Research Results in Fuzzy Controllers with Dynamics

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1 Introduction

The "classical" engineering approach to the reality is essentially a qualitative and quantitative one, based on a more or less "accurate" mathematical modeling. In this context the elaboration of the control strategy and of the control equipment requires an "as accurate as possible" quantitative modeling of controlled plant (CP). The advanced control strategies require even the permanent reassessment of the models and of the parameters values characterizing these (parametric) models. Fuzzy control [1] is more pragmatic from this point of view by the capability to take over and to use a linguistic characterization of the quality of CP dynamics and to adapt it as function of the concrete conditions of CP operation.

The basic FCs with dynamics have a specific nonlinear behavior accompanied by anticipative, derivative, integral and – more general – predictive effects and even of adaptation to the concrete operating conditions. The "coloring" of the linguistic characterization of CP evolution – based on experience – will finally be done by parameters by which the features of the FCs can be modified. The paper presents some research results in the field of development of FCs with dynamics having a large spectrum of applications.

2 Typical Fuzzy Controllers with Dynamics

2.1 Pseudo-Continuous Mathematical Characterization

Basically the FCs are nonlinear controllers; the shape of the non-linearity can be modeled to a large variety of forms by the adequate choice of the variable parameters taking part to FC informational modules.

By additional dynamic processing of some of system variables (by differentiation and / or integration), the FC can “obtain” dynamic features. The effects of these components can be reflected: - in permanent regimes, by the rejection or, from one case to another, alleviation of the control error; - in dynamic regimes, by improving the phase margin (in generalized sense) / reducing the overshoot, and reducing the settling time, and / or improving (relaxing) the stability conditions.

The derivative (D) or the integral (I) components can be accomplished in both analog and digital version.

The digital versions of D and I components create a quasi-continuous (Q-C) equivalent of the analogue D and I components, respectively. There are several methods for the accomplishment of Q-C D and I components, several of them being presented as follows.

For the D component, the usual computation relation is:

$$d_k = \frac{1}{T_s} \cdot (e_k - e_{k-1}) \,, \quad k \in N^* \ (T_s – \text{sampling interval}). \tag{1}$$

If the input variable e(t) has very rapid variation which could be harmful on the accomplishment of the D component, then either e_k is pre-filtered in terms of a first order delay (PT1) law, or the D component is created on the basis of the actual sample e_k and an “old sample” e_{k-m}.

For the I component, a version of computation relation is:

$$\sigma_k = \sum_{i=0}^{k} e_i = e_k + \sum_{i=0}^{k-1} e_i \,, \quad \text{or} \quad \sigma_k = x_k + e_k \quad \text{with} \quad x_k = \sum_{i=0}^{k-1} e_i \,. \tag{2}$$

Such a characterization will also permit a relative Q-C equivalence of the digital case. By using the first order Pàde approximation, the two components with D and I dynamics can be expressed as:

$$d(s) \approx \frac{s}{1 + s \cdot T_s / 2} \cdot e(s) \,, \qquad \sigma(s) \approx \frac{1 + s \cdot T_s / 2}{s \cdot T_s} \cdot e(s) \,. \tag{3}$$

The relations (3) ensure a continuous pseudo-transfer function for the FC with dynamics.

There are widely used two versions of quasi-PI fuzzy controllers (PI-FCs), the position type and the velocity type. The position type PI-FC can be further accomplished in two versions obtaining the integral component on either the output or the input of the FC, respectively.

The first version of position type PI-FC is characterised by the accomplishment of the integral component on FC output. The basic relation of such an FC is:

$$u(t) = k_i \cdot \int_0^t \left[k_{F1} \cdot e(\tau) + k_d \cdot k_{F2} \cdot \dot{e}(\tau) \right] \cdot d\tau \,. \tag{4}$$

The relation (4) characterizes a typical dependence for a PI controller. By expressing (4) in its operational form, the Q-C equivalent of the PI-FC is obtained:

$$u(s) \approx k_i \cdot \frac{1 + s \cdot T_s / 2}{s \cdot T_s} \cdot \left(k_{F1} + k_{F2} \cdot k_d \cdot \frac{s}{1 + s \cdot T_s / 2} \right) \cdot e(s) \,. \tag{5}$$

