improvement of the performance with respect to PID controllers, thanks to the additional controller parameters.

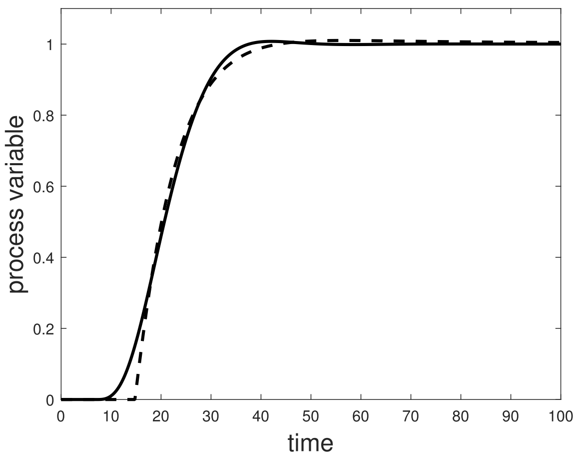

FIGURE 8. Step responses of $F(s)$ (solid line) and $\tilde{F}(s)$ (dashed line) for Example 3.

C. EXAMPLE 3

As a third illustrative example, we consider a high-order process

$$P_2(s) = \frac{1}{8s+1}e^{-5s}, \tag{27}$$

$$P_1(s) = \frac{1}{(5s+1)^3}e^{-2s}. \tag{28}$$

In this case the tuning of the inner controller results in $K_{p2} = 0.952$, $T_{i2} = 3.968$, $T_{d2} = 3.587$, $\lambda_2 = 1$, $\mu_2 = 1.1$. The step response of the series of the inner loop and of the primary part of the process is plotted in Figure 8, together with the step response of the estimated FFOPDT model, which is

$$\tilde{F}(s) = \frac{1}{8.33s^{1.047}+1}e^{-14.76s}. \tag{29}$$

The application of the fractional pole-zero cancellation and of the optimization procedure yields the following parameters for the primary FOPID controller: $T_{d1} = 8.33$, $\mu_1 = 1.047$, $\lambda_1 = 1$, $K_{p1} = 0.26$, $T_{i1} = 6.90$ ($\omega_{gc} = 0.04$). The obtained load disturbance and set-point step responses are plotted in Figures 9 and 10. Once again, they are compared with those obtained with PID controllers tuned by applying an IMC technique [8] after a FOPDT model has been determined for $P_1(s)$ with $K_1 = 1$, $T_1 = 12.21$ and $\theta_1 = 6.027$. We have $K_{p2} = 0.379$, $T_{i2} = 2.5$, $T_{d2} = 8$, $T_{f2} = 0.606$, $K_{p1} = 0.55$, $T_{i1} = 12.21$, $T_{d1} = 1.6$, $T_{f1} = 0.16$ (the obtained maximum sensitivity is $M_s = 1.83$). The resulting values of the integrated absolute error for the load disturbance step response are $IAE = 6.81$ with the FOPID controllers and $IAE = 8.97$ with the PID controllers. Regarding the set-point step response, we have $IAE = 27.4$ with the FOPID controllers and $IAE = 25.4$ with the PID controllers. Thus, a large relative improvement in the load disturbance rejection performance is achieved with a marginal decrement in the set-point following performance. Note that our method does not require a model for $P_1(s)$, which is advantageous because, in general, it might be difficult to apply an input to $P_1(s)$ in order to estimate its dynamics.

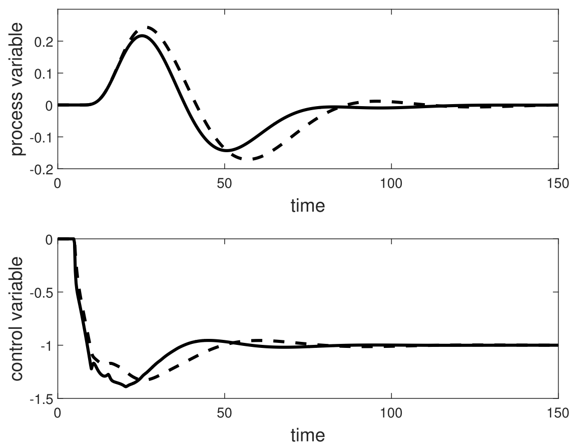

FIGURE 9. Load disturbance step responses for the FOPID (solid line) and PID (dashed line) cascade control schemes for Example 3.

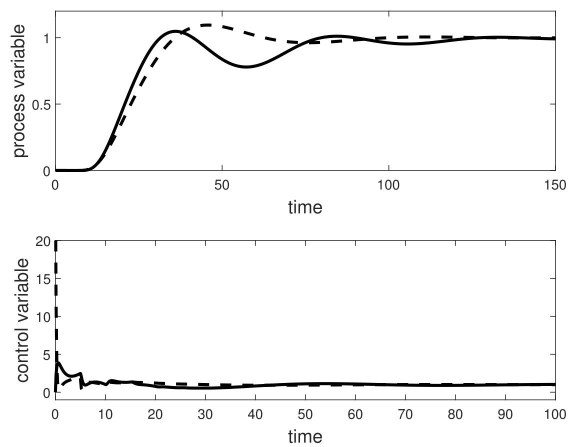

FIGURE 10. Set-point step responses for the FOPID (solid line) and PID (dashed line) cascade control schemes for Example 3.

V. CONCLUSION

In this paper, we have presented a design methodology for FOPID cascade process control systems. The methodology is general in that it can be applied to any (self-regulating) dynamics of the secondary and primary process parts. A key role is played by the use of a FFOPDT transfer function for the series of the inner loop and of the primary process. Differently from an integer FOPDT model, a FFOPDT system can accurately model systems with either overdamped or underdamped dynamics while maintaining the same model structure and lend itself to designing the derivative part of the primary controller through fractional pole-zero cancellation. The presented simulation results have demonstrated that a significant improvement in the load disturbance rejection performance can be obtained while also improving on the set-point following performance. A limitation of the proposed approach is that it can only be applied using FOPID controllers, which are yet to be fully accepted in the industry due to the perceived difficulty of implementing them using standard off-the-shelf hardware. Future work will focus on extending the method to integral and unstable processes and studying the sensitivity to parameter uncertainty, such as inaccurate delay estimation.

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