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First-order Dead-time Compensation with Feedforward Action

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***Abstract*— This work proposes a dead-time compensator (DTC) with feedforward action for first-order plus dead-time processes (FOPDT) with measurable disturbance. The proposed controller structure is based on both feedforward Smith Predictor and the Simplified Dead-time Compensator (SDTC). Simulation results compared with other recent literature propositions show the effectiveness of the proposed controller.**

I. Introduction

In many industrial applications, as well as in several other fields, processes may present dead-time, or transport delay, which is mainly due to transfer of energy, mass or information [1]. Moreover, non-minimal phase and slow dynamics may also be modeled as dead-time. This phenomenon can often cause poor set-point tracking, poor regulatory functions, oscillatory behavior of process output and even instability [2]. This problem can be overcome by using a Dead-Time Compensator (DTC) [1].

DTCs are control algorithms that handle the aforementioned dead-time systems. Initially proposed in 1957, the Smith Predictor (SP) [3] was introduced as an improvement over classical proportional–integral (PI) and proportional–integral–derivative (PID) controllers for time-delayed systems. Tuning rules involved the computation of PID gains for the delay-free plant while an internal time-delayed system model is implemented for the dead-time compensation. The SP, however, cannot cope with either unstable or integrative systems, and presents issues concerning robustness and disturbance rejection performance.

In the last years, several variations of the classic SP have been proposed to overcome those drawbacks. A vast review of these solutions can be found in [1], where the Filtered Smith Predictor (FSP) is highlighted. The control structure introduces a filter that can be tuned to increase the robustness and disturbance rejection performance of the traditional SP. As an evolution of the FSP, the work in [4] presents simplified tuning rules for the FSP, which is called simplified FSP (SFSP). Tuning procedure consists in pole placement of the reference tracking dynamics, performed by the primary controller, and plant pole cancellation performed by the robustness filter. The aforementioned works are mainly focused on solutions for first order plus dead-time (FOPDT) and second order plus dead-time (SOPDT) systems, which are commonly found on industrial processes [5], [6], [7]. In [8], a simplified DTC (SDTC) structure able to deal with multiple-delay single-input single-output (SISO) systems was presented, while the work in [9] presented the tuning of DTCs based on models commonly found in industry.

A recent work [10] proposes simple tuning rules for the SDTC allowing it to cope with stable, unstable and integrative processes. In addition, when compared with previous propositions, the presented results were better or equivalent for disturbance rejection, closed-loop robustness and noise attenuation characteristics. Nevertheless, the problem with processes with measuring disturbances was not considered. In this case, purely feedback controllers may not be efficient. Therefore, a feedforward compensation structure may be necessary to complement the feedback action due to its ability to compensate the disturbance in an enhanced manner [11], [12].

Some works already proposed improvements in the disturbance rejection of model-based control structures by including a feedforward action. In [13], the author proposes the addition of a feedforward compensation to the Generalized Predictive Control (GPC), which is made in a natural way in predictive controllers. The work in [14] proposes analysis and design for the FSP considering measurable disturbances. As expected, the feedforward action is able to improve the performance of the aforementioned controllers.

This paper proposes a DTC control structure for FOPDT processes with measurable disturbances. The proposition consists in modifying the SDTC structure by adding a feedforward control action. Simulations were performed to compare the proposition with both the feedforward FSP and the traditional SDTC.

Next section presents a review of the SDTC. The proposed feedworward DTC structure is detailed in Section III. Comparative simulation is shown in Section IV. Finally, Section V presents conclusion remarks and discuss about future works.

II. The Simplified Dead-Time Compensator

This section presents a brief review of the SDTC. The SDTC control structure is shown in Figure 1, where $P_n(z) = G_n(z)z^{-d_n}$ is the nominal process, $P_q(z) = G_q(z)z^{-d_q}$ is related to the disturbance $q(k)$ to system

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output $y(k)$, $G_n(z)$ and $G_q(z)$ are the nominal fast models of $P_n(z)$ and $P_q(z)$, d_n and d_q are the nominal dead-times of $P_n(z)$ and $P_q(z)$, and P represents the real process.