Accordingly, the expression of the pseudo-transfer function can be then written as:

$$H_c(s) \approx \frac{k_c}{s} \cdot (1 + s \cdot T_i) \text{ with } k_c = \frac{k_i \cdot k_{F1}}{T_s} \,, \quad T_i = \frac{k_{F2}}{k_{F1}} \cdot k_d + \frac{T_s}{2} \,. \tag{6}$$

The second version of position type PI-FC is characterized by the accomplishment of the integral component on FC input. The basic relation of this controller structure is:

$$u(t) \approx k_{F1} \cdot k_p \cdot e(t) + k_{F2} \cdot k_i \cdot \int_0^t e(\tau) \cdot d\tau \,. \tag{7}$$

By expressing (7) explicitly in its operational form, the Q-C equivalent of the PI-FC in this version is immediately obtained:

$$u(s) \approx \left(k_{F1} \cdot k_p + k_{F2} \cdot k_i \cdot \frac{1 + s \cdot T_s / 2}{s \cdot T_s} \right) \cdot e(s) \,. \tag{8}$$

The dependence (8) leads to a PI type transfer function (6), with the parameters obtained by the identification of all coefficients:

$$k_c = \frac{k_{F2} \cdot k_i}{T_s} \,, \quad T_i = \left(\frac{1}{2} + \frac{k_{F1} \cdot k_p}{k_{F2} \cdot k_i} \right) \cdot T_s \,. \tag{9}$$

The incremental (velocity type) quasi-PI fuzzy controller can be accomplished by observing that differentiating (4) and using (1) will result in the form of:

$$\frac{u_k - u_{k-1}}{T_s} \approx k_i \cdot k_{F1} \cdot e_k + k_d \cdot k_{F2} \cdot \frac{e_k - e_{k-1}}{T_s} \,. \tag{10}$$

Then the discrete time equation of the incremental PI-FC becomes:

$$\Delta u_k = (k_i \cdot k_{F1} \cdot T_s + k_d \cdot k_{F2}) \cdot e_k - k_d \cdot k_{F2} \cdot e_{k-1} \,, \tag{11}$$

where $\Delta u_k = u_k - u_{k-1}$ is the increment of control signal.

By using the presented approach there can be developed versions of quasi-PD fuzzy controllers (PD-FCs) and of quasi-PID fuzzy controllers (PID-FCs) [1], [2]. By taking into account the very good control features of the linear PI controller: ensuring a zero steady-state control error required by the majority of applications, enhancement of CS dynamics (alleviation of the settling time and of the overshoot) by the effect of cancellation the large time constants of CP, the positive practical experience gained in implementing the linear PI controller, some versions of PI-FCs can be developed and will be presented in the sequel.

The usefulness of the FCs with dynamics with quasi-PI behavior is in the fact that they can be systematically developed, by starting from the features of a basic linear PI controller.

But, the arbitrary introduction of dynamic components in the FC structure creates a lot of difficulties mainly concerning the interpretation of introducing the dynamics in control system (CS) behavior in different regimes, and the increase of the number of the degrees of freedom in the development and implementation of the controller.

2.2 Fuzzy Controller Development and Discrete Implementation

For the standard PI-FC (Section 2.1) the integral effect can be introduced:

- on the output of the FC, the result being the standard version of the quasi-PI fuzzy controller with output integration (PI-FC-OI);
- on the input of the FC, the result being the standard version of the quasi-PI fuzzy controller with input integration (PI-FC-II).

The standard version of the quasi-PI fuzzy controller with integration of output / control signal (standard PI-FC-OI), Fig.1, is based on:

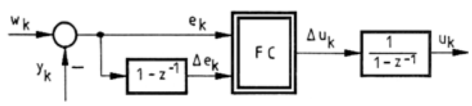

Fig.1. Block diagram of standard PI-FC-OI.

- the numerical differentiation of the control error e_k under the form of the increment of control error:

$$\Delta e_k = e_k - e_{k-1}, \quad k \in N^*; \tag{12}$$

- the numerical integration of the increment of control signal Δu_k.

