IFAC Workshop ICPS'07
2007, July 09-11
Cluj-Napoca, Romania

VIRTUAL REFERENCE FEEDBACK TUNING APPROACH TO FUZZY CONTROL SYSTEMS DEVELOPMENT

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Abstract: The paper proposes Takagi-Sugeno PI-fuzzy controllers (PI-FCs) dedicated to a class of integral plants. Two PI controllers are developed first by Virtual Reference Feedback Tuning to ensure the desired control system (CS) performance with respect to the reference input. Other two PI controllers are developed using the Extended Symmetrical Optimum method to ensure the desired maximum sensitivity equivalent to good CS performance with respect to the disturbance input. Then, accepting the approximate equivalence between the fuzzy controllers and the linear ones, a development method for the PI-FCs is suggested. Experimental results are included to illustrate the effectiveness of the development.

Keywords: servo systems, optimality, PI controllers, fuzzy control, speed control.

1. INTRODUCTION

Several plants being part of servo systems in power systems applications are characterized by second-order integral type mathematical models (MMs). The simplified MMs of these plants can be well approximated by the transfer function (t.f.) $P(s)$ that defines a class of integral plants seen as benchmark type systems (Åström and Hägglund, 2000):

$$P(s) = k_P / [s(1 + sT_\Sigma)] \ , \quad (1)$$

where k_P is the controlled plant gain and T_Σ is the small time constant / the sum of parasitic time constants. The use of PI controllers with the t.f. $C(s)$:

$$C(s) = k_c(1 + sT_i)/s = k_C[1 + 1/(sT_i)], \ k_C = T_i k_c , \quad (2)$$

where k_C is the controller gain and T_i is the integral time constant, can ensure acceptable control system (CS) performance indices when the controllers are tuned in terms of Kessler's Symmetrical Optimum method (Kessler, 1958a, 1958b).

A simple and efficient way to tune the PI controllers is the Extended Symmetrical Optimum (ESO) method (Preitl and Precup, 1999). The ESO method has a single design parameter β. The CS performance indices (σ_1 – overshoot, $\hat{t}_r = t_r / T_\Sigma$ – normalized rise time, $\hat{t}_s = t_s / T_\Sigma$ – normalized settling time with respect to *r*, φ_m – phase margin) can be modified according to designer's option by the choice of this parameter within the domain $1 < \beta < 20$ and a trade off to all indices can be reached using Fig. 1.

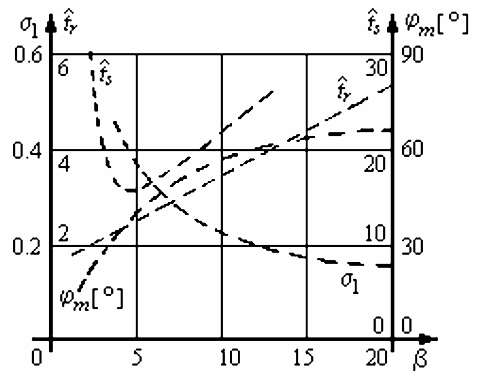

Fig. 1. Control system performance indices versus β.

The PI tuning conditions are:

$$k_C = 1/(\sqrt{\beta}T_\Sigma k_P),\ T_i = \beta T_\Sigma \ . \quad (3)$$

The CS performance indices can be improved by inserting the reference filter with the transfer function $F(s)$ to suppress the action of the zero in the closed-loop transfer function regarding the reference:

$$F(s) = 1/(1+\beta T_\Sigma s) \ . \quad (4)$$

This leads to the two-degree-of-freedom (2-DOF) CS structure (Araki and Taguchi, 2003) presented in Fig. 2, where r is the reference input, y the controlled output, e the control error, u the control signal, r_1 the output of block F, and d stands for the load disturbance input. The 2-DOF CS structure ensures both tracking and disturbance rejection.

CS specifications are expressed generally in terms of responses with respect to the reference and disturbance input, and robustness with respect to model uncertainties. For very good tracking one solution is to deal with the Iterative Feedback Tuning (IFT) approach. IFT is a gradient-based approach based on input-output data recorded from the closed-loop system (Hjalmarsson, *et al.*, 1994, 1998). The CS performance indices are specified by means of objective functions (o.f.s). Solving the optimization problems with such o.f.s usually requires the implementation of iterative gradient-based minimization. This is not a simple task because the o.f.s can be rather complicated functions of plant and eventually of disturbances dynamics. The key feature of IFT is in employing closed-loop experimental data to calculate the estimate of the gradient of the o.f. Several experiments are performed per iteration and the updated controller parameters are obtained based on the input-output data recorded from the closed-loop system.

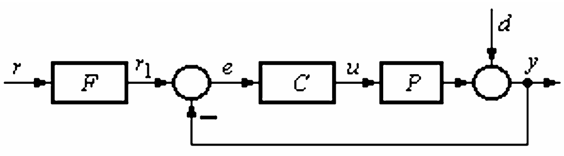

Fig. 2. Control system structure.

However, in order to avoid the iterative calculation of controller parameters the Virtual Reference Feedback Tuning (VFRT) approach has been proposed as version of one-shot direct data-based controller development method complementary to IFT (Campi, *et al.*, 2001, 2006; Lecchini, *et al.*, 2002). Its implementation is challenging in case of power plants applications by the information technologies involved. Since the reference model is fixed, this may lead to problems when dealing with complex plants. Therefore two linear PI controllers will be developed based on different reference models aiming small overshoot and settling time.

But, for very good disturbance rejection it is necessary that the maximum sensitivity M_s should be as small as possible. Since the sensitivity function $S(s)$ represents the closed-loop transfer function with respect to d (Ingimundarson and Hägglund, 2002) and this may be contrary to the desired CS behaviour with respect to r, there is a trade off to performance and robustness. Hence, it is very hard to fulfil all CS specifications simultaneously and a compromise is necessary. Concerning the disturbance input, other two linear PI controllers will be developed, aiming again small overshoot and settling time.

The necessity of fuzzy control for the given problem setting is in ensuring the CS performance enhancement in the conditions of low-cost implementation. Because under certain well-stated conditions the approximate equivalence between the fuzzy controllers and the linear ones is generally acknowledged (Galichet and Foulloy, 1995; Precup, *et al.*, 2007), there are developed first the four linear PI controllers by the ESO method (in combination with the VRFT in case of r and with imposed M_s regarded as design parameter in case of d). Then, the Takagi-Sugeno PI-fuzzy controllers (PI-FCs) are developed accepting the well-established property of Takagi-Sugeno fuzzy systems to be bumpless interpolators between linear controllers (Sala, *et al.*, 2005). In this case, the PI-FCs interpolate between the separately developed linear PI controllers.

The paper is organized as follows. In the next Section the development of PI controllers in the linear case is presented in relation with the VRFT and the necessity to ensure the maximum sensitivity in the frequency domain, M_s, connected to the ESO method. Then, in Section 3 the PI-FCs as extensions of the linear PI controllers together with their new development method are suggested. The 2-DOF CS structure presented in Fig. 2 is accepted, with the PI-FCs replacing the conventional controller for performance enhancement. Section 4 validates the theoretical approach by a case study regarding the speed control of a DC drive servo system with variable load and illustrates experimental results in fuzzy control compared to the linear case results. Finally, Section 5 is focused on conclusions.