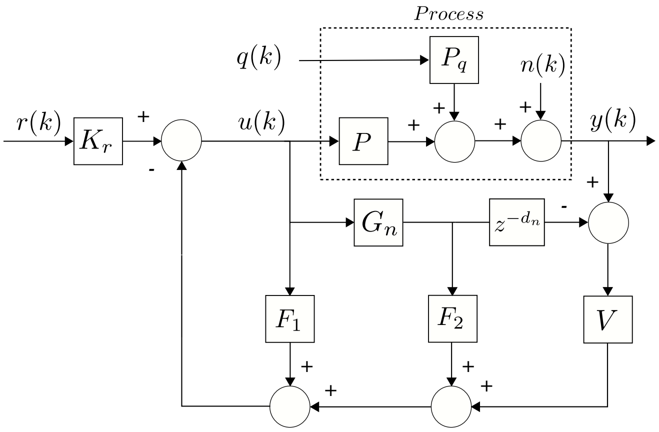

Fig. 1. SDTC conceptual structure.

The input-output relations for the nominal case are given by

$$H_{yr}(z) = \frac{Y(z)}{R(z)} = \frac{K_r P_n(z)}{1 + F_1(z) + G_n(z)F_2(z)}, \qquad (1)$$

$$H_{yq}(z) = \frac{Y(z)}{Q(z)} = P_q(z)\left[1 - \frac{P_n(z)V(z)}{1 + F_1(z) + G_n(z)F_2(z)}\right], \qquad (2)$$

$$H_{un}(z) = \frac{U(z)}{N(z)} = \frac{-V(z)}{1 + F_1(z) + G_n(z)F_2(z)}, \qquad (3)$$

where $Y(z)$, $U(z)$, $R(z)$, $Q(z)$, and $N(z)$ are the z-transforms of the output $y(k)$, control signal $u(k)$, reference $r(k)$, measurable input disturbance $q(k)$, and measurement noise $n(k)$ respectively.

From Eqs. (1) to (3) it is possible to notice that the K_r, $F_1(z)$ and $F_2(z)$ can be adjusted in order to obtain a desired set-point tracking, whereas the filter $V(z)$ can be used to reach a desired disturbance rejection and noise attenuation responses.

$F_1(z)$ and $F_2(z)$ are FIR filters defined as

$$F_1(z) = f_{1_1} z^{-1} + ... + f_{1_{n-1}} z^{-n+1},$$
$$F_2(z) = f_{2_0} + f_{2_1} z^{-1} + ... + f_{2_{n-1}} z^{-n+1},$$

where n is the order of $G_n(z)$, and filters $F_1(z)$ and $F_2(z)$ are calculated in such a way that the characteristic equation of Eq. (1) has the poles accordingly with a desired set-point tracking.

In order to avoid steady state error, the gain K_r is calculated by taking $H_{yr}(z) = 1$ for $z \to 1$. Therefore

$$K_r = \frac{1 + F_1(1) + G_n(1)F_2(1)}{P_n(1)}.$$

The robustness filter $V(z)$ was defined in [10] as

$$V(z) = \frac{v_0 + v_1 z^{-1} + \cdots + v_n z^{-n}}{(1 - \beta_1 z^{-1})(1 - \beta_2 z^{-1}) \ldots (1 - \beta_m z^{-1})},$$

where $m = n + 1$ and $\beta_1 \ldots \beta_m$ are the tuning parameter to setup both disturbance rejection and noise attenuation performances. The coefficients $v_0 \ldots v_n$ are calculated in order to guarantee disturbance rejection and to cancel the undesired poles of $P_q(z)$ in Eq. (2). More details on the tuning of the SDTC parameters and further information regarding the choice of $\beta_1 \ldots \beta_m$ by balancing response time performance and high frequency noise attenuation can be seen in [10].

III. Proposed Feedforward Structure

This section presents a modification of the SDTC for the case that the disturbance $q(k)$ is mensurable. The proposed control structure with feedforward action, namely SDTC-FF, is illustrated in Figure 2 and is valid for FOPDT processes. This structure adds the model of the measurable disturbance ($P_q(z) = G_q(z)z^{-d_q}$), with $G_q(z) = N_q(z)/D_q(z)$, along with filter $F(z)$ for disturbance rejection.