The development and implementation of this controller starts with expressing the discrete equation of the PI quasi-continuous digital control algorithm (Q-C DCA) in its incremental (velocity type) version:

$$\Delta u_k = K_P \cdot \Delta e_k + K_I \cdot e_k = K_P \cdot (\Delta e_k + \alpha \cdot e_k) \ , \quad (13)$$

where the parameters $\{K_P, K_I, \alpha\}$ are functions of $\{k_C, T_i\}$:

$$H_c(s) = \frac{k_C}{s \cdot T_i} \cdot (1 + s \cdot T_i) \, , \; K_P = k_C \cdot \left(1 - \frac{T_s}{2 \cdot T_i}\right), K_I = \frac{k_C \cdot T_s}{T_i}, \alpha = \frac{K_I}{K_P} = \frac{2 \cdot T_s}{2 \cdot T_i - T_s} \, . \quad (14)$$

On the basis of the relation (14) and of the representation of Δu_k in the phase plane $< \Delta e, e_k >$, Fig.2, the pseudo-fuzzy features of the PI Q-C DCA in its incremental version can be highlighted:

– there exists a “zero control signal line” $\Delta u_k = 0$, having the equation:

$$\Delta e_k + \alpha \cdot e_k = 0 \ ; \quad (15)$$

– with regard to this line it is obtained that in the upper half-plane: $\Delta u_k > 0$, and in the lower half-plane: $\Delta u_k < 0$;

– the distance from any point of the phase plane to the “zero control signal line” corresponds to the absolute value of the increment of control signal $|\Delta u_k|$.

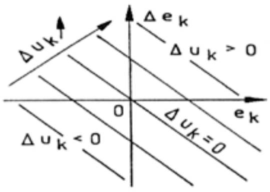

Fig.2. Phase plane representation corresponding to (13).

The fuzzification can be solved as follows: - for the input variables e_k, Δe_k: there are chosen 5 (or more, but an odd number) linguistic terms (LTs) with regularly distributed triangular type membership functions (m.f.s) having an overlap of 1; - for the output variable Δu_k there are chosen 7 LTs with regularly distributed singleton type m.f.s, Fig.3.

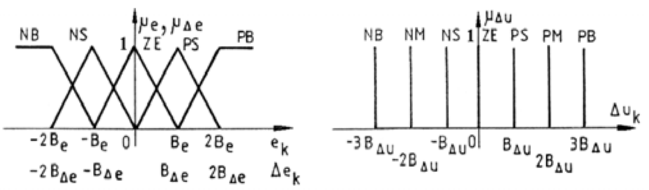

Fig.3. Shapes of m.f.s for standard PI-FC-OI.

The specific parameters of the standard PI-FC-OI are $\{B_e, B_{\Delta e}, B_{\Delta u}\}$, and these strictly positive parameters are in correlation with the shapes of the membership functions (m.f.s) of the LTs corresponding to the input and output linguistic variables (LVs). The complete rule base is expressed as decision table (Table 1).

Table 1. Decision table of standard PI-FC-OI.

Δe_k \ e_k	NB	NS	ZE	PS	PB
PB	ZE	PS	PM	PB	PB
PS	NS	ZE	PS	PM	PB
ZE	NM	NS	ZE	PS	PM
NS	NB	NM	NS	ZE	PS
NB	NB	NB	NM	NS	ZE

The main steps for tuning the parameters $\{B_e, B_{\Delta e}, B_{\Delta u}\}$ are [4]:

– the relation (16) is valid along the "zero control signal line":

$$\alpha = \frac{\Delta e_k}{e_k} = \frac{B_{\Delta e}}{B_e} ; \qquad (16)$$

– the following condition is fulfilled along the "constant control signal line", $\Delta u_k = B_{\Delta u}$:

$$B_{\Delta u} = \Delta u_k = K_P \cdot (\Delta e_k + \alpha \cdot e_k) = K_P \cdot B_{\Delta e} ; \qquad (17)$$

– the relation (24) results in:

$$B_{\Delta u} = K_P \cdot \alpha \cdot B_e = K_I \cdot B_e ; \qquad (18)$$

– based on his own experience, one of the parameters, for example B_e, is chosen, and the other two parameters, $B_{\Delta e}$ and $B_{\Delta u}$, result from (17) and (18).

It has to be pointed out that the parameters of the basic linear PI controller (14), k_C and T_i, are taken into consideration in $\{B_e, B_{\Delta e}, B_{\Delta u}\}$ by applying this method for tuning the FC parameters. The inference method and the defuzzification method choice represent the user's option.

The obtained control signal in its incremental form Δu_k can be further used in the CS: directly, if the actuator is of integral type / it contains pure integral component, or by computing the effective value of control signal according to:

$$u_k = u_{k-1} + \Delta u_k . \qquad (19)$$

Starting from the discrete equation of the PI Q-C DCA in its parallel version develops the standard PI-FC-II:

$$u_k = K_I \cdot e_{I\,k} + K_P \cdot e_k \text{ with } e_{I\,k} = e_{I\,k-1} + e_k , \qquad (20)$$

where e_{Ik} represents the integral of control error computed as the sum, K_I and K_P are expressed in (14).

By using (20), the ("position" type) control signal u_k can be re-written as:

$$u_k = K_P^* \cdot e_{Ik} + K_I^* \cdot e_k = K_P^* \cdot (e_{Ik} + \alpha^* \cdot e_k), \quad (21)$$

with the parameters K_P^*, K_I^* and α^* expressed as:

$$K_P^* = K_I = \frac{k_C \cdot T_s}{T_i}, \; K_I^* = K_P = k_C \cdot \left(1 - \frac{T_s}{2 \cdot T_i}\right), \quad \alpha^* = \frac{K_I^*}{K_P^*} = \frac{1}{\alpha} = \frac{2 \cdot T_i - T_s}{2 \cdot T_s}. \quad (22)$$

The structure of this FC is presented in Fig.4.

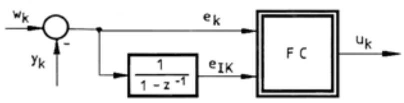

Fig.4. Block diagram of standard PI-FC-II.

The pseudo-fuzzy features pointed out before are also valid. The standard PI-FC-II is developed based on the analogy with the standard PI-FC-OI. This analogy consists in the fact that the remarks concerning the shapes of m.f.s, the decision table, the inference method and the defuzzification method are kept, with the following particular features: - the standard PI-FC-II has the input LVs e_k and e_{Ik} with the m.f.s μ_e (of parameter B_e) and μ_{eI} (of parameter B_{eI}), respectively; - the standard PI-FC-II has the ("position" type) control signal u_k as output LV. These particular features are updated when the rules as part of the rule base are defined.

The structures of standard PI-FCs can give satisfaction in a lot of applications (control of synchronous generators and of electrical driving systems) [3], [4], [5].

The existence of some particular features in the dynamics of the controlled plant could require modifications in the controller structure; these modifications can deal with: - modifications in the rule base, imposed by the effective behavior of the controlled plant caused by some special features (for example, the non-minimum phase character); - modifications in the fuzzification and defuzzification modules; it has to be correlated with the requirement concerning the modification of the operating point of the CP. For exemplifying this aspect, Fig.5 considers non-regularly distributed singleton type m.f.s for Δu_k (in the case of PI-FC-OI); the parameters m, n and p can be imposed by different reasons.

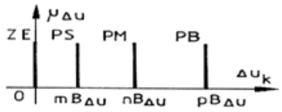

Fig.5. Non-regularly distributed output m.f.s.

By using the above presented approach to PI-FC development, there can be also developed special fuzzy controllers including: - variable structure quasi-PI fuzzy controllers [3], - controller structures with fuzzy adaptation strategy of the parameters of the standard PI-FC [6], [7], [8]; - conventional controllers with fuzzy adaptation of parameters [3], [9], [10], [11] successfully applied to several applications [12], [13], [14], [15]; - PID fuzzy predictive fuzzy controllers [16], [17] different to the well-known approaches to fuzzy predictive control [18], [19]. All these versions contribute to fuzzy control system performance enhancement.

The fuzzy controllers presented in these Sections are Mamdani ones and cen be considered as type II fuzzy systems in terms of [20], [21]). A similar development method for a Takagi-Sugeno PI fuzzy controller (TS-PI-FC, or type III fuzzy system [20], [21]) will be presented as follows.