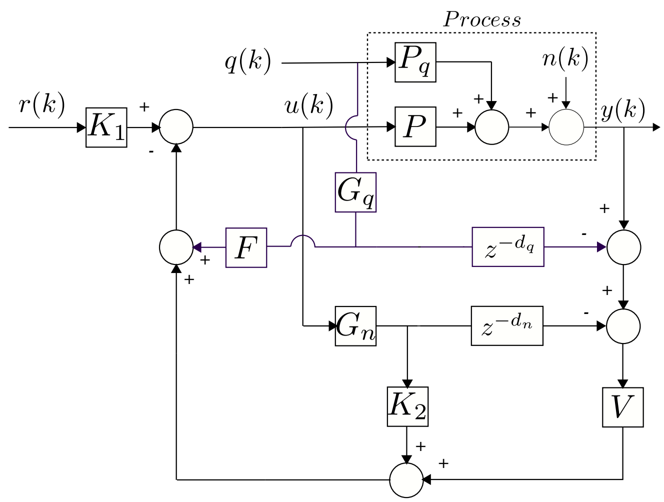

Fig. 2. Proposed SDTC structure with the feedforward compensation for FOPDT processes.

The input-output transfer functions for the proposed structure when $P(z) = P_n(z)$ are

$$H_{yr}(z) = \frac{Y(z)}{R(z)} = \frac{K_1 P_n(z)}{1 + K_2(z)G_n(z)}, \qquad (4)$$

$$H_{yq}(z) = \frac{Y(z)}{Q(z)} = P_q(z) - \frac{F(z)G_q(z)P_n(z)}{1 + K_2(z)G_n(z)}, \qquad (5)$$

$$H_{un}(z) = \frac{U(z)}{N(z)} = \frac{-V(z)}{1 + K_2(z)G_n(z)}, \qquad (6)$$

$$I_{\mathrm{r}}(\omega) = \left| \frac{1 + V(z)G_n(z)}{G_{\mathrm{n}}(z)V} \right|_{z=e^{j\omega T_s}} > \overline{\delta P}(e^{j\omega T_s}), \qquad (7)$$

where $Y(z)$, $U(z)$, $R(z)$, $Q(z)$, and $N(z)$ are the z-transforms of the process output, control signal, output reference, measurable input disturbance, and measurement noise respectively; $I_r(\omega)$ is defined as robustness index, T_s is the sampling time (with $0 < \omega < \pi/T_s$) and $\overline{\delta P}(e^{j\omega T_s})$ is the upper bound of the multiplicative uncertainty norm.

In this structure K_1, K_2 are gains calculated to adjust the set-point tracking response (see Eq. (4)). From Eq. (5) the filter $F(z)$ is tuned in order to guarantee disturbance rejection, whilst from Eq. (7) $V(z)$ is designed to achieve a desired robustness.

A. Tuning of K_1 and K_2

By inspection of Eq. (4), one notices that gains K_1 and K_2 can be tuned in order to obtain a desired set-point tracking response. This can be done in a two step fashion.

Firstly, K_2 is computed by using pole allocation of Eq. (4). For a desired closed-loop pole p_c and considering $G_n = K_p/(z - p_1)$, K_2 is given by

$$K_2 = (p_1 - p_c)/K_p. \tag{8}$$

Then, K_1 is calculated to guarantee zero steady-state error, thus

$$K_1 = \frac{1 + K_2 G_n(1)}{P_n(1)}. \tag{9}$$

B. Tuning of $F(z)$

From Eq. (5), one observes that $F(z)$ must be defined in order to adjust the system response to disturbance $q(k)$. This work proposes the following first-order filter

$$F(z) = \frac{N_f(z)}{D_f(z)} = \frac{f_0 + f_1 z^{-1}}{1 - \alpha z^{-1}} \tag{10}$$

where f_0 and f_1 are computed to: (i) guarantee rejection of step-like disturbances; (ii) cancel the effect of pole of the disturbance process model $P_q(z)$. The parameter α is tuned by the user to achieve a desired disturbance rejection characteristic (faster or slower).