3 Fuzzy Controller Applications for Electrical Drives

3.1 Development Methodology for a Takagi-Sugeno Fuzzy Controller with Dynamics

The specific feature of the development of Takagi-Sugeno fuzzy controllers with dynamics is in the fact that the consequent of the rule base contains expression of conventional control algorithms.

This Section deals with exemplifying the development of a TS-PI-FC with multiple additional functions and applying it to control of electrical drives with variable inertia. The fuzzy control system comprising a TS-PI-FC to be developed here – similarly to the Mamdani case – will be quasi-optimal in terms of quadratic performance indices defined in dynamic regimes with respect to the step modifications of the reference input (w) and of four types of disturbance inputs (v).

For the development of the TS-PI-FC it is necessary to discretize the continuous linear PI controllers of type (14). The use of Tustin’s method results in two incremental PI Q-C DCAs:

$$\Delta u_k = \Delta u_k^{w} = K_P^{w}\Delta e_k + K_I^{w} e_k\,,\ \ \Delta u_k = \Delta u_k^{v} = K_P^{v}\Delta e_k + K_I^{v} e_k\,, \qquad (23)$$

where the parameters of the two incremental digital PI controllers, $\{K_P^w, K_I^w\}$ and $\{K_P^v, K_I^v\}$, are computed in terms of (24):

$$K_P^{w} = k_c^{w}(T_i^{w} - T_s/2),\ K_I^{w} = k_c^{w}\,T_s,\ K_P^{v} = k_c^{v}(T_i^{v} - T_s/2),\ K_I^{v} = k_c^{v}\,T_s, \qquad (24)$$

and the fuzzy fuzzy control system (FCS) structure is a conventional one.

The structure of the proposed TS-PI-FC is presented in Fig.5, and it consists of: the strictly speaking PI-fuzzy controller (PI-FC), the additional fuzzy block FB1 for computing the current regime r_k, the fuzzy block FB2 for computing the current status s_k, and the linear blocks with dynamics.

All three blocks {PI-FC, FB1, FB2} are Takagi-Sugeno fuzzy systems [22], use the max and min operators in the inference engine and employ the weighted average method for defuzzification. The fuzzification is done by the m.f.s from Fig.6 ($\Delta w_k = w_k - w_{k-1}$ – increment of reference input) outlining the parameters of the TS-PI-FC to be determined by the development method: $\{B_e, B_{\Delta e}, B_{\Delta w}, B_s, B_w, B_v\}$.

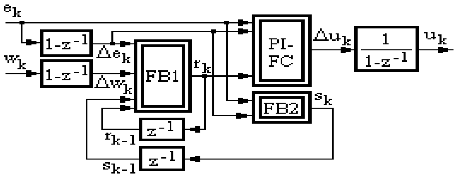

Fig.5. Structure of TS-PI-FC.

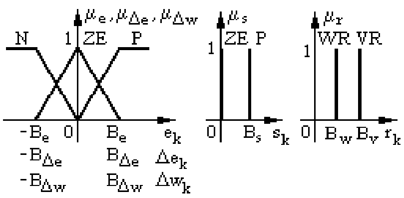

Fig.6. Accepted input membership functions.

The fuzzy block FB1 has the role of observing the dynamic regime by computing the variable r_k. The linguistic terms "WR" and "VR" correspond to the dynamic regimes caused by the modification of w (wr) and v (vr), respectively. The rule base presented in [23] assists the inference engine of FB1.

The fuzzy block FB2 that operates in parallel with PI-FC, computes the variable s_k characterizing the current status of the fuzzy control system. The linguistic term "ZE" corresponds to an accepted steady-state regime with almost zero e_k and Δe_k, and the linguistic term "P" corresponds to the situations when either e_k is non-zero or e_k is zero but it has the tendency to modify. A decision table shown in [23] expresses the rule base of FB2. Since FB1 and FB2 produce singleton consequents, these blocks can be considered as type I fuzzy systems according to [20], [21].