Equation (5) can be rewritten as

$$H_{yq}(z) = P_q(z) - F(z)G_q(z)M(z), \tag{11}$$

where

$$M(z) = \frac{N_m(z)}{D_m(z)} = \frac{N_g(z)}{D_g(z) + K_2 N_g(z)} = \frac{K_p}{1 - p_1 z^{-1}},$$

with $G_n(z) = N_g(z)/D_g(z)$. Further development of Eq. (11) leads to

$$H_{yq}(z) = \frac{D_f(z)D_m(z)N_q(z)z^{-d_q} - N_f(z)N_q(z)N_g(z)z^{-d_n}}{D_f(z)D_q(z)D_m(z)}. \tag{12}$$

Equation (12) illustrates the fact that the poles of $H_{yq}(z)$ are composed by the poles of $P_q(z)$, $H_{yr}(z)$ and $F(z)$. This illustrates the importance of achieving objective (ii), leaving only user adjustment poles p_1 and α as the poles of $H_{yq}(z)$.

Then, in order to achieve both objectives (i) and (ii), the following condition must be obeyed

$$\left[H_{yq}(z) = 0\right]_{z=1, z=p_q}, \tag{13}$$

where p_q is the pole of the process $P_q(z)$ to be cancelled. Finally, Eq. (13) leads to the following condition

$$\left[f_0 + f_1 z^{-1} = \tfrac{D_f(z)z^{-d_q}}{M(z)}\right]_{z=1, z=p_q}, \tag{14}$$

which is used to generate a set of two linear equations for the computation of the filter coefficients f_0 and f_1.

C. Tuning of $V(z)$

In order to understand the tuning of $V(z)$, it is necessary to obtain the two-degree-of-freedom (2DOF) equivalent structure of the SDTC-FF, which is shown in Figure 3, where

$$C_{eq}(z) = \frac{V(z)}{1 + G_n(z)\left(K_2 - V(z)z^{-d}\right)}, \tag{15}$$

$$F_{eq}(z) = \frac{K_1}{V(z)}, \tag{16}$$

$$S_q(z) = \frac{G_q(z)\left(F(z) - V(z)z^{-d_q}\right)}{1 + G_n(z)\left(K_2 - V(z)z^{-d}\right)}, \tag{17}$$

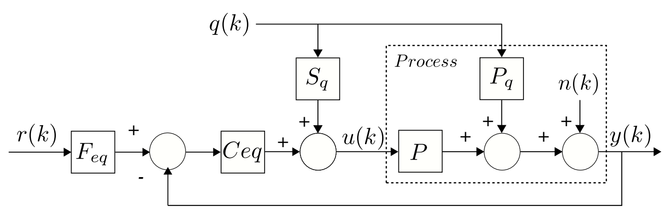

Fig. 3. Two-degree-of-freedom (2DOF) equivalent structure.

Note that to guarantee that the SDTC-FF is able to reject persistent input disturbances even when modelling uncertainties are present, $C_{eq}(z)$ must have at least one pole at $z = 1$. As it can be seen, $V(z)$ is the only left parameter to adjust both $C_{eq}(z)$ and $I_r(\omega)$ (Eq. (7)). Therefore, $V(z)$ should be defined aiming to attend to two design parameters: (iii) to achieve a desired robustness level in $I_r(\omega)$ (Eq. (7)); (iv) to guarantee integral action in $C_{eq}(z)$. Thus, the following first-order filter is defined to meet such goals

$$V(z) = \frac{K_v}{1 - \beta z^{-1}}.$$

Initially, user tuning parameter $0 < \beta < 1$ is set to attend to objective (iii). Note that $V(z)$ appears in the denominator of $I_r(\omega)$, which means that higher values of β yield enhanced robustness.

Then, in order to achieve objective (iv) one can check that K_v must be computed with

$$K_v = (1 - \beta)K_1. \tag{18}$$

D. Implementation structure

It is well known that dead-time compensators need an implementation structure which avoids problems of internal instability. Therefore, for the case of unstable and integrative processes, the conceptual structure can not be directly used. Figure 4 shows the implementation structure of the SDTC-FF, where

$$S(z) = G_n(z)K_2(z) - V(z)P_n(z), \tag{19}$$
$$S_q(z) = G_q(z)F(z) - P_q(z)V(z). \tag{20}$$

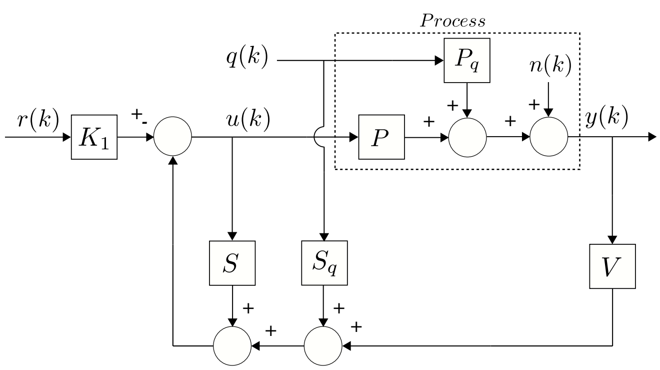

Fig. 4. Implementation Structure.

In the case of integrative or unstable open-loop processes, the robustness filter $V(z)$ can be defined as

$$V(z) = \frac{v_0 + v_1 z^{-1} + v_2 z^{-2}}{(1 - \beta z^{-1})^3}, \tag{21}$$

where coefficients v_0, v_1 and v_2 are calculated to: (a) guarantee integral action in $C_{eq}(z)$; (b) cancel the pole of $P_q(z)$ in $S_q(z)$; (c) cancel the pole of $P_n(z)$ in $S(z)$. These three conditions form a set of three linear equations for the computation of v_0, v_1 and v_2, making the SDTC-FF useful for stable, integrative and unstable FOPDT processes. Note that β is the tuning parameter of Eq. (21), and can be tuned to achieve a desired robustness, as explained in Subsection III-C.

IV. Simulation Results

A. Steam pressure process

In order to evaluate the performance of the proposed strategy the steam pressure process in the boiler no. 2 at Abbott Power Plant in Champaign, IL [15] has been used. This work considers the particular case presented in [14], in which the control objective is to maintain the steam pressure at a desired point while manipulating the fuel rate, despite the steam demand, while the other inputs and outputs are assumed constants [14]. The boiler models were linearized as

$$P(s) = \frac{0.355}{24.75s + 1} e^{-6.75s}, \tag{22}$$
$$P_q(s) = \frac{-0.712}{195.8s + 1}. \tag{23}$$

Models were discretized using Zero-Order Hold (ZOH) and sampling time $T_s = 0.1\ s$, yielding systems

$$P(z) = \frac{0.001431}{z - 0.996} z^{-68}, \tag{24}$$
$$P_q(z) = \frac{-0.0003635}{z - 0.9995}. \tag{25}$$

For this example, the proposed SDTC-FF controller is compared with the SDTC presented in Section II, and the strategy from [14].

By following tuning rules presented in Subsection III-A, one computes gain K_2 and K_1 so that the desired closed-loop pole for set-point tracking performance is $p_c = 0.8$. Computed gains are given by

$$K_2 = 136.9, K_1 = 139.71.$$

Feedforward compensation filter $F(z)$ is computed so that disturbance is rejected at steady state regime and pole of $P_q(z)$ is canceled as described in Subsection III-B. Furthermore, the filter tuning parameter is adjusted with $\alpha = 0.95$ to provide faster disturbance rejection than [14]. Then, by using Eqs. (13) and (14) one gets

$$F(z) = \frac{635.4 - 628.4z^{-1}}{1 - 0.95z^{-1}} \tag{26}$$

For filter $V(z)$, rule from Eq. (18) is applied, with $\beta = 0.99$, yielding

$$V(z) = \frac{1.397}{1 - 0.99z^{-1}}. \tag{27}$$

It is important to highlight that disturbance rejection and robustness tuning are clearly separated in the proposed strategy. Thus, while $\alpha = 0.95$ was chosen to provide fast enough disturbance rejection, the $\beta = 0.99$ parameter was chosen to provide good robustness against model uncertainties.