The inference engine of the strictly speaking PI-fuzzy controller (PI-FC) employs the rule base gathered in the decision table from Table 4. Such a decision table ensures a quasi-PI behavior of the PI-FC. An additional parameter α was introduced, $\alpha \in (0, 1]$, for the sake of FCS performance enhancement.

The fuzzy controller development becomes more complex due to the increased number of fuzzy blocks.

Concerning the computation of controller parameters, the easiest to choose are B_w and B_v, which have to be different in order to create a clear difference between the two regimes, wr and vr. This is achieved by choosing $B_w = 1$ and $B_v = 2$. The values of $B_{\Delta w}$ and B_s must be sufficiently small to clearly point out the constant values of w_k, and of e_k and Δe_k, respectively.

If a unit step modification of w and a 2% settling time is accepted the recommended values for these two parameters are $B_{\Delta w} = 0.02$ and $B_s = 0.02$. For the computation of B_e and $B_{\Delta e}$ there is applied the modal equivalences principle [24] resulting in:

$$B_{\Delta e}= 2T_s B_e/(2T_i^m - T_s)\,, \quad T_i^m = (T_i^w + T_i^v)/[(\beta^w + \beta^v)T_\Sigma]\,, \qquad (25)$$

where B_e is chosen in accordance with the experience of an expert in CSs. The relation (25) will ensure the approximate equivalence between the TS-PI-FC and the two linear PI controllers designed by optimizing the CS behavior with respect to w and four types of disturbance inputs defined in [23].

3.2 Application

Take the class of plants (P) having the transfer functions expressed as:

$$H_P(s)=k_P/[\, s(1+sT_\Sigma)] \ \text{(a)} \ \text{or} \ H_P(s)=k_P/[s(1+sT_1)(1+sT_\Sigma)] \ \text{(b)} \qquad (26)$$

$$H_P(s)=k_P/[(1+sT_\Sigma)(1+sT_1)] \ \text{(a) or } H_P(s)=k_P/[(1+sT_\Sigma)(1+sT_1)(1+sT_2)] \ \text{(b)} \quad (27)$$

(T_Σ – small time constant or time constant corresponding to the sum of parasitic time constants, $T_\Sigma < T_2 < T_1$) which characterize well enough many control applications with electrical drives considered as controlled plants.

The goal of the application is to develop a TS-PI-FC based on two methods for optimal tuning of controller parameters meant for controlling the low order benchmarks (26) and (27) with and without integral character. The classical development methods are the ESO method [25] and a modified form of it [26].

Focussing on the first case of the plants with the transfer functions of the forms (26) the use of a PI or PID controller tuned in terms of ESO method, can ensure very good CS performance [27].

In both cases, the open-loop t.f. and the closed-loop transfer function with respect to w have unique forms with the development parameter β chosen by the developer as a compromise between desired all control system performance.

The CS performance enhancement with respect to the reference input ensured by the TS-PI-FC in comparison with the PI controller is illustrated in Fig.7 when controlling the benchmark (26), with k_P=1 and T_Σ=1 sec, and the controller tuned by means of the previous presented recommendations. The FCS performance are guaranteed by the development.

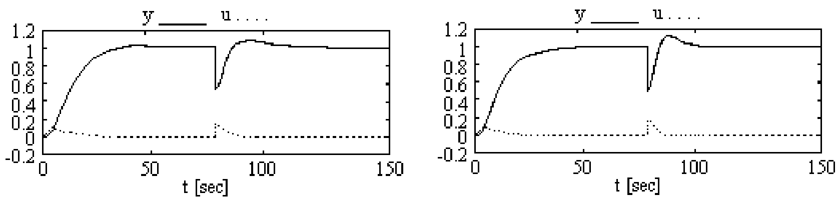

Fig.7. y and u versus time for PI controller and TS-PI-FC.

4 Conclusions

The paper presents analysis aspects and research results concerning the development of fuzzy controllers with dynamics.

The presentation is focussed on quasi-PI fuzzy controllers. The presented attractive approaches enable the development of other fuzzy controllers with dynamics including the quasi-PD and the quasi-PID ones. Some development recommendations to be directly used are offered.

The application illustrated in the paper can correspond to the speed control of a separately excited DC drive, and validates the presented development methods and controller structures for further use in electrical drives control.

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