The SDTC controller from [10] is tuned with $F_1(z) = 0$, $F_2(z) = 136.9$ which gives the same $H_{yr}(z)$ of the SDTC-FF controller. However, in the SDTC strategy filter $V(z)$ is responsible for both robustness and disturbance rejection characteristics, and needs to be tuned in order to obtain a desired trade-off between these two goals. Therefore, for the SDTC controller, filter $V(z)$ is tuned with $\beta_1 = \beta_2 = 0.98$, yielding

$$V(z) = \frac{9.27 - 9.214z^{-1}}{(1 - 0.98z^{-1})^2}. \tag{28}$$

Proposed controller robustness is tested by increasing dead-time of the real process by 10%. For this test, the controller from [14] is defined as therein. Figure 5 shows the output and control signals as a disturbance of 30% enters the system at time $t = 10$ s. Moreover, measurement noise is added as a white noise with zero mean and variance $\sigma = 5 \times 10^{-5}$ throughout the simulation.

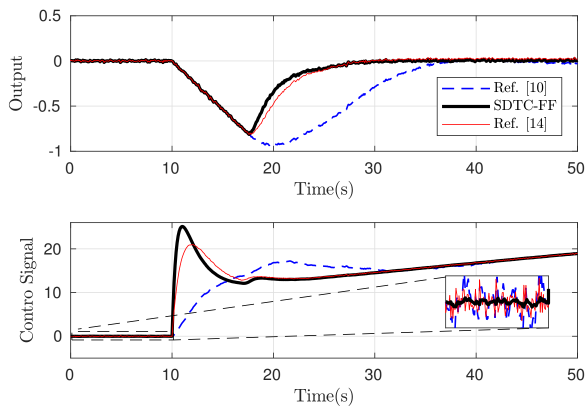

Fig. 5. Simulation results with zero initial conditions.

Observe that both controllers with feedforward compensation exhibit much better response when compared to the pure feedback controller SDTC. This behavior is expected as the disturbance signal is immediately detected and compensated as a result of the inclusion of feedforward blocks $G_q(z)$ and $F(z)$. Also note that the proposed SDTC-FF controllers exhibits the best response among the tested strategies.

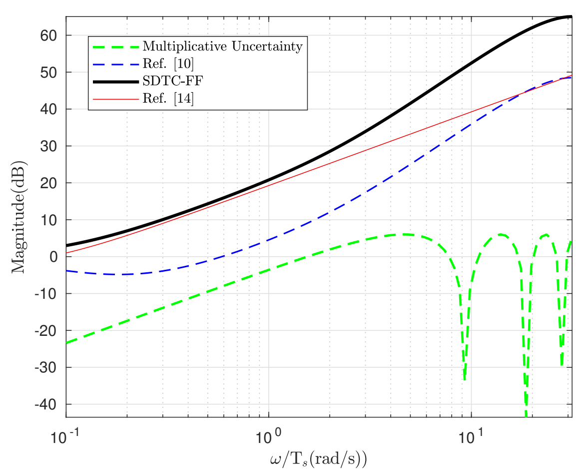

Fig. 6. Multiplicative uncertainty for +10% dead-time error and robustness index for all controllers.

Furthermore, from Figure 6 note that the SDTC-FF controller presents increased robustness indexes compared to the pure feedback controller SDTC and the feedforward controller from [14]. In the traditional feedback SDTC, robustness filter $V(z)$ appear in both $H_{yq}(z)$ and $I_r(\omega)$, meaning that a trade-off between robustness and time response has to be accordingly handled. The proposed feedforward strategy poses no such problem as the tuning strategy involving aforementioned transfer functions may be performed independently. Thus, filter $V(z)$ can be tuned concerning robustness index and noise attenuation alone.

B. Brushless DC motor

Brushless DC motors (BLDCM) are widely used in several applications, such as in aerial drones [16]. This kind of application demands robustness against many uncertainties due to model parameter estimation errors, measurement noise and also possible software or network induced time delays.

Consider the benchmark model from [17] for speed control of an industrial BLDCM drive system, the motor parameters of the experiment realized in [18], and a software addition of 50 ms measurement time delay. Then, the following second-order plus dead-time (SOPDT) system is obtained

$$P(s) = \frac{12825 \times 10^3}{(s + 2414)(s + 14.62)} e^{-0.05s}, \tag{29}$$

$$P_q(s) = \frac{-800(s + 2429)}{(s + 2414)(s + 14.62)}. \tag{30}$$

It is important to highlight that although the disturbance signal in BLDCM models are usually considered to be unknown, in this example we consider the hypothetical case that such a measure is available for simulation analysis only. To apply the strategy proposed in this paper, the following discrete-time FOPDT models approximation of (29) and (30) were obtained with sampling time of $T_s = 0.01\ s$

$$P(z) = \frac{49.41}{z - 0.864} z^{-5}, \tag{31}$$

$$P_q(z) = \frac{-7.486}{z - 0.864}. \tag{32}$$

Once more, comparison against the recently proposed SDTC strategy is performed. In order to evaluate the controller performance and robustness, measurement noise is added as a white noise with zero mean and variance $\sigma = 5 \times 10^{-2}$ throughout the simulation. Also, (29), (30) are used as the controlled system in the simulation.

For the proposed SDTC-FF, primary gains are tuned with

$$K_2 = 0.001295, K_1 = 0.004047,$$

while feedforward compensation filter $F(z)$ is adjusted with $\alpha = 0.95$ to provide fast disturbance rejection, obtaining

$$F(z) = \frac{0.002134 - 0.001891z^{-1}}{1 - 0.94z^{-1}}. \tag{33}$$

Filter $V(z)$ is tuned with $\beta = 0.9$, yielding

$$V(z) = \frac{0.0004047}{1 - 0.9z^{-1}}. \quad (34)$$

The SDTC controller from [10] is tuned to achieve same $H_{yr}(z)$ of the SDTC-FF controller, while its robustness filter $V(z)$ is tuned with $\beta_1 = \beta_2 = 0.94$, yielding

$$V(z) = \frac{(7.647 - 6.19z^{-1}) \times 10^{-5}}{(1 - 0.94z^{-1})^2}. \quad (35)$$

Figure 7 shows the results for a step change in the reference at time $t = 0$ s. Also, a constant disturbance of magnitude 0.5 is applied from $t = 1$ s to the rest of simulation. As expected, the SDTC-FF controller was able to completely reject the disturbance in a much smaller time. Furthermore, both controller showed good robustness characteristics as the performance was not affected by the FOPDT model approximation.

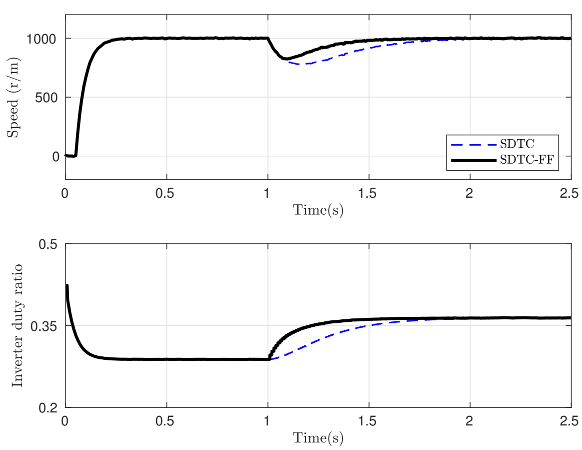

Fig. 7. Simulation results for BLDCM example.

V. Conclusions

In this work, a predictive feedforward controller has been designed and analyzed. The traditional feedback SDTC control structure was used as framework for the feedforward compensation design. Although the proposed strategy is focused on FOPDT systems with measurable disturbance, it can also be applied for SOPDT systems which can be approximated by a first-order model.

Results have shown that the proposed feedforward controller proved to be superior to traditional feedback controllers regarding both disturbance rejection and measurement noise attenuation. The proposed strategy has also shown better results than the recent FSP feedforward structure from [14].

Future work will account for higher order systems for either the system and feedforward plants. Since traditional SDTC may already be used for any plant order, derivation of feedforward tuning rules should be straightforward.

Acknowledgment

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